Brachial Plexus Injuries

Edited by

Alain Gilbert MD
Institut de la Main
Paris, France

Published in association with the
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CONTENTS

List of contributors v

I THE BRACHIAL PLEXUS

1 Anatomy of the brachial plexus
Alexandre Muset i Lara, Carlos Dolz, and Alfonso Rodríguez-Baeza 3

2 Physical examination
Türker Özkan and Atakan Aydın 17

3 Radiological and related investigations
Albert (Bart) CJ Slooff, Corneleus (Cees) WM Versteege, Gerhard Blaauw, and Willem JR van Ouwerkerk 31

4 Clinical neurophysiological investigations
Jan W Vredeveld 39

II THE ADULT TRAUMATIC BRACHIAL PLEXUS

5 Etiology
Panupan Songcharoen 47

6 Surgical techniques: neurolysis, sutures, grafts, neurotizations
Michel Merle and Aymeric Lim 51

7 Supraclavicular plexus injuries
Jean Y Alnot 57

8 Complete palsy
Chantal Bonnard and Dimitri J Anastakis 67

9 Update on the treatment of adult brachial plexus injuries
Hanno Millesi 77

10 Injuries of the terminal branches of the brachial plexus
Rolfe Birch 91

11 The place of arthrodesis
Giorgio A Brunelli 107

12 Palliative surgery: tendon transfers to the shoulder in adults
Aydın Yücetürk 115

13 Palliative surgery: the elbow and forearm
Alfred C Berger, Robert Hierner, and Lutz Kleinschmidt 123

14 Palliative surgery: the hand
Jamal Gousheh 131

15 Palliative surgery: free muscle transfers
Kazuteru Doi 137

III OBSTETRICAL PARALYSIS

16 Aetiology
JM Hans Ubachs and Albert (Bart) CJ Slooff 151

17 Examination and prognosis
Howard M Clarke and Christine G Curtis 159

18 Conservative treatment of obstetrical brachial plexus palsy (OBPP) and rehabilitation
Robert S Muhlig, Gerhard Blaauw, Albert (Bart) CJ Slooff, Jan W Kortleve, and Alfons J Tonino 173

19 Surgical technique
Jose L Borrero 189

20 Indications and strategy
Alain Gilbert 205

21 Results of repair to the obstetrical plexus
Alain Gilbert 211

22 Results of surgery after breech delivery
Gerhard Blaauw, Albert (Bart) CJ Slooff, and Robert S Muhlig 217

23 Palliative surgery: shoulder paralysis
Piero L Raimondi, Alexandre Muset i Lara, and Elisabetta Saporiti 225

24 Palliative surgery: tendon transfers to the shoulder in children
Aydın Yücetürk 239

25 Medial rotation contracture and posterior dislocation of the shoulder
Rolfe Birch 249

26 Palliative surgery: elbow paralysis
Vincent R Hentz 261

27 Palliative surgery: pronosupination in obstetrical palsy
Eduardo A Zancolli (II) 275

28 Palliative surgery: forearm and hand deformities
David C-C Chuang 293

29 Treatment of co-contraction
Robert Hierner and Alfred C Berger 303

IV SPECIAL LESIONS

30 Traumatic brachial plexus injuries in children
Alain Gilbert and Christian Dumontier 315

31 War Injuries
Jamal Gousheh 321

Index 326

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The Brachial Plexus

1

Anatomy of the brachial plexus

Alexandre Muset i Lara, Carlos Dolz, and Alfonso Rodríguez-Baeza

Introduction

The brachial plexus, on account of the progressive unions and divisions of its constituent nerves, is a more or less complex nerve formation whose function is to innervate the muscles, articulations and tegument of the shoulder girdle and upper limb. In humans, the brachial plexus is formed from the anterior branches of the last four cervical nerves, and from the first thoracic nerve (Orts Llorca 1986). Additionally, it is irregularly supplied by the C4 or T2 anterior branches. Such supply determines the so-called plexus standards, pre- and post-fixed, respectively (Hovelacque 1927, Orts Llorca 1986, Williams 1998, Rouvière and Delmas 1999). Furthermore, it forms a union with the sympathetic cervical chain by means of communicating branches (Delmas and Laux 1933); it even forms a union with the paravertebral ganglia nodes of the second and third sympathetic thoracic chain by means of the Kuntz nerves (Orts Llorca 1986).

Topographically, the brachial plexus is located in the lower half of the neck's lateral region, above the cervical pleural, projecting itself via a retro-infraclavicular path towards the axillary cavity (Fig. 1).

Taken as a whole, the brachial plexus presents the morphology of two triangles connected by their vertices (Hovelacque 1927). The upper triangle has a medial side oriented towards the spine, a base that coincides with the upper thoracic aperture, and an oblique lateral side oriented downwards and outwards. The lower triangle, more irregular and mobile with arm movements (Lazorthes 1976), has a base coinciding with the emergence of the terminal branches of the brachial plexus.

The most usual constitutional pattern for the brachial plexus is through the formation of trunks and cords (Feneis 2000). That is, the union of the anterior branches of C5 and C6 forms the superior trunk. The union of the anterior branches of C8 and T1 forms the inferior trunk. The lower branch of C7, situated between these two trunks, forms the middle trunk. Each of the trunks subdivides into anterior and posterior branches. The posterior branches from the three trunks unite to form the posterior cord, thereby giving place to the axillary (circumflex) and radial nerves. The lateral cord will provide the starting point to the musculocutaneous nerve and to the upper component of the median nerve. The medial cord will provide the starting point to the lower component of the median nerve, the ulnar nerve and to the medial cutaneous nerves in the arm and forearm.

The suprascapular nerve, the posterior collateral branch of the superior trunk, is the most lateral branch within the supraclavicular segment of the brachial plexus, and its fibres have the

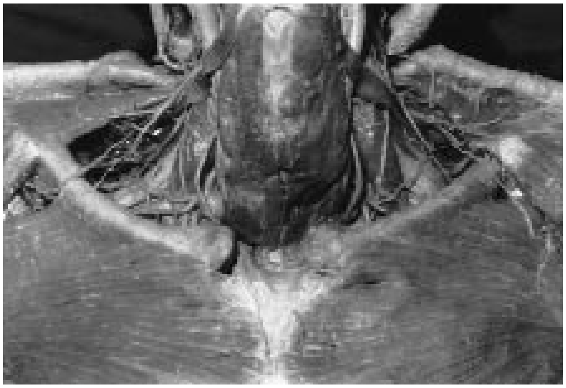

Figure 1

Ventral aspect of the brachial plexus.

function of innervating the supraspinatus and infraspinatus muscles. It can be observed that the infraclavicular part of the brachial plexus is divided into two planes between which the axillary artery is located. The dorsal plane is simple, and is formed by the posterior cord. The ventral plane is more complex, and is made up of the lateral and medial cords.

Although the brachial plexus is essentially directed downwards and outwards, the direction of the different elements of which it is formed varies significantly. Root C5 has a very oblique direction downwards and outwards, whilst T1 has an upward path. At the intervertebral foramen the C5 and C6 roots incline caudally on reaching the edge of the fissure of the spinal nerve made by the costo-transverse process of the corresponding cervical vertebrae. Root C7 illustrates a direction coinciding with the plexus axis. Roots C8 and T1 have an upward direction from the point of reflection realized in the pedicle of the vertebral arch and in the neck of the first rib, respectively. The trunks have an oblique path downwards and outwards that causes them to converge in the posterior edge of the clavicle. The angle of inclination is greater in the superior trunk, and diminishes progressively in the medial and inferior trunks. In the infraclavicular segment, their path is parallel, surrounding the axillary artery. Nevertheless, they are vertically inclined when the limb is in adduction and horizontally inclined upon undergoing an abduction of 90°.

Cervical supply to the brachial plexus

The brachial plexus' cranial limit depends upon the relationship established by roots C4 and C5 in the constitution of the superior trunk. Kerr (1918) suggested a three-group classification depending upon the cervical supply to the plexus.

In the first group, a branch proceeding from C4 anastomoses with C5, its size being highly variable, occasionally attaining diameters similar to the suprascapular nerve. Frequency for this has been established at 63 per cent.

In the second group, the anterior C5 branch does not receive anastomotic branches, combining with the anterior C6 branch in order to constitute the superior trunk. Frequency here is 30 per cent.

In the third group there is no C4 or C5 supply, but C5 contributes a nerve contingent to the cervical plexus. Frequency here is 7 per cent.

The supply of a significant nerve contingent by root C4 to the brachial plexus defines a prefixed plexus. In such cases, part of the scapular girdle's innervating, which in classical patterns is attributed to the anterior C5 branch, may proceed from C4. This fact implies a cranial displacement of all the functions and innervations of the upper limb, particularly when this supply coincides with the scarcity of the T1 nerve contingent supply. Nevertheless, this aspect was neither defined nor correlated in Kerr's work (1918).

The cervical supply implies a cranial displacement of the brachial plexus axis, this being one of the criteria used by certain researchers in order to define a plexus as prefixed. However, no compensation correlation has been established with respect to the presence of cervical and thoracic supply, it being impossible to classify the plexus as pre- or post-fixed in terms of the diameter of the nerves with which they are constituted. Clinical work on quantifying nerve contingents supplied by each one of the roots (Slingluff et al 1996) defines a plexus as prefixed when C5 supply is greater than 15 per cent, and when that of T1 is less than 13 per cent; a plexus is defined as post-fixed when C5 supplies a contingent of between 6.8 and 12 per cent, and T1 from between 13.4 and 24.4 per cent.

With respect to the intra-plexus distribution, Slingluff et al (1996) consider that for prefixed plexus the superior trunk contributes to the formation of the posterior fasciculus in more than 50 per cent, and to the innervating of the pectoral muscles in 75 per cent. The lateral fasciculus receives no root C8 supply and less than 7 per cent of the musculocutaneous nerve contingent comes from C7. These proportions are inverted in the post-fixed plexus, opening thereby a wide range of inter-individual possibilities and varieties in the plexus conformation.

Herzberg et al (1996) studied the radicular anastomoses between roots C4 and C5 on the basis of 20 dissections. These researchers observed that in five cases there was a branch from C4 to C5, in four cases a branch from C5 to C4, and in three of the cases there was no anastomosis.

Attention should also be focused on the relation between the phrenic nerve and the C4 and C5 roots. The origin in C4 frequently presents anastomosis with C5, its neurolysis always being possible in cases of very proximal resection for C5 as donor root in plexus injuries, without this causing any perceivable alteration in diaphragmatic function.

Anatomy of the foraminate region

Knowledge of the topography, relationship and distribution at a foraminate level of the spinal nerves as well as the path within the fissure from the transverse process of the cervical vertebrae is of fundamental practical interest to surgical repair of brachial plexus injuries. Access to the supraclavicular–extrascalenus region of the brachial plexus is undertaken via a lateral–cervical approach. Nevertheless, it is the inter- and pre-scalenus dissection that allows us to highlight the radicular segments that are useful as donors, and to identify the posterior branch for its intra-operational stimulation that will define for us, along with the remaining complementary explorations, the condition of the anterior branch and its validity to the procedure of microsurgical reconstruction.

The intervertebral foramen is a space defined by the imposition of two adjacent vertebrae. At the cervical level, it is determined by the following anatomical elements: cranially and caudally by the transverse process of the superior and inferior vertebrae, respectively; ventrally by unco-vertebral articulation and the inter-vertebral disk; dorsally by the upper articular process (Testut and Latarjet 1979).

The transverse process of the cervical vertebrae is projected ventro-laterally, taking its anterior starting point in the vertebral pedicle, and its posterior starting point in the osseous column oriented vertically, culminating on the superior and inferior levels in articular surface tracks. It presents two lateral bodies and a central canal or fissure through which the spinal nerve runs. In its path proximal to the spinal nerve, with its anterior and posterior branches, it relates posteriorly with articular processes and anteriorly with the vertebral vascular-nerve parcel running through the transverse foramen. Upon reaching the spinal nerve, the external margin of the articular process gives rise to the posterior branch dorsally surrounding the articular process in order to distribute itself in the posterior paravertebal musculature, in the tegument and in the articular capsule itself, providing a mixed sensory and motor innervation. The intra-operational stimulation of this branch offers valuable information regarding the functional state of the spinal nerve (Fig. 2).

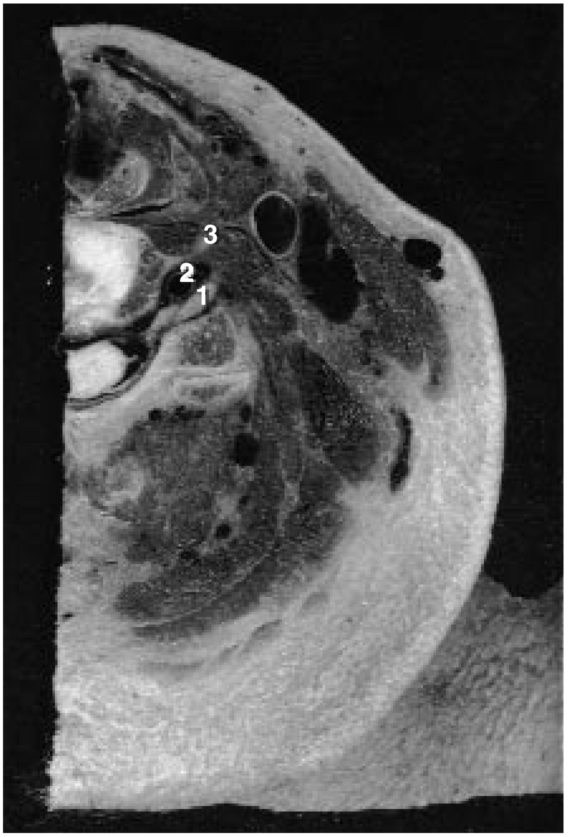

Figure 2

Anatomy of the intervertebral foramen. (1) Spinal nerve; (2) vertebral pedicle; (3) anterior tubercle of transverse process.

The anterior branch in the fissure is located between the anterior and posterior intra-transversal muscles. In this short path the nerve

Figure 3

Foraminal anatomy of C5 and C6 roots (posterior view). (1) Radiculo-medular artery; (2) transverse-radicular ligament; (3) posterior tubercle of transverse process.

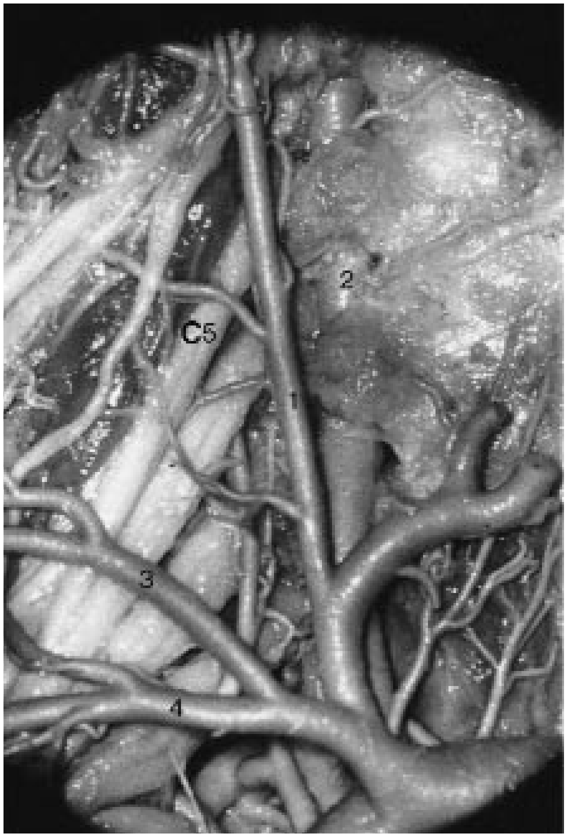

Figure 4

Arterial relationships of the brachial plexus. (1) Ascending cervical artery; (2) vertebral artery; (3) transverse cervical artery; (4) suprascapular artery.

receives the insertion of the transverse-radicular ligament, which originates in the superior transverse process and, through an oblique out-to-in/upward–downward path terminates by fusing itself with the epineuro of the subjacent spinal nerve's upper section (Fig. 3).

From the vascular point of view, the spinal nerves connect with the arteries whose function is the arterial irrigation of the spinal cord (Rodríguez-Baeza and Doménech-Mateu 1993). The radicular and radiculo-medullar arteries of the inferior cervical region are branches of the ascending cervical artery, of the costal–cervical trunk and of the vertebral artery. Supply intended for medullar vascularization reaches the foraminate space by means of an oblique upward and backward path, connecting with the spinal nerve at the front and with the inter-transverse muscle at the back (Fig. 4).

In the external margin of the transverse processes, the anterior branches of the spinal nerves connect with the points of origin for the scalenus muscles, so as to subsequently enter the inter-scalenus space (hiatus scalenicus), delimiting the anterior and middle scalenus muscle.

The foraminal anatomy from C4 to C7 facilitates the systemization of the radicular surgical approach, from distal to proximal, through the localization of the transverse process's posterior tubercle, the dis-insertion of the middle and posterior scalenus muscles, and the section of the posterior inter-transverse muscle. This procedure highlights the nerve path that runs from the inter-vertebral foramen to the inter-scalenus space without risk of injury to the arterial vertebra. Additionally, we can expose the posterior branch, approximately 10 mm of the C5 and C6 anterior branches and some 15 mm of the C7 anterior branch path. These paths are generally protected at this level by the transverse-radicular ligament. The relationship that the anterior C5 branch maintains with the phrenic nerve serves to distinguish it in a certain manner from C6 and C7. The proximal surgical dissection of C5 implies the dissection of anastomotic phrenic branches in their distinct varieties (commented on above). It is important, in this procedure, to bear in mind that the phrenic nerve receives its principal nerve contingent from C4, and therefore, when it requires a proximal resection of C5 in order to obtain correct proximal stump segment quality, it can be sacrificed without detriment to diaphragmatic function, on the condition that a correct neurolysis and neurotomy, exclusive to the anastomotic branch, be undertaken. This surgical action will facilitate both the radicular resection of C5 as well as its proximal dissection without risk of injury to the phrenic nerve.

The foraminate anatomy of roots C8 and T1 differ both in respect to their relationships and also with regard to the means of radiculo-vertebral union. At a vertebral level, the foramen presents distinct limits due to the morphological modification of the transverse process. In the thoracic vertebrae, the process is implanted within the vertical osseous column configuring the articular process, orienting itself in a posterior–lateral direction. In this way, the foramen is delimited cranially and caudally by the superior and inferior pedicle respectively, dorsally by the articular process and ventrally by the posterior–lateral margin of the superior vertebral body and by the inter-vertebral disk. Anterior relationships with the vertebral artery do not exist, and the relationship that C8 and T1 maintain in their immediately extra-foraminate path are established with the neck of the first and second ribs. The markedly upward direction of the anterior T1

Figure 5

Waldeyer's vertebral triangle. (1) Star-shaped node; (2) anterior scalenus muscle; (3) internal thoracic artery; (4) vertebral artery.

branch towards the inter-scalenus space brings about the relationship with the neck of the first rib. Unlike what happens at higher levels, there are no transverse–radicular ligaments here, thereby causing the considerable reduction of resistance to traction; for this reason, radicular avulsions are more frequent. In the pre-scalenus path, C8 and T1 are found in the Sébileau scalenus–vertebro-pleural space (Delmas and Laux 1933), this being an anatomical space delimited on the outside by the transverso-pleural ligament, on the inside by the vertebro-pleural ligament, on the underside by the posterior slope of the cervical pleura, and from behind by the posterior extremity of the first two ribs and the spine. Upon surrounding the neck of the first rib, T1 connects with the star-shaped node, and is crossed by the superior intercostal artery. It moves outwards between the fascicula of the costal–pleural ligament, becoming separated from the subclavian artery by the fibres of the transverso-pleural ligament in its insertion into the cervical pleura.

The cervical–thoracic or star-shaped node is the result of the union of the inferior cervical node with the first thoracic node. Its morphology is levelled, being irregularly rounded, star-shaped or in the form of a half-moon (Testut and Latarjet, 1979). Its length is approximately 8 mm and it can extend itself from the transverse process of the seventh cervical vertebra to the neck of the second rib. The intimate relationship that it maintains with the lower part of the brachial plexus justifies the appearance of a Claude–Bernard–Horner syndrome in proximal injuries of the inferior plexus roots (Fig. 5).

Anatomy of the scalenus region

In the supra-clavicular region of the brachial plexus neck's lateral region, there are connections with the scalenus muscles. These muscles form an irregularly triangular mass that extends from the transverse cervical processes to the first two ribs.

The anterior scalenus muscle originates in the anterior tubercles of the third to sixth cervical vertebrae. The four portions, tendinous in origin, unite in a fleshy body that, orienting itself downwards and outwards, terminates by inserting itself within the first rib's Lisfranc tubercle by means of a cone-shaped tendon. The middle scalenus muscle originates in the posterior tubercles of the last six cervical vertebrae, and terminates by inserting itself within the upper side of the first rib, behind the anterior scalenus. The posterior scalenus originates in the posterior tubercles of the fourth and sixth cervical vertebrae and terminates by inserting itself within the upper edge of the second rib.

The position of the scalenus muscles allows for delimiting a triangular space on the lower base, at the level of the first rib, known as the scalenus hiatus. The anterior margin is oblique, and the posterior is vertical, corresponding to the anterior and middle scalenus muscles respectively. Furthermore, the anterior scalenus muscle helps to delineate what is known as Waldeyer's vertebral triangle. The posterior scalenus muscle is separated from the middle muscle by an interstice in which we may locate the large thoracic nerve (Bell's nerve) (Figs 6 and 7).

Figure 6

Scalenic anatomy. (1) Phrenic nerve; (2) intermediate node; (3) scalenus anterior muscle; (4) subclavian artery; (5) first rib.

Figure 7

Intrascalenic anatomy. (1) Middle scalenus muscle; (2) Bell's nerve; (3) anterior scalenus muscle (dis-inserted).

There are multiple anatomical variations that may be observed in the scalenus muscles (Testut and Latarjet 1979), but, for our purposes, we shall only refer to those that directly affect relationships with the brachial plexus.

The muscle referred to as the middle (or intermediate) scalenus, is a supernumerary muscular fasciculus that extends among the transverse processes of the sixth or seventh cervical vertebrae up to the first rib, interposing itself amongst the brachial plexus and the subclavian artery in the scalenus hiatus. The so-called Albinus and transverso-pleural muscles may be considered as variations of the middle scalenus. The Albinus accessory muscle proceeds from the fourth, fifth and sixth cervical vertebrae, and reaches as far as the first rib, whilst the transverso-pleural muscle proceeds from the seventh cervical vertebra, reaching the cervical pleural.

The low original points for the anterior scalenus muscle leave the extra-foraminate C5 path exposed, illustrating, in these cases, a pre-scalenus topography. In proximal radicular injuries this consideration is important in order not to limit the proximal dissection to the inter-scalenus vertex, which may have an exclusive relationship with C6. In other cases, we have observed C5 paths through the anterior scalenus muscle.

Tendinous insertions in the first rib of the anterior and middle scalenus muscles may be in continuity via a fasciculus referred to as 'the scalenus' sickle'. This formation closes the scalenus hiatus, being a cause of compression for the subclavian artery and the lower part of the plexus; this mechanism may be accentuated when there are inter-scalenus muscular anomalies.

The anterior branches of the C3, C4, C5 and C6 nerves give out direct branches for the anterior scalenus muscle. The posterior and middle scalenus muscles receive branches from the C3, C4 and dorsal scapular nerves, this latter also being known as the rhomboid nerve.

Through the anterior scalenus muscle, the brachial plexus maintains relationships with anatomical structures that must be preserved in the anterio-lateral approaches of the inter-scalenus space. These structures are, in a down-up description, the subclavian vein, the subclavian muscle and the omohyoid muscle. The phrenic nerve and the ascending cervical artery are located vertically in the ventral surface of the muscle, whilst the transverse cervical and superior scapular arteries cross this face transversally. The inferior-medial part of the anterior scalenus muscle tendon connects with the cervical pleural and is ligament support system (a.k.a. Sébileau's).

In the surgical dissection of the plexus' inter-scalenus path, we need to bear in mind the presence of the inter-scalenus artery. Its origin generally lies in the subclavian artery, although on occasions it proceeds from the subscapular or costocervical arteries. Its distribution is by means of muscular branches for the scalenus muscles,

Figure 8

Anatomy of extrascalenus region.

and by means of radicular branches for the brachial plexus itself. Its muscular supplies are complemented by unnamed arterioles proceeding from the subclavian, dorsoscapular and costocervical arteries.

Anatomical studies of NMR anatomy correlation for the pre- and inter-scalenus spaces have allowed us to objectify the presence of fibromuscular structures interposed between the subclavian artery and the brachial plexus, as well as the presence of pre-scalenus roots. Nevertheless, regular clinical resolution does not define the ligament formations in the region of the thoracic inlet, obliging us therefore to review this surgically in approaches for compressive syndromes in the brachial plexus.

Anatomy of the extra-scalenus region

In the lateral region of the neck, we find the posterior cervical triangle, delimited caudally by the clavicle, medially by the sternocleidomastoid and anterior scalenus muscles, and laterally by the trapezius muscle. This triangular space, essentially clavicular, is subdivided by the presence of the omohyoidal muscle, the upper region being omotrapezoidal and the lower being omoclavicular or greater supraclavicular fossa (Fig. 8).

In order to accede to the plexus in this region, after incising the skin and the subcutaneous cellular tissue, the platysma colli muscle is exposed. This muscle is included in the division of the superficial cervical fascia, owing to which its deep face rests on the fascia itself.

The superficial cervical fascia originates in the anterior middle raphe of the neck from where it moves outwards in order to divide itself at the level of the sternocleidomastoid, and to form the muscle sheath. On its posterior edge, the two layers unite and the fascia covers the greater supraclavicular fossa only to divide once again on the medial edge of the trapezius muscle. This plane is separated from the medial cervical fascia by the Meckel's adipose mass, through which runs the external jugular vein (Testut and Latarjet 1979).

The medial cervical fascia (the pre-tracheal layer of the cervical fascia) runs between the two omohyoid muscles, reaching the semi-lunar notches. In the mid-line it reaches the posterior lip of the sternal notch. At the clavicular level, it inserts into its posterior edge, surrounding the subclavian muscle. The fascial expansion that extends between the subclavian muscles and the coronoid process continues with the fascia of the axillary cavity. Therefore, this fascia reaches the superior orifice of the thorax, the sternum, the clavicles, first ribs, pericardium and subclavian fascia. It connects, via its deep face, with the

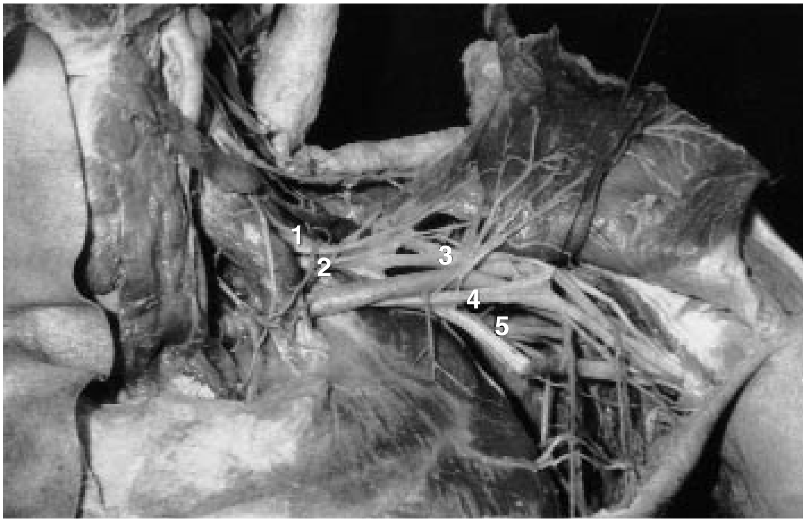

Figure 9

Anatomy of infraclavicular region. (1) Upper trunk; (2) middle trunk; (3) lateral cord; (4) medial cord; (5) posterior cord.

brachial plexus and vascular structures of the neck, which runs superficially to the deep cervical fascia.

The cellular adipose layer extends cranially to the omotrapezoidal triangle via a layer that unites the superficial and deep cervical fasciae with the medial cervical fascia. The external branch of the (accessory) spinal nerve runs within this layer, as well as the transverse artery of the neck, the suprascapular artery and the dorsal artery of the scapula. The path taken by these arteries to the medial cervical fascia tends to be deep, connecting directly with the brachial plexus. The superficial jugular vein remains superficial on this plane, whilst the sensory nerves in the cervical plexus perforate the cellular adipose layer and that of the cervical fascia in order to situate themselves subcutaneously, and to distribute themselves within the anterior–lateral region of the neck and shoulder.

The suprascapular artery, a branch of the thyro-cervical trunk, crosses the anterior–medial section of the tendon pertaining to the anterior scalenus muscle, in order to subsequently locate itself deeply within the omohyoid muscle, and to reach the transverse scapula ligament, to which the artery takes an upper route.

The dorsal artery of the scapula, a branch of the inter-scalenus path of the subclavian artery, leaves the scalenus hiatus and locates itself among the middle and upper trunks of the brachial plexus. It then crosses ventral and laterally to the middle and posterior scalenus muscles and reaches the muscular mass pertaining to the scapula lever, where it gives out the sub-trapeze branch and locates itself below the rhomboids.

The subclavian vein, when passing through the space existing between the clavicle and the first rib, adheres to the fascia of the subclavian muscle in addition to being united to the pre-tracheal layer.

The upper, middle and lower trunks are organized and constituted in the extra-scalenus region of the brachial plexus. The anatomical variations of major surgical relevance for the reconstruction of the plexus, or in canalicular syndromes, correspond to the distribution of C7 with respect to the anterior plane of the brachial plexus, upper and lower trunk. The complex and variable distribution of the anterior C7 fibres has allowed the establishment of a Gilbert's classification of three types of plexus (A, B and C), which explain situations of apparent clinical paradox.

Anatomy of the (axillary) infraclavicular region

The brachial plexus reaches the vertex of the axillary cavity, passing behind the clavicle. It is in this infraclavicular portion where the fascicles and terminal branches of the plexus are organized and structured (Fig. 9).

The axillary cavity is covered by a deep fascia level that runs towards the coracobrachialis and to the axillary edge of the scapular from the pectoral muscle, subdividing itself into a superior (or semi-lunar) portion, and a lower (or scapular) portion (Testut and Latarjet 1979).

The semi-lunar portion is the part of Richet's clavicular–coracoaxillary fascia, or Rouvière's clavipectoral–coracoaxillary fascia (Paturet, 1951), which contributes to the Gerdy's ligament support system. This fibrous range has its vertex in the coronoid process, its internal edge reaches the fascia of the pectoral minor, its lower edge reaches the skin of the axillary hollow, and its external edge reaches the fascia of the arm through the coracobrachialis and the short head of the biceps.

The scapular portion is the continuation of Gerdy's ligament. It covers the anterior face of the trapezius muscle up to its scapular insertion, where it runs anteriorly to the subscapular muscle, and inferiorly it covers the teres major and the latissimus dorsi muscles. Its external edge, close to the glenoid cavity, separates from the scapula, freeing itself to fuse with the fibrous sheath of the coracobrachialis. This path determines the axillary Langer's arch, an inferior–external socket, through which a vascular nerve structure runs from the axillary cavity of the arm (Paturet 1951). On occasions, an accessory muscular fascicle (of a flat or triangular morphology) may be found between the latissimus dorsi and the pectoral major muscles, known as Langer's muscle. On other occasions, there is a dense fibrous layer, or it may be connected with the coracobrachialis or the brachial biceps muscles, representing, in these cases, an incomplete formation of the structure in question.

The fascia of the axillary cavity's internal wall covers the anterior serratus muscle, being a cellular adipose layer in which the large thoracic nerve (Bell's nerve) is located.

The fascia of the axillary cavity's anterior wall in direct relation to the brachial plexus is Richet's clavicular–coracoaxillary fascia. Dense and resistant, it is perforated by the nerves and vessels that supply the pectoral major muscle. It proceeds cranially from the subclavian muscle sheath and from the coronoid processes. It projects itself towards the clavipectoral triangle, dividing itself with respect to the pectoral minor muscle, subsequently reaching the axillary base's superficial fascia and the brachial fascia at the level of the coracobrachialis. The expansion of the dermis constitutes the suspensory ligament of the axilla, triangular in form, with its vertex in the coronoid process, its base at the level of its dermal insertion, an external edge in continuity with the fascia of the coracobrachialis muscle and its internal edge in continuity with that of the pectoral minor muscle.

The lateral cord of the brachial plexus is made up of the union of the anterior branches from the superior and middle trunks. Many variations have been described, but their frequency is scarce. On occasions the middle trunk is supplied from the lower trunk before the point of origin of its anterior branch; it may even unite with the anterior branch itself. On other occasions, the middle trunk receives anastomosis from the posterior branch of the superior trunk before its division (Fig. 9).

In certain cases, the lateral fascicle is directly constituted by the union of the C5, C6 and C7 anterior nerve branches. The non-participation of the middle trunk in the formation of this fascicle implies that, for such patients, the upper median and the musculocutaneous nerves originate in C5 and C6, with supply from C4 in cases with a pre-fixed plexus.

The medial fascicle is formed from the anterior branch of the lower trunk. There is, occasionally, union of the C8 anterior branch with the whole of T1. This may also receive supply from C7. A fascicle making up the inferior median rarely detaches itself from the nerve branch to move towards the posterior fascicle.

The posterior cord is constituted by the union of the posterior branches from the superior, middle and inferior trunks. On many occasions, it may be observed that the posterior branches of the upper and middle trunks are joined, constituting thereby a common fascicle to be subsequently united with the posterior branch of the lower trunk. On other occasions, it is the posterior branches of the middle and lower trunk that are first joined, being then followed by the posterior branch of the upper trunk. Only very rarely can we observe the convergence of all three branches simultaneously.

Other noteworthy variations (though infrequent) are the following: additional supply from the upper and/or lower trunks via double or triple

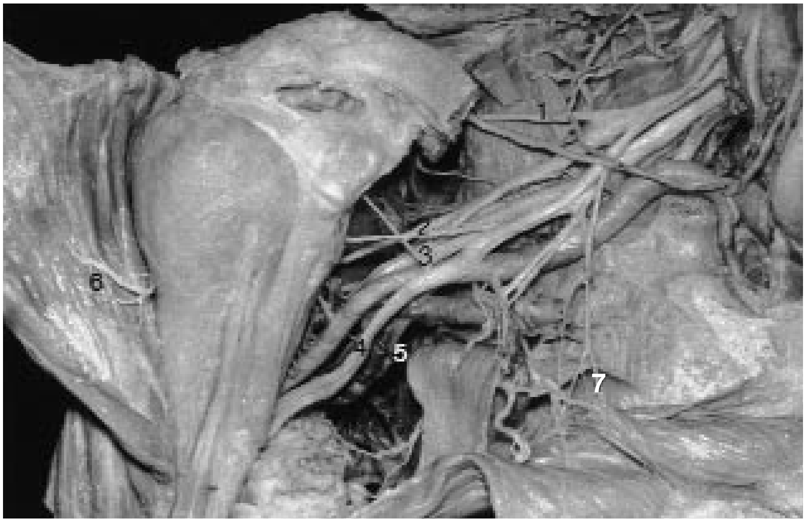

Figure 10

Anatomy of the terminal branches. (1) Suprascapular nerve; (2) musculo-cutaneous nerve; (3) 'V' of median nerve; (4) ulnar nerve; (5) radial nerve; (6) axillary nerve; (7) pectoralis nerves.

branches; supply from the lower trunk proceeding from C8 without the participation of T1; branches proceeding from the lateral cord; and posterior branches proceeding directly from C5 and C6 that join with the middle trunk in order to subsequently anastomose with the inferior trunk (Kerr 1918). Another interesting variation is that in which the posterior cord only gives rise to the radial nerve.

The relationships maintained by the cords with the vascular structures in the axillary cavity determine their topographical denomination. The axillary artery is located among the three fascicles, being entirely surrounded at the front by the median nerve via supply from the lateral and medial cords in the lower middle part of the axillary cavity, in the lower retro-pectoral region.

Collateral branches of the brachial plexus

These are topographically classified into supraclavicular and infraclavicular, and have the function of innervating the muscles of the tronco-scapular apparatus (Orts Llorca 1986). They originate directly from the lower branches of the medulla nerves forming the brachial plexus, or from its trunks or fascicles. The point of origin may lie on the anterior or posterior face, depending upon the ventral or dorsal ontogenic significance, respectively (Fig. 10).

The supraclavicular branches are:

Nerves for the deep muscles of the neck, that is, for the scalenus, longus colli and inter-transverse muscles. These proceed directly from the anterior branches of the lower cervical nerves at the level of the intervertebral foramen.

The dorsal nerve of the scapula. This originates in the posterior face of the anterior C4 and C5 nerve branches, usually via a single trunk. It runs backwards, crossing the middle scalenus muscle in order to reach the angular scapula muscle, which it innervates in its caudal fascicles. It then connects with the dorsal artery of the scapula and innervates the rhomboid muscle.

The long thoracic nerve. This is classically referred to as Bell's external respiratory nerve. It originates in the posterior C5 to C7 faces, although a C7 component only exists in 40 per cent of cases. The C5 component may originate within the dorsal nerve of the scapula. The two upper branches cross the middle scalenus anastomosing at this level, or laterally to it. The resulting branch descends behind the brachial plexus and the first portion of the axillary artery. It crosses the upper edge of the anterior serratus muscle, descending via the lateral face of the thorax in the angle that is formed by the subscapular and anterior serratus muscles. When there is a C7 component, this emerges through the middle scalenus muscle. The long thoracic nerve gives off innervation branches to each one of the digitations of the anterior serratus muscle, as the muscle's upper part is innervated by C5 fibres, the middle part by C6 fibres and the lower part by C7 fibres (Lazorthes 1976).

The subclavian nerve. This originates in the anterior C5 face or in the point of union between C5 and C6 (upper trunk). Descending obliquely in front of the plexus and the anterior scalenus muscle and on the outside of the phrenic nerve. It has anastomosis with this latter nerve, giving rise to the accessory phrenic nerves (Hovelacque 1927), and cranially to the subclavian vein, it moves towards the subclavian muscle that it innervates.

The suprascapular nerve. This is one of the first branches leaving the brachial plexus. It proceeds from the upper trunk or directly from C5, although on certain rare occasions (particularly in prefixed plexus) it may proceed from C4, following a C4–C5 union. It runs downwards and outwards following the deep face of the omohyoid muscle in order to reach the semilunar notch, passing the supraspinous fossa below the upper transverse scapular ligament. It distributes itself throughout all the supra- and infraspinous muscles.

The infraclavicular branches are:

The pectoral nerve. This may originate in the anterior divisions of the upper and middle trunks or directly from the lateral fascicle via a single branch. It crosses in front of the axillary artery and vein, passing through the clavipectoral fascia, distributing itself in the clavicular fascicle of the pectoral major muscle. It gives out an anastomotic branch that participates in the formation of the pectoral loop situated in front of the first portion of the axillary artery, around the point of origin for the acromio-thoracic artery. Fibres for the pectoral minor originate from the loop.

The medial pectoral nerve. This proceeds from C8 to T1 at the level of the medial fascicle, lying behind the axillary artery. It runs forwards by the interstice between the axillary artery and vein, joining with the lateral pectoral nerve, under the acromio-thoracic artery, participating in the pectoral loop. It gives off innervation branches to the pectoral minor muscle and to the sternal fascicle of the pectoral major. The branches leading to the pectoral major muscle reach their destination either by crossing the clavipectoral fascia or through the muscular fibres of the pectoral minor itself (Rouvière and Delmas 1999).

The subscapular nerves. There are two or three branches that proceed from the posterior cord of the brachial plexus, although on occasions the upper branch proceeds from the upper face of the upper trunk (Lazorthes 1976). Their function is the innervating of the subscapular and teres major muscle.

The thoraco-dorsal nerve. This belongs to the group of subscapular nerves, but is identified by its long pathway, parallel to the axillary edge of the scapula, accompanying the subscapular vessels. It innervates the latissimus dorsi and teres major muscles.

Terminal branches of the brachial plexus in the axillary region

The terminal branches of the brachial plexus are classified into ventral and dorsal groups, and proceed from the lateral, medial and posterior fascicles, respectively. The posterior fascicle gives rise to the axillary (circumflex) and radial nerves. The axillary nerve is considered by some researchers to be a collateral branch to the plexus because of its distribution in muscles of the shoulder girdle (Orts Llorca 1986). It carries C5 and C6 fibres and runs downwards and outwards, applied to the anterior face of the subscapular muscle, to which it may provide innervation, accompanying the posterior humeral circumflex artery. It leaves the axillary cavity by the Velpeau quadrilateral.

The radial nerve is the largest nerve in the brachial plexus, and carries fibres from C5 to T1 roots in most cases (Orts Llorca 1986, Feneis 2000). It is the most posterior and internal element in the axillary vascular nerve structures, lying behind the axillary artery and the median nerve. It is located between the axillary vein and the cubital nerve (which lie outside), and the musculocutaneous nerve (which lies inside). It leaves the axillary cavity in connection with the lower edge of the latissimus dorsi tendon.

The ventral terminal branches are:
The musculocutaneous nerve. This proceeds from the lateral fascicle and carries C5 fibres to C7. It runs downwards and outwards, lying laterally with respect to the median nerve, and anterio-laterally with respect to the axillary artery. In its path it crosses circumflex humeral vessels and perforates the coracobrachialis muscle upon reaching it, hence it is also referred to as Casserius' perforating nerve.
The median nerve. This is formed by the junction of two roots, one lateral and one medial, proceeding from the lateral and medial fascicles, respectively. It carries C6 fibres to T1. The union of the two roots gives rise to the V-shape of the medial nerve (Paturet 1951), located in front of the axillary artery, in the lower edge of the lesser pectoral muscle. The anterior humeral circumflex artery lies behind the nerve. It leaves the axillary cavity (Rouvière and Delmas 1999) in order to situate itself within Cruveilhier's brachial duct.
The cubital nerve. This proceeds from the medial fascicle of the brachial plexus, and carries C8 and T1 fibres. It may occasionally receive C7 fibres proceeding from the lateral fascicle (Lazorthes 1976). It is located in the anterior face of the interstice separating the artery from the axillary veins, amongst the median nerve and medial cutaneous nerves of the forearm. Behind this are the subscapular and thoraco-dorsal vessels and nerves.

The medial cutaneous nerves of the arm and forearm originate from the medial fascicle, and have been considered as sensory branches of the cubital nerve (Orts Llorca 1986). The arm's medial cutaneous nerve is situated more deeply than the forearm's medial, and establishes anastomosis with the second intercostal nerve, giving rise to the so-called Hyrtl's intercostobrachial nerve (Lazorthes 1976). Both nerves are exclusively sensory and carry C8 and T1 fibres.

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2
Physical examination

Türker Özkan and Atakan Aydın

Introduction

Evaluation of brachial plexus injuries needs an understanding of many factors before a management plan can be tailored. The site of the lesion, nature and degree of the injury and expected prognosis are part of this diagnostic process.

In the physical examination of the patient, the purpose is to determine the type and the site of the brachial plexus injury. This is performed by a careful clinical examination including muscle function (Table 1), (Kendall et al. 1993, Tubiana et al. 1995, Clarkson 1999), sensorial examination and specialized testing. At initial examination, the nature of the injuries (traction, penetrating, etc.), the entrance and exit wounds of penetrating injuries, amount of bleeding at the time of the injury, and associated fractures are recorded. All the muscles of the upper extremity and shoulder girdle innervated by the brachial plexus must be examined and graded on a scale from 0 to 5 by the manual muscle tests according to the Medical Research Council scale on a brachial plexus chart (Alnot 1995, Boome 1997a) (Fig. 1).

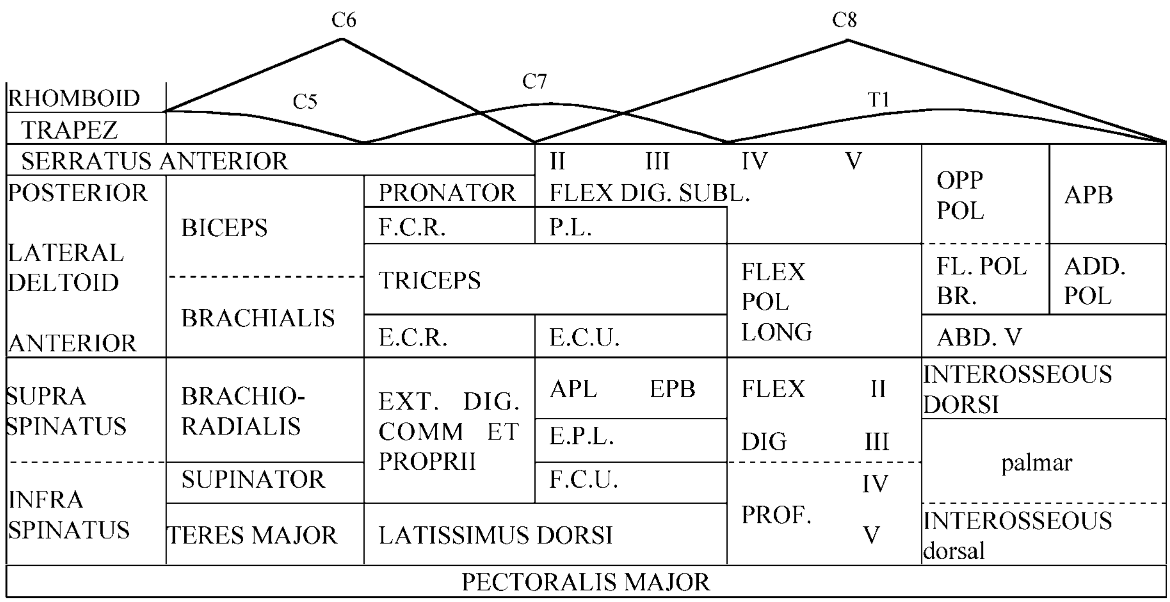

Figure 1

Brachial plexus muscle test chart.

	TH	J	M	R	L
Deep Pressure Sense	☐	☐	☐	☐	☐
Digit Localization	☐	☐	☐	☐	☐
Digit Side Localization	☐	☐	☐	☐	☐
Proprioception	☐	☐	☐	☐	☐
Temperature	☐	☐	☐	☐	☐
Stereognosis	☐	☐	☐	☐	☐
Directional Touch	☐	☐	☐	☐	☐
Vibration	☐	☐	☐	☐	☐
2 PD	☐	☐	☐	☐	☐
Mild Paresthesia	☐	☐	☐	☐	☐
Normal	☐	☐	☐	☐	☐
Final Grading	☐	☐	☐	☐	☐

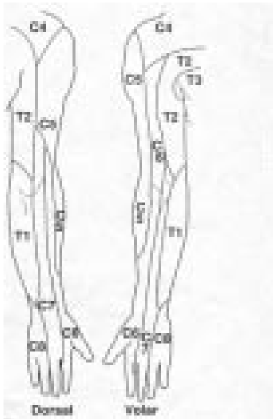

Figure 2

Brachial plexus sensibility assessment chart.

Sensibility tests are performed for each dermatome, including cervical and brachial plexus. Pain and temperature appreciation, static and moving two-point discrimination, constant touch and vibration with a tuning fork at 30 and 256 cycles per second, and the ninhydrin test described by Moberg (Aschan and Moberg 1962) are tested and recorded (Fig. 2).

Physical examination is repeated, hours or days later, and changes in the clinical findings must be recorded by a different colored ink on the same chart or on a fresh chart. The functional grading of nerve compression compares the motor and sensory losses if they do not correlate. Such a discrepancy may result if there is nerve compression rather than nerve division or rupture (Millesi 1984; Boome 1997b) (Table 1).

Severe neuropraxias may persist for up to 6–8 weeks. Root avulsions, ruptures or neuromas in continuity are possibilities when a specific root function is completely absent, or each pathology may be found at different root levels in the same patient (Boome 1997b).

The paralysis of some muscles can give specific information related to the level of the injury (Table 2).

A serratus anterior muscle paralysis in association with total or upper trunk palsy suggests a C5 and C6 root avulsion, as its nerve supply arises close to the vertebral foramen; while paralysis of the levator scapulae, rhomboids and deep muscles of the neck points to a proximal injury or avulsion of C4 and C5 roots. A diaphragmatic palsy suggests a C4 avulsion: if associated with a C5 and C6 palsy, it is likely that C5 and C6 roots are ruptured close to the foramen within the vertebral canal.

Table 1 Functional grading of nerve compression

Grade	Sensory	Motor
0	Nil	Nil
1	Deep Pressure Sense	Nil
2	Deep Pressure Sense and Digit Localization	Gross weakness
3	Gross paresthesia and Digit Side Localization Gross Stereognosis Minimal directional touch 2PD>10 mm	Mild weakness
4	Mild paresthesia	Normal
5	Normal	Normal

(Compression ↑)

If brachioradialis and teres major muscle paralysis is associated with paralysis of supraspinatus, infraspinatus, deltoid, teres minor and biceps muscles, then upper trunk injury is likely. However, if the brachioradialis and teres major muscles are intact, a more peripheral injury of the nerves to the shoulder abductors and external

Table 2 Major motor and sensory functions of the various parts of the brachial plexus

Anatomic Level	*Sensory*	*Motor*
Root C5	Deltoid chevron	Shoulder external rotation and abduction
Root C6	Cubital fossa, tip of the thumb	Elbow flexion, extensor carpi radialis longus
Root C7	Thumb, index and middle fingers, dorsal radial hand	Wrist and finger extensors, flexor carpi radialis, brachioradialis, pronator teres
Root C8	Ring and little fingers, dorsal ulnar hand	Wrist and finger flexors
Root T1		Hand intrinsics
(Upper trunk) Suprascapular nerve		Shoulder external rotation
(Upper trunk) Posterior cord branch (circumflex nerve)	Deltoid chevron	Shoulder abduction
(Upper trunk) C7 contribution to lateral cord	Thumb, index and middle fingers	Pronator teres Flexor carpi radialis
Lateral cord	Cubital fossa Radial forearm Thumb, index and middle fingers (not back of the thumb)	Elbow flexion Flexor carpi radialis Pronator teres
Musculocutaneous nerve	Cubital fossa, radial forearm	Elbow flexion
Middle trunk	Thumb, index and middle fingers, radial forearm, radial dorsal hand	Not external rotators of shoulder, elbow extension, brachioradialis, wrist and finger extensors
Posterior cord	Deltoid chevron, back of thumb, index and middle fingers	Shoulder abduction, elbow extension, brachioradialis, wrist and finger extensors
Lower trunk and medial cord	Ring and little fingers, medial arm and forearm	Most of wrist and finger flexors, median and ulnar intrinsics

rotators and elbow flexors is likely. A normal supraspinatus muscle function excludes a C5 root avulsion or rupture in a normally fixed plexus (Bonnard and Narakas 1997).

Sensory evaluations also give some clues about the level and pattern of brachial plexus injury.

Pain is usually a symptom correlating to an avulsion lesion of C7, C8 or T1 roots. The deafferentation pain from root avulsion usually begins after a week or more, but if it appears immediately, more severe long-term deafferentation pain can be expected. The presence of any pain in an anesthetic hand or limb marks a root avulsion and severe pain syndrome points to C4–C5 root avulsion in 80 per cent of cases (Bonnard and Narakas 1997).

The presence of a proximal Tinel's sign in the neck while testing in a disto-proximal fashion of the major peripheral nerves usually indicates a proximal neuroma and a sign of good prognosis. However the absence of a Tinel's sign in the neck is an important clinical finding pointing to a total plexus avulsion.

Moisture of the skin can give useful information about the lesion: dry skin in an anesthetic area suggests a postganglionic lesion; on the contrary, a normal moist skin suggests a preganglionic lesion. Sliding a plastic pen over the skin of the affected limb and comparing to the normal side can be used to test sweating function of the skin. The ninhydrin test is a more scientific test to detect sweating function.

The deep pressure sense (pinch) test is done to determine whether continuity exits in a root with small nerve fibers which is least affected by compression of a nerve trunk following injury and swelling. To perform the pinch test, full pinch pressure is applied to the patient's fingertips at the base of the nail and then the patient's finger is pulled sharply out from the examiner's thumb and index finger, a maneuver that is painful in a normal finger. In an apparently anesthetic finger, any burning sensation points to some continuity of the nerve supplying that finger. The tip of the thumb is used to test the C6 root with median nerve, the tip of the middle finger for the C7 root through median nerve, and the little finger for the C8 root with ulnar nerve, respectively. Neuropraxia can also affect transmission in these fibers, therefore the absence of a deep pressure sense up to 6 weeks of the injury is still not diagnostic of a rupture of that particular nerve (Boome 1997b).

Root C8–T1 avulsion or a lesion close to the vertebral column of the corresponding spinal nerves compromises the sympathetic preganglionic fibers on the same side of the head and causes vasodilatation, anhydrosis, miosis, enophthalmos and ptosis which is known as *Horner's syndrome*. The absence of Horner's sign is a good prognostic feature. If the avulsion of the rootlets accompanies a partial lesion of the spinal cord, *Brown–Sequard syndrome* occurs. Clinical signs of the patient show dissociated changes in the lower limbs, including spasticity and loss of tactile discrimination, position sense and vibration in the ipsilateral lower limb, while there is loss of pain and temperature discrimination in the contralateral lower limb. Possible paralysis of the intercostal nerves precludes neurotization of these nerves for reconstruction of the plexus (Boome 1997b).

Associated vascular injuries, bone and joint pathologies must also be taken into consideration and recorded during examination. Arterial rupture usually accompanies a infraclavicular plexus lesion but can be seen at the supraclavicular level with C8–T1 root avulsions. Expanding swelling in the axillary area with or without a bruit is a strong evidence of an arterial injury even in the presence of distal intact pulses. Progressive loss of function with increasing paralysis and sensory deficit suggests an expanding hematoma or aneurysm compressing adjacent nerve trunks (Birch 1997).

Cervical transverse process fractures can be seen with C8–T1 root avulsions but also with C5–C6 root ruptures. Glenohumeral dissociation can lead to peripheral plexus lesion and dislocated shoulder (scapulothoracic dissociation) is a sign of complete avulsion with peripheral lesion (double level lesion). Upper humeral fractures suggests infraclavicular nerve injuries and severe abrasions on the tip of the shoulder and the side of the head or helmet suggest supraclavicular injuries (Millesi 1984; Bonnard and Narakas 1997).

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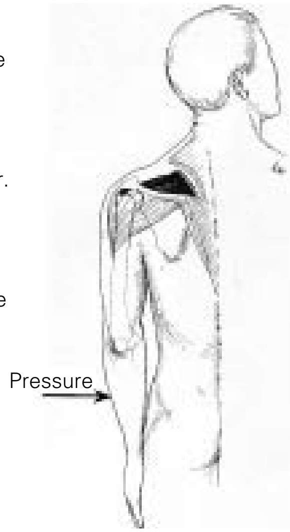
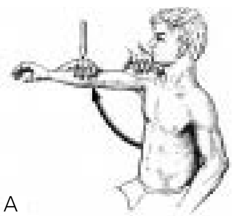
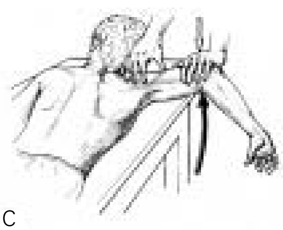
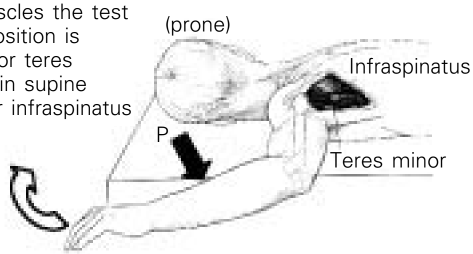
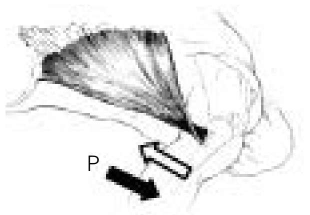
Table 1 Clinical examination of brachial plexus injuries

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Supraspinatus muscle Suprascapular nerve C4, 5 and 6	Abducts the shoulder joint, stabilizes the head of humerus in the glenoid cavity	Initiation of abduction of the humerus while applying pressure against forearm in the direction of adduction Fixation is not necessary	No effort is made to distinguish the supraspinatus from the deltoid in the strength test for grading, as these muscles act simultaneously in abducting the shoulder. To palpate the supraspinatus, the trapezius must be relaxed by extending and laterally flexing the head and neck	
Deltoid muscle Axillary nerve C5 and 6	Shoulder abduction (chiefly by middle fibers) Shoulder flexion and medially rotation (anterior fibers) Shoulder extention and lateral rotation (posterior fibers)	*Middle deltoid* (sitting position): shoulder abduction without rotation (A) *Anterior deltoid* (sitting position): shoulder abduction in slight flexion with the humerus in slight lateral rotation (B) *Posterior deltoid* (prone position): shoulder abduction in slight extension with the humerus in slight medial rotation (C) If the scapular fixation muscles are weak the examiner must stabilize the scapula	In the presence of paralysis of the entire deltoid and supraspinatus muscles, the humerus tends to subluxate downwards because the capsule of the shoulder joint permits almost 2.5 cm of separation of the head of the humerus from the glenoid cavity	 A  B  C

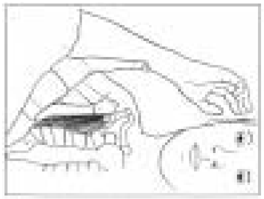
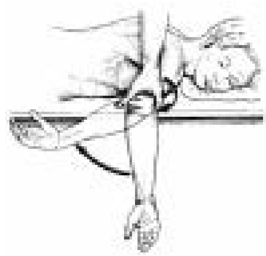
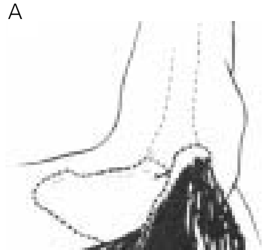
continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Infraspinatus muscle Suprascapular nerve C(4),5 and 6 Teres minor muscle Axillary nerve C5 and 6	Laterally rotates the shoulder joint and stabilizes the head of the humerus in the glenoid cavity	(Prone position) Lateral rotation of the humerus with the elbow held at right angles against pressure applied in the direction of medial rotation (Supine position) Lateral rotation of the humerus with the elbow held at right angle against pressure applied in the direction of medial rotation This test requires strong fixation of trapezius	For the purpose of objectively grading a weak lateral rotator group against gravity and for palpation of the rotator muscles the test in prone position is preferred for teres minor and in supine position for infraspinatus	
Latissimus dorsi muscle Thoracodorsal nerve C6,7 and 8	Medially rotates, adducts and extends shoulder joint. Also depresses the shoulder girdle and assists lateral flexion of the trunk	(Prone position) Adduction of the arm with extension in the medially rotated position against pressure on the forearm in the direction of abduction and slight flexion of the arm Counter pressure is applied laterally on pelvis		
Teres major muscle Lower subscapular nerve C5,6 and 7	Medially rotates, adducts and extends shoulder	(Sitting position) Extension and adduction of the humerus in the medially rotated position against pressure on the arm above the elbow in the direction of abduction and flexion		
Pectoralis major muscle (Upper fibers) Lateral pectoral nerve C5,6 and 7 (Lower fibers) Lateral and medial pectoral nerve C6,7,8 and T1	Adduction and medial rotation of the humerus; depression of shoulder girdle.	Upper fibers (supine position). Starting with the elbow extended and the shoulder in 90° flexion and slight medial rotation, the humerus is horizontally adducted toward the sternal end of the clavicle against pressure in the direction of horizontal abduction. Lower fibers (supine position). Starting with the elbow extended and the shoulder in flexion and slight medial rotation, adduction of the arm obliquely toward the opposite iliac crest against the forearm obliquely in a lateral and cranial direction		

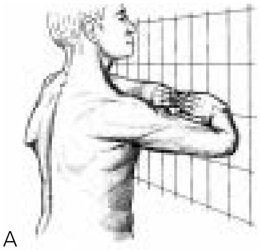
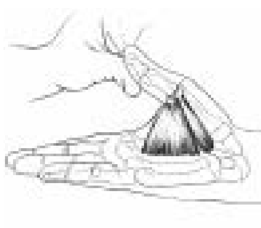
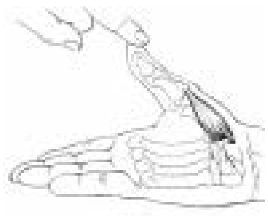
continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Pectoralis minor muscle Medial and lateral pectoral nerve C(6),7,8 and T1	Tilts the scapula anteriorly and rotates the scapula so that the coracoid process moves anteriorly and caudally	(Supine position) While the shoulder is in external rotation and 80° flexion and the elbow is flexed, the examiner moves the shoulder girdle cranially and dorsally along the shaft of the humerus to test muscle strength	Weakness of this muscle will increase respiratory difficulty in patients already suffering from involvement of respiratory muscles	
Subscapularis muscle Upper and lower subscapular nerve C5,6 and 7	Medially rotates the shoulder joint and stabilizes the head of the humerus in the glenoid cavity during movements of this joint	(Supine/prone) Medial rotation of the humerus with arm at side and elbow held at right angles against pressure in the direction of laterally rotating the humerus using the forearm as a lever		
Rhomboid muscles Dorsal scapular nerve C4 and 5	Adduct and elevate the scapula and rotate it so the glenoid cavity faces caudally	Rhomboid (prone) The patient raises the arm away from the back.The weight of the raised upper extremity provides resistance to the scapular test motion. Rhomboid major can be palpated medial to the vertebral border of the scapula lateral to the lower fibers of trapezius, near the inferior angle of the scapula. Note: inability to lift the hand off the buttock may be due to shoulder muscle weakness, notably subscapularis not rhomboid muscle weakness. Ensure that the hand is maintained over the non-test side buttock and patient adducts, medially rotates scapula (A).		 A
Levator scapulae muscle Cervical 3 and 4, and dorsal scapular nerve C4 and 5	Elevates scapula and assists in rotation so the glenoid cavity faces caudally	Middle trapezius (prone) Adduction of the scapula with upward rotation (lateral rotation of the inferior angle) and without elevation of the shoulder girdle against pressure on the forearm in a downward direction toward the table (B).		 B
Trapezius muscle Spinal portion of cranial nerve XI and ventral ramus C2,3 and 4	Adduction of the scapula performed chiefly by the middle fibers with stabilization by the upper and lower fibers	Upper trapezius (sitting) Elevation of the acromial end of the clavicle and scapula; postero-lateral extension of the neck bringing the occiput toward elevated shoulder with the face turned in opposite direction (C)		 C

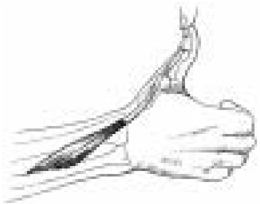
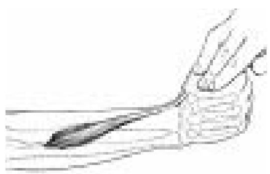
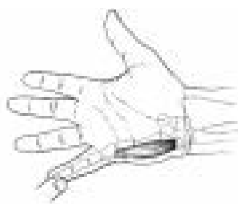
continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Serratus anterior muscle Long thoracic nerve C5,6,7 and 8	Abducts the scapula, rotates the inferior angle laterally and the glenoid cavity cranially and holds the medial border of the scapula firmly against the rib cage	(Standing position) Facing a wall with the elbows straight, the subject places hands against the wall and pushes against the wall. This test is useful to differentiate only between strong and weak for the purpose of grading (A). A more objective test is to evaluate the ability of the serratus to stabilize the scapula in a position of abduction and lateral rotation with the arm in a position of approximately 120 to 130 flexion against pressure on dorsal surface of the arm between shoulder and elbow downward in the direction of extension and slight pressure against the lateral border of scapula in the direction of rotating the inferior angle medially (B)		 A  B
Adductor pollicis muscle Ulnar nerve C8 and T1	Adducts the carpometacarpal (CMC) joint and adducts and assists in flexion of the metacarpophalangeal (MCP) joint so that the thumb moves toward the plane of the palm	Adduction of the thumb toward the palm against the pressure on the medial surface of the thumb in the direction of abduction away from palm. The hand may be stabilized by the examiner or rest on the table for support	A test that is frequently used to determine the strength of the adductor pollicis is the ability to hold a piece of paper between the thumb and second metacarpal which can be difficult in a patient having muscle bulk preventing close approximation of these parts	
Abductor pollicis brevis muscle Median nerve C6,7,8 and T1	Abducts the CMC and MCP joints of the thumb in a ventral direction perpendicular to the plane of the palm	Abduction of the thumb ventralward from the palm against pressure on the proximal phalanx in the direction of adduction toward the palm. The examiner stabilizes the hand		
Opponens pollicis muscle Median nerve C6,7,8 and T1	Opposes the CMC joint of the thumb in a position so that by flexion of the MCP joint it can oppose the fingers	Flexion, abduction and slight medial rotation of the metacarpal bone against pressure on metacarpal bone in the direction of extension and adduction so that the thumbnail shows in palmar view. The examiner stabilizes the hand		

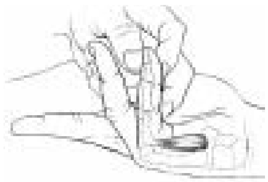
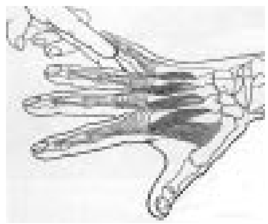
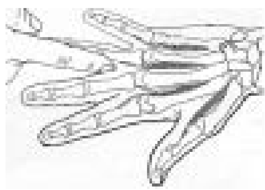
continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Flexor pollicis longus muscle Median nerve C(6),7,8 and T1	Flexing the interphalangeal (IP) joint of the thumb	Flexing the IP joint of the thumb against pressure on the palmar surface of the distal phalanx in the direction of extension. The examiner stabilizes the metacarpal bone and proximal phalanx of the thumb in extension		
Flexor pollicis brevis muscle (Superficial head) Median nerve C6,7,8 and T1 (Deep head) Ulnar nerve C8 and T1	Flexes the MCP and CMC joint of the thumb	Flexing the MCP joint of the thumb without flexion of the IP joint against pressure on the palmar surface of the proximal phalanx in the direction of extension. The examiner stabilizes the hand		
Extensor pollicis longus muscle Radial nerve C6,7 and 8	Extends IP joint and assists in extension of the MCP and CMC joints of the thumb	Extension of the IP joint of the thumb against pressure on the dorsal surface of the IP joint of the thumb in the direction of flexion. The examiner stabilizes the hand and gives counterpressure against the palmar surface of the first metacarpal and proximal phalanx	In a radial nerve lesion, the IP joint of the thumb may be extended by the action of abductor pollicis brevis, flexor pollicis brevis, oblique fibers of the adductor pollicis or by the first palmar interosseus, by virtue of their insertions into the extensor expansion of the thumb	
Extensor pollicis brevis muscle Radial nerve C6,7 and 8	Extends the MCP joint of the thumb, extends and abducts the CMC joint	Extension of the MCP joint of the thumb against pressure on the dorsal surface of the proximal phalanx in the direction of flexion. The examiner stabilizes the wrist		
Abductor pollicis longus muscle Radial nerve C6,7 and 8	Abducts and extends the CMC joint of the thumb	Abduction and slight extension of the first metacarpal bone against pressure on the lateral surface of the distal end of the first metacarpal and the ability to abduct the wrist. The examiner stabilizes the wrist		
Abductor digiti minimi muscle Ulnar nerve C(7),8 and T1	Abducts, assists in opposition, and may assist in flexion of the MCP joint of the little finger	Abduction of the little finger against pressure on the ulnar side of the little finger in the direction of adduction toward the midline of the hand. The hand may be stabilized by the examiner or rest on the table for support		

continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Opponens digiti minimi muscle Ulnar nerve C(7),8 and T1	Opposes the CMC joint of the little finger	Opposition of the fifth metacarpal toward the first against pressure on the palmar surface along the fifth metacarpal in the direction of flattening the palm of the hand. The hand can be stabilized by the examiner or rest on the table for support.The first metacarpal is held firmly by the examiner		
Flexor digiti minimi muscle Ulnar nerve C(7),8 and T1	Flexes the MCP joint of the little finger and assists in opposition of the little finger toward the thumb	Flexion of the MCP joint with IP joints extended against pressure on the palmar surface of the proximal phalanx in the direction of extension The hand may rest on the table for support or be stabilized by the examiner		
Dorsal interossei muscles Ulnar nerve C8 and T1	Abducts the index, middle and ring fingers from the axial line through the third digit. Assist in flexion of MCP joints and extension of IP joints of the same fingers	Abduction of the index, middle and ring fingers against pressure		
Palmar interossei muscles Ulnar nerve C8 and T1	Adducts the thumb, index, ring and little finger toward the axial line through the third digit	Adduction of the corresponding fingers against pressure		
Lumbricales muscles Lumbricales I and II Median nerve C(6),7 and 8 Lumbricales III and IV Ulnar nerve C(7),8 and T1	Extends the IP joints and simultaneously flexes the MCP joints of the second through fifth digits	Extension of IP joints with simultaneous flexion of MCP joints against pressure first on the dorsal surface of the middle and distal phalanges in the direction of flexion and then against the palmar surface of the proximal phalanges in the direction of extension. The examiner stabilizes the wrist in slight extension if there is any weakness of wrist muscles		

continued

Table 1 *Continued*

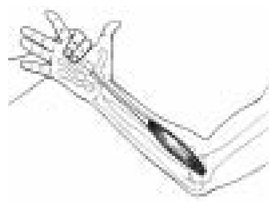
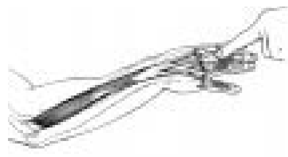
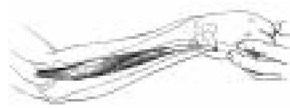
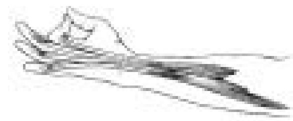
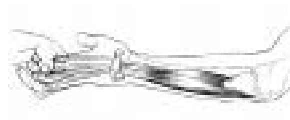
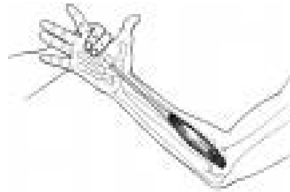
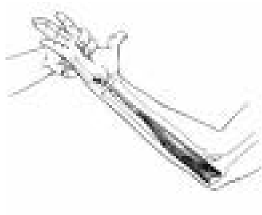
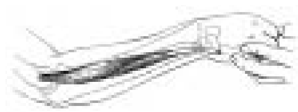
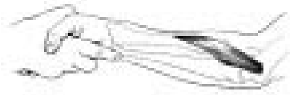
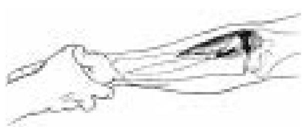
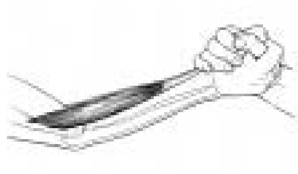
Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Palmaris longus muscle Median nerve C(6),7,8 and T1	Tenses the palmar fascia, flexes the wrist. It may assist in flexion of the elbow	Tensing of the palmar fascia by strongly cupping the palm of the hand and flexion of the wrist against pressure on thenar and hypothenar eminences in the direction of the flattening the palm of the hand and against the hand in the direction of extending the wrist. The forearm rests on the table for support in a position of supination		
Extensor indicis muscle Extensor digiti minimi muscle Extensor digitorum muscles Radial nerve C6,7 and 8	Extends the MCP joints and in conjunction with the lumbricales and interossei; extends the IP joints of the second through fifth digits	Extension of the MCP joints of the second through fifth digits with IP joints relaxed against pressure on the dorsal surfaces of the proximal phalanges in the direction of flexion. The examiner stabilizes the wrist avoiding full extension		  
Flexor digitorum superficialis muscles Median nerve C7,8 and T1	Flexes the proximal IP joints of second through fifth digits, assists in flexion of the MCP joints and in flexion of the wrist	Flexion of the proximal IP joint with the distal IP joint extended of the second, third, fourth and fifth digits against pressure on the palmar surface of the middle phalanx in the direction of extension. The examiner stabilizes the MCP joint with the wrist in neutral position or in slight extension. It appears to be the exception rather than the rule to obtain isolated flexor superficialis action in the fifth digit		
Flexor digitorum profundus muscles Profundus I, II Median nerve C7,8 and T1 Profundus III, IV and ulnar nerve C(7), 8 and T1	Flexes distal IP joints of index, middle, ring and little fingers and assists in flexion of proximal IP and MCP joints	Flexion of the distal IP joint of the second, third, fourth and fifth digits against pressure on the palmar surface of the distal phalanx in the direction of extension. With the wrist in slight extension the examiner stabilizes the proximal and middle phalanges		
Flexor carpi radialis muscle Median nerve C6,7 and 8	Flexes and abducts the wrist and may assist in pronation of the forearm and flexion of the elbow	Flexion of the wrist toward the radial side against pressure on the thenar eminence in the direction of extension toward the ulnar side. The forearm is in slightly less than full supination and rests on the table for support. The palmaris longus can not be ruled out in this test		

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Flexor carpi ulnaris muscle Ulnar nerve C7,8 and T1	Flexes and adducts the wrist and may assist in flexion of the elbow	Flexion of the wrist toward the ulnar side against pressure on the hypothenar eminence in the direction of extension toward the radial side.	The forearm is in full supination and rests on the table for support or is supported by the examiner. Normally fingers will be relaxed when the wrist is flexed.If the fingers actively flex as wrist flexion is initiated, the finger flexors are tempting to substitute for the wrist flexors	
Extensor carpi radialis Longus and brevis muscles Radial nerve C6,7 and 8	Extends and abducts (longus) the wrist and assists in flexion of the elbow	Extension of the wrist toward radial side against pressure on the dorsum of the hand along the second and third metacarpal bones while the fingers are allowed to flex.	The forearm is in slightly less than full pronation and rests on the table for support	
Extensor carpi ulnaris muscle Radial nerve C6,7 and 8	Extends and adducts the wrist	Extension of the wrist toward the ulnar side against pressure on the dorsum of the hand along the fifth metacarpal bone in the direction of flexion toward the radial side.	The forearm is in full pronation and rests on the table for support or supported by the examiner. Normally fingers will be in a position of passive flexion when the wrist is extended.If the fingers actively extend as wrist extension is initiated, the finger extensors are attempting to substitute for the wrist extensors	
Pronator teres muscle Median nerve C6 and 7	Pronates the forearm and assists in flexion of the elbow joint	Pronation of the forearm with the elbow partially flexed against pressure at the lower forearm above the wrist in the direction of supinating the forearm.	The elbow should be held against the patient's side or be stabilized by the examiner to avoid any shoulder abduction movement	
Pronator quadratus muscle Median nerve C7,8 and T1	Pronates the forearm	Pronation of the forearm with the elbow completely flexed in order to make the humeral head of the pronator teres less effective by being in a shortened position.	The elbow should be held against the patient's side to avoid shoulder abduction	
Supinator muscle Radial nerve C5,6,(7)	Supinates the forearm	Supination of the forearm against pressure at the distal end of the forearm above the wrist in the direction of pronation.	The examiner holds the shoulder and elbow in extension (tested with biceps elongated)	

continued

Table 1 *Continued*

Muscle and innervation	*Function*	*Muscle test and fixation*	*Notes*	*Test picture*
Brachioradialis muscle Radial nerve C5 and 6	Flexes the elbow joint and assists in pronating and supinating the forearm when these movements are resisted	Flexion of the elbow with the forearm neutral between pronation and supination. The belly of the brachioradialis must be seen and felt during this test. The examiner places one hand under the elbow to cushion it from table pressure		
Coracobrachialis muscle Musculocutaneous nerve C6 and 7	Flexes and adducts the shoulder joint	Shoulder flexion in lateral rotation with the elbow completely flexed and forearm supinated against pressure on the anteromedial surface of the lower third of the humerus in the direction of extension and slight abduction. Assistance from the biceps in shoulder flexion is decreased in this test position because the complete elbow flexion and forearm supination place the muscle in too short a position to be effective in shoulder flexion. Fixation is not necessary		
Biceps brachii and brachialis muscles Musculocutaneous nerve C5 and 6	Flex shoulder and elbow joint and supinates the forearm (biceps)	Elbow flexion slightly less than or at right angles with forearm in supination against pressure on the lower forearm in the direction of extension. The examiner places one hand under the elbow to cushion it from table pressure	If the biceps and brachialis are weak as in a nervus musculocutaneous lesion, the patient will pronate the forearm before flexing the elbow using brachioradialis, extensor carpi radialis longus, pronator teres and wrist flexors	
Triceps brachii muscle Radial nerve C6,7,8 and T1	Extends the elbow joint. In addition the long head assists in adduction and extension of the shoulder joint	(Supine position) Extension of the elbow against pressure on the forearm in the direction of flexion. The shoulder is at approximately 90° flexion with the arm supported in a position perpendicular to the table	While the triceps and anconeus act together in extending the elbow joint, it may be useful to differentiate these two muscles. As the belly of the anconeus muscle is below the elbow joint, it can be distinguished from the triceps by palpation. It is possible for a lesion to involve the branch of radial nerve to anconeus leaving triceps unaffected. The grade of good elbow extension strength is actually the result of a normal triceps without anconeus	

3
Radiological and related investigations

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X-ray

Radiological investigations of brachial plexus lesions are both revealing and necessary. However, the value of the plain X-ray is underrated: it may show the site and severity of the injury.

X-rays of the cervical spine can reveal a luxation and/or fracture, pointing to the possibility of associated lesions of the spinal cord and/or cervical spinal nerves or roots. Fracture of the transverse process of the cervical spine often implies a severe local (intraforaminal) lesion of the spinal nerve. Clavicular fracture or luxation is rarely a cause of the brachial plexus lesion but referes to the site of impact. A severe fracture/dislocation will certainly have caused an injury to the underlying plexus structures, which will require reconstruction (Fig. 1). In the same way, X-ray of the shoulder can reveal the severe condition of a scapulo-thoracic dissociation (depression of the scapula and lateral displacement), in which the extensive neural injury is always associated with a serious vascular lesion

Figure 1

Fracture/dislocation of the clavicle with pseudoarthrosis (arrow).

Figure 2

Scapulo-thoracic dissociation: lateral displacement of the scapula (arrows); fracture of the clavicle (white arrow), and traumatic aneurysm of the subclavian artery (black arrow).

Figure 3

Subcapital humerus fracture.

Figure 4

Fracture of the collum scapulae.

Figure 5

Left-side diaphragmatic paralysis.

(Fig. 2). Shoulder dislocation or fractures can be accompanied by neural injuries, sometimes in combination with a cuff lesion (Fig. 3). A scapula fracture running close or into the scapular notch may cause an injury to the suprascapular nerve. It is interesting to know that a fracture of the collum scapulae can be associated with a selective injury of the nerve to the infrapinatus muscle (Fig. 4). A severe dislocated fracture of the humerus can be followed by an injury to the radial nerve and thus present as one of the second level lesions in brachial plexus injuries in adults. The same problem occurs with the axillary nerve – or other adjacent neural structures, such as the lateral and posterior and/or even medial cord – in fracture-dislocation of the humeral head. Other injuries of the upper extremity do not have a diagnostic significance but have to be considered in the context of the total treatment of the patient with brachial plexus injury. X-ray of the chest is important in several ways, e.g. for diagnosing a diaphragmatic paralysis (C4) (Fig. 5), costal fractures, a pulmonary lesion, but also in the overall treatment and more specifically in relation to possible extraplexal (intercostal nerves) neurotizations.

In obstetric patients, a chest X-ray has to be a standard preoperative procedure, especially to rule out a hemi-paralysis of the diaphragm.

Generally, this paralysis has to be treated first by plication of the diaphragm, if possible by an endoscopic approach. A persisting phrenic paralysis is often associated with a homolateral severe upper brachial plexus lesion, which has to be treated surgically. Normally, fractures of the clavicle and humerus in obstetric cases have no consequences, and certainly have no prognostic value in predicting spontaneous recovery; they can be associated injuries of the obstetric plexus lesions and these fractures are sometimes wrongly supposed to be the cause of the malfunction of the extremity instead of the plexus injury itself.

CT-myelography

In the last decade myelography has been supplemented and standardized as CT–myelography. Although MRI is the major tool in diagnostic neuroradiology for the assessment of rootlet avulsions in brachial plexus lesions, CT-myelography still proves more reliable (Miller et al 1993, Francel et al 1995, Panasci et al 1995, Burge 1997, Carvalho et al 1997, van Es 1997, Chow et al 2000).

Sunderland (1991) stated that traction of the brachial plexus will normally result initially in tearing of the arachnoidal and dural sheet of the nerve tract. But rootlet avulsions may exist without a concomitant meningocele, probably because of a so-called central mechanism (see Chapter 16). A meningocele is a sign that the patient has suffered from a traction force, but is not proof of an avulsion. Also ‘complete’ recovery is possible in children with multiple meningoceles. The existence of a meningocele is a complicating diagnostic factor because it is often impossible to follow the course of rootlets, depending on the size of the meningocele. Sometimes the rootlet is displayed very clearly in the middle of the meningocele but the meningocele can also push the rootlets away, even intact rootlets at adjacent levels, so that they cannot be judged to be secure.

Birch et al (1998) observe and remark on the differences in intradural injuries of the roots: intradural rupture and avulsion. The lesion may

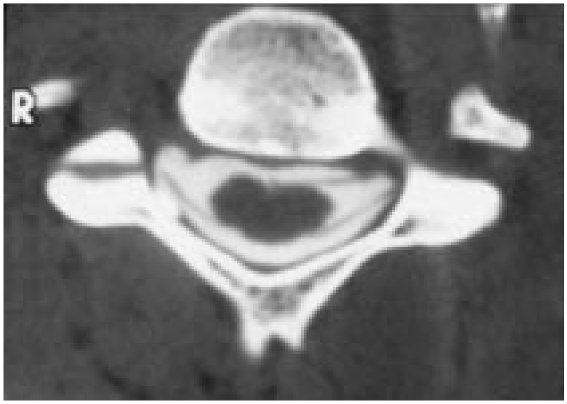

Figure 6

Absent (avulsed) right ventral root (C5).

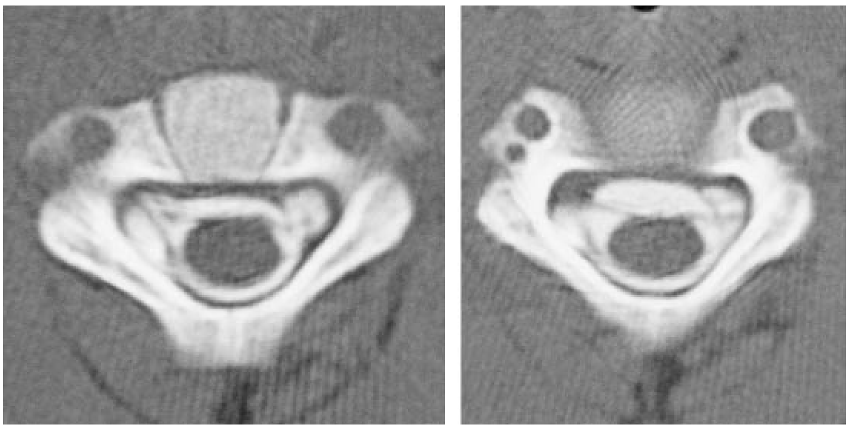

Figure 7

Avulsed roots on the left side, bilaterally and anteriorly located meningoceles.

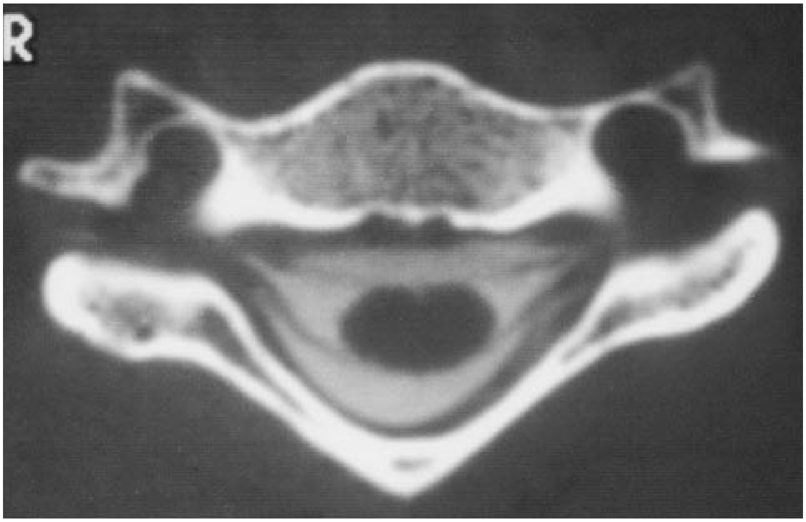

Figure 8

A picture of a normal CT myelogram, revealing clearly the central and dorsal roots (C6).

be confined to either ventral (Fig. 6) or dorsal rootlets, or even be partial as we find more often in obstetric patients. These findings may have their operative consequences. In our departments, CT-myelography is routinely performed, mainly in candidates for surgical treatment. The correlation between radiological investigations, the clinical picture and operative findings is still higher in adults than in children, although important progress has been made over recent years to improve delineation of the rootlets using thin slices. Today we are convinced about the value of CT-myelography in obstetric patients (Fig. 7). Based on our experience with more than 600 surgically treated patients with brachial plexus lesions, including more than 300 children, we have reached the following conclusions:

- The presence of intact dorsal and ventral rootlets without a meningocele rules out an avulsion (Fig. 8);
- The absence of dorsal or ventral rootlets or both without a concomitant meningocele is considered to suggest a partial or complete avulsion;
- The presence of a meningocele is not proof of an avulsion and can mask the existence of intact rootlets, so that this level has to be examined with special care;
- If the meningocele extends outside the foramen, which is less frequent in obstetric patients, then an avulsion is very likely;
- Deformation and/or displacement of the spinal cord indicates a severe intradural injury (Figs 9 and 10).

Technical notes for CT-myelography

For adults (16 years and older). Introduction of 10 ml Omnipaque 300 by lateral C1–C2 puncture; this prevents post-puncture headache. The contrast is introduced under fluoroscopic guidance. The parameters cited below define the quality of the picture and the units quantify them.

Parameters:	– slice thickness	1.5 mm
	– translation	3 mm
	– mAs	300
	– kV	120
	– FOV	80

Axial slices are taken from the level C2–T2.

For obstetric patients. CT-myelography is performed under general anesthesia, normally at the age of 3–4 months and we prefer to introduce 3–4 ml Omnipaque 240 by lumbar puncture.

Parameters:	– slice thickness	1.5 mm
	– translation	2 mm
	– mAs	200
	– kV	120
	– FOV	80

Axial slices are taken from the level C2–T2.

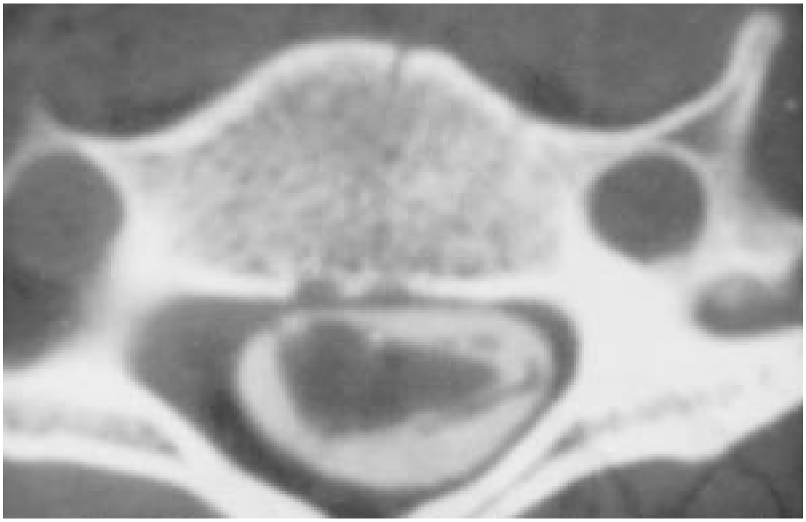

Figure 9

Deformation of the spinal cord.

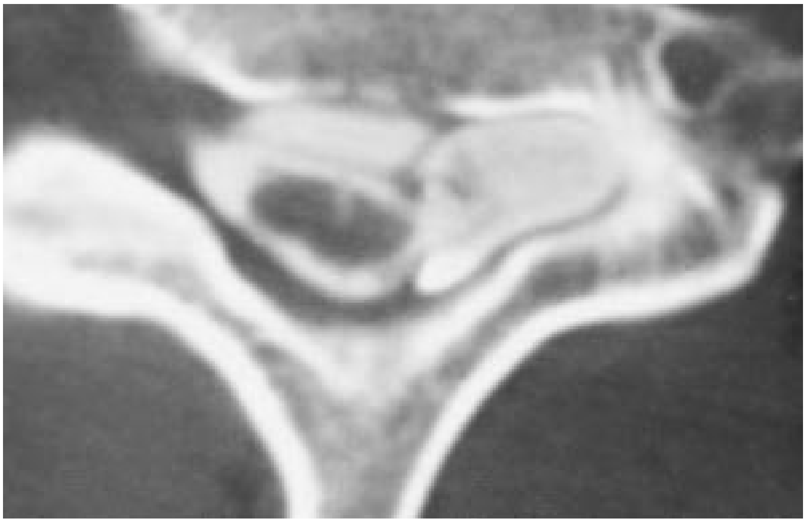

Figure 10

Displacement of the spinal cord with lateral and anterior meningoceles; rootlets are difficult to distinguish.

Magnetic resonance imaging

At present, in our opinion, MRI is not able to discriminate the course of the rootlets better than CT-myelography quite apart from problems like flow artifacts. Currently, variant MR techniques for visualizing intradural lesions are under evaluation. The 3D-CISS (three-dimensional constructive interference in steady state) procedure is especially promising for obstetric lesions (Fig. 11). With this technique the course of rootlets can be followed, even in the presence of meningoceles. Advantages of the MRI are the lack of radiation and a less invasive type of investigation, although general anesthesia, necessary in obstetric patients, may pose a problem. MRI visualization of the plexus structures beyond the vertebral foramen is the best of all other imaging techniques. Traumatic injuries such as large neuromas may be followed along

Figure 11

3D-CISS picture with clearly visible intact rootlets on the right side (two white arrows), and absent rootlets on the left side at the level of the meningocele (black arrow).

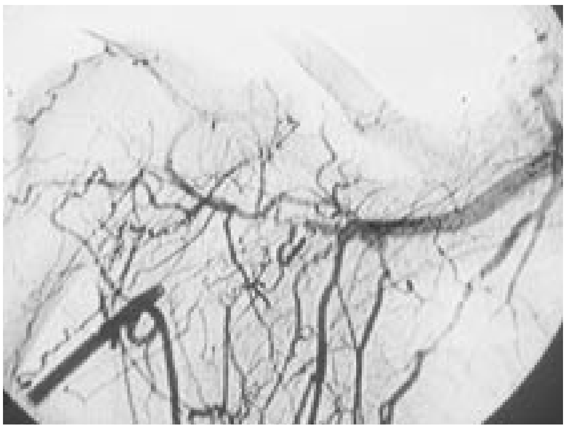

Figure 12

A traumatic occlusion of the axillary artery, with abundant collateral circulation.

the plexus structures as well as entrapments and tumor formation and also the relation to vascular structures. Hematomas in the vertebral canal, when avulsion is suspected, may be visualized as well as hematomas in the paravertebral muscle, indicating the severity of trauma. Later, MRI can reveal the joint deformity, capsula tears and atrophy of muscles.

Angiography

In adult traumatic brachial plexus lesions, conventional angiography was frequently indicated but is at present mainly replaced by MRA. This is evident in an associated clinical vascular deficiency (Fig. 12), but there will certainly be 'silent' vascular lesions that could pose a danger during the exploration and/or reconstruction (Fig. 13). Also this angiographic

Figure 13

A 'silent' traumatic aneurysm of the axillary artery. (From Blauuw 1999.)

information is necessary after a primary vascular reconstruction. In our series we found a total of 12 per cent associated vascular injuries in adult patients. Vascular injuries in obstetric cases are very rare (or exceptionally mentioned).

Future techniques

In the near future, endoscopic investigations within the vertebral canal may reveal avulsions or ruptures of the roots more accurately, such as partial avulsions or separate avulsion of motor and sensory roots. Apart from this aspect we are not convinced of the necessity to perform a diagnostic cervical laminectomy. Moreover, especially in obstetric cases, the non-invasive technique of sonography is sometimes capable of detecting neuroma formation in the supraclavicular region and may also be advantageous in exploring, for example, shoulder pathology.

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4
Clinical neurophysiological investigations

Jan W Vredeveld

Introduction

Neurophysiology is the study of the function of the central and peripheral nervous systems and of the muscles, and in clinical neurophysiology techniques are employed to measure these functions. It is important to realize that these techniques only measure electrical function. Anatomical information can be derived, but this is secondary. Anatomical factors can also limit the scope of measurements. However, because function is measured at the level of single cells, it is sometimes possible to collect more information than with other methods, or with clinical examination. Clinical neurophysiological techniques which are routinely used are electroencephalography (EEG), electromyography (EMG), cortical, spinal or peripheral magnetic stimulation (Magstim) and evoked potential measurement (EP). This paper will discuss the various methods and their significance for the clinician in cases of brachial plexus lesions.

The EEG

The EEG is a measurement of the electrical function of the brain. Apart from its use in research, this technique offers no information about lesions in the peripheral nervous system and will therefore not be discussed further.

The EMG

The EMG, in this chapter also including nerve conduction studies (NCS), measures the function of the motor unit and the peripheral sensory fibres and is thus the most important technique for analysing peripheral nerve lesions. Important definitions are CMAP (compound muscle action potential) and SNAP (sensory nerve action potential). CMAP is measured by stimulating the motor nerve supramaximally and recording the electrical activity from a muscle innervated by this nerve by means of surface electrodes. It is the summated potential of all muscle fibres below the electrodes and thereby indicative of the number of motor units that can still be activated. The same is true for sensory fibres in a sensory or mixed nerve when measuring the SNAP. To understand the outcome, potential and limitations of these tests, it is important to have some knowledge of the pathophysiology of a nerve lesion and to understand what can be measured.

Pathophysiology

As described by Sherrinton, the motor unit consists of the anterior horn cell in the myelum, the axon, neuromuscular synapse and all muscle fibres connected to it. A lesion of the motor unit, wherever it takes place, results in more or less the same findings on EMG: loss of function and, when the lesion is sufficiently severe, denervation. Severance of a nerve can result in neuropraxia, axonotmesis or neurotmesis.

In neuropraxia, the myelin sheath of the axon is damaged but the axon itself remains intact. The result of this is conduction loss over the damaged segment so that the action potentials from the anterior horn cell cannot reach the muscle fibres. Voluntary contraction of these motor units is not possible. However, as the axon is still intact, denervation does not occur. Stimulating and measuring distal to the lesion results in a normal CMAP or SNAP; stimulating proximal to and measuring distal to the lesion results in (partial) loss of the CMAP or SNAP. This is already the case immediately after the occurrence of the lesion.

In the case of axonotmesis or neurotmesis, denervation occurs. Initially the nerve can still be stimulated distal to the lesion, but as Wallerian degeneration takes place, stimulation becomes less effective and when the degeneration of nerve fibres is complete, stimulation no longer results in a (normal) CMAP or SNAP. This means that the residual function of the nerve can be measured after about 1 week, following which no further deterioration will occur. However, in older children and in adults it takes at least another 1–2 weeks before the muscle cells develop spontaneous activity like fibrillation potentials and positive sharp waves, also called denervation activity. In neonates these processes seem to follow a completely different time course, as we have found spontaneous activity already 4–5 days after a well-documented lesion (unpublished data, Vredeveld).

As small changes in the CMAP or SNAP will be overlooked, it is necessary to await the appearance of this spontaneous muscle activity (i.e. at least 2–3 weeks after the accident) before the EMG is a reliable indicator of the extent of the lesion. The spontaneous muscle activity disappears as the denervated muscle fibres degenerate or become reinnervated. It usually takes 1–2 years, but sometimes much longer, for spontaneous muscle activity to disappear completely.

Once Wallerian degeneration is complete, the proximal axonal stump starts to sprout and a new axon grows at a speed of roughly 0.5–1 mm per day, provided the correct path to the end-organ can be found.

Technique

To analyse a lesion in the peripheral nervous system, it is necessary to combine sensory and motor measurements. As the anterior horn cell lies within the myelum and the dorsal root ganglion outside it, the combination of a preserved SNAP and denervation in the same myotome is indicative of a root or anterior horn cell lesion. In our laboratory, the EMG starts with measurement of the SNAPs. If necessary, e.g. in the case of suspected or underlying (poly)neuropathy, CMAPs are also measured. Both techniques measure at the level of the nerve. Thereafter, needle EMG is performed using concentric needles. Monopolar needles can also be used. The needle EMG is a measurement of the motor unit. Thus, finding spontaneous muscle activity indicates a lesion in the anterior horn cell or in the muscle fibre itself, or somewhere between the two. It is impossible to differentiate between these options using a single measurement. Only the combination of several measurements from several muscles, preferably innervated by the same root but by different nerves, or by the same nerve but different roots, and the measurement of the SNAPs can give a more or less correct analysis of the lesion. Therefore, the following rules are important:

- Always sample a sufficient number of muscles, unless it is only necessary to check reinnervation in a single muscle;
- Combine needle EMG with SNAPs; as stated above, the dorsal ganglion is located outside and the anterior horn cell inside the spinal cord;
- In the case of a lesion, all muscles innervated by that root, trunk, cord or nerve must show spontaneous muscle activity in accordance with the degree of innervation by this root, trunk, cord or nerve, unless there is a partial lesion. Thus, finding partial denervation in some muscles innervated by a nerve and complete denervation in one muscle innervated by the same nerve strongly suggests a second lesion in that nerve somewhere proximal to the latter muscle.

Intra-operative EMG

The advantage of intra-operative EMG is that selective stimulation of roots, trunks, cords or nerves is possible. However, being able to measure something means that the neuromuscular synapse is still functioning, otherwise it would only be possible to measure nerve action potentials if there were functioning nerve fibres. By stimulating a nerve and measuring at some distance along that nerve, it is evident whether there are still functioning nerve fibres. However, it is impossible to tell if these are sensory or motor fibres unless it is possible to record activity from the muscle innervated by this nerve. Even then, the neuromuscular synapse must be functioning to allow some measurement, indicating that no neuromuscular blocking agents are effective. This severely limits the use of intra-operative EMG. Furthermore, in our experience it proved possible to obtain most of the necessary information before the operation by using an investigation protocol including nearly all the desired nerves and muscles. Thus, only when selective information is required is there still a place for intra-operative measurement (see also SEP).

Protocol

Based on these rules, we have developed a protocol for the analysis of brachial plexus lesions. As the findings in obstetric lesions differ from those in older patients with the same lesion, the neonatal EMG will be dealt with separately.

The standard EMG and NCS protocol used in our department is as follows:

- SNAPs from:
  Radial nerve to digit I
  Median nerve to digits I and III
  Ulnar nerve to digit V
  and, if necessary, lateral cutaneous antebrachial nerve;
- Concentric needle EMG from the following muscles:
  Abductor pollicis brevis
  First dorsal interosseous
  Flexor carpi radialis
  Flexor carpi ulnaris
  Extensor digitorum communis
  Brachioradialis
  Biceps brachii
  Triceps brachii
  Deltoid
  Pectoralis major
  Trapezius
  Infraspinatus
  Latissimus dorsi
  and Serratus anterior (not routinely sampled in neonates).

‘Adult’ lesions

This protocol has been verified in patients with a traumatic brachial plexus lesion (accepted: J Clin Neuromusc Dis). The patient group consisted of 184 consecutive patients, 153 males (6–66 years, mean 25) and 31 females (11–74 years, mean 33), admitted to our hospital because of a traumatic brachial plexus lesion. Nearly all patients were admitted between 6 weeks and 6 months after the accident, none after 1 year. In 155 patients (84 per cent) our analysis was confirmed by imaging and operative findings. This leaves 29 patients (16 per cent) in whom we missed or under-diagnosed the severity or extent of the lesion. Why?

In 22 patients we missed at least one root avulsion. As all 22 patients had a more or less complete plexus lesion, the only way to find root avulsions was by paraspinal EMG. However, innervation of the paraspinal muscles shows a considerable overlap, spanning up to six segments, and, when there is a limited number of root lesions, paraspinal denervation might disappear early. Therefore, paraspinal EMG will indicate the possibility of a root lesion, but it is impossible to be sure of exactly which root or of the exact number of roots using paraspinal sampling alone. Partial root lesions present an even greater problem. Correct location of a root lesion depends on the combination with the findings in other muscles and the SNAPs. When there is a second more peripheral lesion, the correct analysis of root lesions sometimes becomes impossible.

In one patient we missed a syrinx at the level of C5 and C6, found by MRI. This patient had a lesion of the upper and middle trunk, and the denervation we found could well be explained by the plexus lesion.

In five patients we found a normal SNAP in a severely denervated area, and hence diagnosed root avulsion. However, surgery revealed that these patients all had a peripheral lesion (neuroma) and no root avulsion. We have no explanation for this finding. So, why perform EMG?

As is apparent from our study, the EMG was reliable in detecting and analysing brachial plexus lesions in 84 per cent of the patients. Furthermore, in 37 patients lesions outside the brachial plexus were also found, most of them unexpected on clinical grounds but still important for the surgeon when operative treatment is being considered. What we found in these patients were additional, sometimes multiple, lesions outside the brachial plexus: 12 in the axillary nerve, eight in the radial nerve, seven in the musculocutaneous nerve, five in the ulnar nerve, five in the median nerve including two carpal tunnel syndromes, and three in the long thoracic nerve. Without knowledge of these lesions, a nerve graft to one of these nerves would have resulted in a very long wait for an absent recovery.

Another advantage is that reinnervation can be found and quantified even before this can be done clinically.

'Obstetric' lesions

The EMG in obstetric lesions differs essentially from the EMG in older patients: first, denervation occurs and disappears much earlier than in adults. We found that denervation can already be found on the 4th or 5th day after a lesion and has usually disappeared by 4 months, unless the lesion is severe with multiple root avulsions or ruptures. Mostly, the EMG in obstetric brachial palsy is far too optimistic compared to the clinical picture. To find an explanation for this we have selected infants with a complete avulsion of roots C5 and C6 and compared them with patients with the same lesion from the adult group. We found that after 4 months the infants showed a nearly normal EMG on reflex activated contraction of the biceps brachii, whereas the adults showed (almost) complete denervation. However, when we looked at infants with a complete avulsion of C5 and C6 and with an additional lesion of C7 or the middle trunk, the EMG showed the same picture of almost complete denervation of the biceps brachii as the adults with only avulsion of C5 and C6. This means that the innervation of the muscles in neonates differs from that in older children and adults, at least for the biceps brachii. Other studies also indicate a difference. Gramsbergen's group, from Groningen University (Netherlands), found that in rats there was polyneural innervation of the muscle fibres after birth, and they found the same in a 2-week-old full-term baby (personal communication). This polyneural innervation of the neuromuscular synapse was considered not to exist after birth but to have disappeared around the 26th post-conceptional week. Many still believe this. However, it has been shown to exist after birth in term infants, and is now believed to disappear within the first few months of life. This also explains the massive contractions and movements seen in healthy neonates. Such a process of disappearance, also called apoptosis or programmed cell death, plays an important role in the motor and sensory development. We think that, as we found in infants with an obstetric brachial plexus lesion, when the original innervation of a muscle is lost or severely damaged, this extra innervation (or so-called 'luxury innervation') stemming from other roots becomes the dominant innervation due to lack of the original dominant innervation and remains present probably during the rest of life. However, as the central motor pathways do not project primarily to the anterior horn cells of these roots, these muscles are clinically more or less paretic. They can be activated by reflex contraction, but this happens at the spinal level. This explains the far too optimistic EMG in these infants, and indicates that a second process of central development (learning) is necessary for normal motor development. This learning process largely depends on sensory input and is, therefore, also hampered by the plexus lesion.

All this does not explain yet another difference in the EMG in neonates. As mentioned, the denervation has largely disappeared by 4 months. This is not true when there is complete denervation, as in the example of the brachial biceps in avulsion of C5, C6 and C7. Provided there is still some innervation of the muscle, we have shown by single-fibre EMG that this very early reinnervation is due to massive collateral sprouting. This process is apparently much quicker in neonates than in adults, although ingrowth of new axons after a nerve graft seems to occur at about the same speed as in adults, but the distances are much shorter.

The above has led us to the hypothesis that it is very important to start trying to get sensory information into the central nervous system as early as possible (physiotherapy, caressing and training, playing), and not to wait too long before repair measures are attempted, but also not to operate too early and thus prevent spontaneous recovery. Here the EMG can help to differentiate between the infants with a good prognosis, i.e. spontaneous recovery, and a bad prognosis, i.e. the need for operative treatment. The above-mentioned facts also indicate that the EMG in obstetric lesions has to be viewed in a different way compared to the EMG in 'adult' lesions; it is important that the electromyographer assesses after reinnervation (i.e. high amplitude potentials), sometimes even more than after denervation, to reach a correct analysis of the lesion. He or she also has to be aware of the fact that normal motor unit potentials in neonates are much smaller than in adults. Thus, finding a normal 'adult amplitude' may already indicate reinnervation.

The Magstim

The first, cortical, motor neurone can be stimulated electrically using high voltage stimulators, but this is very unpleasant and more or less the same can be achieved by magnetic stimulation. A coil is placed over the cortical motor area and, using a brief, high-powered current, a short magnetic pulse is produced. This gives a rapidly changing magnetic field in the brain, resulting in a very small electric current, which can activate the motor neurones in the cortex, probably by activating some interneurones. These cortical motor neurones then activate the anterior horn cells, which in turn start firing and activating the muscle fibres. A contraction can then be registered. Theoretically, this method is ideal for testing the anterior roots. However, more peripheral lesions will hamper the measurement and also the activation is dependent on the patient's co-operation. The best results are obtained with a slight pre-test contraction of the muscle. Other disadvantages are that it does not differentiate the route by which the impulses reach the muscle, and cortical magnetic stimulation during narcosis is almost impossible. This method is thus less suitable for routine use and its value in analysing brachial plexus lesions has yet to be established.

The somatosensory evoked potentials (SEP)

The somatosensory evoked potentials are a measurement of the somatosensory pathway from a peripheral nerve up to the sensory cortex. Measurement is done by electrical stimulation of a peripheral nerve, e.g. a digital nerve, and recording from electrodes overlying the somatosensory pathway up to the cortical representation area. This pathway can be divided into smaller segments for more precise localization. When a normal cortical response is measured, the conclusion must be that at least a sufficient number of sensory fibres, both peripheral and central, is functioning normally. This includes the plexus and the dorsal roots. When the response is lost, there must be a significant lesion somewhere between the site of stimulation and the site of measurement. Other lesions more central to this lesion can no longer be measured. This is also the limitation of the use of the SEP in brachial plexus lesions; the response will be lost at the most distal lesion in the somatosensory pathway.

However, it is still possible to register SEP during narcosis. Hence, by stimulating the roots during surgery it can be established whether the dorsal roots (= somatosensory input!) are more or less intact.

Conclusion

In lesions of the peripheral nervous system, the EMG and SEP are the most important techniques for analysing the severity and extent of the lesion, the EMG being the most important. In 'adult' brachial plexus lesions the reliability of the EMG is high, the limitations are few and are known, and even clinically undetected but important lesions can be found, provided the investigation has been sufficiently thorough. Reinnervation can also be detected even before it becomes clinically evident. In obstetric brachial plexus lesions, the EMG presents more problems due to the different anatomy and the early appearance and disappearance of denervation, and to the very early reinnervation. However, bearing this in mind, the EMG in neonates also offers a reliable analysis of the lesion.

Recommended reading

For EMG, most handbooks can be used. One of the most recent and detailed handbooks of EMG dealing with brachial plexus lesions is:

Dumitru D (1994) Electrodiagnostic medicine. In: *Brachial Plexopathies and Proximal Mononeuropathies*. Hanley & Belfus Inc: 585–642.

For EMG prognosis of obstetric lesions:

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For the difference in findings between obstetric and adult lesions:

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The Adult Traumatic Brachial Plexus

5

Etiology

Panupan Songcharoen

Historical introduction

Knowledge about the brachial plexus can be traced back to the second century when Galen accurately described its anatomy (McHenry 1969). Early on, the brachial plexus was viewed only as a part of the peripheral nervous system and has been treated accordingly for nearly two millennia. At the beginning of the nineteenth century, brachial plexus injury became a separate clinical entity from other peripheral nerve lesions (Malessy 1999). The etiologic factor in brachial plexus injury has gradually shifted from one of 'open injury' in the American Civil War and two World Wars to 'closed injury' arising from road traffic accidents of the present day, especially involving motorcycles.

Brachial plexus injury can be caused by a wide variety of circumstances. These etiologic factors can be categorized according to their causative mechanisms as follows:

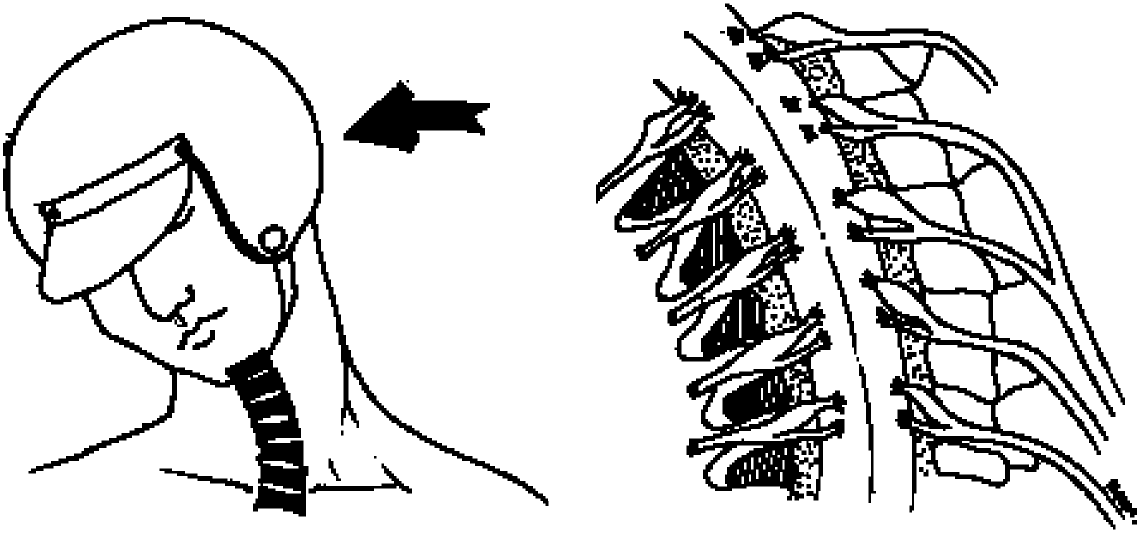
- Closed injuries
  - traction
  - compression
  - combined lesion
- Open injuries
  - sharp
  - gunshot
- Radiation

In closed brachial plexus injuries, the most commonly found causative mechanisms were traction or contusion. In some circumstances, the injuries were the result of a combination of traction and contusion. At present, traction is the most frequently found mechanism of brachial plexus injury. In our series of adult brachial plexus injuries, 95 per cent were caused by traction.

Traction lesions

Traction lesions result from forceful separation of the neck and shoulder or upper arm and trunk. The nerve pathology occurs between the two anchoring points. The proximal anchoring point is at the spinal cord and nerve root junction, and the distal point is at the neuromuscular junction. The coracoid process is regarded as a temporary lever in forceful hyper-abduction of the shoulder. It is not only the direction of the applied force to brachial plexus that determines the severity of the nerve damage, but also the speed of application of the traction force.

High velocity traction injury is the overall leading cause of brachial plexus injury in almost all reports (Alnot 1987, Songcharoen 1995). The majority of traction injuries result from road traffic accidents. In our series of 1173 adult brachial plexus patients, 82 per cent were caused by motorcycle accidents. The victim falls off a speeding motorcycle and lands on the head and shoulder. On ground impact, the shoulder is depressed and the head is forcefully flexed to the opposite side. The sudden widening of the neck–shoulder angle causes a severe traction injury to the clavicle and the underlying structures including the brachial plexus and subclavian vessels. If the clavicle which is the strongest link between the shoulder to the neck is broken, all the traction force is then transmitted to the neurovascular bundle (Fig. 1). This mechanism of injury causes greatest damage to the upper roots. While hyper-abduction of the shoulder or forceful widening of the scapulo-humeral angle mostly affects the C8 and T1 roots, the high velocity traction injury can cause nerve root avulsion from spinal cord (Fig. 2). The structures protecting the cervical nerve root from traction



a b

Figure 1

(a, b) The sudden widening of the neck–shoulder angle causes a severe traction to the brachial plexus.

force are, firstly, the cone-shaped dural continuation in to the epineurium of the cervical spinal nerves, and secondly, fibrous attachments between the epineurium of spinal nerves C5, C6, and C7 and the cervical transverse process at the neural foramen. The absence of these ligaments at C8 and T1 is the rationale behind the higher incidence of C8–T1 root avulsions compared with C5, C6, which sustain a higher incidence of extraforaminal rupture. High velocity traction injuries are also incurred in speed-boat, car and ski accidents.

Figure 2

Complete C5 to T1 root avulsion from the spinal cord from traction injury.

Low velocity traction injury has a much lower incidence than the high velocity injury. Only 4 per cent of patients in our series suffered this kind of injury. This injury is usually incurred by the victim falling from a height and landing on the shoulder, or may be caused by a heavy object falling on an unprotected shoulder. In industrial situations, the worker's arm may be caught and pulled by a machine causing a stretch injury to the plexus. In sports, a rugby or American football player tackling an opponent with head and shoulder or a volleyball player practising heavy overhead smashes may experience a transient paresthesia in the upper extremities. These lower velocity injuries usually produce a lesser degree of brachial plexus pathology.

Improper patient positioning in the operating room during general anesthesia can cause traction injuries to the brachial plexus (Cooper 1991). The upper trunk can be injured due to prolonged extension and lateral bending of the head to one side with the patient in the supine or lateral decubitus position. This posture will increase the angle between the head and the affected shoulder. The shoulder that is positioned on a sandbag or a roll can put the brachial plexus under tension. Suspension of the arm from the operating table screen in the lateral decubitus position may stretch the brachial plexus, especially when the arm is in hyper-abduction.

Excessive abduction of the arms in either the prone or supine position (e.g. position for spinal procedure) also causes stretching of the brachial plexus.

Compression lesions

The brachial plexus may be compressed between the clavicle and first rib. The compression occurs when the traumatic force exerts itself on the shoulder in the cephalocaudal direction. The bone fragments from a cervical transverse process fracture can compress the cervical nerve roots and a coracoid process fracture can compress the lateral cord and musculocutaneous nerve. The fracture of the neck of scapula, humeral neck fracture and anteriorly dislocated humeral head compresses the posterior cord and axillary nerve. The fracture of the scapular spine can compress the suprascapular nerve.

Acute compression by seat belts may also cause brachial plexus injuries in car accidents. Chronic compression by carrying heavy weights on the shoulders may cause a temporary brachial plexus lesion.

Iatrogenic compression injuries to the brachial plexus in the operating room can occur by improper placing of shoulder pads on an abducted arm while the patient is in a steep Trendelenburg position (Cooper 1991). If the shoulder pads are placed medial to the acromioclavicular joint instead of indirectly over the joint, the pads directly press the brachial plexus against the first rib. Compression of brachial plexus can also occur as the arm and shoulder lie between the patient's chest and the operating table when in the lateral decubitus position. The bony structure of the shoulder and the arm compress the plexus against the rib cage.

Traction and compression

The complex trauma with multiple fracture of cervical transverse process, clavicle, scapula, rib and proximal humerus can cause both compression and traction injury to the brachial plexus. The pathology on the plexus is usually diffuse from nerve roots through terminal branches, disruption of brachial plexus can be found on more than one site. This injury is usually associate with vascular damage.

Open injury

Open injury of the brachial plexus is normally much less common than closed injury. In our series 4.3 per cent of patients sustained open injury to the brachial plexus.

Sharp injury secondary to assault by knife in the neck, chest or shoulder can directly injure the brachial plexus. The open injury usually involves only part of the plexus. Associated vascular and intrathoracic injury can commonly be found. This kind of injury to the brachial plexus carries a good prognosis. The injured plexus can usually be treated by neurorrhaphy and nerve grafting. Iatrogenic sharp injury to the brachial plexus may occur in brachial plexus block, tumor mass resection at the neck and supraclavicular area, occasionally an intact brachial plexus may be damaged during attempts to stop severe bleeding from vascular injury or by insertion of subclavian lines.

Gunshot injuries to the brachial plexus may be encountered under several military and civilian circumstances. This kind of injury may be accompanied by life-threatening vascular or thoracic lesions. Gunshot injuries should be separately considered from sharp open injuries as there are significance differences in the extent and character of the neural and surrounding tissue damage. In gunshot injuries, the cause of tissue disruption is the high velocity and the spin of the bullet. The tissue is firstly crushed from direct contact with the high velocity bullet and then stretched from temporary cavitation. The potential for tissue disruption depends on the bullet mass, shape, construction and striking velocity (Omer 1991).

Low velocity gunshot injury is commonly found in civilian practice. This kind of injury was found in 2.7 per cent of patients in our series. This type of brachial plexus injury without any associated vascular injury carries a good prognosis. More than half of the patients have a significant functional recovery with non-operative treatment.

High velocity gunshot injury has a greater tissue penetration. This kind of injury produces a more extensive and diffuse lesion where it is difficult to define the extent of neural tissue damage at the early stage. High velocity gunshot injury is less common in civilian practice, and spontaneous functional recovery in less likely.

Shotgun injury usually produces extensive tissue damage and contamination. This kind of injury has less chance of spontaneous recovery than low velocity gunshots.

Radiation injury

In general, peripheral nerves are considered to be relatively radioresistant due to their deep situation and low metabolic rate.

Radiation brachial plexus injury is sometimes found in patients several years after radiation therapy to the ipsilateral breast or axilla after treatment for breast cancer. Patients usually present with progressive motor and sensory deficit which may be caused by radiation or compression of recurrent neoplasm. Investigations and meticulous clinical examination can clarify the diagnosis in some patients, but a number of patients will remain undiagnosed until a later stage. Surgical exploration is difficult because of the fibrotic and ischemic nature of the surrounding tissues. Despite the unrewarding results, surgical exploration is usually insisted upon by the patient because of the intractable pain.

Adult traumatic lesions of the brachial plexus can also be classified according to the anatomical level within the plexus and their relation to the clavicle. By using the clavicle as a reference, the lesion can be localized at three levels: supraclavicular, retroclavicular and infraclavicular. To be more specific, the supraclavicular lesions are separated into two types in relation to the dorsal root ganglion: supraganglionic and infraganglionic. Although the clinical significance of this classification is rather limited, because of the variation in other factors such as extent of the lesion, mechanism of injury, multilevel lesion, etc, this anatomical classification more or less helps the plexus surgeon to determine the suitable type of surgical treatment and prognosis of the patient.

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6
Surgical techniques: neurolysis, sutures, grafts, neurotizations

Michel Merle and Aymeric Lim

Introduction

Direct surgery of the brachial plexus necessitates the level of technical equipment and team proficiency found in all vascular and nerve microsurgical centers. Operating times are relatively long, from 3 to 10 hours depending on the nature of the lesions. The incision starts at the mastoid, follows the sternocleidomastoid muscle, then the anterior aspect of the clavicle and the deltopectoral groove, and may extend, with a Z-shaped plasty, into the axillary region and even into the brachial canal. When the preoperative diagnosis is precise, a shorter incision may suffice, centered on either the supraclavicular or the deltopectoral area.

In the first 100 operations of our series, we were led three times to divide the clavicle; this was done to gain better access to the C8 and D1 roots that were adhering to the subclavian artery or was made necessary by a significant retraction of the fasciculi behind the clavicle.

Conversely, in the last 100 cases, the percentage of clavicle divisions rose to 13 per cent. We now consider that this gives safety in controlling the whole length of the subclavian artery and permits better identification of lesions of the C8 and D1 roots. Division of the clavicle has a low complication rate when the osteosynthesis is performed using screwed-on plates. To date, in 23 clavicle divisions we have seen only one septic condition, and that had no adverse consequence on bone healing. Finally, this procedure does not lengthen the operative time; on the contrary, it may shorten it by making dissection easier, especially when the most proximal roots of the brachial plexus are retracted behind the clavicle.

Therapeutic options in the field of direct repair of brachial plexus lesions keep getting better. Only one matter remains controversial today, namely neurolysis. In our view, end-to-end suture of brachial remains the most frequently used technique. Neurotizations are procedures of last resort, reserved for the most severe plexus lesions.

Neurolysis

Microsurgical neurolysis of the brachial plexus is a controversial procedure with uncertain results, but could be indicated if a conduction block (neuropraxia) does not resolve itself spontaneously. This condition is generally caused by a dense perineural fibrosis. Fibrotic reaction is usually triggered by post-traumatic hematoma, but can also be found following stretch injuries. Operative palpation of roots and fasciculi reveals the characteristic intraneural sclerous nodules. Only intraneural and interfascicular neurolysis can free the fasciculi, but the method provokes devascularization with a risk of a new fibrosis.

It is often the surgeon's experience that determines the type of neurolysis used. The danger in performing a strictly extraneural neurolysis is that it may leave undetected a complete rupture hidden under the apparent continuity of fibrotic epineurium. Fibrosis and lack of flexibility of the nerve trunk must impel the surgeon to be aggressive and look for the fascicular rupture by intraneural dissection.

Our results demonstrate the difficulty of the procedure. Objective amelioration after neurolysis was observed in less than 50 per cent of our patients; 10 per cent were made worse, and 40 per cent had no amelioration following this microsurgical technique.

Experience has shown that when clinical and electromyographic manifestations of nerve regeneration tend to stagnate, it is legitimate to propose a neurolysis before the sixth month post-injury.

Sutures

End-to-end suture

In our series of 386 cases of surgical procedures on the brachial plexus, we have done only five primary repairs for lacerations, all of them by suture.

In these cases of partial lesions the prognosis is good, because it is relatively easy to reconstitute the general fascicular organization of the nerve trunks. Such partial wounds must be repaired immediately. Neglecting them leads to dangerous and complex secondary microsurgical procedures; during these, intraneural dissection is required to separate the neuroma from uninjured fasciculi, with a significant risk of lesion to these intact structures.

Early in the series we attempted immediate repair of stretch injuries of the brachial plexus. The four cases operated on following this scheme had to undergo secondary surgery, with fascicular grafting or neurotization. Fresh lesions of the brachial plexus usually necessitate dissection in the middle of a diffuse hematoma. Because we had underestimated the extent of the plexus lesions, the primary repairs by suture (or in a few cases by grafts) failed, and secondary procedures were necessary.

End-to-side nerve suture

In 1992, Viterbo et al re-established the principle of neurotization by end-to-side nerve suture be demonstrating its efficacy in the rat. Kennedy (1901), Ballance et al (1903), Harris and Low (1903) and Gatta (1938) were the first to apply this concept, but the results were far from convincing. Eventually, Lundborg et al (1994) were able to show that it is possible for axono-lateral regeneration to produce function in secondarily innervated muscles. Mennen (1998) reported a series of 22 patients, all of whom had undergone an end-to-side nerve suture. An epineural window was made in that intact and receiving nerve, taking care not to disrupt the fascicles. The proximal extremity of the other was then implanted with 8.0 prolene sutures. Four of the 22 cases involved neurotization of the biceps, and of these, two patients recovered power of M4.

Grafts: free and vascularized

Most traumatic ruptures of the brachial plexus can be repaired by fascicular grafts according to Millesi's principles (Millesi et al 1973; Millesi 1977). Appropriate restoration of the fascicular organization of the brachial plexus is a 'mission impossible'. In the last 100 years or so, there have been numerous attempts at clarifying the anatomy of the brachial plexus; these studies started with Herringham (1886), Agostini (1887) and Adolfi (1898), followed by Kerr in 1918, Ko Hirasawa (1928) and Billet (1933). More recently, Sunderland (1977) and Seddon (1972a, 1972b) have contributed to the study of the fascicular organization of the brachial plexus. Their studies show that there is no systematization of the brachial plexus, that variations from root to root among individuals are great, and that both sides of the same individual do not have the same organization.

The in-depth studies of Bonnel (Bonnel and Rabischong 1976; Bonnel 1977) have shown that fascicular organization in a given root varies with each subject. Microsurgery helps to analyze the fascicular disposition and enhance the quality of graft/fascicle abutments. The quality of these abutments and the rapidity with which surgery can be performed have been further improved by the recent availability of biologic glues such as Biocol and Tissucol (Merle et al 1987).

Microsurgical techniques also make it possible to remove the connective tissue surrounding the fascicular groups. Bonnel has showed that 70 per cent of a cross-section of the axillary nerve is occupied by connective tissue; the ulnar nerve contains even more at 82 per cent (Bonnel and

Rabischong 1976; Bonnel 1977). The repair strategy is greatly influenced by the type of lesion and by the number of roots or trunks that can be repaired.

First, the brachial plexus is dissected and the lesions are precisely identified, keeping in mind that supraclavicular lesions are often in continuity; then plexus root trunks are sharply cut back to healthy neural tissue using Meyer's guillotine knife. Nerve grafting is performed according to Millesi's technique (Millesi et al 1973; Millesi 1977). In the past few years, this technique has been modified by the use of biologic glues such as Tissucol (Merle et al 1987). Formerly we used two or three stitches of 9.0 and 10.0 polypropylene monofilament to suture each fascicular group. This procedure was time-consuming and somewhat damaging to perineural and neural tissue.

Our experience of gluing nerve grafts has shown that results obtained are significantly superior to those observed following conventional suturing; gluing facilitates abutment of the nerve substance and also minimizes handling of the nerve ends, thereby reducing unwanted mushrooming.

Short grafts (5–7 cm long) are used to repair the upper trunk; surrounding tissues have a favorable influence on graft revascularization, which is obtained in a few days. Conversely, extensive lesions necessitate long grafts (10–15 cm), and the tissue environment is less favorable. In these cases, we prefer to use vascularized nerve grafts. The principle of vascularized grafts was developed by Taylor for the repair of large losses of substance in peripheral nerves (Taylor and Ham 1976). Later, Comtet put into use the principle of vascularized transfer of the cutaneous antebrachii medialis nerve. Birch presented a large series of plexus brachial grafts using the vascularized ulnar nerve of the forearm (Bonney et al 1984). In our protocol, we use the ulnar nerve vascularized by the collateral proximal ulnar artery originating at the brachial artery. This donor site has the advantage of not interrupting the continuity of the principal vascular axis, which are the cases when the forearm ulnar nerve is used. According to Lebreton, the collateral proximal ulnar artery exists in 94 per cent of cases (Lebreton et al 1983). The vascularized graft can be used as a free graft as well as a transposed local graft. The vascularization of the graft facilitates axonal progression, and within the first 6 months after vascularized grafting, progression of the Tinel sign averages 2 mm per day. Contractions of the biceps muscle appear at about the ninth month. With conventional grafts, equivalent results are not seen before the twelfth month. We have observed, however, that results obtained with conventional grafts and with vascularized grafts tended to be similar in the long run. Nevertheless, we believe that results are more consistent after vascularized grafts, as long as there is no embolization of the anastomosis. In our series of 13 cases of vascularized grafts on the brachial plexus, seven were free grafts with arteriovenous anastomosis and six were pediculized grafts. The length of the free grafts varied from 12 to 18 cm; that of the pedicled grafts varied from 23 to 26 cm. We have observed three results at M4, six at M3+, two at M3–, and two at M2.

This technique, however, is of limited use because it implies the intradural avulsion of the C8 and T1 roots. Also, in the event of thrombosis of the vascular anastomosis, results will be inferior to those of conventional grafts because the central part of the grafts will undergo necrosis.

Vascularized allografting is a way of getting around the problem of donor site scarcity, but makes immunosuppressant treatment indispensable. Studies by Bour et al (1986) have shown that nerve regeneration is possible through vascularized allografts as long as cyclosporine is administered; interruption of the immunosuppressive treatment brings about deterioration of the graft and, consequently, of the functional condition.

In the present state of experimental studies, use of these vascularized allografts is not justified because continuous postoperative immunosuppressive treatment is unacceptable in reconstructive surgery.

Neurotizations

Intradural avulsions can involve one, several or even all the roots of the brachial plexus. Neurotization aims to salvage the functional or trophic condition of the upper limb. The principle of neurotization dates from the turn of the century. Harris and Low were the first to propose it in 1903, followed by Tuttle who, in 1913, suggested the use of the spinal accessory nerve. Vulpius and Stoeffel (1920) suggested the use of the N. pectoralis. In 1929, Foerster used the thoracicus longus nerve. In 1948, Yeoman and Seddon (1961) and Fantis and Sîezak (1965) performed neurotization with the intercostal nerves, and the concept was taken up again by Tsuyama in Japan in 1972 (Tsuyama and Hara 1972). In 1980, Brunelli proposed using the whole cervical plexus (Brunelli and Monini 1984). As for us, we followed Kotani and Allieu and used the spinal accessory nerve, which comprises about 1700 fibers, to reinnervate the biceps muscle (Kotani et al 1971; Allieu et al 1982).

Neurotization of the biceps using the spinal nerve

The spinal accessory nerve is used at its exit point from the sternocleidomastoid muscle; a 5–10 cm long graft connects it to the fascicular group of the musculocutaneous nerve, which has usually been dissected interneurally for a length of 4 cm in the lateral cord.

Out of 14 neurotizations of the biceps muscle, we obtained six good or very good results, two average, and six poor or null results. Narakas, by pooling the results of all spinohumeral neurotizations performed by seven surgical teams, has shown that 37 per cent of the cases had useful results as far as the biceps was concerned (Narakas 1989; Narakas et al 1989).

We continue to neurotize the biceps using this technique; it is advantageous because functional results are acceptable in nearly 40 per cent of the cases and because the inferior portion of the trapezius muscle is preserved, being innervated in most cases by rami from the cervical plexus (Bonnel and Rabischong 1976).

Neurotization using the intercostal nerves

There is an alternative to the use of biceps neurotization; neurotization by intercostal nerves. Seddon's idea was taken up again by Tsuyama (Seddon 1972b; Tsuyama and Hara 1972). Three or four intercostal nerves are used.

Respiratory potentials sent into the biceps muscle can restore true function to the elbow after a period of time. The fatigue phenomenon sets in relatively quickly, but there is some adaptation in the long run: respiratory potentials fade away and are replaced by voluntary muscle activity. This method is presently pursued in Japan, where it was developed by Tsuyama (Tsuyama and Hara 1972). In Europe it is used equally with neurotization by the spinal accessory nerve and complementary neurotization by the cervical plexus as developed by Brunelli (Brunelli and Monini 1984). Narakas prefers to use the spinal accessory nerve to neurotize the suprascapularis muscle, and to neurotize the biceps muscle by intercostal nerve transfer (Narakas 1989).

Neurotization of the biceps using the intact ulnar nerve

In C5, C6, C7 root avulsions, Oberlin et al (1994) have suggested using 10 per cent of the fascicles of the ulnar nerve for direct anastomosis with the motor nerve to the biceps. The suture is technically easy, because the musculocutaneous and the ulnar nerves are found side by side. In a series of 18 cases reported by Loy et al (1997), seven out of eight patients who presented with a C5, C6 avulsion recovered elbow flexion, and four out of nine patients presenting with C5, C6, C7 root avulsions recovered flexion by this neurotization technique only. Clinically, no sensorimotor deficits were created in the territory of the ulnar nerve. By intraoperative electrostimulation, the authors prefer to use one or two of the fascicles destined for the extrinsic flexors, flexor digitorum profundus or flexor carpi ulnaris.

Neurotization of the brachial plexus by the C7 contralateral nerve root

In 1989, Chuang (1999) reviewed the principle of contralateral C7 transfer, a technique first proposed by Gu in 1986 (Gu 1989). Gu had proceeded in two operative stages. The first involved anastomosis of the contralateral C7 nerve root with a pedicled ulnar nerve graft taken from the side of the paralyzed limb. Then, 8–12 months later, the distal part of the reinnervated ulnar nerve graft was sutured to the avulsed plexus, giving precedence to the muscolocutaneous nerve, the median nerve, the axillary nerve and then other nerves.

Chuang prefers to transfer the ulnar nerve with the ulnar artery and thus directly neurotize the plexus. In a series of 67 patients (Chuang et al 1993), Chuang reported useful results in 67 per cent of cases. He noted that sectioning of the C7 root can create a temporary weakness of the triceps of the donor upper limb and dyesthesias over the skin of the dorsum of the hand supplied by the radial nerve. The main difficulty for the patient is producing movement on the contralateral side. In our experience, 18–24 months are required before the patient can integrate the movement of elbow flexion. This technique should only be used when no homolateral neurotizations are possible.

Whichever technique is used, neurotization has two goals; to avoid amputation of the paralyzed arm and to provide trophic condition and comfort compatible with everyday life. The result is usually a live arm that performs as poorly as a prosthesis or even worse. The brachial plexus contains at least 150 000 fibers, and the number of fibers usable by the surgeon for arm neurotization is no greater than 1300 in each intercostal nerve and 1700 in the spinal accessory nerve.

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7 Supraclavicular plexus injuries

Jean Y Alnot

Traumatic brachial plexus injuries are characteristic of young adults aged 18–20 who have sustained a motorcycle or car accident. Whatever the clinical presentation, a patient showing no recovery at 4 or 6 weeks after a traumatic palsy must undergo investigation (CT-myelography and EMG) in order to identify the surgical indications early enough.

Our experience at Bichat Hospital includes more than 1200 cases operated on between 1975 and 1998, the results of which have been published (Alnot 1993, Alnot et al 1993, Alnot and Oberlin 1993, Alnot 1995, Alnot et al 1996, Alnot et al 1998), as have the results of many other authors (Narakas 1978, Brunelli and Monini 1984, Millesi 1984, Sedel 1986, Terzis 1987, Allieu et al 1997). A better comprehension of pathological lesions (Sunderland 1978, Millesi 1984, Alnot et al 1996) leads to a clearer classification of injuries, because classifications are essential if we want to evaluate the results, particularly after nerve repair, and the use of charts and diagrams describing the nerve injuries and the type of repair is a great help for further follow-up.

Lesions can be situated at any level from the base of the nerve roots to the division of the brachial plexus in the axillary regions, and several types of lesions can be differentiated:

- Supraclavicular lesions at root or primary trunks level (75 per cent of cases);
- Infra- and retroclavicular lesions of secondary trunks (10 per cent of cases);
- Terminal branches (15 per cent of cases).

Among the palsies due to *supraclavicular lesions*, the following can be distinguished:

- C5–C6 or C5–C7 palsies which occur in 20–25 per cent of cases;
- C8–T1 palsies which occur in 2–3 per cent of cases;
- C5–C8–T1 lesions which are the most frequent, occurring in 75–80 per cent of cases.

It is important to determine the exact site of the lesions as this will greatly bear on prognosis and on the future of the patient.

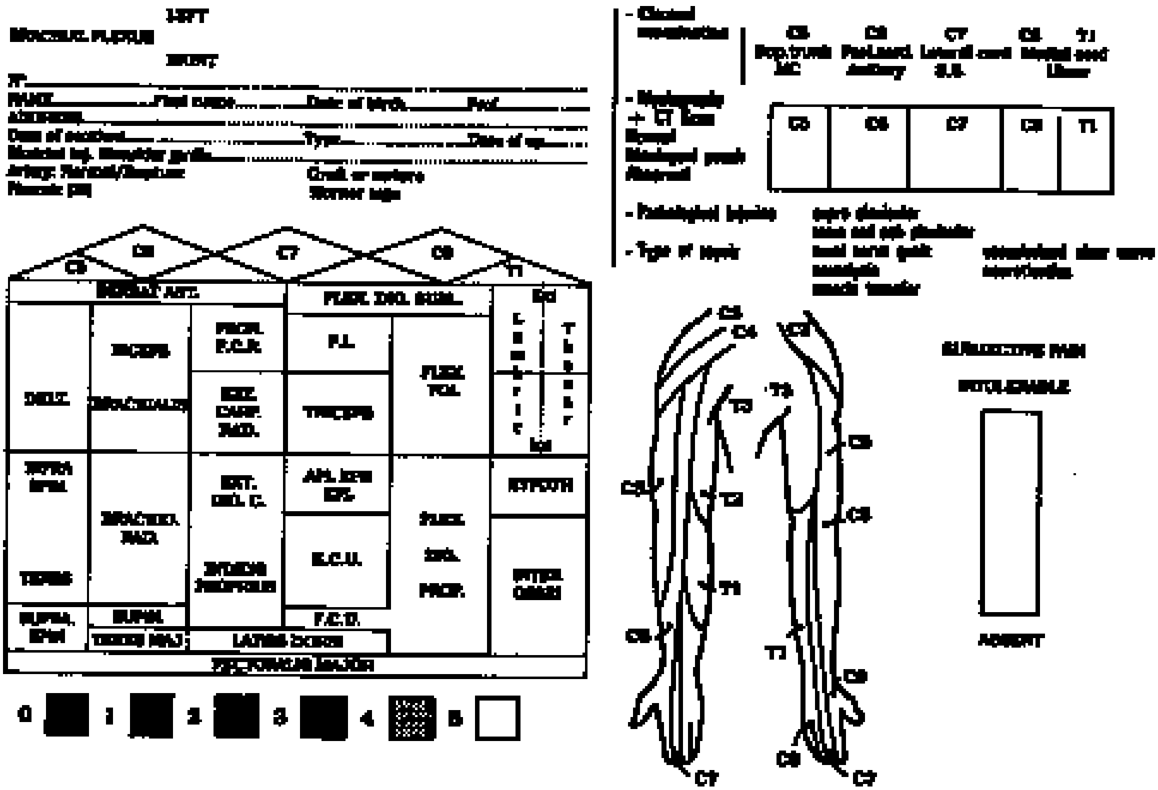
Careful clinical as well as paraclinical examination should be rapidly undertaken in order to obtain an exact diagnosis and permit intervention within a period of 6 weeks to 3 months after trauma (Fig. 1).

Clinical examination, supported by paraclinical investigations, permits evaluation of nerve lesions according to the roots that have been affected, after which therapeutic indications and a prognosis can be made.

Some factors can be considered favorable and, for example, a patient with a brachial plexus palsy secondary to dislocation of the shoulder due to a minor trauma has a 90 per cent chance of recovery (Sunderland grades 1 to 3) but in some cases there are ruptures at the level at terminal branches with indication for repair.

By contrast, the following factors carry a poor prognosis:

- Violent trauma involving the upper limb as well as the plexus. Multiple bone fractures and other traumatic lesions are frequently found in the injured upper limb (21 per cent of all cases); bone lesions are found in 58 per cent of these cases and vascular lesions in 11 per cent;
- Serratus anterior involvement and presence of Horner's syndrome, both of which indicate a proximal lesion;
- Presence of pain and medullary signs suggesting injury to the cord.



a b

Figure 1

(a, b) Charts for recording clinical and paraclinical findings.

Repeated clinical examination shows the evolution over time, and if there is no clinical recovery within a period of 30 days, paraclinical investigations such as CT-myelography and EMG should be done. The value of CT scan-myelography is to establish the existence of root lesions and especially root avulsion with pseudomeningocele (rupture of the dura sheath and rootlets).

In peripheral mechanisms, depending on the direction of traction, the forces have an action on anterior and posterior rootlets.

Avulsion is a very specific injury at the level of spinal rootlets, and is beyond surgical possibilities for repair. The rootlets are avulsed from the spinal cord, notably C7 and mostly C8 and T1 which become horizontal with abduction of the arm. Superior C5 and C6 roots, because of their oblique route, are often ruptured more distally in the scalenic region. Nerve injury can also be located immediately next to the transverse canal with frequently longitudinal disruption injuries and staged ruptures of the nerve fascicular groups, from the transverse canal to the interscalenic space. Nerve repair remains possible in some cases, but the proximal stump may, to some extent, have lost its possibility of axonal regeneration. Besides, damage to the fascicular groups in the transverse canal can cause retrograde degeneration of nerve fibres, involving the motor cell in the ventral horn or the sensory cell in the posterior ganglion, which is equivalent to avulsion.

Rupture can be more distal in the supraclavicular area, between the scalen muscles and beyond, preserving a proximal stump of root or of trunks of variable length and quality, possibly available for nerve repair; EMG is also a part of the assessment and is particularly useful in C5–C6 and C5–C7 palsies.

The surgical indications depend on the clinical evolution and decisions can be based on all the factors discussed above. In our experience there is no indication for immediate nerve repair; the palsy is assessed by repeated motor and sensory examination and CT-myelography must be done if there is no clinical and electrical recovery after 4 to 8 weeks, depending on the general condition of the patient. The prognosis depends on the anatomy and type of lesions and the early therapeutic indications (first to third month) also depend on knowledge of the anatomical lesions.

Surgical procedure

The operation is carried out through a long zig-zag cervico-axillary incision and the whole plexus must be explored. Two types of skin incision are described depending on the authors:

- A large 'Z' incision including a vertical cervical incision at the posterior border of the sternocleidomastoid (SCM) muscle; a horizontal subclavicular incision, and a vertical incision in the deltopectoral groove;
- Multiple zig-zag incision at the level of the cervical area to avoid a retractile scar, and open 'V' incisions in the subclavicular area and in the deltopectoral groove.

The key of the *cervical approach* is the omohyoid muscle. It must be located at the beginning of the dissection and must be transsected in its middle and retracted laterally in order to expose the supraclavicular plexus. The approach is done at the posterior border of the SCM muscle; the external jugular vein must be preserved with the posterior SCM muscle belly. The lateral transverse branches must be ligated but the nerve branches of the superficial cervical plexus must be preserved.

At the upper part of the triangle made by the SCM and the trapezius muscle, the C4 loop must be preserved on to the SCM muscle belly and it represents an important topographic landmark. Then, the scalene outlet must be exposed and the phrenic nerve, at the anterior aspect of the anterior scalenus muscle, must be located and stimulated. The transverse cervical artery and vein must be ligated to complete the exposition of the plexus.

The suprascapular nerve is an essential landmark as there is no nerve element lateral to it. It is also important to locate the Charles Bell nerve which must be preserved. Finally, the spinal accessory nerve must be dissected if a neurotization is scheduled. It is important not to dissect it proximally in order not to destroy the branches for the upper and mid-trapezium. If neurotization must be done with the distal accessory spinal nerve the section can be performed after the departure of the branches for the upper trapezius muscle.

The key of the *subclavicular and axillary approach* is the pectoralis minor muscle. The approach in the deltopectoral groove must be wide and must respect the cephalic vein. Disinsertion of the lateral part of the clavicular insertion of the anterior pectoralis major can be convenient.

The pectoralis minor must then be dissected and exposed, and in certain cases it may be necessary to divide it.

A communication between the cervical area and the axillary area is then established under the clavicle using a sponge held with a clamp. In the majority of cases, it is not necessary to cut the clavicle; this additional step which has been recommended systemically by some authors is now only done in sub- and retroclavicular brachial plexus palsies.

The musculocutaneous nerve is identified as it enters the coracobiceps muscle. This must be systematic in all explorations in order to avoid a double level lesion.

The other nerves are identified and the dissection is performed distal to proximal and proximal to distal.

The axillary artery can be also located.

A complete evaluation of the lesions is made after exploration of the whole plexus. However, if there are meningoceles on C8 and T1 it is not necessary to explore these roots locating in a deep area with a dangerous dissection.

At the end of the procedure, depending on the types of exploration and on the repair, closure is done plane by plane without drain, or only in certains cases with a superficial drain at the distal part of the incision, at some distance from the nerve grafts.

In the immediate postoperative period, immobilization of the resected area with the elbow against the thorax is done for a period of 3 weeks, associated with a cervical collar if nerve grafts have been performed at the level of the roots.

The type of the repair depends on the localization of the lesions and, in a majority of cases, there is a C7–C8 and T1 avulsion. C5 and C6 roots are vertical and will have lost their oblique direction and they will then be explored in the scalene outlet.

Nerve grafts (sural nerve or more rarely the ulnar nerve as a free or vascularized graft) will be performed depending on the root rupture in the scalenic area. Neurotizations must also be performed (spinal accessory nerve, intercostal nerves, etc).

For intercostal nerve neurotization, a skin incision is performed below the pectoralis major muscle. Three intercostal nerves (D3, D4, D5) are transected anteriorly to perform a direct suture with the musculocutaneous nerve, for example. Several clinical pictures can be described.

Complete palsy without recuperation

Total palsies with avulsions of the lower roots (64 per cent of cases)

CT-myelography shows pseudomeningoceles at C8 and T1 and often at C7. Root C6 may have an abnormal aspect and C5 is usually normal in the CT scan. In these total palsies with avulsion of the lower roots (C7, C8, T1) when there is only one or two roots that are ruptured in the scalenic area, it is not possible to graft all the plexus. The surgery must be performed early (6 weeks to 3 months) and our approach is to aim for re-innervation of the proximal territories. The patients must be informed that they will have definitive paralysis of the hand.

The results depend on the anatomo-pathological lesions. When only one root (C5) can be grafted (Fig. 2a), our choice will be to repair the anterior part of the first trunk with the C5 root and the suprascapular nerve by neurotization (direct suture) with the spinal accessory nerve which is divided distal to the origin of the

a

b

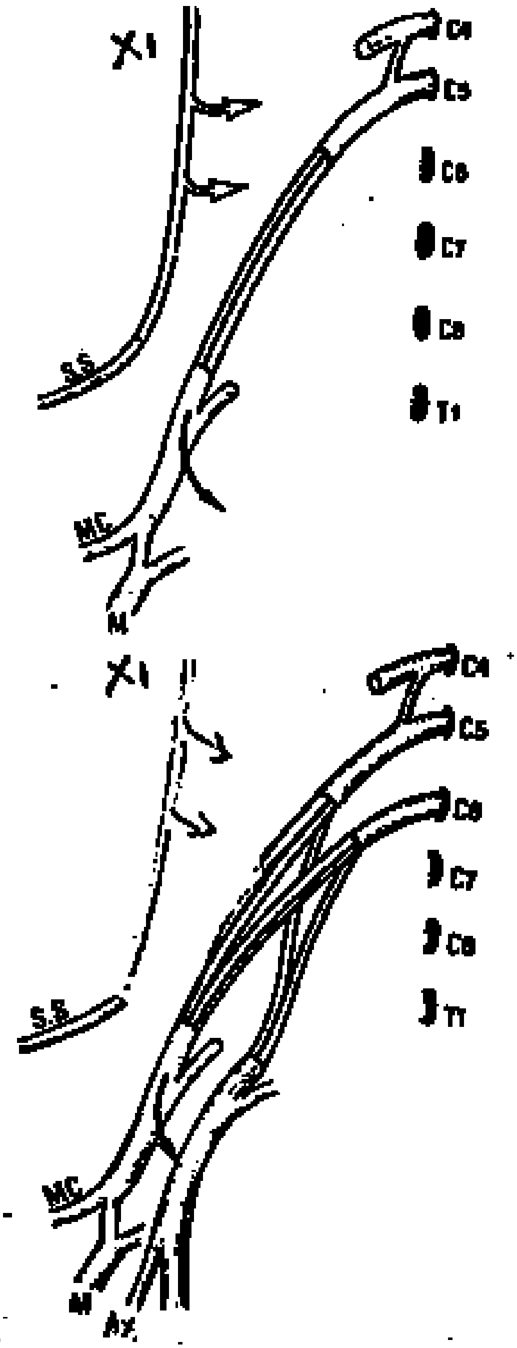


Figure 2

Total palsies. (a) Avulsion C6–C7–C8–T1, one graftable root. (b) Avulsion C7–C8–T1 two graftable roots. Ax: axillary; M: median; MC: musculocutaneous; SS: suprascapular; X1: spinal accessory.

branches for the superior and middle parts of the trapezius. The goal is to obtain stabilization of the shoulder, an active pectoralis major to adduct the arm, flexion of the elbow and some palmar sensibility in the forearm and palm.

When there are two roots (C5–C6) (Fig. 2b) that can be grafted, it is possible also to graft some parts of the posterior cord for radial or axillary nerve function. Every effort is made to connect the anterior plane of the root grafts with the anterior plane of the plexus and the posterior plane of the root with the posterior plane of the plexus in order to respect the cortical representation and to avoid cocontractions between antagonist muscles. One must not try to graft everything, and if the roots are thin the technique is similar to that used for one graftable root. From the technical viewpoint, we most frequently use the sural nerve but when T1, C8 and C7 are proved to be avulsed, it is possible to use a vascularized ulnar nerve graft either free or pedicled when the aspect and size of C5 or C5–C6 are good and when the length at the nerve defect is longer than 15 cm.

The results must be analyzed critically evaluating both motor and sensory function. They can be evaluated only after sufficient time has elapsed because re-innervation after nerve grafting is always delayed. This requires 2 to 3 years, depending on the type of lesion and its location (roots, trunks, cords, and terminal branches), and the results must be evaluated according to the function of the structures that have been repaired and, therefore, the therapeutic objectives achieved.

Finally, the pain syndrome and it is important to stress that surgical interventions with nerve repair for any given region considerably modify the afferents originating in the upper limb.

The final functions (Allieu et al 1997, Alnot et al 1993, Alnot et al 1996, Alnot and Narakas 1996, Alnot 1995, Brunelli and Monini 1984, Narakas 1986, Rusch et al 1995, Sedel 1986, Terzis 1987) must be studied according to the nerve repair and depend on the number of grafted roots, and a useful result means at least that elbow flexion is possible. In our experience 75–80 per cent of the patients have had satisfactory results with good elbow flexion M3 + M4. The pectoralis major function is obtained in 60 per cent of cases, allowing the possibility to hold objects against the thorax.

The shoulder poses problems but it is possible to obtain stabilization of the shoulder, some active abduction and external rotation in 50 per cent of cases by spinal accessory nerve neurotization; some authors perform shoulder arthrodesis.

It is rare to obtain function in the hand but in the majority of the cases, a 'shovel hand' or 'paperweight hand' is still useful to stabilize an object on a table. Finally, some sensation in the forearm and hand is obtained and this in fact may explain why 80 per cent of the patients do suffer little or no pain.

Total palsies with avulsions of all roots (24 per cent of cases)

CT-myelography shows meningocele or lacuna on all the roots, and therefore no root is available for repair. In these cases (Fig. 3), neurotizations are indicated using the spinal accessory nerve, the cervical plexus, the intercostal nerves,

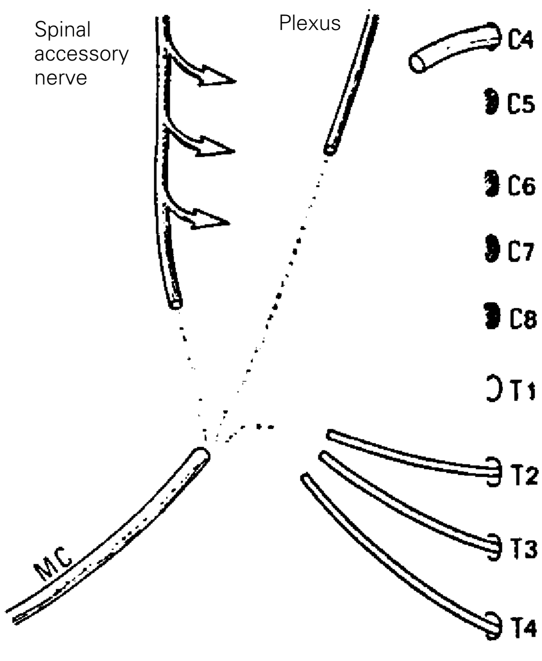


Figure 3

Total palsies with avulsion of all the roots. Possibilities of neurotizations. MC: musculocutaneous.

and more rarely the hypoglossus nerve or the contralateral C7 root (Narakas 1996, Brunelli and Monini 1984, Alnot et al 1993, Allieu et al 1997). The goal is to provide elbow flexion by neurotization of the musculocutaneous nerve; this can be associated with shoulder arthrodesis.

When using the spinal accessory nerve associated with the superficial cervical plexus, an intervening autograft is necessary with two strands of sural nerve. The spinal motor fibres are connected to the lateral part of the musculocutaneous nerve trunk and we add sensory fibres from the cervical plexus connected to the medial part of the musculocutaneous nerve. When using intercostal nerves, the neurotization can be performed by direct suture between three intercostal nerves 3–5 divided in their anterior portion and the musculocutaneous nerve (Hara's technique).

The results are good in 75 per cent of cases with elbow flexion at M3 + M4 and the only issue that remains is to know whether we can do better using some other neurotization.

Partial palsies C5–C6 or C5–C7 (25 per cent of cases)

The clinical pictures can be either C5–C6 or C5–C7 palsies or an initial total palsy with rapid recovery in C8–T1.

The prognosis is dominated by the fact that the hand is normal or only partially involved but useful. Surgery must be done early because the lesions are often in the scalenic area on the roots or upper trunk with a good possibility for nerve repair with a satisfactory result.

Concerning the surgical approaches the musculocutaneous nerve is identified as it enters the coracobiceps muscle and dissection from distal to proximal then allows to dissect the lateral cord and the anterior component of the upper trunk, as well as the posterior trunk and then the posterior component of the upper trunk.

Then, the lesions must be located and repaired in the scalene space between the anterior and middle scalene muscles.

Lesions of C5–C6 and possibly C7 roots, are evaluated and if there are ruptures in the scalenic area it is possible to perform grafts.

On the other hand, in C5–C6 avulsion we perform a medial approach of the upper arm, approximately 120 mm distally below the acromial process in order to perform a neurotization of the biceps nerve with a bundle of the ulnar nerve (Oberlin 1994).

Nerve reconstruction and muscular transfer will be studied according to a global scheme (Alnot and Oberlin 1993, Alnot et al 1998, Rostoucher et al 1998) and the indications are derived from the anatomo-pathological lesions (Fig. 4).

In C5–C6, palsies, when the two roots are disrupted in the scalenic area (Fig. 4a) it is possible, if they are a good size and aspect, to graft all the lesions. However if the size of the roots is too small or when only one root is available (Fig. 4b), one must not disperse the nerve fibres and the graft must be performed to the anterior part of the first trunk.

A neurotization of the spinal accessory nerve added to the suprascapular nerve gives better results than a graft from C5 with one strand of the sural nerve.

We can also perform a graft on the axillary nerve and use ulnar biceps neurotization. Finally, in C5–C6 palsies when no roots are available (Fig. 4c), we neurotize the spinal accessory nerve to the suprascapular nerve and perform at the same operation a neurotization using a fascicular group of the ulnar nerve with direct suture on the biceps nerve (Oberlin 1994, Loy et al 1997, Leechavengvongs et al 1998) or perhaps after end to side neurorraphy (Viterbo et al 1994, Franciosi et al 1998).

The present results of this ulnar biceps neurotization are good in C5–C6 palsies but the results are still uncertain in C5–C7 palsies and muscular transfer must be discussed and performed in the same operating time.

Concerning C5–C7 palsies, the overall plan is similar but is complicated by the severity of the lesions. When all the roots are avulsed and when there are no acceptable possibilities for muscular transfer, we perform associated neurotizations to restore elbow flexion and shoulder stability.

In C5–C6 palsies, active elbow flexion must be obtained in all cases by nerve surgery or muscular transfer. The shoulder can be stabilized after accessory nerve neurotization with recovery active anteposition, and active external rotation is essential in order to allow more functional elbow flexion. However, the shoulder remains the main problem with 73 per cent of good results in C5–C6

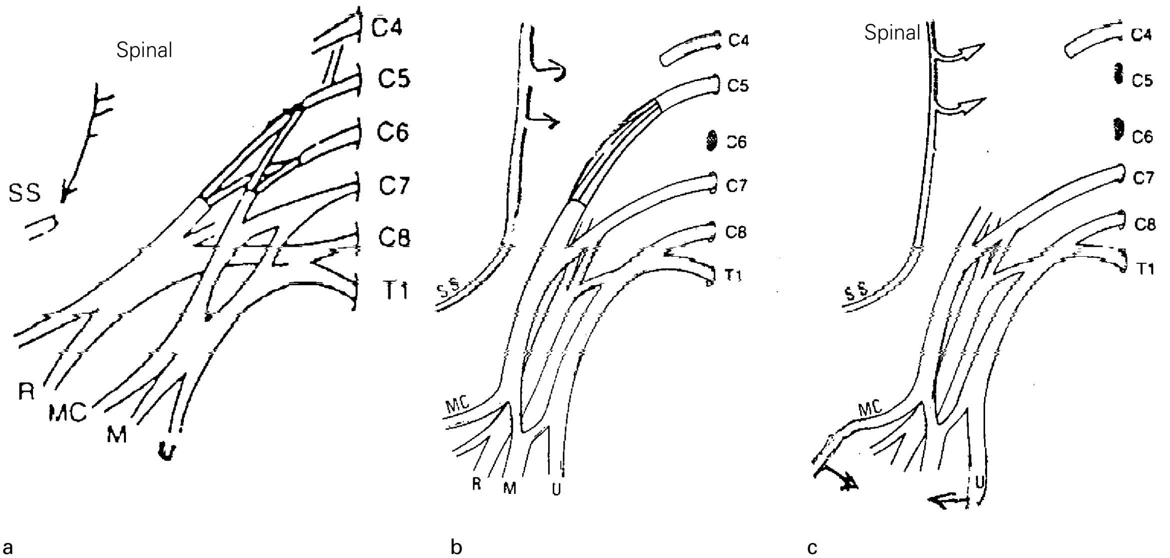


Figure 4

C5–C6 palsies. (a) Two graftable roots with good aspect and size. It is possible to graft all the lesions. (b) One graftable root C5 possibilities of repair associated with accessory nerve neurotization. A similar repair is performed if there are two graftable roots with a small size. (c) C5–C6 avulsion. Accessory nerve neurotization and ulnar biceps neurotization. Muscular transfers are also possible in C5–C6–C7 palsies. R: radial; M: median; SSsuprascapular; MC: musculocutaneous; U: Ulnar.

cases and only in 49 per cent of C5–C7 cases because of the greater severity of the lesions.

Rotation osteotomy of the humerus, ligamentoplasty and arthrodesis can all be used. Concerning the axillary nerve an end-to-side neurorraphy is a new possible way (Viterbo et al 1994, Franciosi et al 1998). Finally, concerning the wrist and the hand in C5–C7 palsies, there is always the possibility of muscular transfers which can be decided on early.

Partial palsies C8–T1

In these cases a decision regarding surgery will be based upon results of the clinical examination and other diagnostic studies. Here again, the prognosis is determined by the degree of hand function and the severity of the nerve lesions. Myelography will reveal the presence of absence of pseudomeningoceles, and based on the degree of diagnostic certainty of the existence of avulsion of different roots, the clinical status should be re-evaluated and a decision regarding surgical exploration made. If pseudomeningoceles involve the lower roots, exploration is not justified and one proceeds to muscle transfers (Alnot 1993, Alnot and Oberlin 1993).

However, if the myelograms are normal but spontaneous regeneration has not occurred, surgery is appropriate for assessment and possibly nerve repair. It is important to remember if C8 and T1 roots or even some more distal lesions of the trunk and cords can be repaired by nerve grafts; the distance between the nerve lesions and hand precludes re-innervation of the intrinsic muscles.

Conclusion

An update of this problem has been published in the monograph of Alnot and Narakas (1996) with many contributors.

Nerve repair and muscular transfers must be evaluated in a global plan. Preoperative diagnosis is fundamental, and clinical evaluation and other investigations (CT-myelography and EMG) must be used to come to coherent therapeutic indications.

If surgery is indicated, the preoperative assessment must anticipate any pathological lesions that may be encountered in order to allow a specific surgical plan. Early surgical exploration (from 6 weeks to 3 months) will permit evaluation of these lesions and determination of the possibilities for neurolysis, nerve grafts or neurotization.

Results must be analyzed critically and any regeneration should be credited to the nerve repair only if there is not other possible explanation for recovery. In any event, the results can be evaluated only after sufficient time has elapsed because re-innervation after nerve grafting is always delayed. As mentioned earlier, this requires 2 to 3 years, depending on the type of lesion and its location (roots, trunks, etc) and must be evaluated according to the function of the structures that have been repaired and the resulting therapeutic objectives achieved.

When evaluating motor function based on the international scale of 0 to 5, it is advisable to take into account the fatigability of the re-innervated muscles and the total function of the shoulder, elbow and arm. Return of sensory function is difficult to evaluate, but recovery of function of bridged structures confers considerable protective sensitivity and definite improvement in the trophic state of the extremity.

The pain syndrome must be treated. The majority of our patients who underwent surgery do not have pain, or have only some intermittent pain localized in the hand in the form of cramps or 'electrical shocks', which do not necessitate any medical treatment.

It is important to stress that surgical interventions with nerve repair for any given region considerably modify the afferents originating in the upper limb and that almost no patients have pain after surgery. This last observation is a very important point that indicates the value of the surgical treatment.

Finally, it is necessary to appreciate the psychological aspect in young patients and professional consequences in the future.

The best results evidently occur in the upper root partial palsies involving C5–C6 supraclavicular lesions. However, in total root paralysis, the increasing percentage of useful return of function, depending upon the roots grafted and the structures repaired, suggests that this type of surgery must be carried out with precise and early indications.

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8
Complete palsy

Chantal Bonnard and Dimitri J Anastakis

Introduction

Brachial plexus lesions result in complete palsy of the upper extremity in 50–64 per cent and an incomplete palsy in 50–36 per cent of cases (Songcharoen 1995, Birch et al 1998). Brachial plexus lesions are commonly classified as supraclavicular or infraclavicular.

Supraclavicular lesions result from violent distraction of the head away from the upper extremity. The roots are ruptured or avulsed from the spinal cord. The subclavian vessels are injured in 15 per cent and the spinal cord is damaged in 5 per cent of cases (Birch et al 1998). Infraclavicular lesions occur following shoulder hyperextension. With this mechanism of injury, an associated axillary artery lesion is present in 30 per cent of cases. In our experience, a combined supra- and infraclavicular lesion occurs in 15 per cent of cases – the most frequent association being an avulsion of C8T1 combined with a rupture of the lateral and posterior cords or rupture of the axillary and musculocutaneous nerves. Over one half of patients presenting with a complete palsy may have single or multiple fractures (Songcharoen 1995, Terzis et al 1999).

In this chapter, we will describe the most common reconstructions used for complete brachial plexus palsy following supraclavicular lesions, and their results. Our ability to compare functional results following brachial plexus reconstruction in complete palsy remains a challenge. The difficulty lies in the heterogeneity of each series, the lack of brachial plexus reconstruction standardization, and because the evaluation of functional results varies from one author to the next. Surgical techniques such as the use of contralateral C7, rootlet reinsertion, and the role of free functioning muscle transfer will not be covered in great depth, as they are discussed elsewhere.

Anatomy

In supraclavicular plexus injuries, the lesion is located either above the spinal ganglion (preganglionic) or below it (postganglionic). Numerous combinations of lesions exist (Narakas 1993). The most common combination is a rupture of the upper roots (C5C6 ± C7) and an avulsion of the lower roots (C8T1 ± C7) – this occurs in 48–54 per cent of cases studied (Bonnard et al 1996, Bentolila et al 1999, Terzis et al 1999). Roots C5 and C6 are less likely to be avulsed than the lower roots (C8T1) because of ligaments that unite them to the osseous margin of the foraminal outlet (Herzberg et al 1996).

The second most common combination is an avulsion of four roots with one ruptured root – this occurs in 23–27 per cent of cases (Bonnard et al 1996, Bentolila et al 1999, Terzis et al 1999). Typically, either root C5 or C6 is ruptured and the other roots are avulsed. Rarely, C5C6 and C8T1 are avulsed and C7 is ruptured. Complete avulsion of C5 to T1 occurs in 13–25 per cent of cases. In Birch's series, complete avulsion was more frequent (Birch et al 1998). We have never seen rupture of the lower trunk associated with an avulsion of the upper roots. If this pattern exists, it must be extremely rare.

In preganglionic lesions, rootlets and roots may still be within or out of the foramen, and with or without a tear of the dura. In the first situation, the peri-operative diagnosis is possible with intra-operative somatosensory evoked potentials or with histological and histochemical evaluation of the proximal stump during surgery (Terzis et al 1999). In postganglionic lesions the diagnosis of rupture is easier since the root stumps may be dissected and their electrical stimulation results in contraction of the serratus and the deep neck muscles.

A double level lesion may exist in 15 per cent of cases. Proximal avulsion and distal lesions are associated with fractures of the clavicle (lateral and posterior cords), or of the scapula (suprascapular nerve), with humeral fracture or glenohumeral dislocation (axillary nerve), humerus fracture (musculocutaneous and radial nerve) and elbow dislocation (median and ulnar nerve). These peripheral nerves should be assessed intra-operatively. Double level injuries are associated with a poor final outcome and may limit proximal reconstruction. For example, it is of no value to repair the lower trunk when the ulnar and median nerves have been stretched at the elbow level. Up to 48 hours following trauma, a double level lesion is easier to detect because the injured root still responds to electrical stimulation intra-operatively. When stimulation of the avulsed spinal root fails to elicit a contraction of the corresponding muscle(s), it suggests that a lesion exists between the avulsed root and the target organ (Birch et al 1998).

Clinical finding

Complete paralysis of the serratus anterior and the deep neck muscles suggest a C5C6C7 avulsion. Horner's syndrome suggests a C8T1 avulsion. A complete palsy with sparing of the spinatii suggests an infraclavicular lesion (combined with C8T1 avulsion if Horner's syndrome is present). Sweat is present in the avulsed roots dermatomes. The skin is dry when the spinal roots are ruptured. Root avulsion causes central pain. Patients describe a constant crushing or burning pain in the anesthetic hand with episodes of excruciating shooting pain in the whole limb. Pain typically appears within 2 weeks post-trauma (Bonnard and Narakas 1985, Narakas 1992) and is common. Rarely, the pain may be associated with phantom-limb sensation.

Treatment

Nerve transfers/neurotizations

When a root is avulsed from the spinal cord, its distal stump must be reinnervated either by another root (intraplexal neurotization) or by a healthy nerve which resides outside the plexus (extraplexal neurotization).

Intraplexal neurotization: We abide by the 'proximity' rule, which states that C6 should be reinnervated either with C5 or C7 but not with C8. This rule is valid in adults but not in children, where an avulsed C8T1 may be grafted to a ruptured C6 (Birch et al 1998).

Extraplexal neurotization: The spinal accessory nerve, intercostal nerves, cervical plexus, phrenic nerve, hypoglossal nerve and the contralateral C7 root have been used as nerve transfers in the reconstruction of complete brachial plexus palsy.

Spinal accessory nerve

The spinal accessory nerve is commonly transferred to the suprascapular or musculocutaneous nerves. The branches to the upper trapezius must be preserved to maintain scapular control and allow for future trapezius transfer. A C4 injury is a contraindication to using the spinal accessory nerve, due to the risk of complete shoulder instability post-operatively (Songcharoen et al 1996).

Intercostal nerves

The intercostal nerves can be harvested from T2 to T6. T2 is commonly transferred directly to either the lateral pectoral or the long thoracic nerve. Intercostal nerves T3 to T5 may be directly coapted to the plexus at the upper arm level. Intercostal nerves from T6 and lower require nerve grafts to reach the plexus. The intercostal nerves are commonly transferred to the motor portion or to the entire musculocutaneous nerve. They have also have been used to reinnervate the radial, median, ulnar and axillary nerves, and free functioning muscle transfer(s).

Intercostal nerves must not be used when the patient suffers from Brown–Séquard syndrome because the nerves are not functional. Brown–Séquard syndrome is present in 5 per cent of complete brachial plexus palsy cases.

The harvesting of the intercostal nerves with an intact diaphragm does not change pulmonary function (Allieu et al 1986, Giddins et al 1995). When there is a diaphragmatic paralysis, we do not use the intercostal nerves. We do not use a combined intercostal and phrenic nerve transfer.

This last recommendation is contrary to the experience of other surgeons who harvest the spinal accessory and phrenic nerves to reanimate the shoulder and intercostal nerves to reanimate the elbow (Chuang 1999).

Three donor intercostal nerves provide similar results to two intercostal nerves when transferred to the musculocutaneous nerve (Nagano et al 1989). Recently, Berman et al (1996) have transferred intercostal nerves to the lateral or the medial cord (depending of the location of the pain) for the sole purpose of pain relief.

Cervical plexus

Brunelli uses the cervical plexus to neurotize the axillary and musculocutaneous nerves (Brunelli 1980). Motor branches to the levator scapulae, rhomboids, upper trapezius, medial scalenus and deep muscles of the neck may be transferred. We use only one or two motor branches to avoid complete denervation of the rhomboids and levator scapulae muscles. Usually we transfer motor branches to the suprascapular nerve when the spinal accessory nerve is too small, or to the long thoracic nerve to improve scapular mobility. Sensory nerves of the cervical plexus have been used to reinnervate the median nerve. The results following this nerve transfer have been disappointing.

Phrenic nerve

The phrenic nerve is commonly used as a nerve transfer by Asian surgeons (Gu et al 1987, Chuang et al 1995, Songcharoen et al 1996, Waikakul et al 1999a). Its use by Western surgeons is less common (Terzis et al 1999). Following phrenic nerve transfer, Gu found that vital capacity dropped within the first post-operative year but recovered to normal after 2 years (Gu 1989). We use the phrenic nerve only when it is accompanied by an accessory phrenic nerve.

Hypoglossal nerve

Narakas first used this transfer for brachial plexus reconstruction in 1992. Results are encouraging when it is transferred to the musculocutaneous nerve. In our series, transfer resulted in biceps motor strength of M3 or M4 and a mean elbow flexion of 109° in five out of eight cases. The results of hypoglossal nerve transfer to the median or ulnar nerve were uniformly disappointing. This is most likely due to the long distance between the proximal stump and the distal end organ. Harvesting of the hypoglossal nerve is associated with no significant complications. Tongue hemiatrophy was well tolerated in this group.

Contralateral C7 root

All or part of the contralateral C7 root may be used without severe sequelae. An entire chapter is devoted to the use of contralateral C7. We have not used this donor nerve to date.

Nerve root reimplantation

Since the early nineteen-nineties, Carlstedt has shown that avulsed spinal roots can be reimplanted in the spinal cord under limited conditions. A separate chapter is devoted to this new technique.

Reconstructive goals

In complete palsy, the reconstructive goals are: (1) reconstruction of brachiothoracic pinch; (2) reconstruction of elbow flexion; and (3) reconstruction of a basic hand function (i.e. sensation in the thumb and index finger, wrist extension, and finger flexion). Plexus reconstruction may also be indicated to alleviate or improve pain (Berman et al 1996). These reconstructive goals are well accepted amongst most brachial plexus surgeons. However, a few surgeons prefer to restore elbow flexion first followed by wrist extension and finger flexion, the last priority being the shoulder, which may be arthrodesed (Bentolila et al 1999).

Lesions, reconstruction and results

Total avulsion C5–T1

When there are no associated orthopaedic or vascular lesions, we transfer the spinal accessory

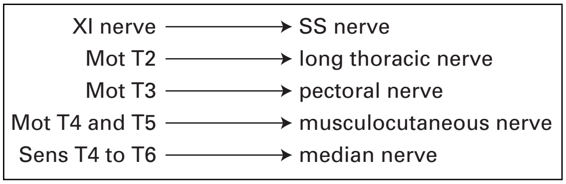

Figure 1

Plexus reconstruction following C5T1 avulsion.

nerve to the suprascapular nerve and an intercostal nerve to the long thoracic nerve to effect opening of the brachiothoracic pinch. When the rhomboid muscles are functional, the serratus anterior needs to be reinnervated using intercostal nerve transfers to avoid overaction of the rhomboids. The T3 intercostal nerve is transferred to the lateral pectoral nerve to improve brachiothoracic pinch closure. Finally, intercostal nerves T4 and T5 are transferred to the musculocutaneous nerve to restore elbow flexion and forearm sensation. Intercostal nerves T6 and T7 are transferred to the median nerve (Fig. 1).

When the scapula is fractured through the notch or when exploration confirms suprascapular nerve avulsion, we neurotize the long thoracic nerve to improve scapulothoracic joint function. Later, in a second stage, we perform glenohumeral arthrodesis. The musculocutaneous nerve is neurotized either with the spinal accessory nerve (only when C4 is intact) or with intercostal nerves. When neither transfer is available, we use the hypoglossal nerve. In our experience, these various transfers provide useful brachiothoracic pinch, elbow flexion and minimal sensory recovery of the thumb and index finger. Hand motor function has never been useful (Table 1).

Alnot (1995) and Bentolila et al (1999) recommended transfer of the spinal accessory nerve to the anterolateral portion of the musculocutaneous nerve. The remainder of the musculocutaneous nerve is covered by sensory branches of the cervical plexus (Alnot 1995) or by intercostal nerves (Bentolila et al 1999). The authors described biceps motor strength greater than M3 in 75 per cent of their cases (Alnot 1995, Bentolila et al 1999).

In 1999, Chuang recommended four neurotizations in reconstruction of complete avulsion: the spinal accessory nerve transferred to the suprascapular nerve, the phrenic nerve to the contribution of the upper trunk to the posterior cord, the intercostal nerves to the musculocutaneous nerve, and the contralateral C7 to the median nerve. When the phrenic nerve is not available, Chuang uses the hypoglossal nerve (Chuang 1999).

In 1999, Waikakul (1999b) presented a prospective study of 205 patients with complete palsy. He compared elbow flexion recovery following transfer of the spinal accessory nerve or intercostal nerves to the musculocutaneous nerve. The strength of elbow flexion was greatest following spinal accessory nerve transfer. Superior sensory recovery and improved pain control were noted following intercostal intercostal nerve transfers.

In another study by Waikakul (1999a), 96 patients with complete root avulsion were reviewed. Waikakul transferred the phrenic nerve to the suprascapular nerve, the spinal accessory nerve to the musculocutaneous nerve and the anterior portion of the contralateral C7 root to the median nerve, obtaining shoulder abduction (> 60°) in 85 per cent, elbow flexion (≥ M3) in 88 per cent, forearm pronation (≥ M3) in 33 per cent, wrist flexion (≥ M3) in 29 per cent and finger flexion (≥ M3) in 21 per cent of cases.

The importance of the patient's age (Nagano et al 1989, Waikakul 1999a) and the interval between trauma and plexus reconstruction (Nagano et al 1989, Akasaka et al 1990, Krakauer and Wood 1994, Chuang et al 1996, Songcharoen et al 1996, Bentolila et al 1999, Terzis et al 1999) have been well-studied recently. These two important variables have had an impact on the methods of brachial plexus reconstruction used.

In 1989, Nagano described a series of 144 adult patients undergoing neurotization of the musculocutaneous nerve with the intercostal nerves. Failure rates increased as the interval between

Table 1 Results after reconstruction following C5–T1 avulsion

	No. of patients	*≤ M2*	*M3*	*≥ M3+*
Thoracobrachial grip				
closure	28	7	8	13
opening	28	5	11	12
Elbow flexion	32	9	6	17

trauma and plexus repair increased. Based on this work, Nagano recommends that intercostal nerve transfers must be performed in patients less than 40 years of age and within 6 months post-trauma.

Akasaka et al (1990) noted that intercostal nerve transfers resulted in poor results after a delay of more than 6 months post-trauma. For late cases they recommend using a free functioning muscle transfer to restore elbow flexion. Krakauer and Wood (1994) suggest that 9 months post-trauma should be the cut-off time for intercostal nerve transfer to the musculocutaneus nerve. After 9 months, they perform a free functioning muscle transfer innervated by the intercostal nerves.

Songcharoen et al (1996) presented a series of 216 patients – 158 cases with a total palsy and 58 cases with a incomplete palsy. All patients had an avulsion of C5C6 that was reconstructed with a transfer of the spinal accessory nerve to the musculocutaneous nerve. He studied the effects of patient age and the interval between trauma and surgery. These factors were statistically significant. Allieu again confirms that the results of brachial plexus reconstruction are poor in patients over the age of 40, and notes that the best results occur when reconstruction is performed before 8 months post-trauma (Allieu et al 1997).

Chuang alters his reconstruction method based on the time post-trauma. If the patient is less than 6 months post-trauma, he transfers three intercostal nerves to the musculocutaneous nerve. If the patient is between 6 and 12 months post-trauma, he transfers two intercostal nerves to the musculocutaneous nerve and uses two intercostal nerves to innervate a free functioning muscle transfer. Finally, if the patient is greater than 12 months post-trauma, he does not neurotize the musculocutaneous nerve but rather uses the three intercostal nerves to innervate a free functioning muscle transfer. The author prefers to innervate a free functioning muscle transfer with the intercostal nerves rather than the spinal accessory nerve because direct nerve coaptation is possible (Chuang et al 1993, 1996). In 1999 Terzis demonstrated that, in the restoration of finger flexion, a denervation time of less than 6 months resulted in significantly better outcomes than a denervation time of 6–12 months.

Doi describes a series of 26 patients with complete brachial plexus injury in whom upper limb function was reconstructed using two free functioning muscle transfers (Doi et al 1995, 2000). The reader is referred to the chapter on free functioning muscle transfers for further information.

Rupture C5 and avulsion C6C7C8T1

Reconstruction depends on the quality of the C5 root. When the stump of C5 is small or when its quality is doubtful, we graft it to the posterior division of the upper trunk. This graft is done to obtain shoulder function. The rest of the reconstruction is the same as that in total avulsion. When the stump of C5 is of good quality, we graft it with a vascularized ulnar graft to the lateral cord. The intercostal nerve T2 is transferred to the lateral pectoral nerve and the intercostal nerve T3 to the C7 contribution of the long thoracic nerve (Fig. 2).

To avoid co-contraction, Alnot grafts C5 to the anterior division of the upper trunk (lateral cord) only (Alnot and Narakas 1996) On the other hand, Nagano usually grafts C5 to the posterior division of the upper trunk and transfers the intercostal nerve to the musculocutaneous nerve

a **C5 is small**		b **C5 is large**	
C5 ⟶	C5C6 (post)	C5 ⟶	lateral cord (vascularized ulnar nerve graft)
XI ⟶	SS nerve	XI ⟶	SS nerve
T2 ⟶	long thoracic	T2 ⟶	long thoracic
T3 ⟶	pectoral	T3 ⟶	pectoral
Mot T4T5 ⟶	MC		
Sens T4T6 ⟶	median		

Figure 2

Plexus reconstruction following C5 rupture and C6T1 avulsion. (a) C5 is small. (b) C5 is large.

Table 2 Results after reconstruction following C5 rupture + C6T1 avulsion

	No. of patients	*≤ M2*	*M3*	*≥ M3+*
Brachiothoracic grip				
closure	19	7	6	6
opening	19	8	3	8
Elbow flexion	26	7	7	12

(Nagano et al 1989). The spinal accessory nerve is transferred to the suprascapular nerve. Other surgeons (Allieu, Merle; see Bonnard et al 1996) perform selective grafts from C5 to the musculocutaneous nerve, combining it with a graft from C5 to the radial nerve and even to the median nerve if C5 is large enough (Terzis et al 1999). When C5 is small, Terzis grafts it to the musculocutaneous nerve and neurotizes the axillary nerve and the branch to the triceps with intercostal nerves.

Results following these classic reconstructions are nearly the same as in total avulsion (Table 2). In Bentolila's study, results were better when grafts from C5 were coapted distally to the lateral or posterior cord than when they were coapted to the musculocutaneous or the radial nerves (Bentolila et al 1999). This finding was not statistically significant. The authors argued that when the length of graft is short there is more nerve tissue available for grafting, which is a significant factor in distal recovery.

Increasingly, surgeons are now combining these common reconstructions with a contralateral C7 transfer to the median nerve using an ulnar vascularized nerve graft (Chuang 1999, Terzis et al 1999, Waikakul et al 1999a).

C5C6 rupture and C7C8T1 avulsion

We graft C5 and C6 to C5C6C7, respecting the anterior and posterior distribution of the fascicles, or C5 and C6 to the lateral and posterior cord (Alnot et al 1992). The intercostal nerves are transferred to the ulnar nerve, giving a positive trophic effect and some wrist or finger flexion. The suprascapular nerve is reinnervated with the spinal accessory nerve (Fig. 3; Table 3). Several authors (Allieu, Sedel) prefer to leave the spinal accessory nerve intact and use C5 to reinnervate the suprascapular nerve (Bonnard et al 1996, Bentolila et al 1999). Terzis et al (1999) has recently shown that there is no statistically significant difference following suprascapular nerve reconstruction with intraplexal neurotization or with spinal accessory nerve. Allieu et al (1997) studied elbow flexion recovery following grafting from a ruptured root or nerve transfer with the spinal accessory or intercostal nerves, and noted that the results were better following nerve grafting (from a proximal stump of C6) (Allieu et al 1997).

Figure 3

Plexus reconstruction following C5C6 rupture and C7T1.

Table 3 Results after reconstruction following C5C6 rupture + C7T1 avulsion

	No. of patients	*≤ M2*	*M3*	*≥ M3+*
Brachiothoracic grip				
closure	26	6	5	15
opening	26	8	10	8
Elbow flexion	28	12	6	10
Wrist flexion	26	19	6	1
Finger flexion	26	25	1	

Chuang prefers to transfer the intercostal nerves to the musculocutaneous nerve and uses C5 for the shoulder (i.e. suprascapular nerve and posterior part of the upper trunk), with or without the phrenic nerve. He uses C6 for the hand (i.e. C8 or the median nerve) (Chuang et al 1995, Chuang 1999).

Terzis et al (1999) grafts C5 and C6 to the musculocutaneous nerve, radial and median nerves distally using a vascularized ulnar graft. She uses intercostal nerves for transfer to the triceps, the axillary nerve, the nerves to the serratus and to the latissimus dorsi. Later, she performs a free muscle transfer for the hand reinnervated by a contralateral C7.

C5C6C7 rupture and C8T1 avulsion

Our preferred reconstruction includes grafting C5C6C7 to the upper and middle trunks and to C8 (for active finger extension), and transferring the spinal accessory nerve to the suprascapular nerve (Fig. 4).

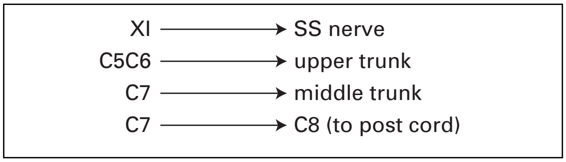

Figure 4

Plexus reconstruction following C5C7 rupture and C8T1 avulsion.

Chuang (1999) grafts C5 to the suprascapular nerve and the posterior part of the upper trunk, C6 to the median nerve, C7 to C7 itself, and transfers three intercostal nerves to the musculocutaneous nerve.

The main difficulty is the availability of donor nerve tissue for grafting – two sural nerve grafts are insufficient. The sensory branch of the radial nerve may be harvested, as well as a vascularized ulnar nerve nerve graft. Clavicle osteotomy may shorten the length of grafts needed (Bentolila et al 1999).

The results in this group are better than in the group presenting with three or more avulsions (Tables 4 and 5). This is probably due to the better quality of the proximal ruptured spinal roots C5C6 and C7. In Bentolila's series (Bentolila et al 1999), results were equivalent when five, four or three roots were avulsed (biceps ≥ M3+ in 55.3 per cent of cases). Results are much better (biceps ≥ M3+ in 80 per cent of cases) when only two roots are avulsed.

Table 4 Biceps recovery according to the number of avulsions

No. of avulsions	*Biceps ≥ M3+*	*%*	*Biceps ≤ M2*	*%*
5	17/32 patients	53	9/32 patients	28
4	12/26 patients	46	7/26 patients	27
3	10/28 patients	36	12/28 patients	43
Total	39/86 patients	45	28/86 patients	33
2	14/20 patients	70	4/20 patients	20

Table 5 Results after reconstruction following C5C6C7 rupture + C8T1 avulsion

	No. of patients	*≤ M2*	*M3*	*≥ M3+*
Brachiothoracic grip				
closure	20	3	2	15
opening	20	8	7	5
Elbow flexion	20	4	2	14
Wrist flexion	20	14	5	1
Finger flexion (hand is useful as a hook)	20	18	2	

Table 6 Results after reconstruction following C5T1 rupture

	No. of patients	*≤ M2*	*M3*	*≥ M3+*
Brachiothoracic grip				
closure	9	0	2	7
opening	9	2	2	5
Elbow flexion	9	1	3	5
Wrist flexion	9	5	1	3
Finger flexion (hand is useful as a hook)	9	7	1	1

C5T1 rupture

All surgeons attempt an anatomical reconstruction. The total amount of available nerve graft is limited; two sural nerves are usually not enough, and sometimes the ulnar nerve must be harvested and used as a vascularized nerve graft (Table 6). Reconstruction of the lower trunk is worthwhile when the patient is young (less than 20 years of age), when the interval between trauma and surgery does not exceed 2 months, and when the nerve graft is short.

Conclusions

Based on our experience and the reported experience of others, we reach the following conclusions:

1. Evaluating the quality of avulsed roots is very important. In our experience, we overestimate the quality of the roots, which may explain our poor results following C5 and C6 lesions associated with C7 to T1 avulsions.
2. Patient age and the interval between trauma and plexus repair are statistically significant variables, and the type of reconstruction must be adapted accordingly. When the interval between trauma and repair is greater than 9 months, a free functioning muscle transfer is recommended for biceps reconstruction.
3. The use of the phrenic nerve or the contralateral C7 root remains a controversial subject, despite studies demonstrating low postoperative morbidity.
4. Regarding the shoulder; we prefer to avoid glenohumeral arthrodesis. In extensive lesions (four or five root avulsions), reconstruction of the suprascapular, long thoracic and pectoral nerves improves scapular control and provides the patient with brachiothoracic pinch. When C4 is avulsed, nerve surgery to reanimate the shoulder should be abandoned. A long thoracic nerve reconstruction is not required because of rhomboid paralysis. The spinal accessory nerve should be preserved to avoid complete scapular instability.
5. Regarding the elbow, following reconstruction of a complete plexus palsy, biceps motor strength recovery was greater than M3+ in over 50 per cent of cases.
6. Regarding the hand, neurotization of the lower trunk using extraplexal transfers does not work. Neurotization of the ulnar or the median nerves with intercostal nerves may result in useful wrist function and a protective sensation. Functional results following free functioning muscle transfers are promising.
7. Plexus reconstruction alleviates central pain caused by root avulsion (Alnot et al 1992, Berman et al 1996, Bonnard et al 1996) and, if only for this purpose, plexus repair is worthwhile.

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9
Update on the treatment of adult brachial plexus injuries

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Introduction

The brachial plexus is formed by the spinal nerves C5, C6, C7, C8 and T1, and it supplies the whole upper extremity except for a small strip of skin on the inner side of the upper arm which receives sensory fibres from T2.

At one extreme, a complete lesion of the brachial plexus leads to a flail arm which is not only useless but represents an obstacle: due to the body asymmetry a scoliosis with consequent pain develops, and the patient not only has no function in the arm but also has additional problems.

The other extreme is a partial lesion, involving only one root. In this case the loss of function is minimal, because the vast majority of the muscles receive nerve fibres from at least two roots. The best example is an isolated lesion of C7, which under normal anatomical fibre distribution produces a weakness of the triceps and the extensor muscles of the forearm and a reduced sensibility of the thumb and the index finger, but all these functional losses are temporary.

If, however, two or three neighbouring roots are involved, a characteristic paralysis pattern develops:

- A lesion of C5 and C6 is followed by reduced function of the shoulder muscles and lack of elbow flexion;
- A lesion of C5, C6, and C7 produces, in addition, a loss of wrist and finger extension;
- A lesion of C8 and T1 produces a loss of hand function, with the shoulder and elbow functioning normally.

The normally functioning uninvolved muscles with paralysed antagonists become too strong and cause contractures. In lower brachial plexus lesion (C8 and T1) a supination contracture may develop by the supinating action of the unopposed biceps muscle, and in the shoulder joints much stronger inner rotators produce an internal rotation contracture.

In such cases, muscle transfers can be planned in order to restore the lost function. However, these partial brachial plexus lesions are different from those lesions that originally produced a complete loss of function but have partially recovered. In the latter case some muscles remain permanently paralysed and others recover, but the recovered muscles are not as valid for muscle transposition as those in the former.

There are variations in the fibre distribution that must be considered. The brachial plexus may receive more fibres from C4 and less from T1 (prefixation), or more from T2 and less from C5 (postfixation).

The vast majority of brachial plexus lesions are caused by motorcycle accidents, followed by other traffic accidents, sports injuries, work injuries, and gunshot injuries.

The rootlets may be avulsed, i.e. no proximal stump is available. The spinal nerve, the trunks and the divisions of the cords may be interrupted, which means that a proximal stump is available or there might be a lesion in continuity. A lesion in continuity may be very severe with damage of the fascicular pattern (grade IV according to Sunderland 1951), or less severe (grades I, II or III). A grade IV lesion does not offer the possibility of spontaneous recovery, and has to be treated like a complete loss of continuity. The involved segment must be resected and the defect bridged by nerve grafts.

A grade I lesion is usually followed by a complete spontaneous recovery. The same is true for a grade II lesion, but this takes more time. The spontaneous recovery can be impeded or prevented by compression of the nerve tissue by fibrosis. A grade III lesion may show spontaneous recovery, but this is always incomplete. In grade III lesions in particular, the chances of spontaneous recovery may be impeded by external or internal compression. These grades may be treated by neurolysis, and good functional results can often be achieved.

With increasing severity of the lesion the chances of a good result after surgery decrease and they are, of course, the worst in cases of avulsion of all five roots. In these most severe cases a high degree of recovery cannot be expected, and the patient may be unable to return to his original job. Even if function can be improved significantly, it will always be impaired and the patient may need to be trained for a job that requires only one hand. However, this incomplete recovery is extremely important for daily living, and therefore reconstructive efforts are justified even if the patient cannot resume his former occupation.

A significant problem for many patients with brachial plexus lesions is pain. The pain may be neuromal pain in cases with loss of continuity, pain produced by irritation of nerve fibres in lesions with preserved continuity, or pain caused at higher levels in cases of avulsion. The first two types of pain can be tackled by surgery, but the real problem is central pain. Pain syndromes develop independently of attempts at surgery and are also present in unoperated cases. However, there are theories that patients who have undergone surgery develop pain syndromes to a lesser degree and less frequently (Narakas 1986).

Before the 1960s, successes in brachial plexus surgery were achieved in cases of clean transections without defects, and in cases of preserved continuity after external neurolysis. Attempts to achieve restoration of continuity by resection of segments of the humerus failed, and the general strategy was to perform an amputation of the upper arm in cases of complete brachial plexus lesions with root avulsions.

The basis for current surgery of the brachial plexus was the introduction of new successful techniques of nerve grafting (Millesi 1968, Millesi et al 1972, 1976).

Timing of surgery

If there is an open injury, primary surgical treatment is indicated. In a clean transection the involved segments of the brachial plexus are repaired by neurorrhaphy. Fracture of the clavicle has to be osteosynthesized and the vascular lesion dealt with accordingly. The question arises whether the emergency vascular repair should be combined with elective surgery of the brachial plexus. Such a procedure should be considered only if an experienced surgeon is available. An inexperienced surgeon does more harm than good, and frequently even the diagnosis is unreliable. If available the surgeon must consider whether the small advantage of gaining some time outweighs the increased risk for the patient due to the extended (10 or more hours) operation in the emergency situation. Experience suggests that in this situation surgeons tend to reduce the time of surgery by performing as yet unproven procedures, e.g. end-to-side coaptations between trunks, and do not fully exploit the available possibilities.

Bonney (1983) preferred early surgery a few days after the accident, even in closed injuries, for two reasons:

1. The anatomical situation can be easily clarified because a few days after the accident there is no fibrosis or scar tissue formation;
2. Early primary surgery may save time.

However, the first argument is based on an error in basic thinking. The fibrosis or scar tissue formation is caused by the trauma. In cases of early surgery, it will develop after surgery and the surgeon accepts this risk in order to deal with nerve stumps that can be easily seen but will become fibrotic in 2–3 weeks time. With early surgery the surgeon cannot allow for this. In addition, the eventual damage to neurons is dependent on the trauma and will happen anyway. There is good evidence that early secondary repair offers a better chance for regeneration. The neurons will be in an active phase, and the secondary trauma creates greater axon sprouting than the initial repair. It must also be remembered that with present diagnostic tools it is not possible to establish an exact diagnosis immediately, and there is therefore the possibility that a patient with the chance of spontaneous recovery will be operated on.

Based on these considerations, the following conclusions were reached regarding indications and timing:

1. If there is a clean transection, a primary repair with neurorrhaphy is indicated;
2. If there is an open injury with blunt trauma to the nerves and complicating factors such as vascular injury or fracture, it is advisable to deal primarily with the other injuries and to perform reconstruction of the brachial plexus as a secondary procedure;
3. If there is a closed injury in a brachial plexus lesion, an elective reconstruction of the brachial plexus may be planned after clarifying the diagnosis and excluding the possibility of spontaneous recovery.

Diagnosis

The diagnosis of brachial plexus lesion is established clinically, and the following differentiation can be made:

- Complete brachial plexus lesion;
- Upper brachial plexus lesion C5, C6;
- Upper brachial plexus lesion C5, C6, C7;
- Lower brachial plexus lesion C8 and T1;
- Irregular brachial plexus lesion.

Information regarding the presence and absence of root avulsions is desirable. In the early years this was very important, because in cases of avulsion of all five roots no surgery was performed. However, we have since learned to deal with these worst scenarios, and knowledge of root avulsions does not play any role in establishing the indication for operation.

The clinical examination provides important information about the severity of the lesion. If the serratus anterior muscle is not innervated it can be assumed that an avulsion of the roots C5, C6, and C7 has occurred, because the origin of the long thoracic nerve is located very proximal at these spinal nerves. If the serratus anterior is functioning, generally at least one of these three roots is not avulsed; however, there is the rare situation when C4 contributes to the innervation of the serratus anterior muscle.

The innervation of the deep muscles of the neck comes from the dorsal branch of the spinal nerves, and these muscles do not work in an extensive avulsion. Evaluation becomes more difficult if there is a mixed situation, with some roots avulsed and others not.

The suprascapular nerve usually leaves the superior trunk at its distal end. If this nerve is conducting, the lesion should be distal to this level.

Two or three weeks after the trauma a Tinel's sign may become positive at the level where axon sprouts are formed. In case of avulsion a Tinel's sign does not occur. In this situation a positive Tinel's sign will be present only if an element of the cervical plexus is involved. This can be differentiated by the differing extent of the Tinel's sign, which will, in case of involvement of the cervical plexus, spread towards the auricle or the anterior neck.

If a present Tinel's sign starts to advance towards the periphery, the beginning of the neurotization of originally denervated distal segments is indicated. Advancement and progress of the Tinel's sign does not, however, allow any prognosis as far as the quality of the regenerative process is concerned, because it may depend on a few 'pioneer' nerve fibres. It is the lack of occurrence or progression of the Tinel's sign that allows a conclusion.

Ten days or so after the accident Wallerian degeneration has to be far enough advanced that conductivity in the distal segments ceases. This fact – no conductivity in distal segments of motor fibres – allows exclusion of a grade I lesion of the nerve fibres.

The conductivity of sensory nerve fibres is lost if there is a lesion distal to the spinal ganglion (infraganglionic lesion). It remains positive in case of a pre-ganglionic lesion because the sensory nerve fibres are still in connection with the neurons and do not develop Wallerian degeneration.

By clinical examination and simple electrophysiologic studies 3 weeks after the accident, the following conclusions can be reached:

- If motor conductivity remains positive, there is grade I damage (neurapraxia). Spontaneous recovery can be expected;

- If there is no Tinel's sign, avulsion of all five roots may be suspected;
- If the Tinel's sign is positive with radiation into the arm and hand, at least one root is not avulsed.

During the following weeks further observations allow the following conclusions:

- If the Tinel's sign remains consistently negative, avulsion of all five roots may be suspected. This can be confirmed by CT-myelography or MRI. Surgery is strongly indicated;
- If the Tinel's sign becomes consistently positive but does not move, a grade IV or V infraganglionic lesion may be suspected. Surgery is indicated;
- If the Tinel's sign becomes strongly positive and moves in a distal direction, a grade II or III infraganglionic lesion may be suspected. For the moment surgery is not indicated, because there is the chance of spontaneous recovery;
- If further observation over the fourth and fifth months reveals satisfactory recovery, a grade II lesion (axonotmesis) can be diagnosed. No surgery is indicated;
- If there is an initial recovery of the proximal muscles, a grade III lesion is diagnosed. Surgery is indicated if recovery does not progress;
- If the Tinel's sign progresses without recovery, there is a grade III lesion with external or internal compression. Surgery is indicated.

Summary

Surgery is indicated in all patients who do not show full recovery within 6 months. Patients with root avulsions and loss of continuity should be operated upon as soon as the diagnosis is well established and a lesion with preserved continuity can be excluded.

MRI gives a satisfactory indication that a root avulsion is possible, but not safe enough on which to base a decision for the surgical planning. There is good reason to believe that MRI techniques will improve and become 100 per cent reliable, and may also provide information about the status of a damaged nerve trunk with preserved continuity.

Due to the complexity of lesions and the different possibilities of combinations, a classification system is required.

Surgical options for treatment of patients with brachial plexus lesions

A variety of possibilities exists to improve function of patients with brachial plexus lesions. In partial brachial plexus lesions muscle transposition may achieve this goal. The conductivity of non-conducting nerve segments with preserved continuity may be restored by neurolysis. Lost continuity of original pathways is restored by neurorrhaphy or nerve grafting, and nerve fibres may be transferred from one nerve to another if the original pathway cannot be reconstructed. New muscle tissue can be used if the original muscles are atrophied and beyond repair. This section describes various surgical options and demonstrates the enormous range of surgical possibilities.

Neurolysis

Lesions in continuity with external compression can be treated successfully by neurolysis. If there is fibrosis of the paraneurium and the epifascicular or interfascicular epineurium, a para- or epineuriotomy, or an epi- or interfascicular epineuriectomy respectively can be performed. These procedures only have a good chance if the fascicular pattern and the endoneurial tissue is preserved. If there is an interfascicular fibrosis or a loss of the fascicular pattern, neurolysis will not be successful. In this situation, resection of the involved segment with restoration of continuity by nerve grafts is indicated. Occasionally it is very difficult to make this differentiation, and if neurolysis ends in failure then an incorrect decision was made. For the author, it is a rule that, in case of doubt, it is better to resect and graft than to attempt neurolysis.

In some situations the surgeon may finish an operation as a neurolysis at the level of the spinal nerve because the continuity seems to be preserved into the intervertebral canal. However, in some of these cases the rootlets might be avulsed but the spinal nerve not extracted from the intervertebral canal and the situation not recognized. To avoid such situations it was suggested that hemilaminectomy be performed in order to clarify avulsion of the rootlets, and the surgical procedure be performed in a second stage. However, since it is possible to prove or exclude this situation by intraoperative stimulation (Turkof et al 1995, 1997) using stimulation of the gyrus praecentralis, the author believes that a hemilaminectomy is not indicated just for diagnostic reasons.

Direct neurorrhaphy

Direct neurorrhaphy is a very successful treatment in clean transections, e.g. with a stab wound. In a typical brachial plexus lesion with loss of nerve substance, a direct neurorrhaphy has no chance and should not be attempted.

Nerve grafting to bridge the defect

Seddon attempted nerve grafting in five cases with upper brachial plexus lesion with some result in three patients before 1948, but he gave up these attempts after Clark (1946) published details of transfer of the major pectoralis muscle to replace the biceps function. With the development of a reliable grafting technique (Millesi 1968, 1972, Millesi et al 1972, 1976), free autologous nerve grafting became the standard technique in brachial plexus surgery. It is obvious that without grafting, modern brachial plexus surgery would not be possible. All available proximal stumps are connected with their corresponding distal stumps. For instance neuromas at C5 and C6 are connected with the distal stump of the superior trunk, or a proximal neuroma of a superior trunk is connected with a distal stump on the superior trunk. In other words, attempts are made to reconstruct the anatomical situation as well as possible. It is obvious that such an anatomical reconstruction is possible only if the defects are limited. In long defects, e.g. between the proximal end of a trunk and the distal stump in the corresponding cord, regenerating nerve fibres will not always proceed to the target muscles, and there will be a mixed innervation of antagonistic muscles with co-contractures. Anatomical reconstruction is also limited by the fact that not enough autologous nerve grafts are available to restore the continuity of all structures. Therefore, priority must be established to neurotize distal stumps serving very important muscles and muscles with good chances of recovery. Less important muscles and muscles with poor chances of recovery are excluded. Chances of anatomical reconstruction will increase when artificial nerve grafts with cultivated Schwann cells of the patient become available; this will solve the problem of allografting.

After the description of the use of vascularized nerve grafts (Taylor and Ham 1976) the ulnar nerve was utilized as a vascularized nerve graft, and there were great expectations of this technique. The many reports can be summarized as follows:

Vascularized nerve grafts provide a quicker neurotization; the end result does, however, not differ from the use of free nerve grafts. There are certain indications for the use of vascularized nerve grafts, especially in nerve transfers (see below). If one wants to benefit from the ulnar nerve as a graft donor without utilizing it as a vascularized nerve graft, the ulnar nerve has to be split into minor units, in order to be sure of survival. A nerve trunk the size of the ulnar nerve will not survive free grafting well because the relation between surface and tissue masses is unfavourable. After the preparation of minor units from the nerve trunk of the size of the sural nerve, survival is assured (Eberhard and Millesi 1996).

Nerve transfer (nerve fibre transfer)

In a nerve transfer, nerve fibres from one nerve are transferred to another denervated nerve in order to neurotize this nerve. This can be from a peripheral nerve, for example the ulnar nerve, in order to bring nerve fibres to the musculocutaneous nerve

(Oberlin et al 1994). The majority of nerve transfers, however, are performed with axon donors outside the brachial plexus, in order to achieve particular functions within the brachial plexus.

It is evident that motor nerves have to be used as axon donors to achieve a motor function, and sensory nerves to achieve a sensory function. There are a few cases in which nerve transfers can be performed by direct neurrorhaphy. In the majority of cases, nerve grafts are necessary.

In a classical nerve transfer, the function of the axon donor has to be sacrificed in order to be able to transfer the nerve fibres to the recipient nerve. With the technique of end-to-side coaptation (Viterbo 1994), this is not necessary. By using this method, it is possible to achieve neurotization of a denervated nerve without loss of function of the donor nerve. This works very well with small monofunctional nerves; however, whether it works with major mixed nerves has still to be proven.

Transfer of normal muscles, arthrodesis, tenodesis

In cases of partial brachial plexus lesions the lost function can be replaced by the transfer of functioning muscles. Examples include:

- The Steindler operation, consisting of transposition of the origin of the common head of the forearm flexors to the humerus shaft in order to give a better lever arm for flexion of the elbow joint (Steindler 1918);
- Transfer of a segment of the major pectoralis muscle to restore elbow flexion (Clark 1946);
- Transfer of the trapezius muscle for the shoulder joint (Saha 1967).

It is obvious that these procedures are applicable only in cases with partial lesions. Without a functioning muscle, a muscle transfer is not possible.

The above-mentioned techniques mainly refer to upper brachial plexus lesions of the type C5 and C6.

A Steindler operation will not be successful if the wrist joint is not to be stabilized, as in cases of the upper brachial plexus lesion of C5, C5, and C7. Here, wrist arthrodesis must be performed before the Steindler operation.

The lost radial nerve function in partial lesions of C5, C6, C7 frequently needs a tendon transfer, as for a radial nerve paralysis.

In a lower brachial plexus lesion, restoration of gripping function can be attempted by transfer of extensor tendons.

Arthrodesis or tenodesis of the wrist provides wrist flexors or extensors for transfer to the fingers.

If there is a very good serratus anterior and trapezius muscle, arthrodesis of the shoulder joint may provide sufficient active motility and may be a good solution. If, however, there is a serratus anterior, arthrodesis of the shoulder joint is less good than with the above-mentioned trapezius transfer. Several patients have been unhappy following shoulder joint arthrodesis.

Transfer of regenerated muscles

Experience shows that a regenerated muscle is less functional than an original one. Usually, for nerve transfer it is required that the muscle to be transferred has a force of M4. In the case of extensive brachial plexus lesions, transfers are performed with weaker muscles with the hope that muscle strength can be improved by exercise.

Adding new muscles by microvascular muscle transplantation

If the local muscles of the paralyzed extremity have undergone atrophy and degeneration, the only way to achieve a functional result is by transplantation of a muscle from another place, using microvascular anastomosis.

Different basic approaches to dealing with post-traumatic brachial plexus lesions

Limited neurotization

After having given up an attempt to bridge defects by nerve grafts, Seddon (1975) successfully performed a nerve transfer from an intercostal nerve via a nerve graft to the musculocutaneous nerve (Seddon 1963). This became a standard approach in Tokyo (Tsuyama et al 1968). He did not explore the brachial plexus, but only performed the intercostal nerve transfer to the musculocutaneous nerve if there was a suspicion of avulsion. All recently denervated muscles with potential of regeneration are neglected.

Using two or three intercostal nerves (2, 3, 4) and dissecting in a longway the intervertebral direction to have the nerves long enough for a neurorrhaphy, a high percentage of useful recoveries been achieved (Nagano et al 1992, Ogino and Naito 1995).

Primary free muscle grafting

The use of free muscle grafting in inveterated cases or in connection with impaired motor branches has been mentioned already. Doi (1995) suggested immediate application of two free muscle grafts without exploring the brachial plexus, in order to re-establish elbow flexion and finger extension with one of these muscles, and elbow extension and finger flexion with the other. The use of one muscle for two different functions is always problematic, but Doi demonstrated good results. However, he achieved no satisfactory shoulder function; the muscles of the extremity, which could at least have partially responded if the brachial plexus had been operated on, were wasted.

Combined treatment

Brachial lesions are such complex injuries with such severe consequences that all available techniques should be applied. This concept was summarized in 1973 (Millesi et al 1973); at first the brachial plexus is operated, and all available techniques are then applied to achieve as much neurotization as possible. After a period of physiotherapy, the result of nerve regeneration can be evaluated. In a second phase, all suitable muscle transfers are performed to maximize the result.

Description and discussion of Millesi's personal strategy and technique

The principle is to use as many axon donors as possible to apply as many nerve grafts as possible, and to neurotize as many muscles with chances of recovery as possible. The problem is not should we do this or should we do that; all reasonable chances must be exploited. The treatment starts with surgery on the brachial plexus and ends 5 years later, once all the possibilities of conservative treatment, reconstructive surgery and mechanical improvement have been utilized.

Position

The patient lies supine with the scapular region supported; the arm, the left part of the upper thoracic wall and the neck are scrubbed. The arm is completely mobile and can be lifted and positioned in lateral and medial directions. This is especially important because during the surgical dissection underneath the clavicle it is important to lift the elbow and the upper arm in order to provide space between the clavicle and the first rib.

Incision

Three separate incisions are used instead of the single zig-zag used in the early years but abandoned in about 1995. The main incision is performed in the flexion crease, which is visible when the head is bent to the paralysed side and the shoulder is lifted. This line has an acute angle to the clavicle, is in an area where least traction is manifested during head and shoulder movements, and can be extended in dorsal direction to the trapezius muscle. If necessary the dissection can explore the brachial plexus from above and behind. With a zig-zag incision the supraclavicular fossa is exposed after lifting a dorsally-based flap, and the base of this flap prevents good access to the plexus from above and behind. The incision should not be extended too far ventrally because the final scar will not be as good in the pectoral area as in the supraclavicular fossa.

Dissection

By undermining in both directions, the clavicle is exposed. By entering across the fascia of the supraclavicular fossa, the superior and medius trunk are easily accessible between the anterior and medius scalenous muscle.

The dissection enters the infraclavicular fossa between the pectoralis major and the deltoid muscle. To gain more access, the lateral origin of the major pectoralis muscle can be disinserted from the clavicle.

It is a basic principle to start dissection in normal tissue and to proceed to pathologic tissues. If, therefore, a lot of fibrosis is encountered in the supra- or infraclavicular fossa, the plexus in the deltopectoral sulcus is explored via third incision, which extends to and follows the anterior axillary fold. After entering between the two muscles, the fascia between the minor pectoralis and the coracobrachial muscle is transected and the individual structures of the brachial plexus including the axillary artery, are defined. The dissection can now proceed to the infraclavicular fossa.

If the area of the deltopectoral sulcus is also involved in scar tissue, which is frequently the case if there was a vascular lesion, the incision is extended to the midline of the medial aspect of the upper arm. The nerves and vessels are explored in the upper arm and dissection proceeds from here to the axilla and to the deltopectoral sulcus.

The minor pectoralis muscle is also isolated. If the dissection from the deltopectoral sulcus has reached the infraclavicular fossa, the situation has been cleared here. The clavicle is isolated, as well as the subclavius muscle.

In the supraclavicular fossa, the A. transversa colli and the omohyoideus muscles are identified, as well as the external jugular vein. The two operative fields in the supra- and infraclavicular fossae are now united by elevating the clavicle. At this point the arm is lifted, with a flexed elbow joint, in order to increase the space between the clavicle and the first rib.

The supra- and medius trunks have been explored already from the supraclavicular fossa. The inferior trunk, however, is best identified by following the medial cord underneath the clavicle while lifting the clavicle. The formation of the spinal nerves C8 and T1 is reached at the level of the Sibson's fascia. Both spinal nerves can then be followed to the exit of the respective intervertebral canal. The phrenic nerve is identified on top of the anterior scalenous muscle. At the lateral side of the scalenus medius muscle, the dorsalis scapulae nerve and the long thoracic nerve are apparent.

The medial and lateral pectoral nerves, the thoracodorsal and the subscapular nerves must also be identified. The suprascapular nerve is identified at its origin from the superior trunk and followed in a distal direction. If there is suspicion of a compression site at the incisura scapulae, the dissection is extended to this structure and the incisura scapulae opened.

By the end of the dissection, the whole length of the brachial plexus is exposed and access is available through a series of 'windows' – across the first incision at the neck; in the supraclavicular fossa cranial and caudal to the omhyoideus muscle; between the clavicle and the subclavius muscle; between the subclavius muscle and into the pectoral sulcus medial and lateral to the pectoralis minor muscle; in the axilla from the cranial direction; and, if the incision has been extended to the upper arm, to the axilla from the caudal direction.

It is never necessary to perform an osteotomy of the clavicle bone. As a rule the transversing muscles are saved; only if the major pectoralis muscle causes an internal rotation contracture is it disinserted and reinserted under reduced tension.

Dealing with the lesion

If there is a lesion in continuity, neurolysis is performed as described above. If the paraneurium or the epifascicular epineurium have developed a fibrosis, a para- or epineuriotomy is performed in order to achieve decompression. If this is not sufficient, a para- or epineuriectomy is performed.

If no fascicular pattern can be detected, a grade IV lesion is assumed and a resection of the involved segment is performed, with restoration of continuity by free nerve grafts.

The problem of involvement of the rootlets with the spinal nerve being still located in the intervertebral canal, has already been discussed. Even in cases of grade VI damage where it is necessary to resect and bridge the defect, it is a limited defect with well-defined proximal and distal stumps.

Root avulsions

If the roots are avulsed there is no proximal stump, and all axons to be directed into the denervated nerves come from another source. Under these conditions it is impossible to neurotize all distal structures and, therefore, a list of priorities must be established.

The most important function is active elbow flexion, and therefore neurotization of the biceps has highest priority. The best available axon donor is reserved for the musculocutaneous nerve. This is very frequently the accessory nerve. Two or three intercostal nerves also provide a good chance for the biceps.

Secondly, it is extremely important for the patient to be able to stabilize the shoulder joint and to have at least a little abduction. This is provided by neurotizing the suprascapular or the axillary nerve from nerve fibres coming from motor branches of the cervical plexus.

Thirdly, innervation of the serratus anterior muscle to give a stable scapula is extremely important. Neurotization of the long thoracic nerve is therefore necessary. This can be achieved by using the dorsalis scapulae nerve. For several years we have not transected the dorsalis scapulae nerve but have preserved its continuity and applied a distal stump of the long thoracic nerve as an end-to-side coaptation to the trunk of the dorsalis scapular nerve. This has given excellent results in all cases in which this technique was utilized.

Finally, even the best recovery of elbow flexion does not help very much if the patient is unable to perform external rotation. For this function the major pectoralis muscle is earmarked. This muscle is reinnervated by neurotizing both the medial and the lateral pectoralis nerves. In our series this has been done via nerve grafts, which have been coapted end-to-side to the phrenic nerve with excellent results. Motor branches of the cervical plexus can also be used for this. Following successful reinnervation of the major pectoralis muscle, it is later transferred to perform external rotation.

Nerve fibres from the phrenic nerve have also been successfully applied via nerve grafts coapted end-to-side to the nerves supplying the major pectoralis muscle and going to the suprascapular nerve. Intercostal nerves are used to neurotize the radial nerve, with special reference to the triceps branches.

Good recovery of the triceps is frequently obtained by using intercostal nerves. In cases in which several intercostal nerves have been used to achieve biceps function, the triceps muscle has also been neurotized. Of course, the biceps and triceps are antagonists, but this is with the intention to transfer the triceps to the biceps tendon in order to have both acting as elbow flexors. This has been useful in several cases in which the biceps was neurotized by intercostal nerves and did not respond well, and the triceps was the second line of defence.

The second intercostal nerve is coapted by end-to-end neurorrhaphy to the thoracodorsal nerve, in order to achieve a latissimus dorsi function. This can be used for external rotation if the major pectoralis does not recover.

It is, of course, also the aim to achieve at least a primitive gripping function, even in patients with avulsion of all five roots. For this reason a C7 transfer is performed. There are several options. The C7 transfer can be performed as a second stage. It can be performed using the ulnar nerve as a vascularized nerve graft, connecting its original distal end with the contralateral C7 and its original proximal end with the median nerve. This has, in a majority of cases, provided reinnervation of the finger flexors, the flexor pollicis longus and the flexor carpi radialis. In other cases, especially in children, free saphenous nerve grafts have been used for the C7 transfer and the median as well as the ulnar nerve have been neurotized. In these cases one graft was connected to the anterior and one graft to the posterior division of the medius trunk. In several of these cases flexor and extensor function returned, which of course offers the best chances for reconstruction of gripping function.

If only the flexor pollicis longus, finger flexors and the flexor carpi radialis recover, arthrodesis of the wrist joint is performed and the flexor carpi radialis is transferred for finger extension. In this case, of course, only a key grip function can be achieved.

In some of these patients a considerable source joins the brachial plexus from C4, and this is used as an axon donor for shoulder muscles.

In cases of avulsion of the roots 6, 7, 8, and T1 with C5 present as a stump after rupture, C5 (as the best available axon donor) is used for the musculocutaneous, and the accessory nerve for the suprascapular nerve. Otherwise, the same transfers are applied.

With avulsion of three roots (C5, C6, C7), a similar transfer is performed but no C7 transfer is necessary.

With avulsion of C7, C8, and T1, the stumps of C5 and C6 are utilized to neurotize the superior and medius trunks. For the inferior trunk, a C7 transfer is considered.

In cases of avulsion of two roots (C5 and C6), nerve transfers from the accessory nerve and the cervical plexus are performed for the subscapular and axillary nerve; the anterior division of C7 is connected to the musculocutaneous nerve and the posterior division to the radial nerve. The continuity of C8 and T1 and the inferior trunk is restored.

In cases of avulsion of C6 and C7, C5 is utilized to neurotize the musculocutaneous and the median nerves, the accessory nerve is used for the suprascapular, the intercostal nerve for the radial nerve, and the continuity of C8 and T1 is restored.

In cases of avulsion of C8 and T1, the stumps of C5 and C6 are utilized to neurotize suprascapular, axillary and radial nerve (C5), respectively, musculocutaneous and lateral median nerve (C6).

In cases of avulsion of C8 and T1, the continuity of 5, 6, and 7 with the peripheral structures of the lateral and dorsal cord are restored, and for the inferior trunk a C7 transfer may be considered. If there is only an avulsion of one root, it can be ignored.

Rupture at root level

It has already been mentioned that with short defects we prefer to bridge the defect with long grafts, connecting the proximal stump directly with the corresponding peripheral nerves. It is obvious that the continuity of as many structures as is possible by the availability of graft donors will be restored.

Lesions at the level of trunks and cords

These are treated according to the general rules of peripheral nerve surgery.

Axon donors

Accessory nerve

The accessory nerve is a very good axon donor; it is very useful for the suprascapular nerve and also for the median nerve. It is transected after the first branch has left it. The trapezius muscle is usually not completely denervated by this.

Motor branches of the cervical plexus are useful donors, they are identified by electric stimulation and connected by grafts, preferably with shoulder muscles.

Phrenic nerve

The phrenic nerve is a very potent axon donor, but there is the danger of the loss of diaphragm function. End-to-side coaptation offers a good opportunity to use this nerve without transection. It has proven its value in neurotizing and achieving recovery of the suprascapular nerve and supraspinatus muscle, and the pectoralis nerve and the major pectoralis muscle.

Hypoglossus nerve

We have no personal experience of using this nerve.

Supraclavicular nerves

These purely sensory nerves have been successfully connected via a nerve graft with the median nerve, to improve sensation.

Second intercostal nerve

This is useful for neurotizing the thoracodorsal nerve for the latissimus dorsi muscle.

Intercostal nerves

Intercostal nerves III and IV can be mobilized and brought into direct contact with the distal stump of the musculocutaneous or the radial nerve to achieve direct neurotization. Intercostal nerves V, VI, VII, and VIII have been used for musculocutaneous and/or radial nerve (triceps); a nerve graft is always necessary.

Intercostobrachialis nerve

In selected cases these nerves have been successfully connected with fascicles of the median nerve by long nerve graft.

Dorsalis scapulae nerve

This is a useful donor for the long thoracic nerve, preferable by end-to-side coaptation.

Contralateral C7

It is well known that the transection of C7 alone under normal anatomical conditions produces a weakness of the radialis nerve innervated muscles, especially the triceps and the wrist and finger extensors; however, there is no paralysis. These muscles regain their original strength by internal sprouting. This relates to the posterior division. The anterior division innervates the pectoralis muscle and other muscles to a much lesser degree without visible loss of function. There is always a small sensory loss in the thumb and the index finger. In some cases this loss is very important and is not well tolerated by patients. In cases of pre- or post-fixation the composition of the spinal nerve C7 is different, and may contain more important fibres. There was one case in our series in whom biceps and deltoid function was supplied by C7, and this patient had a considerable loss of function.

For this reason, a C7 transfer is never performed immediately. Ligature of the anterior and posterior divisions of C7 is always performed first and the patient is carefully examined the next day. The real loss of function can then be assessed. If there is a major loss of sensory function, only the posterior division is used. If there is a more important loss of motor function, the transfer is not performed at all. In the above-mentioned patient, after cutting the ligature, function recovered completely. In this particular case the nerve grafts were applied in end-to-side fashion and some regeneration from C7 to the contralateral arm was achieved after end-to-side coaptation, but without useful recovery.

End-to-side coaptation

Viterbo (1994) noted good neurotization in a denervated nerve after end-to-side coaptation to an innervated nerve. Many further experimental studies have confirmed this observation. Apparently a denervated nerve poses such a stimulus to the axons that they start to sprout even if uninjured, and even across an intact perineurium. That a nerve graft can also stimulate this sprouting is very helpful, because it enlarges the possibilities of end-to-side coaptation. The problem, however, is that there is no control whatsoever over which fibres will start to sprout – sensory or motor and, if motor, which function. This might be the reason for failures of end-to-side coaptation in experiments with peripheral nerves.

Graft donors

The following nerves have been used as donors for free nerve grafts:

- Sural (bilateral);
- Cutaneus antebrachii medialis;
- Cutaneus antebrachii lateralis;
- R. superficialis nervus radialis;
- Cutaneus fem. lateralis nerve (bilateral);
- Saphenous (bilateral);
- Split ulnar.

The following nerves have been used as donors for vascularized nerve grafts:

- Ulnar nerve, based on the superior ulnar collateral artery and vein;
- Saphenous nerve (bilateral).

Postoperative care

Patients who have undergone brachial plexus surgery with neurolysis only are immobilized for 2 days and start active and passive exercises from the third day. Patients having had nerve grafts are immobilized for 8 days and start active exercises (using non-paralysed muscles) and passive exercises from the third week. Electric stimulation with exponential currents is recommended. The use of splints and prostheses is encouraged.

Reconstructive surgery

It has already been mentioned that during surgery on the brachial plexus, muscles are earmarked for secondary transfer.

The best example is the major pectoralis nerve, which is neurotized as a priority and has the scope to be transferred for external rotation after recovery. In cases of intercostal nerve transfer to the biceps and triceps, the triceps is earmarked for transfer, in order to support the biceps which may be too weak alone. The triceps, of course, has to perform elbow flexion alone if the biceps does not recover.

A similar procedure (triceps transfer) is performed in cases in which a simultaneous innervation of biceps and triceps occurs with co-contractions. Biceps and triceps neutralize each other, and the procedure is sometimes registered as a failure. In such cases there are two options. The first is to paralyse the triceps with botulinum toxin. During paralysis the force of the biceps muscle is increased as much as possible by physiotherapy. If the triceps recovers, the biceps should be much stronger and perform elbow flexion in spite of co-contractions. Before botulinum toxin was available, a lengthening operation of the triceps tendon was performed in order to diminish its force. If, however, co-contractions are so strong that the force of biceps and triceps are equal, or that the triceps is even stronger than the biceps, then a transfer of the triceps on the biceps tendon is performed; both muscles then act as elbow flexors and extension is provided by gravity. The lack of active extension in these cases is not as important as in other patients because, due to the weakness of the shoulder muscles and the reduced function in the shoulder joint, the patient will be unable to work at the level where strong active extension is needed.

Weak elbow flexion by a weak biceps can be improved by transferring the biceps insertion more distally to the radius, thereby increasing the lever arm.

In cases of an upper brachial plexus lesion, a Steindler operation may be performed if the force of the returning elbow flexion is insufficient.

In cases of partial brachial plexus lesions, the pectoralis major (Clark 1946) or the latissimus dorsi (Zancolli and Mitre 1973) may be utilized to restore elbow flexion. The function of the shoulder joint can be improved, as far as abduction is concerned, by a trapezius transfer. Disinsertion of the trapezius muscle and reinsertion on the humerus provides little active abduction but good stability. A better option is to isolate the trapezius muscle, mobilize the supraspinatus, and suture the trapezius to the supraspinatus with its distal part across the canal to the humerus, and to perform the insertion at the rotator calf.

Active external rotation can be achieved by transfer of the pectoralis major and, eventually, the pectoralis minor, the latissimus and the teres major; also by transferring the tendon of the subscapularis.

In rare cases a supination contracture, as frequently happens in obstetric brachial plexus lesions, may develop in a patient with an upper brachial plexus lesion. It is corrected by transection of the interosseus membrane and transfer of the biceps tendon or, to give the biceps tendon its pronating effect, by reinserting the biceps in a neutral position. In this case, of course, active supination is lost, but the effect of the biceps in flexing the elbow joint is increased.

In cases of a C5, C6, and C7 lesion a tendon transfer is performed, as in radial nerve palsy.

The most challenging problem is the restoration of gripping function with the few muscles of the forearm that might have recovered. In spite of the fact that arthrodesis is not always a successful procedure, this is performed in cases where only very few muscles are working and the wrist flexors or extensors are needed. It is performed using a plate between the third metacarpal bone and the radius in the neutral position, or even in slight flexion. Patients do not appreciate a dorsiflexion position (as would be used in other cases) because they want to be able to put the hand in their pocket of their trousers. In many cases a tenodesis can be performed to stabilize the wrist. For each individual patient a particular plan has to be developed. If there are three muscles, one muscle may be used to provide MP joint flexion and the second for finger flexion, being connected to the flexor digitorum profundus tendons and the flexor pollicis longus tendon. The third muscle is used for finger and thumb extension. It is obvious that only a very primitive gripping function can be achieved. In order to provide a sufficient key grip, arthrodesis of the IP joint in the neutral position is done. The tendon of the flexor pollicis longus is disinserted and transferred to the lateral dorsal aspect of the first phalanx, in order to give the thumb a good adduction and a small amount of pronation. If there are four muscles, one muscle is connected to the flexor pollicis longus tendon to give independent thumb adduction and, if there are five muscles, the fifth muscle is used for thumb extension.

Results

In almost 40 years of brachial plexus surgery, there has been a constant improvement in results. Even in cases of five root avulsions, sufficient active elbow flexion can be expected in about 80 per cent of cases, useful control of the shoulder joint and external rotation in about 60 per cent of cases, and gripping function in the form of a key grip in at least 30 per cent of cases.

Critical remarks

The majority of cases achieve some sensory input, very often in the form of paraesthesia without being able to localize the touch. Patients with intercostobrachial to distal radial transfers get protective sensibility.

The results of brachial plexus surgery depend on many individual factors, and, therefore, every surgeon has a certain percentage of failure. However, cases are frequently seen which, although declared as final results by the original surgeon, still have the potential for further improvement by muscle or tendon transfer, tenodesis, arthrodesis or other reconstructive procedures. It is not unusual for a patient to be regarded as a failure because active elbow flexion was not achieved, due to co-contractures between biceps and triceps.

It is also necessary to emphasize that, in the author's view, it is a failure if all available options are not explored.

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10
Injuries of the terminal branches of the brachial plexus

Rolfe Birch

Introduction

There are profound differences between supra- and infraclavicular lesions; chief amongst these is the high incidence of intradural (preganglionic) lesion in the former (Bonney 1954, Bonney and Gilliatt, 1958).

Injuries to the infraclavicular plexus and terminal branches of the brachial plexus are often caused by great violence and there is frequently severe damage to the scapula, clavicle and humerus. Damage extends not only to the skeleton but also to the nerves, where wide retraction of the stumps in traction injury or extensive destruction of nerve substance is common.

Rupture or transection of the subclavian/axillary/common brachial arterial axis is frequent; the author found this in 25 per cent of closed traction lesions, with a greater incidence in knife wounds or injuries caused by penetrating missiles.

The neurological lesion is a complex one, with ruptures of nerves at different levels and with avulsion of nerves such as the musculocutaneous or circumflex directly from the relevant muscle bellies. This complexity is increased by the combination of lesions at two levels, which occurs in about 15 per cent of cases (Fig. 1).

The notion of 'motor' and 'sensory' nerves should be abandoned, for no such distinction exists within the peripheral nervous system. The spinal accessory nerve has no cutaneous component and, as Bremner-Smith et al (1999) have shown, the majority of its fibres are non-myelinated and are probably afferent nociceptors. The suprascapular nerve, another trunk with no cutaneous innervation, contains many myelinated afferents from the muscle spindles, tendon and capsule.

Diagnosis

A distinction must be made between degenerative and non-degenerative lesions. When an axon is cut, Wallerian degeneration follows, the axon degenerates, and conduction is lost at about 3–4 days. All function is lost. A particularly

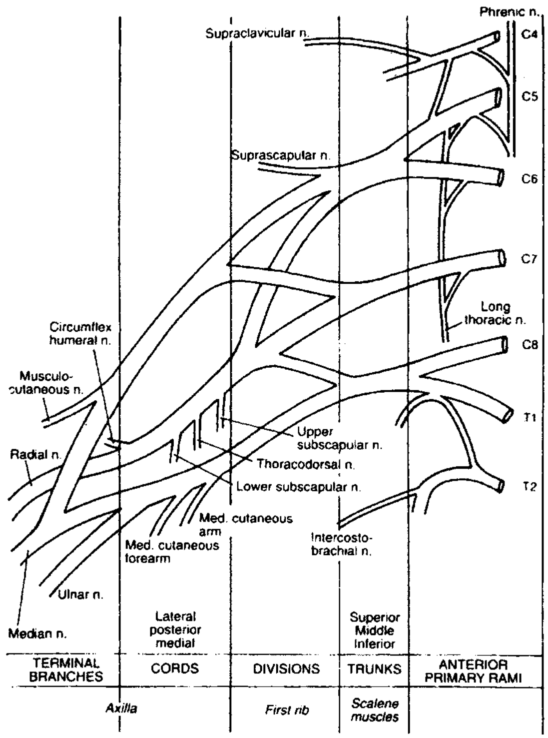

Figure 1

Diagram of brachial plexus.

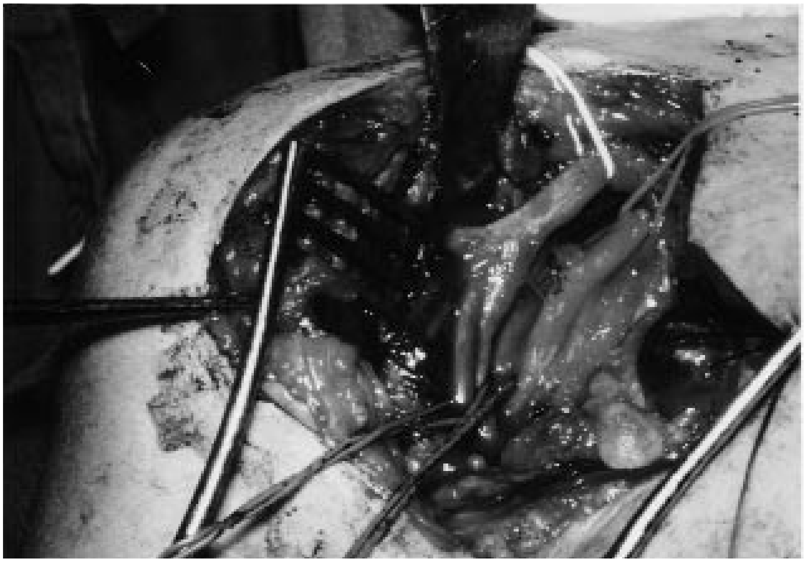

Figure 2

Axillary artery and lateral cord were encircled by sutures during anterior stabilization of shoulder.

important clinical sign in this situation is vaso- and sudo-motor paralysis owing to interruption of the post-ganglionic sympathetic efferent fibres. The skin in the territory of the affected nerve becomes red and dry.

The progressive changes in the target organs of muscle, skin, blood vessels and the sensory organelles are well known. Muscle denervated for 2 years or more is lost to function, but of equal significance are the changes that occur proximally after transection of the axons. The proximal portion narrows, and in the parent neurone there is chromatolysis and retraction of dendrites. According to Bonney (1998), 'these processes may continue to actual dissolution of the cell body'. Dyck et al (1984) were able to study the effect of permanent axonotomy in the spinal cord of two patients years after amputation of a lower limb, and they found that 'a loss of target tissue by axonotomy leads to atrophy and then loss of motor neurones'. These central changes are more extreme and more proximal in extensive and violent injuries, and they are fundamental factors in the prognosis after repair; they are the most important reasons for minimizing the delay in effecting nerve repair.

Seddon (1943) classed nerve injuries into three groups:

1. Neuropraxia (the nerve not working), which implies a physiological block to conduction but no anatomical disturbance of the nerve. Distal conduction persists in this non-degenerative lesion;
2. Axonotmesis (axon cutting), in which the axon is severed; there is degeneration of the distal axon, but the basal lamina of the Schwann cell remains intact;
3. Neurotmesis (nerve cutting), which is where there is interruption of continuity of all elements of the nerve.

In the latter two types, Wallerian degeneration occurs and distal conduction is lost; the clinical features are very similar.

A favourable lesion may become a much less favourable one if the cause is not removed. Recovery of a nerve accidentally encircled by a suture or crushed under a plate is likely if treatment is immediate (Fig. 2). If the offending cause remains for days or weeks, then a far less successful outcome is inevitable.

Sunderland (1951) introduced a more elaborate system of classifying injuries, recognizing five degrees of severity. Some clinicians may find Sunderland's classification an improvement on Seddon's, and of more practical use than the

Table 1 Classification of focal mechanical nerve injury (from Thomas and Holdorff 1993, with permission)

I. *Focal conduction block*
- Transient
  - Ischaemic
  - Other
- More persistent demyelinating
  - Axonal constriction

II. *Axonal degeneration*
- With preservation of basal laminal sheaths of nerve fibres
- With partial section of nerve
- With complete transection of nerve

earlier method, but we tend towards a further simplification: to classification as 'degenerative' or 'non-degenerative'. This is how clinicians should regard nerve injuries; the first question should be, is this lesion degenerative or non degenerative? (Table 1.)

Severe pain indicates substantial nerve injury that cannot be consistent with a diagnosis of non-degenerative conduction block (neuropraxia). Tinel's sign (1917) is an important clinical feature. A strongly positive Tinel's sign over a lesion soon after injury indicates rupture or severance, and will not be found in a conduction block or a non degenerative lesion. Failure of distal progression of the Tinel's sign in a closed lesion indicates rupture or another injury not susceptible to recovery by natural process.

In closed injuries with associated fracture or dislocation, the history of the injury is all-important. The force expended upon the nerve trunk can be estimated from knowledge of the velocity and the force of impact of an object, or the height of the fall. Local bruising or abrasions or linear bruising along the course of the nerve is important evidence of this force. X-rays are valuable in showing the extent of the displacement of bone fragments, and imperfect reduction or obstruction to reduction implies interposition of muscle, nerve or artery (Fig. 3).

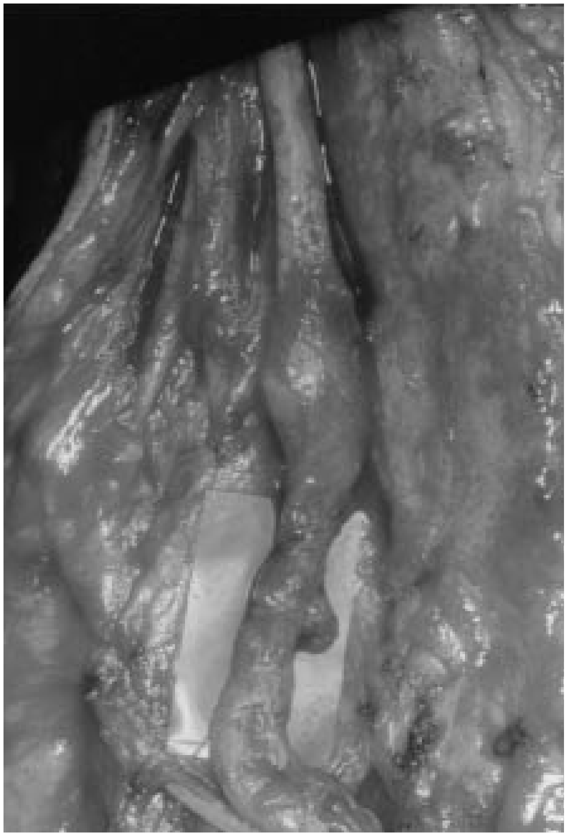

Figure 3

Long segment of disruption of radial nerve from closed fracture of the shaft of humerus.

Classification of wounds

The single most important determinant of outcome is the violence of injury to the nerve and the limb; the extent of destruction of the tissue is a reflection of this. Rank et al (1973) classified injuries of the hand as 'tidy' (amenable to primary repair) or 'untidy' (characterized by extensive destruction of tissue and by contamination). This important distinction can be applied to nerve injuries.

In a tidy wound, caused by a knife, glass or the surgeon's scalpel, damage is confined to the wound itself and primary repair of all divided structures is desirable. Associated arterial injury is common.

An untidy wound, commonly caused by open fractures or by penetrating missile injuries,

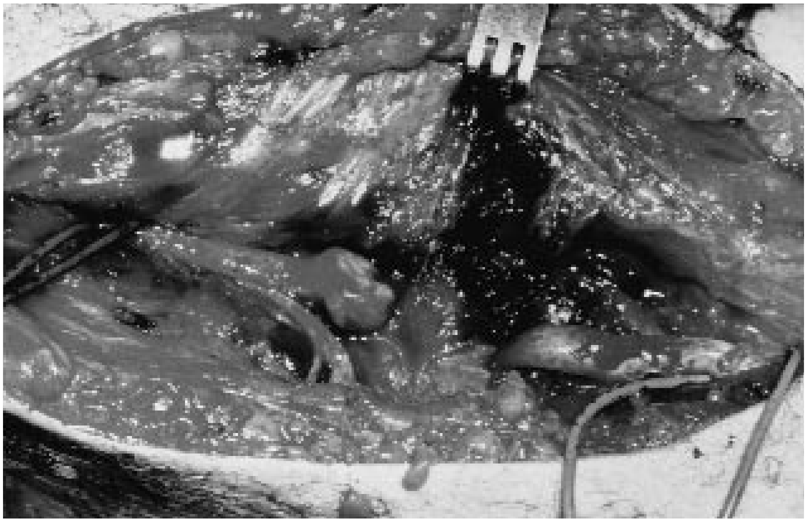

Figure 4

Closed fracture of the shaft of humerus in a 34-year-old woman. Rupture of radial nerve, with the distal stump entrapped within the fracture. The fracture had been pinned.

presents with extensive tissue damage and a high risk of sepsis. Arterial injury is common. The initial aims include restoration of the stability of the skeleton and of the circulation, with delayed closure of the skin or early recourse to a pedicle or free cutaneous/myocutaneous flap. Nerves will almost always require grafting, and timing is a matter of fine judgement. Wounds caused by industrial or agricultural machinery, burns or penetrating missiles do not, as a rule, permit primary repair. An amputated limb affords the most uncompromising model of this type of injury. Primary repair of the nerve gives the best results in these severe cases.

The closed traction rupture – nerves injured by fractures or dislocations

Damage to the adjacent skeleton can cause nerve injury by traction, laceration (by fragments of bone), entrapment within the dislocated joint or in a fracture, and later, entrapment or compression by callus. On the whole, dislocations are more damaging. It seems to be widely assumed that the prognosis for nerves injured in this manner is good, but this is not generally the case. Seigel and Gelberman (1991) reviewed the subject thoroughly, finding 85 per cent of nerve palsies after closed fractures and 65–70 per cent after open fractures. Of those nerves that went on to recover, 90 per cent had done so by 4 months; these *cannot* have been wholly degenerative lesions. Seigal and Gelberman's indications for intervention include: that the fracture needs internal fixation, that there is associated vascular injury; that wound exploration of an open fracture is necessary; or that fracture or dislocation is irreducible. Two more indications may be added; if the lesion worsens whilst under observation; and if the lesion occurrs during operation for internal fixation of a fracture (Fig. 4).

It is important to distinguish the true infraclavicular lesion, in which multiple ruptures of nerve trunks with associated fractures and arterial damage owing to lower energy transfer injuries is associated with fracture dislocation of the shoulder, in which damage to the rotator cuff, mal- or non-union of the proximal humerus, or intra-articular damage to the gleno-humeral joint are very unfavourable features. The infraclavicular lesion is a distinct entity, generally caused by violent hyperextension at the shoulder; there is almost always a fracture of the shaft of the humerus or injury to the gleno-humeral joint, the incidence of vascular injury is high, and

Figure 5

25-year-old patient, high-speed road traffic accident causing infraclavicular traction lesion. Rupture of axillary artery and radial nerve.

the level of proximal rupture is deep to the pectoralis minor, which acts as a guillotine on the neurovascular bundle.

These injuries are immensely destructive of nerves and axial vessels. They are characterized by retraction of the ruptured nerves and vessels and by considerable longitudinal damage within the ruptured trunks. When complicated by arterial lesions, which occur in about 25 per cent of cases, the outcome following nerve repair is the worst of all groups (Fig. 5).

Indications for operation and principles of nerve repair

The decision to intervene with a nerve injury is never easy, except perhaps in the acute case of an open wound, and in cases in which nerve injuries are associated with major bones and blood vessels. The indications for such operations are probably as follows:

1. Deep paralysis after wounding over the course of a main nerve or injection close to the course of the main nerve;
2. Deep paralysis after a closed injury, especially high energy transfer injury associated with severe damage to soft tissues, bones or joints;
3. Deep paralysis after a closed traction injury;
4. Association of a nerve lesion with evidence of an arterial lesion;
5. Association of a nerve lesion with fracture of a related bone requiring early internal fixation;
6. Worsening of a nerve lesion whilst under observation; failure to show evidence of recovery at a fixed time after a closed lesion initially thought to be an axonotmesis;
7. Failure to show evidence of recovery in conduction block within 6 weeks of injury;
8. Persistent pain at almost any interval after injury.

Where direct suture of a nerve is not possible, then the mainstay technique remains autologous grafting. The results of operating on peripheral nerves depend, to an extent hardly matched in any other branch of surgery, on the skill of the surgeon and the quality of the technique. Nerve suture is performed when the gap after resection is small, little mobilization of the nerve is needed to close it, and the repaired nerve lies without tension and without excessive flexion of adjacent joints. The experimental work of Clark et al (1992) clearly showed the ill effects of tension on the repaired nerve.

Table 2 Arterial injuries in association with nerve lesions, 1975–1996 (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

	Closed		*Open*	
	Total	*Repaired*	*Total*	*Repaired*
Vertebral	1	0	4	1
Subclavian	82	40	9	9
Axillary	63	54	31	27
Brachial	7	6	35	31

Traumatic false aneurysms and arteriovenous fistulae with associated nerve lesions

Region – artery	*Aneurysms*	*Arteriovenous fistulae*
Posterior triangle of neck	3	2
Axillary	14	3
Brachial	4	1

Vascular lesions

George Bonney introduced the policy of urgent primary repair of nerves and vessels in the combined neurovascular injury unit at St Mary's Hospital in the mid 1960s, and this policy has been followed ever since. Of the cases described here, repair of nerves and vessels was performed within 48 hours in 98 cases, and later than this time in 66 cases. It was necessary to revise arterial repairs performed in the referring hospital in 32 more cases. Diagnosis of aneurysm or arteriovenous fistula was made between 10 days and 4 years from causal injury. Proper repair of a vascular lesion is the single most important factor governing prognosis amongst all of those within the surgeon's control. Delay in the repair of nerves after arterial repair presents technical difficulties, which are sometimes insuperable and invariably diminish the level of functional return (Table 2).

Open injuries

The level of the arterial injury is not necessarily related to the entry wound. Complete resection of the artery does not inevitably lead to exanguination, as the vessel constricts in spasm (an observation first made by John Hunter). The slowly expanding false aneurysm causes profound loss of conduction in adjacent nerve trunks; the deep-seated aneurysm may not be clinically diagnosed unless the potential significance of an earlier wound is noted (Fig. 6).

Closed traction injuries

The first injury is fracture of the intima, which in more violent injury progresses to rupture of all

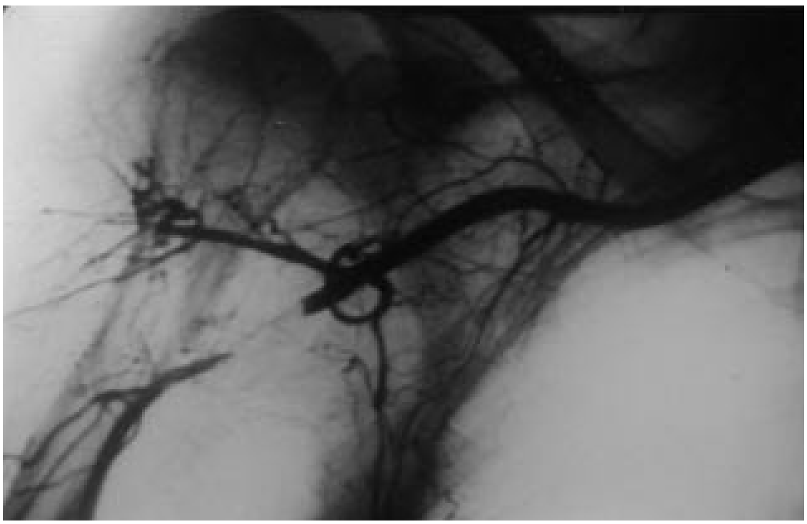

Figure 6

Transection of axillary artery from knife wound in a 33-year-old woman. There was little bleeding because of spasm within the divided artery.

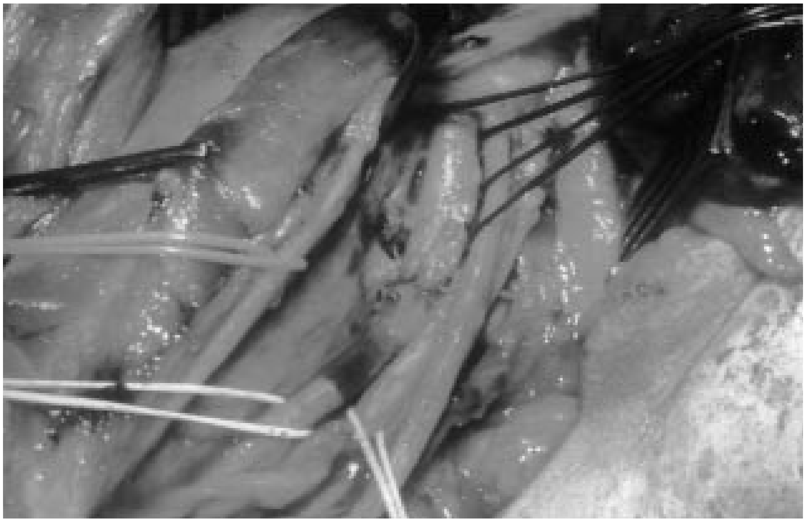

Figure 7

63-year-old man. Rupture of axillary artery after fracture dislocation of shoulder.

coats of the vessel. The intimal injury can easily be seen as a pale crescent-shaped line, the damaged segment of the artery being filled with thrombus (Fig. 7). Attempts to restore flow using embolectomy catheters are invariable futile. The level of the arterial injury is consistent in closed traction injuries, the axillary artery being found occluded deep to pectoralis minor. Urgent amputation was performed in two cases of gas gangrene occurring with 24 hours of successful repair by prosthesis, in four cases with upper limbs so badly damaged that there was no possibility of functional recovery, and in two cases (limbs amputated through the gleno-humeral joint) where operation for replantation was abandoned because of uncontrollable bleeding. Reasonable circulation to the skin is not the issue; what is important is whether muscle is perfused, and failure to restore the flow through a damaged axillary or common brachial artery within 6 hours of injury is almost always followed by a degree of post-ischaemic fibrosis. The exposure of choice is that developed by Fiolle and Delmas (1921); the reader is referred to *Surgical Disorders of the Peripheral Nerves* (Birch, 1998) for further discussion of this and other technical issues.

Distal circulation was successfully restored in 148 cases, with strong peripheral pulses. In three cases, failure to restore bloodflow necessitated amputation.

Results

Measurement of outcome

Seddon (1975) described a system for measurement of outcome which was drawn from the Medical Research Council system, and classified results of nerve repair as fair, poor or bad. We have simplified this further into good, fair or poor, using the grade ‘excellent’ rarely and in exceptional cases where function is indistinguishable from normal. For some nerves muscular function is a good deal more important than recovery of sensation, and for such nerves (e.g. the spinal accessory, suprascapular, circumflex, musculocutaneous and radial) little significance is attached to the extent of recovery of cutaneous sensation except when recovery is complicated by severe pain, when the result is considered poor. Recovery for sensation has been given equal importance to muscle function in the description of results in median and ulnar nerves, and it could be argued that sensibility is the most important function of the median nerve. There are of course defects and limitations of the MRC system, but it has stood the test of time. Kline and Hudson (1995) described a valuable grading system for motor and sensory function, and for the whole nerve. The particular difficulties of measurement of limb function in cases of injury to the adult brachial plexus were addressed by Narakas (1989), and his system is certainly useful in the measurement of outcome of the more severe cases of multiple ruptures of trunk nerves (Tables 3, 4).

Spinal accessory nerve injury

The XIth cranial nerve innervates the sternocleidomastoid and trapezius muscles, and has no cutaneous distribution. The nerve is particularly at risk from surgeons where it emerges from deep to the sternomastoid into the posterior triangle of the neck. Damage may be inevitable during radical neck surgery for cancer. In most cases injuries were inflicted during the course of lymph node biopsy or other operations for a benign condition within the posterior triangle of the neck. Williams et al (1996) have described the characteristic syndrome of symptoms and clinical signs as pain, drooping of the shoulder, loss of abduction, winging of the scapula, and numbness of the face and ear caused by damage to the adjacent transverse cervical and greater auricular nerves (Fig. 8; Tables 5, 6).

Table 3 Classification of outcome of nerve recovery (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

Motor recovery	
M0	No contraction
M1	Return of perceptible contraction in the proximal muscles
M2	Return of perceptible contraction in both proximal and distal muscles
M3	Return of perceptible contraction in both proximal and distal muscles of such degree that all *important* muscles are sufficiently powerful to act against resistance
M4	Return of function as in Stage 3, with the addition that all *synergic* and independent movements are possible
M5	Complete recovery
Sensory recovery	
S0	Absence of sensibility in the *autonomous area*
S1	Recovery of deep cutaneous pain sensibility within the *autonomous area* of the nerve
S2	Return of some degree of superficial cutaneous pain and tactile sensibility within the *autonomous area* with disappearance of any previous over-reaction
S3+	Return of sensibility as in Stage 3, with the addition that there is some recovery of two-point discrimination within the *autonomous area*
S4	Complete recovery

Table 4 Grading of results (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

Motor recovery	*Sensory recovery*
M4 or better	Good
M3	Fair
M2	Poor
M1 & O	Bad
S4 (normal) or S3+	Good
S3	Fair
S2	Poor
S1 & 0	Bad

Figure 8

Lesion of the spinal accessory nerve. Note the apparent winging of the scapula.

Table 5 Accessory nerve lesions: classification of recovery (from Williams et al 1996)

	Outcome	*Grade*	*Number*
A	No change	Poor	7
B	Pain improved Movement improved	Fair	10
C	Almost normal (difficulty with overhead work)	Good	15
D	Normal (from patient's point of view)	Excellent	4

Table 6 Results of repairs of the spinal accessory nerve

Cause	*Number of repairs*	*Outcome*			
		Poor	*Fair*	*Good*	*Excellent*
Stab	7	2	1	2	2
PMW	5	1	2	2	0
Traction	3	1	1	1	0
Iatropathic	63	7	12	36	8
TOTAL	78	11	16	41	10

Nerve to serratus anterior

This nerve is most commonly damaged in lesions of the brachial plexus, but it is particularly vulnerable to accidental damage where it crosses the first and second ribs. When the serratus anterior is paralysed, the inferior pole of the scapular does not move forwards but slides medially and cranially. Confusion with spinal accessory palsy is a common error. Deep, aching pain is usual, and is sometimes severe. When the nerve was repaired after a stab wound (seven cases) or intra-operative damage (11 cases), results were very good, perhaps better than in almost any other peripheral nerve. In cases where the proximal stump was unavailable intercostal transfer to the distal stump of the nerve regularly restored useful function within the muscle (Fig. 9).

Figure 9

Serratus anterior palsy. The scapula moved cranially and towards the midline.

Figure 10

Rupture of circumflex nerve. Full elevation of shoulder through the suprascapular nerve and rotator cuff.

Table 7 Grading of results for the circumflex and suprascapular nerves (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

Circumflex nerve				
Good	Deltoid	MRC 4 or better	Abduction	Elevation at least 120°
Fair	Deltoid	MRC 3+ or better	Abduction	Elevation 90–120°
Poor or bad	Deltoid	Less	Less	

Suprascapular nerve		
Good	Abduction 120° or more	Lateral rotation 3° or more
Fair	Abduction 90–120°	Lateral rotation 0–30°
Poor	Less	Less

The circumflex and suprascapular nerves

Ochiai and colleagues (Ochiai et al 1997, Mikami et al 1977) showed that the suprascapular nerve might be severely damaged in several places, and the recommended exposure is described in detail in his valuable paper. We reported findings in 129 nerve injuries in 98 patients (Birch and Spilsbury 1996). Spilsbury's myometric study suggested that the deltoid muscle was responsible for over 50 per cent of the power of abduction, about 30 per cent of forward flexion power and 80 per cent of extension power of the shoulder. Improvements in strength and stamina were not impressive, even in those cases where the outcome was considered good. Results were particularly bad when there was associated rupture of the rotator cuff. Intra-articular fracture provoked post-traumatic arthritis in a number of cases. All circumflex nerve repairs performed more than 1 year after injury failed; most of those repaired after an interval of 6 months fared better. Bonnard et al (1999) presented a detailed analysis of 146 cases, and amongst the many notable findings was the fact that: 'the dramatic decrease in the rate of success seen with longer delays suggests that surgery should be undertaken within three months of injury'.

It is extremely unwise for the clinician to make a diagnosis of isolated circumflex nerve palsy in a patient who is unable to abduct the arm. Patients with an intact suprascapular nerve and rotator cuff have a good range of abduction, and in many cases that range is full. Patients who present with paralysis of the deltoid and who cannot abduct the arm must have rupture of the rotator cuff and/or rupture of the suprascapular nerve unless proven otherwise (Fig. 10). Our prefered investigation in these situations is MR scanning.

Table 8 Results of repairs to the circumflex and suprascapular nerves

Good	*Fair*	*Poor*	*Total*
Circumflex nerve			
35	31	15	81
Suprascapular nerve			
24	8	6	38

Another remarkable feature about injuries to the circumflex nerve, which is not widely appreciated, is the high incidence of damage to the offsets of the axillary artery, most especially the circumflex-humeral and subscapular vessels.

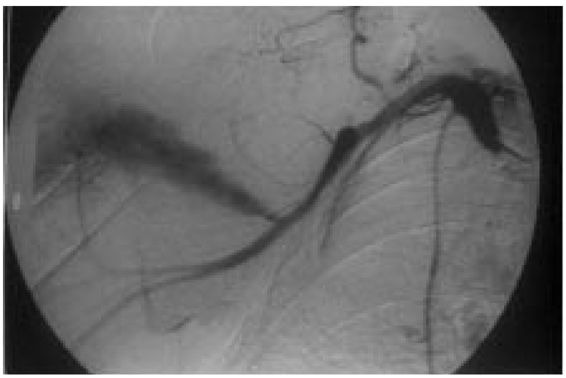

Figure 11

Delayed rupture of false aneurysm of subscapular artery in 83-year-old woman 8 weeks after dislocation of shoulder and with rupture of circumflex nerve.

These injuries lead to considerable fibrosis or even to false aneurysm formation (Tables 7, 8; Fig. 11).

The Radial nerve

This is the largest terminal branch of the brachial plexus, and was the most commonly injured nerve trunk in 16 500 cases of war wounds (Sunderland 1978). In civilian life, the radial nerve seems to be injured less commonly than the median or ulnar nerves. Zachary (1954) studied 113 cases of repair by direct suture within 6 months of injury, the maximum amount of nerve resected being 5 cm. There was a good or fair outcome in 61.5 per cent of cases. In Seddon's series (Seddon 1975) of 63 nerve sutures, 77.8 per cent of results were graded good or fair. Kline and Hudson (1995) described 171 operated cases of radial nerve injuries, and found that the results were best in more distal lesions. The outcome after repair of lacerated nerves was better than that following repair of nerves damaged by fracture or gun shot. Results were best after primary repair, followed by those with secondary repair; the worst results were in those cases requiring grafting. Birch et al (2001) described the outcome of 242 repairs of radial nerves, finding only 30 per cent good results and 28 per cent fair. The violence of injury was the most important factor in prognosis. Of the open, tidy repairs, 79 per cent achieved a good or fair result; 36 per cent of cases with arterial injury reached this level. Most repairs failed when the defect in the nerve trunk exceeded 10 cm. Of repairs performed within 14 days of injury, 49 per cent achieved a good result; only 28 per cent of later repairs did so. All repairs undertaken beyond 12 months failed. It is perhaps significant that in this series no less than 16 of 18 repairs of the posterior interosseous nerve achieved a good result (Table 9).

The musculocutaneous nerve

Lesions of this nerve accounted for less than 2 per cent of a series of 14 000 nerve injuries

Table 9 Results of repair of radial nerve by wound type

Wound	*No. of nerves repaired*	*Good*	*Fair*	*Poor*
Open 'tidy'	73	38% (28)	41% (30)	21% (15)
Closed traction	62	31% (19)	27% (17)	42% (26)
Open 'untidy'	52	25% (13)	25% (13)	50% (26)
Associated vascular injury	55	22% (12)	14% (8)	64% (35)
Total	242	30% (72)	28% (68)	42% (102)

Table 10 Results of repair of musculocutaneous nerve (85 nerves)

Type of injury	*Good (elbow flexion M4 or better)*	*Fair (elbow flexion M3, M3+)*	*Poor (elbow flexion M2 or less)*	*Total*
Open 'tidy'	12	0	1	13
Open 'untidy'	15	7	2	24
Closed traction	30	10	8	48
Effect of rupture of axillary or brachial artery				
Arterial injury	25	10	8	43
None	32	7	3	42
Effect of skeletal injury				
Associated skeletal injury	23	10	10	43
None	34	7	1	42

The Chi-square test was used to analyse these data.
The *P*-value for type of injury and outcome was 0.1779, for association with arterial injury was 0.1617, and for association with skeletal injury was 0.0067.

Table 11 Results related to interval between injury and repair (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

Lesion	*Good*	*Fair*	*Poor*	*Total*
Median and ulnar	14	13	6	33
Radial and musculocutaneous	19	10	1	30
Suprascapular and circumflex	7	2	2	11
Total	40	25	9	74
Late: after 14 days (22 weeks on average)				
Median and ulnar	1	8	13	22
Radial and musculocutaneous	10	10	7	27
Suprascapular and circumflex	5	1	1	7
Total	16	19	21	56

incurred in World War II, and it was rarely damaged in isolation (Sunderland 1978). Results of repair are rather better than for other nerves in the upper limb. Seddon (1975) reported satisfactory results in all 10 of his cases, and Kline and Hudson (1995) obtained a useful outcome in 29 cases of rupture in 'infraclavicular/stretch injuries'.

Osborne et al (2000) recently published a study of results of 85 repairs, in which there were 57 good results. The type of injury was the most important factor in determining the result; twelve of 13 open, tidy lesions gave good results, compared with 30 of 48 closed traction lesions. Results were better when the nerve was repaired within 14 days of injury and when grafts were less than 120 cm long. They were worse in the presence of an associated arterial or bony injury. Four of the 16 repairs performed after 180 days or more failed (Table 10).

Median and ulnar nerves

The effects of age and level of injury are particularly evident for these two nerves. Of equal importance, if not even more so, is the effect of the cause of injury and the delay between injury and repair. Cavanagh et al (1987) described the outcome in 74 adults with complex infraclavicular injury in which several nerve trunks were torn or ruptured by severe traction or by missiles. There was rupture of the axillary artery in nearly one-half of cases. Results were significantly better in the 'open' wounds, and were very poor indeed in those cases where there was a 'double level' lesion above and below the clavicle.

Table 12 Grading of results in high median and ulnar nerve repair (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

Median	
Good	Long flexor muscles MRC 4 or better Localization to digit, without hypersensitivity Return of sweating
Fair	Long flexor muscles MRC 3 or 3+ 'Protective sensation', moderate or no hypersensitivity Sweating diminished or absent
Poor or bad	Long flexor muscles MRC 2 or less 'Protective sensation' but severe hypersensitivity *or* no sensation
Ulnar	
Good	FCU and FDP little and ring MRC 4 or better Intrinsic muscles MRC 2 or better Localization to little and ring fingers, no hypersensitivity Return of sweating
Fair	FCU and FDP little and ring fingers MRC 3 or 3+ No intrinsic muscle function 'Protective' sensation little and ring fingers Moderate hypersensitivity Little or no sweating
Poor or bad	FCU and FDP little and ring fingers MRC 2 No intrinsic muscle function 'Protective' sensation with severe hypersensitivity *or* no sensation No sweating

Results for the median and ulnar nerves were distinctly worse than for the other nerve trunks studied. This was particularly evident when results were related to the interval between injury and repair. The results after repair of a high median and ulnar nerve lesion in the adult

Table 13 Results in 85 repairs of median nerves in axilla or arm: adults and children (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

	Tidy	*Untidy (incl. penetrating missile injuries)*	*Traction*	*Total*
Good	6	4	3	13
Fair	8	8	15	31
Poor or bad	3	12	26	41
TOTAL	17	24	44	85

This includes 28 repairs of either lateral or medial root of the nerve in the axilla

Table 14 Results in 60 repairs of medial cord or ulnar nerve in axilla and arm: children and adults (from *Surgical Disorders of the Peripheral Nerves* (Bonney 1998))

	Tidy	*Untidy (incl. penetrating missile injuries)*	*Traction*	*Total*
Good	3	2	0	5
Fair	5	13	7	25
Poor or bad	2	10	18	30
Total	10	25	25	60

All five good results followed repair within 48 hours of injury – two in children. The results of repair 3 months after injury were always poor in the untidy and traction lesions.

are, on the whole, much more modest than those following more distal repairs, and so a less demanding a system of assessment is used (Tables 11, 12).

Nonetheless, we were able to follow the course of recovery in 145 repairs of the median or ulnar nerves in the axilla or arm, and found that useful recovery was seen in more than one-half of cases of the tidy and of the untidy wounds. Results were poor or bad in well over one-half of repairs in the closed traction group (Tables 13, 14).

Penetrating missile injuries

Delorme (1915), then Inspector General of the Medical Services of the Armies of France, outlined a method of treatment for shell and bullet wounds based on three principles: resection of the scar until a healthy bed is secured; excision of damaged nerves until healthy stumps are reached; and tension-free suturing for grafting by adequate immobilization and flexion of adjacent joints. His paper was heavily criticized by the great and good, even before the days of so-called evidence-based medicine, but history has proved him right.

The largest published series regarding civilian gunshot injuries comes from Kline (1989), who described 141 wounds to the brachial plexus (90 operated cases), and from Kline and Hudson (1995), who described over 150 cases of wounds to the lumbo-sacral plexus, femoral nerve and the sciatic nerve and its divisions. In nearly one-third of the brachial plexus injuries there was major vascular injury. A total of 125 nerve elements were repaired, and recovery was useful for C5, C6 and C7 lesions, for lesions to the upper and middle trunks, and for the posterior and lateral cords.

Stewart and Birch (2001) studied a series of 58 patients with penetrating missile injuries. Patients were operated for known or suspected vascular injury (16 cases), severe persistent pain (35 cases) or complete loss of function in the distribution of one or more plexus elements. False aneurysms or arteriovenous fistulae were repaired in 13 cases. Repair of the nerve and vascular lesions abolished or significantly reduced severe pain in 31 (94 per cent) cases. Fifty-six nerve trunks (36 patients) were grafted; useful results were seen in 35. External neurolysis of lesions in continuity produced good or useful results in 21 (91 per cent) of cases. A vigorous approach is justified in the treatment of penetrating missile injury to the brachial plexus, and primary intervention is mandatory where there is evidence of a vascular lesion. Worthwhile results can be achieved with early secondary intervention in cases with debilitating pain, failure to progress and deterioration of the lesion under observation. There is cause for optimism in nerve repair, particularly for the C5, C6 and C7 roots and for the lateral and posterior cords, but the prognosis for complete lesions of the plexus associated with damage to the cervical spinal cord is particularly poor.

One striking finding from this study is the devastating effect of close-range shotgun injury, in which there is massive energy transfer leading to gross destruction of the skeleton and of the soft tissues (Figs 12, 13).

Figure 12

The nerve lesion in causalgia. A 23-year-old, shot in the axilla with a handgun (low energy transfer). The bullet partially severed the median nerve; the ulnar nerve was unscathed. Relief by sympathectomy and repair of the nerve.

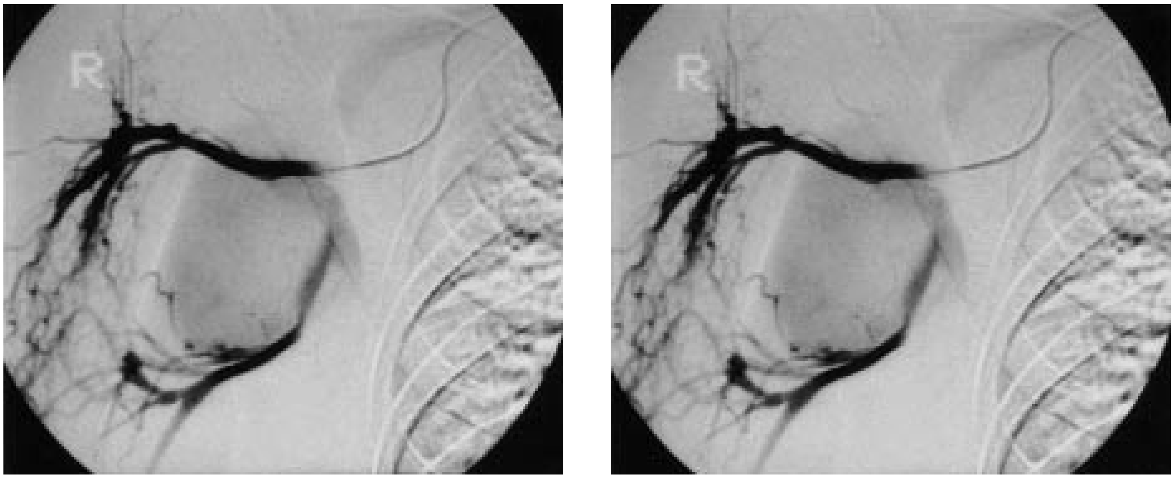

Figure 13

37-year-old man with a low energy transfer bullet injury. At 2 months he presented with causalgia, cardiac failure and median, musculocutaneous and radial nerve palsies. Digital subtraction angiogram confirmed a broad-based arteriovenous fistula.

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11
The place of arthrodesis

Giorgio A Brunelli

Introduction

The treatment of brachial plexus palsies has improved greatly over the last quarter of a century due to better knowledge of the lesions themselves and of the pathophysiology of healing of the peripheral nerves, as well as improvements in surgical techniques and the new possibilities of neurotizing the paralysed muscles. However, in a large number of cases results are still unsatisfactory, especially regarding the shoulder.

According to the most recent theories, this is partially due to the fact that, when the surgeon decides how to distribute the limited nervous fibres surviving after trauma, the hand is the priority because its function is certainly more important. As a consequence, in many cases the shoulder remains paralysed in spite of the result of surgery at the elbow and hand because of the palsy of the muscles from the scapula to the humerus.

Complete shoulder palsy is a severe functional handicap. However, the muscles moving the shoulder upon the thorax are often preserved and the scapula can be displaced in all directions. An operation blocking the humerus to the scapula therefore allows movement of the arm by the action of the thoracoscapular muscles. This operation is called arthrodesis, and prevents any movement of the joint, transforming the useless joint into a rigid lever (AOARC 1942, Botteri 1960, Brittain 1952, Charnley 1966, Cofield 1979, Delitala 1940, Hawkins 1987, Johnson 1986, Nagano 1989, Richards 1993, Ron 1991, Rowe 1974, Scaglietti 1933, Vidal 1987).

Indications

Scapulo-humeral arthrodesis can give extremely satisfactory results provided that hand function and elbow flexion are good. These are prerequisites. That said, in few cases the author has performed contemporary arthrodesis at the elbow and wrist or opposition osteodesis of the first metacarpal when the function of the shoulder arthrodesis alone would have been useless. In these cases, multiple arthrodeses supplied rudimentary but useful movements.

Results of arthrodesis are more consistent and efficient than any muscular recovery due to muscular tendinous transfer; the result is permanent whereas transferred muscles may deteriorate with the time.

Of course, shoulder fusion is an admission of the surgeon's incapacity to restore normal movement. Sacrificing a joint is also repellent to the surgeon, but it is a matter of 'propitiatory sacrifice' to obtain active movement of the paralysed glenohumeral joint. Palagi, quoted by Logroscino (1960), cleverly said that arthrodesis at the shoulder 'creates a new movement of the arm, whilst also satisfying some cosmetic requirements (Figs. 1 and 2).

Shoulder arthrodesis was performed first by Albert in 1879 and then by Vulpius in 1898 (Mezzari 1960). The operation was later taken up by many other authors, including Albee, Putti, Delitala and Straub. Even so this operation was initially harshly criticized by many other authors because of the poor results due to inaccurate indications, and lack of detailed advice regarding the position of the humerus and the type of techniques to be performed.

At the present time shoulder fusion in upper arm palsies receives general support provided that indications are correct. Moreover, results improve over the years due to a series of tricks and functional adaptations by the patient. Even the results obtained by means of other operations on the hand improve, because they can be better exploited thanks to the improved dynamic positioning of the hand itself.

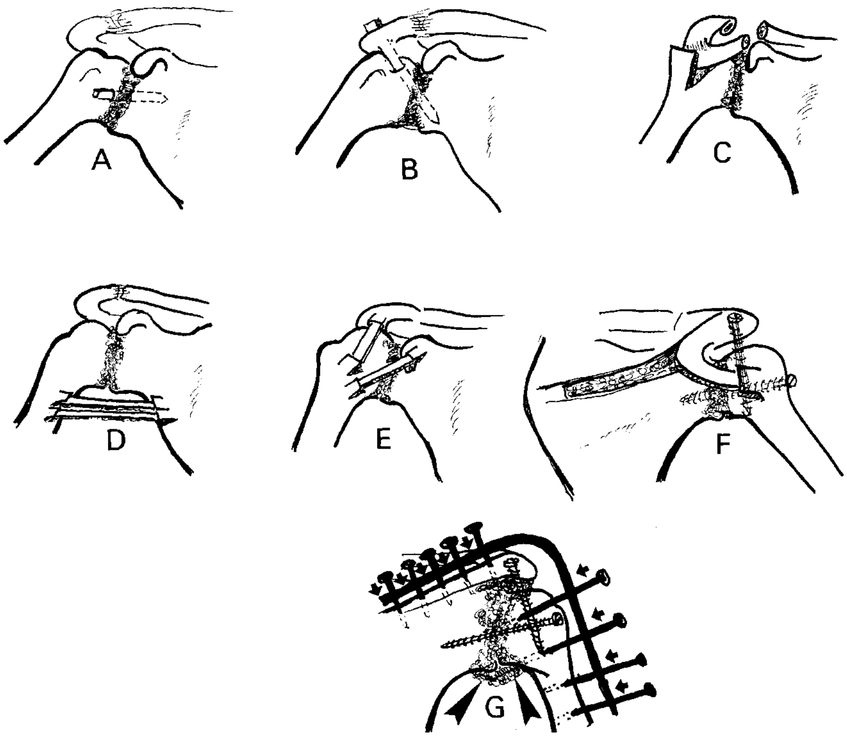

Figure 1

Various types of arthrodesis:
A: Vulpius
B: Albee
C: Watson Jones
D: Zancolli
E: Lange
F: First type of personal arthrodesis
G: Present type of arthrodesis with decortication, plate bent at 100° and addition of spongious bone (long arrows).

Indications for shoulder arthrodesis are fundamentally the palsies of abduction of the upper limb (trapezium and supraspinatus).

Prerequisites are:

- Good function of the thoraco-scapular muscles; the trapezium, levator scapulae, rhomboids and, above all, the serratus anterior (partial impairment of one of these muscles can be tolerated, but it must be remembered that strength is necessary to raise a whole upper limb). The function of the pectoralis major muscle must also be taken into consideration, not because its strength may prevent abduction (in fact the pectoralis major muscle is an antagonist), but because its presence is essential for the thoraco-brachial pliers.
- Good distal function of the arm. It is useless to perform a shoulder arthrodesis if the hand is completely paralysed.
- Integrity of the joints of the scapular belt; the acromioclavicular, sternoclavicular and scapulothoracic joints. Stiffness of these joints following joint fracture, or post-fracture adhesions, reduce or annul the results. It is also important to avoid any involvement of the acromioclavicular joint during surgery.

It must be remembered that those joints which take the place of the glenohumeral joint, must sustain extra work and will therefore undergo deterioration and arthritis with the years. Also, the muscles suffer extra stress, which may lead to hypertrophy or exhaustion and atrophy.

Lack of distal function is not an absolute contraindication to shoulder fusion. As previously stated, in very severe cases (mainly bilateral and especially in polio) the author has associated shoulder fusion with arthrodesis of the elbow or wrist in a functional position, and sometimes with opposition of the first metacarpal. This serial arthrodesis gave rudimentary function.

Arthrodeses can be classified as intra-articular, extra-articular or mixed. They can be simple or

Figure 2

X-rays of an ancient shoulder arthrodesis fixed by two screws.

modelling, i.e. performed in such a way as to give a particularly favourable position. They can be done by decortication alone, or with the addition of bone grafts. Numerous types of arthrodesis have been suggested, some of which are shown in Figure 1. The position for arthrodesis has been the subject of much discussion. In shoulder fusion, we must obtain an abduction sufficient to position the hand in the working plane but not so great as to prevent efficient active adduction for the thoraco-brachial pliers, which is very important. There must be enough strength to hold an object under the arm. Too great an abduction would cause muscle fatique and prevent the thoraco-brachial pliers.

The author therefore considers that the arm should be placed in 30° of abduction from the thorax (Fig. 3). In this position, movement of the scapula would allow active abduction of about 60° whilst still allowing the contact with the thorax (Fig. 4). After surgery, X-rays should show an angle of about 65° between the lateral border of the scapula and the medial cortex of the humerus.

The arm should be placed in 45° of anteposition. Movement of the scapula will in time allow an anteposition of 65–75° as well as a resting position almost vertical. The rotation should be graduated so that, by the residual movements of the scapula, the hand can touch the abdomen, reach the mouth with a fork and be put in a pocket (intra-rotation of 40°).

Figure 3

By positioning the arm at 30° of abduction, the active movement of the scapula allows an abduction of 60°.

Figure 4

The limited abduction allows a strong grasp which is very important, especially if the hand is not valid.

In reality, the ideal position for fusion depends upon the individual functional goals, the global neurological deficit, and possible elbow or wrist deformities (Ducloyer et al 1991).

Surgical techniques

Surgical techniques are numerous and vary in their approach, in the type of arthrodesis itself, the type of immobilization and the type of bone graft (autologous) etc. Here, the authors preferred technique is described. This consists of a reversed V-shaped approach on the posterior aspect of the shoulder, following the spine of the scapula throughout its length and then continuing on the lateral aspect of the deltoid region for 10 cm. This approach is not considered too large as it has to allow the positioning of a plate bent at 100° and of sufficient length for the number of screws required for solid and stable fixation.

After retraction of the skin edges, the paralysed deltoid muscle is severed (as if a military epaulette), detaching it totally from the spine, the acromion and the clavicle. This allows a clear view of the joint. This region is very rich in vessels, and therefore the procedure should be performed very carefully with progressive haemostasis. The capsule is then severed and the head of the humerus subluxed. Decortication of both the humeral head and the glenoid is performed by means of a large hollow chisel, until bleeding spongious bone is achieved. Great care must be taken not to alter the congruity of the bony heads. The inferior aspect of the acromion is also decorticated, taking care to spare the acromioclavicular joint.

At this point, the head of the humerus is pushed into the cavity of the glenoid and against the acromion. The arm is placed in 45° of anteposition, 30° of abduction and 40° of internal rotation. This position is temporarily fixed by means of two screws, one from the humerus to the glenoid and one from the acromion to the humeral head. All authors have stressed the difficulty of estimating the correct position of the arthrodesis during the operation.

A large pedicled bonegraft may now be elevated from the acromion or from the spine of the scapula, by means of progressive osteotome strikes from medial to lateral. This chip is inserted into the humeral head, leaving a 'bridge' in continuity with the scapula.

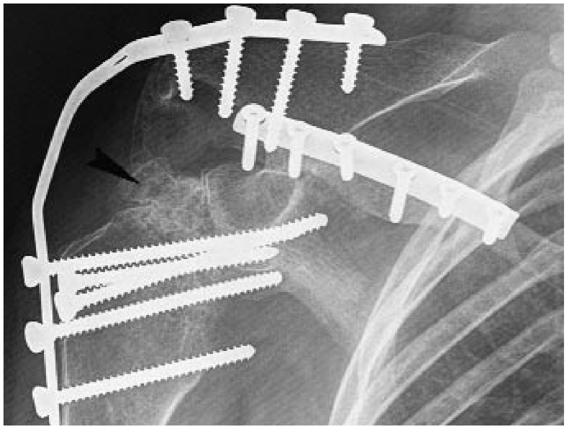

Figure 5

X-rays of a recent arthrodesis fixed by means of plate, screws and cancellous bone addition (arrow).

While an assistant maintains the arm in position (held by the two screws), a 10- or 12-hole plate is modelled to fit above the spine of the scapula, the acromion and the lateral aspect of the humerus, with an approximate angle of 100°. The plate is then screwed according to the routine technique.

In more recent years, to avoid possible non-consolidation, the author performed spongious autologous bone grafts (Fig. 5). The bone is taken (by means of a large curette) from the proximal meta-epiphysis of the tibia, and is then crushed using a pestle and mortar. Using the thumb, the resultant pulp is pushed into all the gaps of the arthrodesis like a 'stucco', according to the technique described 35 years ago (Brunelli 1963, 1972). Careful haemostasis follows. A drain is introduced for 2 days and the tissues are reconstructed. Skin sutures and an immobilizing cast follow (the cast should be prepared 48 hours in advance and opened for the operation).

Although techniques vary, it is important to follow five fundamental rules:

1. Thorough decortication;
2. Careful alignment of the bone surfaces;
3. Addition of cancellous bone;

Table 1 Evaluation of the results of shoulder fusion

	Abduction (active)	*Fork to the mouth*	*Thoraco-brachial pliers*	*Manual work*	*Daily activity*
Very good	⩾ 60°	Yes	Yes	Yes	Yes
Good	45–60°	Long fork	Yes	±	Yes
Fair	30–45°	Very long fork	Weak	No	±
Poor	≤30°	No	No	No	No

4. Solid fixation;
5. Immobilization until there is complete fusion.

Regarding timing of the operation, it is important:

1. To wait until nerve regrowth up to the muscles has occurred;
2. To first perform all the other operations required for the hand and elbow, since it would be very difficult to perform them after shoulder fusion and might give poor results.

In general, patients prefer the safe stiffness of arthrodesis to the pre-operative instability. If the function of the hand and elbow are good, the result of shoulder fusion may be excellent. However, even with poor function of the hand the result greatly improves daily activities because the paralysed arm becomes an aid to the contralateral one, it may serve as a paperweight, achieve a thoraco-brachial pliers and be used raising light objects.

Evaluation of results is shown in Table 1.

Since 1963 the author has performed 58 shoulder arthrodeses, 20 of which have been lost to follow-up. Most of these 20 were cases of polio and were operated in the 1960s (Fig. 6).

- Thirty-eight cases have been followed up; of these, 23 male and eight female, average age 23 years (range 8–65) were reviewed. Twenty-one were scored 'very good', 13 'good', three 'fair' and one 'poor';
- Twenty-five cases had obtained a pretty good recovery of both the function of the hand and flexion of the elbow following nerve surgery;
- Three cases were sequelae of polio. In three cases (elderly people), arthrodesis had been performed primarily;
- In the first nine cases, fixation was obtained by screw only. In nine more cases, a pedicled bone graft from the spine of the scapula was added;
- In the last 20 cases, arthrodesis was performed by decortication, addition of pulped cancellous bone and fixation by a long plate and screws;
- External fixation was never used;
- Healing was obtained on average in 4½ months (range 3–7 months).

Regarding complications:

- There was one case of non-consolidation at 7 months due to abandoning immobilization too early (45 days). It was cured by a secondary operation where a cortical spongious wedge graft was inserted into the anterior opening of the joint;
- There was no pseudoarthrosis (which is one of the commonest complications in other authors' series). This was probably due to the primary addition of cancellous bone;
- There were no fractures of the humerus, another common complication reported in literature (Chamas et al 1995). This was probably due to the modest degree of abduction of the humerus;
- There was one delayed consolidation, which healed at 7 months;
- In two cases the plate gave decubitus of the skin and further surgery was required to mobilize the surrounding skin for a better coveraged;
- In three cases, the plate had to be removed following bone consolidation because it protruded under the skin at the acromion region;
- In two more cases loosening screws had to be removed.

All the patients were able to reach their mouths; very easily if elbow flexion was good, or by

Figure 6

Demonstration of the movement allowed by arthrodesis. This patient also had a clavicle non-union, which had been previously cured by cancellous bone graft and plate.

means of long spoons or forks if flexion was poor (Fig. 6). The position in internal rotation obviously gives a lack of external rotation, making it difficult or impossible for patients to reach the back of their neck, but it is very useful to reach the abdomen and the side pocket. The rigid position of the shoulder may cause some trouble sleeping. Almost all the patients were unable to sleep on their fused shoulder. Young people were able to resume sporting activities that did not involve the upper arm.

From the subjective point of view, all the patients were satisfied.

Conclusion

Shoulder arthrodesis gives a predictable result. This result is certainly partial but improves the function of the upper limb greatly. The strength of movement of the arthrodesed shoulder is certainly better than that obtained by muscular transfers. The range of movement of the arm depends on the pre-operative condition of the scapulothoracic muscles, of which the serratus anterior is the most important. Of course, the function of the limb after shoulder arthrodesis depends upon the function of the elbow and the hand. However, even in an almost flail limb multiple arthrodeses can give a very rudimentary function, which is much appreciated by patients. In the general planning of surgery, foreseeing a shoulder arthrodesis for a paralysed upper limb allows the surgeon to distribute the nervous elements to the nerves for the elbow and hand, so obtaining a much better result.

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12

Palliative surgery: tendon transfers to the shoulder in adults

Aydın Yücetürk

Introduction

An estimated 25–30 per cent of the nerve fibres within the brachial plexus pass to the shoulder girdle, with its large number of muscles and complex shoulder movements (Birch 1995, Allieu 1999). Movement about the shoulder requires the coordinated moment of four joints and over 20 muscles, and the shoulder and scapular muscles and their innervations are shown in Tables 1 and 2 (Kendall et al 1993).

Table 1 Shoulder muscles (Kendall et al 1993)

Flexors: anterior deltoid (C5-6), biceps (C5-6), pectoralis major upper (C5-6-7), coracobrachialis (C6-7)
Abductors: deltoid (C5-6), supraspinatus (C5-6), biceps long head (C5-6)
Lateral rotators: infraspinatus (C5-6), teres minor (C5-6), posterior deltoid (C5-6)
Extensors: posterior deltoid (C5-6), teres major (C5-6-7), latissimus dorsi (C6-7-8), triceps long head (C6-7-8-T1)
Adductors: pectoralis major (C5-6-7), teres major (C5-6-7), latissimus dorsi (C6-7-8), triceps long head (C6-7-8-T1)

Table 2 Scapular muscles (Kendall et al 1993)

Abductor – full flexion: serratus anterior (C5-6-7-8)
Lateral rotators: serratus anterior (C5-6-7-8), trapezius (nerve XI – accessory) and ventral ramus (C2-3-4)
Adductor – full abduction: trapezius (nerve XI – accessory) and ventral ramus (C2-3-4)
Lateral rotators: trapezius (nerve XI – accessory) and ventral ramus C2-3-4), serratus anterior (C5-6-7-8)
Adductors, medial rotators and elevators – full extension: rhomboids (C4-5), levator scapula (C3-4-5)
Ant. tilt of scapula by pectoralis minor (C6-7-8-T1)
Adductors – to side against resistance: rhomboids (C4-5); trapezius (nerve XI – accessory) and ventral ramus (C2-3-4)

Thirty-three per cent of shoulder elevation is from the scapulothoracic joint. Saha believed that good elevation requires prime movers (deltoid or clavicular head of the pectoralis major), a steering group (supraspinatus, infraspinatus and subscapularis) and a depressor group (pectoral head of pectoralis major, latissimus dorsi, teres major and teres minor) (Karev 1986, Price and Grossman 1995, Kotwall et al 1998). Saha confirmed that when any two of the steering group of muscles were paralysed, a single muscle transfer to replace the deltoid would not provide abduction beyond 90° (Kotwall et al 1998). Therefore, in paralysis of the prime movers the importance of the steering group of muscles must be considered when performing a tendon transfer to restore shoulder abduction: with paralysis of all the steering group, transfer of one muscle (such as the trapezius into the deltoid attachment) permits arm lifting only to 90° and results in the loss of synchronous scapulohumeral rhythm. If the patient has one of the steering group muscles, the subscapularis, this avoids the necessity for one additional tendon transfer to restore their function (Karev 1986). Abduction of the shoulder to 90° is provided by the supraspinatus and deltoid; for abduction greater than this at the glenohumeral joint, the main external rotators of the scapula are serratus anterior and trapezius, while other muscles are involved in rotating and stabilizing the humeral head.

Paralytic shoulder may be caused by:

1. Supraclavicular and infraclavicular injuries;
2. Nerve injuries of the terminal branches of the brachial plexus (axillary, suprascapular and musculocutaneous nerves);

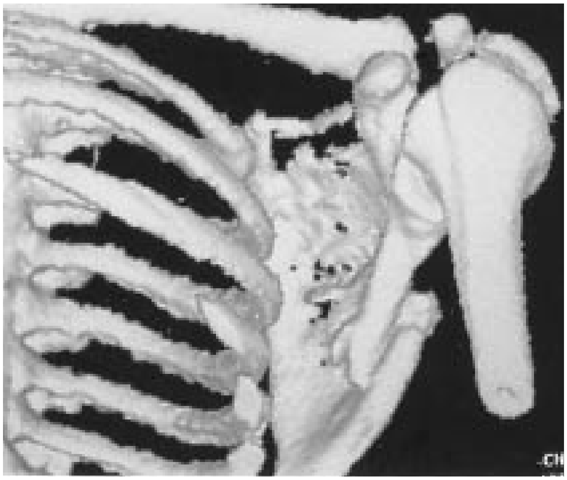


Figure 1

Brachial plexus injury and fractured scapula. Axillary and suprascapular nerve possible double crush injury.

Figure 2

Flail shoulder and multidirectional instability.

3. Lesions of the nerves to the shoulder – the accessory nerve (trapezius) and long thoracic nerve (serratus anterior) (Alnot 1996).

For the best functional recovery, both the axillary and the suprascapular nerves must be repaired surgically (Alnot 1996). It is important to remember that these two nerves can be crushed twice in trauma; besides damage at Erb's point, the suprascapular nerve can also be injured in the scapular notch and the axillary nerve in the axillary fossa (Fig. 1). Reinnervation of the pectoralis major is also important. If just the suprascapular nerve is repaired, no more than 30° of shoulder abduction and flexion can be expected.

In complete shoulder palsy (active trapezius and serratus anterior muscles) shoulder instability is obvious, with inferior subluxation and the weight of the upper limb causing pain and disability (Alnot 1996) (Fig. 2).

Axillary ± suprascapular nerve palsy

Over the past 30 years, the efficacy of brachial plexus surgery has been established for the treatment of certain injuries. Although some muscle function returns spontaneously or following surgery, certain muscles (most notably the deltoid) may remain paralysed. In traction injuries the axillary nerve is that most commonly damaged, followed in order of frequency by the musculocutaneus nerve and the suprascapular nerve. Because the axillary nerve is composed mostly of motor fibers and travels only a short distance from its origin to its muscle insertion, there is a good prognosis for full functional recovery after surgical repair. This nerve is rarely completely severed but is usually stretched over several centimetres. Stretch injuries of the infraclavicular brachial plexus have a better prognosis for spontaneous recovery than suprascapular injuries (Fiedman et al 1990). Suprascapular nerve repair is difficult because of the route of the nerve, and because it may also be avulsed from the muscle (Alnot 1996).

Secondary shoulder surgery following traumatic brachial plexus injuries includes:

1. Ligamentous plasty – acromial insertion of the coracoacromial ligament transfer onto the lesser tubercule;
2. Arthrodesis;
3. Rotational osteotomy;
4. Muscle transfer, which may include any combination of the following:

- Transfers for deltoid and supraspinatus paralysis – trapezius (if spinal accessory nerve was not done before) (Alnot 1996); pectoralis major and teres major; latissimus dorsi; gracilis; combined biceps and triceps;
- Other combinations of teres major, latissimus dorsi, levator scapula, biceps, coracobrachialis and pectoralis major (Ruhmann et al 1998).

Alnot's surgical aproach according to shoulder muscle palsies is shown in Table 3.

Table 3 Alnot's surgical aproach according to shoulder muscle palsies

Only deltoid muscle palsy:
Trapezius transfer with acromial portion to deltoid insertion (Bateman's procedure) or transfer of the long head of the triceps to acromion (Sloaman)
Both deltoid and infraspinatus palsy:
Derotation osteotomy of the humeral shaft for external rotation
Deltoid, infraspinatus and supraspinatus palsy:
Stabilization by long head of biceps muscle
Derotation osteotomy
Shoulder arthrodesis
Trapezius transfer

Ligamentous plasty

Ligamentous plasty is not effective for shoulder function, but can be used for shoulder subluxation.

Arthrodesis

According to Allieu, neurotization of the musculocutaneous nerve by the intercostal nerve without interpositional graft and shoulder arthrodesis gives the best and most constant functional results for shoulder and elbow (Allieu 1999). According to Kline, substitutive procedures for loss of shoulder abduction with proximal brachial plexus injuries remain controversial (Kline and Hudson 1995).

Fusion of the glenohumeral joint is probably the procedure of choice when the plexus injury spares hand function. The advantage of a shoulder arthrodesis is the greater increase in powerful active function, and this must be selected for those patients who have physically demanding work and still retain good function in the elbow and hand (Ruhmann et al 1999). The transfer of a portion of the lateral trapezius to provide active abduction of the shoulder is a less certain procedure, and it can be difficult to achieve a balanced and therefore usable transfer with this operation (Kline and Hudson 1995).

Disadvantages of shoulder fusion include technical difficulties, long rehabilitation, complications, the loss of passive mobility, and the irreversibility of the procedure (Aziz et al 1990). Saha argues against arthrodesis after poliomyelitis and points out that the fulcrum is moved to the scapulothoracic joint, which gives a much longer lever arm for the thoracic muscles (Kotwell et al 1998). Cofield and Briggs point out that the disadvantages of arthrodesis include a high incidence of fracture, worsening of pain, and relative reduction of passive movements (Kotwell et al 1998).

In summary, arthrodesis permits only a limited range of abduction and has a high incidence of complications. It inhibits the passive mobility of the joint making some daily activities such as dressing, putting the hand in the pocket and pulling a zipper difficult (Mir-Bullo et al 1998). It is irreversible, and gives less active and passive movement than trapezius transfer (Aziz et al 1990).

Rotational osteotomy

Derotation osteotomy of the humeral shaft can be performed, and enhances recovery of elbow flexion. Alnot advises rotational osteotomy when both the deltoid and the infraspinatus are palsied (Alnot 1996) (Table 3).

Muscle transfer

Muscular transfers of the latissimus dorsi and teres major are not satisfactory in adults,

Table 4 Muscle transfers to shoulder

Pectoralis major transfer	Hildebrandt (1906)
Trapezius muscle transfer	Hoffa (1902) Bateman (with acromium and spina scapula bone *en bloc*)
Long head of triceps to acromium	Sloaman
Short head of biceps	Ober, Hass, Davidson, Harmon
Latissimus dorsi	Shultze-Berge L'Episcopo

although they are very effective in children (Alnot 1996). Different muscle transfers have been used (Table 4); trapezius transfer was used for deltoid paralysis by Hoffa in 1891, Lewis in 1910, Lange in 1911 and Mayer in 1927 (Ruhmann et al 1999). Today, trapezius transfer is commonly used for deltoid palsy (Karev 1986, Aziz et al 1990, Kotwell et al 1998, Mir-Bullo et al 1998, Ruhmann et al 1998, 1999).

Indications for trapezius transfer include:

- Failure of nerve repair;
- Late brachial plexus injuries;
- Paralysis of deltoid and supraspinatus clinically and by EMG;
- Trapezius strength of at least M4, ideally M5;
- A normal glenohumeral joint;
- At least 80° of passive abduction;
- An intact rotator cuff.

Contraindications include:

- Trapezius strength of less than M4;
- Glenohumeral joint problems, including degenerative arthritis, septic arthritis sequelae, old unreduced shoulder dislocation, and malunited humeral head or glenoid fractures;
- Workers with physically demanding jobs.

Relative contraindications are: complete rotator cuff tears, spinal accessory nerve neurotization to the musculocutaneous nerve (even partial), and no elbow flexion.

Difficulties may include:

- A preoperative stiff shoulder that needs physiotherapy;
- Scars from previous nerve repair;
- Humeral fractures;
- Humerus osteomyelitis following an open fracture;
- Acromioclavicular dislocation;
- Severe osteoporosis.

Complications may include: infection, loosening of screws, non-union of the acromial bone fragment, and nerve injuries.

Trapezius muscle transfer has several advantages (Aziz et al 1990, Ruhmann et al 1999):

1. It reduces shoulder subluxation and dislocation;
2. It gives a functional improvement;
3. It eliminates pain;
4. Muscle transfer operations are more successful in terms of passive function and have lower complication rates;
5. Surgery is relatively short.

According to Aziz et al, the absence of clear indications for trapezius transfer and expecting too much from this transfer alone have led to its infrequent use, and the only contraindication is advanced degeneration of the shoulder.

Saha's modification of the trapezius transfer, described by Bateman, provides a more distal fixation of the transfer after a more proximal release. Distal fixation has the following advantages: it gives a longer lever arm; the bony insertion transfered from the acromium allows better fixation; it allows transfer for paralysed muscles of the rotator cuff; it improves control of the humeral head; and it prevents subluxation (Kotwell et al 1998).

Even when functional recovery is incomplete, trapezius transfer is strong enough to keep the shoulder stable and allow some active abduction, while allowing a full passive range (Aziz et al 1990).

Trapezius transfer can be combined with other transfers to achieve maximum use of the arm, e.g. latissimus dorsi transfer to the elbow, Steindler's elbow flexorplasty, and tendon transfer to the wrist or wrist fusion (Aziz et al 1990).

The acromion should be transferred to below the greater tuberosity of the humerus and fixed with screws (Figs 3 and 4). The point of fixation to the humerus is a decisive factor regarding the extent of postoperative function, especially

Figure 3

Trapezius transfer with acromium bone block.

Figure 4

Trapezius transfer and acromium bone block fixation to humerus.

a

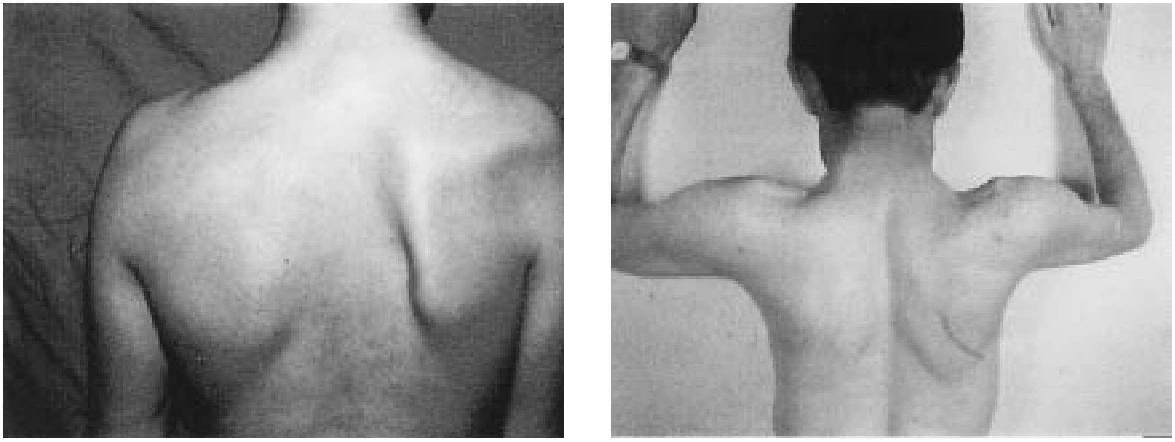
b

Figure 5

(a) Preoperative shoulder abduction, (b) Postoperative 45° of abduction after trapezius transfer.

abduction and forward flexion. Sometimes trapezius transfer distalization is limited by the restricted degree of mobilization. Multidirectional shoulder instability is reduced by the procedure (Ruhmann et al 1999) (Fig. 2).

For successful trapezius transfer, Karev (1986) points that the muscle must be at least M4, there must be excellent passive shoulder motion, the direction of the muscle must be straight, and tension must be adequate. After trapezius transfer with the acromion in traumatic patients, Ruhmann et al (1998) achieved a satisfactory improvement in stability and function (Fig. 5).



a b

Figure 6

(a) Scapular winging, (b) After pectoralis major transfer to the medial border of scapula.

Long thoracic nerve palsy

Seventeen muscles are attached to or take their origin from the scapula, the most important of which are the serratus anterior, trapezius, rhomboids and levator scapula. These muscles help the scapula to remain in position during the full range of motion of the shoulder.

The normal function of the serratus anterior is to maintain the scapula in apposition to the thorax when the arm is elevated forward at the shoulder. The trapezius and rhomboid muscles control scapular rotation and provide a mobile yet stable base for moment of the upper extremity. Paralysis of the serratus anterior muscle causes the scapula to rotate posteriorly on its vertical axis, producing the characteristic appearance of 'winging'. Spontaneous recovery of the long thoracic nerve occurs within 1 year, on average, in 70–80 per cent of cases (Alnot 1996).

Paralysis of the serratus anterior muscle can be functionally disabling (Perlmutter and Leffert 1999) and may result from a variety of causes, including:

- Acute traumatic and traction injuries;
- Viral illnesses;
- Brachial neuritis;
- Iatrogenic injuries (transaxillary resection of the first rib, cervical dicectomy and arthrodesis, mastectomy and axillary nodes dissection, Bankart procedure, acromioclavicular joint reconstruction etc.) (Alnot 1996, Perlmutter and Leffert 1999).

Indications for pectoralis major transfer include:

- Marked scapular winging;
- Loss of shoulder strength;
- Difficulty with the activities of daily living;
- Electrodiagnostic evidence of chronic denervation of the serratus anterior present for 12–18 months (with the exception of the Parsonage–Turner syndrome – brachial neuritis) (Perlmutte and Leffert 1999).

Electrical evidence of long thoracic nerve injury is required to confirm that scapular winging is being caused by serratus anterior dysfunction (Warner and Navarro 1998).

Long thoracic nerve recovery may take as much as 2 years, but patients with severe symptoms who have undergone 12 months of conservative treatment may benefit from surgery treatment (Winter and Flatow 1999). Several procedures have been reported in the literature, including transplantation of the pectoralis major muscle into the serratus itself, fascial sling suspension, pectoralis minor transfer, rhomboid transfers, scapulo-thoracic articulation arthrodesis, and pectoralis major transfer with fascia lata autogenous graft to the scapula medial border. Pectoralis major tendon transfer is an effective treatment for scapular winging (Fig. 6). This surgical approach sometimes gives unacceptable cosmosis, and there may be local morbidity to the donor site of the iliotibial band graft that is used to augment the tendon transfer (Warner and Navarro 1998).

Povacz and Resch (2000) stabilized the scapula by split pectoralis major tendon transfer directly attached to the inferior angle of the scapula, and autogenous graft complications were removed. Medial and lateral pectoral nerve injury resulting in recurrent scapular winging after pectoralis major transfer was reported by Litts et al (2000). Scapulo-thoracic arthrodesis reduces the symptoms, but decreases the motion of the shoulder (Perlmutter and Leffert 1999).

Spinal accessory nerve palsy

Trapezius paralysis may be seen after biopsy of the cervical nodes, trauma, or radical dissection in the neck. Spinal accessory nerve paralysis symptoms include pain, visible deformity and dysfunction of the shoulder girdle. The functional disability is compounded by discomfort, which may be secondary to traction on the brachial plexus, pericapsular muscle spasm, frozen shoulder, subacromial impingement, or acromio-calvicular synovitis. Thoracic outlet syndrome may also develop (Bigliani et al 1996).

Physical examination findings include asymmetry of the neckline, dropping of the shoulder girdle with lateral displacement of the scapula, and weakness of active elevation.

The spinal accessory nerve provides the sole motor innervation to the trapezius muscle, while branches of the third and fourth cervical nerves provide proprioceptive function. Reconstructive procedures to substitute for a paralysed trapezius include stabilization of the scapula to the spinal processes of the thoracic vertebra with the fascia lata and/or transfer of the levator scapula, and transfer of the levator scapula and rhomboid major and minor muscles together (Eden–Lange procedure). This combined transfer is a reasonable salvage procedure for a patient who has pain, deformity and diminished function of the shoulder girdle caused by irreparable injury of the spinal accessory nerve (Bigliani et al 1996).

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13
Palliative surgery: the elbow and forearm

Alfred C Berger, Robert Hierner, and Lutz Kleinschmidt

Introduction

The reconstruction of elbow flexion in patients with a complete paralysis of the upper extremity leads to highly improved arm function. Regarding amplitude of motion and power of the elbow flexion, grades of function can be differentiated. For high quality restoration an integrated concept is necessary, which includes:

- a precise description of the brachial plexus lesion and/or ventral muscles of the upper arm;
- correct timing of the operation;
- preconditions for successful tendon transfer;
- specialist knowledge of brachial plexus lesions;
- awareness of all therapeutic options;
- knowledge of patient-related factors.

Classification of the lesion

A precise preoperative analysis of the lesion is extremely important, and the following clinical situations should be differentiated:

- complete paralysis of the upper extremity;
- partial paralysis after spontaneous regeneration or operative revision without any regeneration of the muscles for elbow flexion (M0);
- partial paralysis after spontaneous regeneration or operative revision with insufficient regeneration of the muscles for elbow flexion (M1 or M2).

For partial paralysis, the residual function has to be balanced. Special attention should be paid to the important muscles of the forearm for elbow flexion. In a few cases the forearm muscles are so powerful that active elbow flexion is possible (M2+ or M3). This is called the Steindler effect.

In partial paralysis after spontaneous regeneration or operative revision with insufficient regeneration of the muscles for elbow flexion (M1 or M2), better results can be reached by augmenting the function by using certain operative techniques when compared to the results that can be achieved by patients with complete paralysis (M0). This may be a result of the better sensory-motor regulation of joint function by regenerated muscles.

Timing

Reconstructive operations should be performed after 2–3 years in brachial plexus patients with insufficient regeneration, spontaneous regeneration, or after operative revision. In patients without the option of neurotization and patients with additional destruction of muscles, an immediate muscle and/or tendon transfer is indicated.

Preconditions for successful tendon transfer

Very important basic preconditions for successful muscle and tendon transfer are gliding tissues and sufficient skin coverage. Sometimes it is necessary to provide a bed for the muscles and tendons by local or distant flap transfers. There has to be free passive motion of the joints because contracture of the tissue can lead to a significant loss of motion and power. The muscles chosen for the transfer should have a similar function or should be at least activated in the same movement phase. The muscle must be transposed completely. It is not possible to use a muscle both as an agonist and as an antagonist. There must be sufficient amplitude of motion and a sufficient power available for the operation to succeed.

To avoid unnecessary loss of power a straight run of the tendon must be chosen. If it is necessary to change the direction, a pulley is required. Appropriate tension of the muscle and tendon transfer is important for later function. Lesions of the paratendineon should be avoided, and attention must be paid to the donor site defect. The gain in function must be greater than the functional loss at the donor site.

An optimal result for the patient can only be gained when all those involved in the treatment (surgeon, anesthesiologist, nursing staff, physical therapist, general practitioner and almoner) are co-operating. Pre- and postoperative physiotherapy in particular are very important. To achieve a good result, it is beneficial if the patient has preoperatively learned to contract and isolate the muscle to be transferred.

Specialist knowledge of brachial plexus lesions

In patients with a brachial plexus lesion, the use of regenerated muscles for a reconstruction is often necessary. Therefore, it is important to follow some basic rules.

Only muscles graded > M3 are useful for a transposition. Owing to a higher rate of fibrosis, a smaller mass of muscle tissue and a disturbed innervation, regenerated muscles are normally less resistant. Excessive tension during the operation and premature exertion after the mobilization should be avoided.

Postoperatively the elbow is fixed in 100° flexion in a whole-arm splint (wrist and fingers fixed in intrinsic plus). Six weeks after the operation active and passive exercises can normally be started, although still protected against extension by the splint. Each week the splint is modified so that the elbow is extended by a further 10°. After 3 months, there should be a deficit of extension of 30–40°.

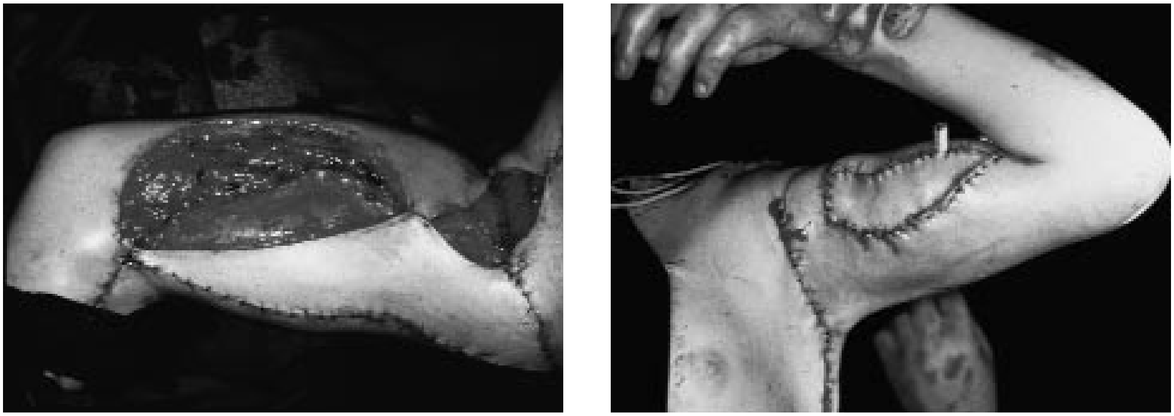
Therapeutic options

Different techniques are possible for secondary reconstruction of elbow flexion. These techniques differ regarding the innervation, amplitude of motion, power, donor defect and influence on the joints. Besides reconstructing bimanual use of the extremity, there is the possibility of achieving stabilization of the glenohumeral joint and supination in the forearm. A summary of results in the literature is given in Table 1.

The latissimus dorsi is innervated by the thoracodorsalis nerve (C6/C8), which is a branch of the fasciculus posterior. It is a very powerful

Table 1 Results after muscle/tendon transfer for elbow flexion restoration

Treatment option	*TAM (°)*	*Extension lag (°)*	*Flexion (ex/flex) (°)*	*Rom (°)*	*Power (kg)*
Nerve reconstruction (Narakas 1989)	100	0–60	–	0/30/130	6–16
Latissimus dorsi transfer (Zancolli and Mitre 1973)	65–140	0–20	65–140	0/0/115	0.5–4
Pectoralis major transfer (Schottstaedt et al 1955)	20–150	0–60	80–150	0/20/150	1–4.5
Triceps transfer (Narakas 1989)	–	–	–	–	1–2
Steindler transfer (Literature review)	20–140	0–90	20–40	0/22/115	1–2
Modified Steindler transfer (personal results)	20–140	20–40	95–140	0/33/113	3–4



a c

b d

Figure 1

Bipolar latissimus dorsi transfer for elbow flexion reconstruction: (a) intraoperative aspect (proximal fixation of the tendon at the coracoid); (b) intraoperative aspect after flap insetting; (c,d) postoperative clinical aspect (active elbow flexion and lifting of 8 kg).

muscle with a constant anatomic position and a long neurovascular pedicle. By bipolar transposition of the latissimus muscle, an average range of motion of 0–0–115° and power of 0.5–4 kg can be achieved. In our series ($n = 10$), one muscle showed a significant loss of power postoperatively although there was very good perfusion of the skin island. Nine of the 10 patients achieved an average active range of motion of 0–30–130° and power of 4 kg (in 90° flexion of the elbow). With this technique it is possible to gain stabilization of the glenohumeral joint and moderate supination of the lower arm (Fig. 1a–c).

The pectoralis major is innervated by the ansa pectoralis (C5–T1). The clavicular part is innervated from the fasciculus lateralis (C5/C6/C7) and the sternocostal part from the fasciculus medialis (C8/T1). Because of the broad innervation, this muscle can often be used in partial lesions. Preparation of the neurovascular pedicle is more difficult than in the latissimus dorsi because of anatomical variations. Owing to the unaesthetic scar, this transfer should not be used for women. The pectoralis major is a strong motor muscle for thoracohumeral function, and therefore it should only be used in a transfer when the latissimus dorsi or the teres major facilitate active adduction of the upper arm against the thoracic wall. Patients with a pectoralis major muscle transfer achieve an average range of motion of 0–20–150° and power of 1–4.5 kg. We do not have any experience of this transfer.

The pectoralis minor is innervated by the ansa pectoralis (C5–T1) and, because of the broad innervation, this muscle can also be used in partial lesions. The pectoralis minor is a comparatively weak and short muscle, and therefore should only be transferred in combination with a Steindler transfer or as an augmentation transfer of the elbow (M2). Some recentralization of the caput humeri can be reached by this transfer.

The triceps is innervated by the radial nerve (C7/T1). Because the triceps is an antagonist of the biceps, there are few difficulties in the postoperative learning period. In our series ($n = 15$), one muscle lost its function. The other 14 patients reached an average active range of motion of 0–40–100° and power of 2 kg. This muscle transposition has one disadvantage in that the patient loses the possibility of active elbow extension. If abduction in the shoulder or flexion greater than 90° is not possible, the donor site morbidity is not very important; however, this transfer should not be used in patients who need elbow extension for daily living – for example when they have to use crutches or a wheelchair. Because it is only a monopolar transfer, there is no further stabilization of the glenohumeral joint. In co-contraction of the biceps and triceps, the triceps transfer provides a very good technique and excellent results (Fig. 2).

The muscles for the flexion and pronation of the forearm are innervated by the median nerve (C6–T1). These muscles are proximalized by a Steindler transfer and an average range of motion of 0–22–115° and power of 0–2 kg can be achieved. In our series ($n = 6$), we used a modification of the Steindler operation with a more proximal position of the flexor muscles, 8–10 cm proximal to the elbow joint. We lost one case because of deep infection; five of the six patients reached an average active range of motion of 0–20–101° and power of 3.2 kg. This transfer should be avoided if active extension from the wrist and fingers is not possible or cannot be reconstructed by transfer of the flexor carpi ulnaris tendon, owing to the pronation and flexion contracture that follows this technique (Fig. 3).

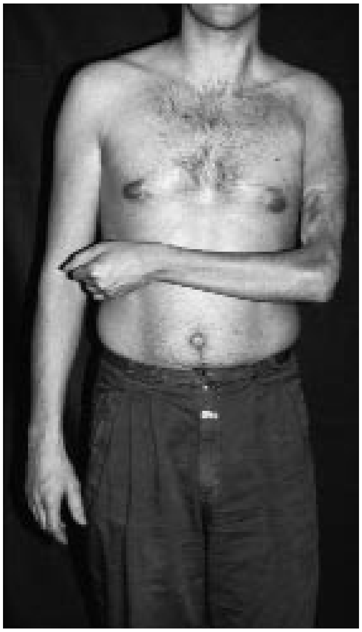
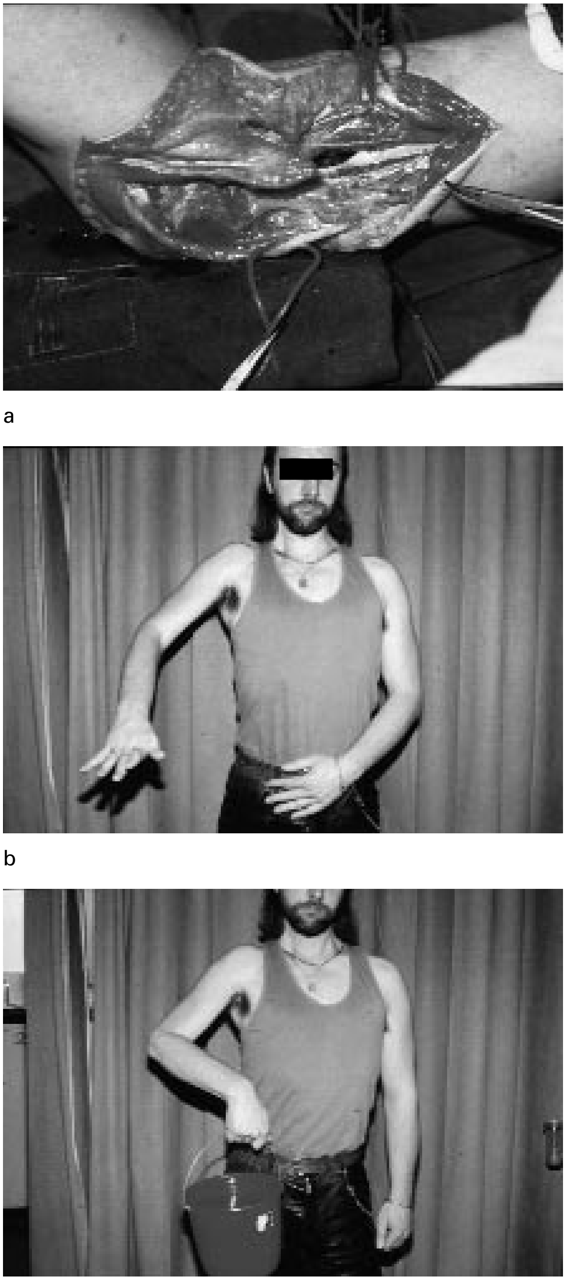


Figure 2

Triceps transfer for elbow flexion reconstruction.

In patients with a complete paralysis, elbow flexion can only be achieved by microsurgical methods. The first stage is a nerve grafting procedure. The accessory nerve, intercostal nerves or parts of the contralateral C7 radicula are used as axon donors. Twelve to 18 months after the first operation a biopsy of the distal end of the grafts is performed to assess the quality of the nerve regeneration. The number and quality of the axons will be quantified. If this shows a useful number of motor functions, a free microvascular muscle transfer with the latissimus dorsi or rectus femoris or gracilis is performed. To reconstruct elbow flexion and flexion or extension in the wrist, the muscle can be used bifunctionally and placed under a pulley in the elbow area. This means an insertion in two joint areas, but of course the power in both areas will be diminished. In 50 per cent of these patients, useful functional motion can be achieved. In our series ($n = 4$), the range of motion was on average 0–45–95° and the power 0.7 kg (Fig. 4a,b).



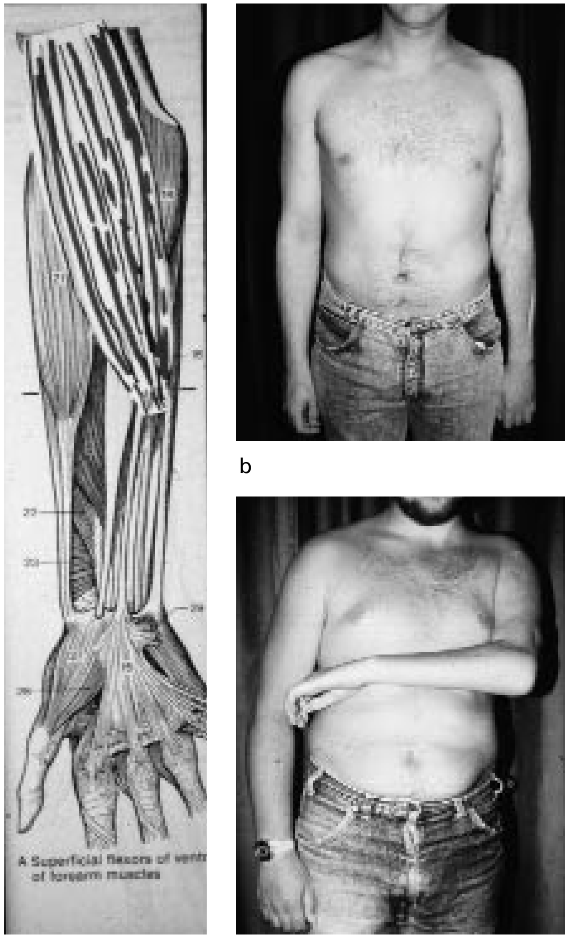
a

b

c

Figure 3

Modified Steindler transfer for elbow flexion reconstruction: (a) intraoperative aspect; (b) postoperative clinical aspect (elbow extension); (c) postoperative clinical aspect (elbow flexion).



a

b

c

Figure 4

Free functional muscle transfer for reconstruction of elbow flexion: (a) schematic drawing of transfer using the FCU as pulley; (b) postoperative clinical aspect (elbow extension); (c) postoperative clinical aspect (elbow flexion).

Patient-related factors

These factors influence the choice of method of reconstruction and the outcome of the procedure, and include age, sex, state of health, profession and hobbies, intelligence, expectations of the patient, compliance, social environment and motivation.

Discussion

For the treatment of brachial plexus lesions, an integrated therapy concept is used. Nerve reconstruction has the highest priority because with the different techniques of neurolysis, direct suture of the nerve (rare) and nerve transplantation the best functional results can usually be gained.

Specific movements can be reconstituted or augmented by single or multiple tendon transfers. Monopolar or bipolar tendon transposition can be performed. One joint (monoarticular) or multiple joints (polyarticular) can be moved. If no local muscle is available, a free microvascular functional muscle transfer can be performed. If there is no sufficient innervation available, a multiple stage procedure is necessary. The first step is nerve grafting, and after histological assessment of the grafts a free microvascular functional muscle transfer can be performed.

All these techniques for reconstruction can be improved further by using adjuvant operations or techniques such as tenodesis or capsulodesis.

In our concept, reconstruction of the elbow flexion has highest priority. Next, active function in the wrist and finger area should be achieved. When possible, the function of the thumb should be reconstructed. Finally, motion in the shoulder area should be improved.

Selection of the replacement muscle depends on the degree of the defect, the necessity of further transfers and the age of the patient.

In patients with a complete paralysis, elbow flexion can only be gained by microsurgical methods with primary nerve grafting and secondary free microvascular muscle transfer with the latissimus dorsi. Junctions of the nerve grafts are the ipsilateral accessory nerve, the ipsilateral intercostal nerves or parts of the contralateral C7 radicula. Because of the disappointing results of the bifunctional transfers, elbow flexion only should be reconstituted. If there is complete loss of elbow flexion, latissimus dorsi transfer is the method of choice because of the motion amplitude, the power, the limited donor defect and the additional stabilization of the glenohumeral joint. Of course, if this muscle is necessary for the shoulder area it should not be used for elbow reconstitution. If there is the possibility of re-establishing external rotation, the shoulder must be able to abduct more than 90°. When this is possible, the teres major or pectoralis major can be considered as a second choice for reconstructing the external rotation of the shoulder.

Triceps to biceps transfer can also be used, but it should be remembered that when a shoulder abduction of more than 90° is possible, the hand can sometimes hit the patient's face because there is no active extension in the elbow. This method should not be used in children because of the possibility of dysarthrosis.

Owing to the donor defect, pectoralis major transfer is used only as a third choice, especially in women.

Modified transfer of the pronator and flexor muscle mass (Steindler) is a good indication in lesions from the C5/C6 area. Absent active wrist and finger extension is a relative contraindication. It is possible to reduce this functional impairment in these cases by doing a primary transfer of the flexor carpi ulnaris tendon for wrist and finger extension.

In partial lesions and partial regenerations of elbow function (M1 or M2), all these methods can be used as augmentation transfers.

One particular case should be noted; if there is a co-contraction of the triceps and biceps, the triceps to biceps transfer is the therapy of first choice.

In partial paralysis after spontaneous regeneration, after operative revision with regeneration in the elbow flexion muscles of grade M3 or if a Steindler effect is present, further treatment should be discussed with the patient. If the patient does not need to lift heavy weights in daily life or at work, the indication to operate is questionable. In these patients, muscle or tendon transfer should only be performed after precise evaluation and when the patient understands what may be lost or achieved.

Summary

Elbow flexion plays a key role in the global function of the upper extremity. In the case of unilateral complete brachial plexus lesion, restoration of elbow flexion will dramatically increase the patient's chance of regaining bimanual prehension. Furthermore, depending on the type of reconstruction, stability of the glenohumeral joint

as well as some supination function of the forearm can be restored to a varying degree at the same time. Depending on the level of brachial plexus lesion and/or reinnervation, different reconstructive procedures are available. In order to select the best treatment option for the patient, it is necessary to know the extent of the lesion of the brachial plexus and/or ventral upper arm muscles, to time the operation appropriately, to be aware of all treatment possibilities and to have specialist knowledge of tendon transfer for brachial plexus patients. Our concept is based on our experience with more than 1100 patients presenting a brachial plexus lesion between 1981 and 1996 and treated in our institution. There were 528 operative revisions of the brachial plexus. Some 225 patients underwent secondary muscle/tendon transfers. In 35 patients elbow flexion was reconstructed by bipolar latissimus dorsi transfer ($n = 10$), triceps-to-biceps transfer ($n = 15$), modified flexor/pronator muscle mass proximalization ($n = 6$) and multiple-stage free functional muscle transfer after intercostal nerve transfer ($n = 4$).

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14
Palliative surgery: the hand

Jamal Gousheh

Reanimation of digital flexion or extension by latissimus dorsi muscle island flap

The latissimus dorsi muscle has been used for the restoration of elbow flexion (Zancolli and Mitre 1973), but it has not often been used to restore digital flexion. This restriction in the use of the latissimus dorsi muscle seems to stem from the fact that the thoracodorsal artery had been designated as the main blood supply for the upper two-thirds of this muscle, and the perforating branches of the intercostal and other collateral arteries as the main supply for the rest of the muscle (Tobin et al 1981). However, our experiences revealed that the thoracodorsal artery is sufficient for the nourishment of the entire length of the muscle. If the entire length of the muscle from the axillary fossa to the iliac crest is dissected and freed, it will usually exceed 40 cm, and this is long enough to reach the wrist and be sutured to the flexor or extensor tendons of the fingers. Moreover, the range of contraction of this muscle is quite sufficient for generating the complete range of digital movement. Therefore, the use of this method and some re-educating of the patient can restore the digital flexion or extension (Gousheh et al 2000).

Operative technique

Under general anesthesia with the patient in the lateral position and the affected side uppermost, the entire upper extremity is prepared along with half the chest down to the iliac crest. During the operation any prolonged or sudden pulling or excessive abduction of the limb is avoided.

The skin incision, from the axillary fossa to the posterior iliac crest, is made in the shape of a large 'S'. For cases in which overlying skin is required, the length and width of the skin is marked on the anterior part of the muscle and the connection between the muscle and the skin is entirely preserved. Since the perforating arteries from the muscle supply the skin, the edges of this skin are sutured to the muscle by a few separate stitches to prevent possible sliding of the skin on the muscle and damage to the nutrient arteries. The skin flap can be used only for covering the upper part of the forearm, because the arteries in the distal part of the muscle are incapable of nourishing the skin. The width of the skin flap should also be small enough that the edges of the donor side can be approximated and sutured directly.

Dissection of the muscle starts from its anterior edge, where it is gradually separated from the serratus anterior muscle, and is continued downwards. At the lower part, the muscle is separated from the last three ribs and finally from the iliac crest. We prefer to harvest a part of the gluteal aponeurosis along with the latissimus dorsi muscle, and this aponeurosis is used for covering the tendon suture line to prevent subsequent adhesion. At this point the entire muscle can be lifted and the neurovascular pedicle on the superior part of this muscle is revealed. A relatively large and important branch enters the serratus anterior muscle, which is ligated and disconnected. All the small hemorrhagic vessels are carefully coagulated. The entrance of the vascular pedicle into the muscle is approximately 9 cm below the axillary artery and 1.5 cm away

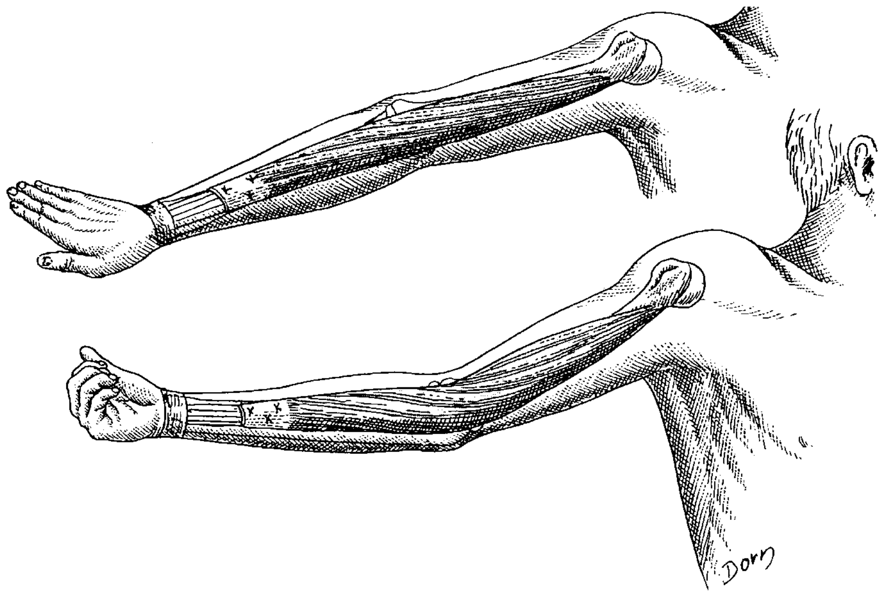

Figure 1

The latissimus dorsi is transferred to the flexor or the extensor tendons.

from the anterior edge of the muscle (Manktelow 1986). Dissection of this pedicle must be performed carefully and continued up the axillary artery. Transection of the circumflex scapular artery is not usually necessary. Finally the action of the nerve is checked by an electrical stimulator, and with this stimulation the entire length of the muscle must contract. At this point the entire muscle up to its highest point is released and only its connection to the humerus and the neurovascular pedicle are left intact. It is better to transect the proximal attachment of the muscle, which is located at the proximal part of the humerus bone, and transfer and fix it to the coracoid in case flexion of the elbow is also required.

The anterior and posterior edges of the muscle are sutured with a few separate stitches, and the muscle is then shaped like a tube with a length, usually, of more than 40 cm in adults. It is then prepared for transfer into the arm (Fig. 1).

Restoration of digital flexion

In the lower third of the forearm the tendons, arteries and nerves are identified, and the profundus flexor tendons are prepared for suture to the muscle. A few horizontal incisions are made along the axillary fossa, the medial aspect of the arm, and the anterior aspect of the elbow and the forearm. A tunnel is then made under the skin and the muscular tube guided through the tunnel and sutured to the profundus flexor tendons of the fingers and the thumb. The harvested part of the gluteal aponeurosis is used for covering the suture area. This significantly reduces the possibility of subsequent adhesions in the region of the suture. Attention must be paid to the following:

- The neurovascular pedicle must be free of tension and torsion;
- The tension of the muscle must be appropriate. We keep the elbow at 90° flexion while suturing the muscle to the tendons. With this tension, there will be automatic digital flexion when the elbow is extended;
- Haemostasis should be done carefully and a good drain placed appropriately.

Postoperatively the elbow is kept in 90° flexion by the use of a cast. The drain can usually be removed on the second or the third day after the operation, and the cast after 3 weeks for children and 4–5 weeks for adults. During this period the patient is trained to contract this muscle. After removal of the cast, extensive physiotherapy and exercises are recommended.

Restoration of digital extension

An analogous procedure can be used to restore digital extension. For this, a few horizontal incisions are made along the axillary fossa, the medial aspect of the arm, and the posterior aspect of the elbow and the forearm. A tunnel is then made under the skin and the muscular tube guided through the tunnel and sutured to the extensor tendons of the fingers and the thumb. Again the harvested part of the gluteal aponeurosis is used for covering the suture area. The tension of the muscle must be appropriate. We keep the elbow and the fingers completely extended while suturing the muscle to the tendons. With this tension, there will be automatic digital extension when the elbow is extended.

Additional procedures

To obtain optimal results it is necessary that the antagonist muscles also function properly. For cases with complete paralysis of flexion and extension of the fingers, one of these deficiencies can be remedied by transfer of the latissimus dorsi muscle and the other by transfer of the gracilis muscle. We prefer to use the latissimus dorsi muscle for generation of digital flexion and the gracilis muscle for digital extension. This is particularly applicable in cases with severe Volkmann's ischemic contracture, in which a suitable nerve exists for the reinnervation of the transferred muscle. It should be mentioned that in some patients with complete flexor and extensor paralysis the effect of a preexisting extensor tenodesis is sufficient for relatively useful function, and we feel that it is unnecessary to transfer a second muscle for these cases. In some cases we can increase the efficiency and improve the function of the transferred muscle by tenodesis of the antagonist tendons. For good function, it is necessary for the thumb to have sufficient opposition. In some cases, use of tenodesis for proper adjustment of the thumb tendons will improve the function. For good results the wrist joint must have a relatively good function. Although in general we do not agree with arthrodesis of the wrist, in some rare cases, for example when the wrist is completely unstable, it can help to generate effective flexion of the fingers due to contraction of the latissimus dorsi muscle.

Discussion

We believe that this procedure is a good practical solution for the following types of cases:

- Old and permanent paralysis in the territory of the lower elements of the brachial plexus, due to war or traction injuries;
- Permanent paralysis of the hand due to irreparable lesions to the median, radial and ulnar nerves above the elbow;
- Cases in which there has been a loss of the flexor and/or extensor muscles of the fingers due to extensive debridement (e.g. in some war injury cases (Gousheh 1995)).

The transferred muscle is usually strong, and after the operation patients are capable of carrying out daily activities such as writing; some can even carry objects weighing up to 10 kg.

One problem that we have not yet been able to correct is the bowstring deformation of the limb in the area of the elbow during contraction of the muscle. However, experience has shown that after a few years this is reduced due to formation of new fascia, and in some cases even becomes unnoticeable.

Free muscle transfer for old complete paralysis of brachial plexus

For cases in which all of the brachial plexus elements have been damaged, for example in the case of complete root avulsion, or when surgical repairs of brachial plexus elements have failed, free muscle transfer can be used. The gracilis muscle is the most suitable one for this purpose. For the innervation of this muscle we can use the local nerves of the paralyzed side for example the spinal accessory or intercostal nerves (Samardzic et al 1992). The use of the nerves from the contralateral (healthy) side has also been suggested:

1. Some authors have recommended the use of the seventh cervical root of the healthy side (Chwei-Chin Chuang et al 1993). They believe

that transferring this nerve does not induce any major problem or side effect in the upper extremity of the healthy (donor) side. However, our experience indicates that relative atrophy of the triceps and the latissimus dorsi will develop. Moreover, mild sensory disruption of the index and the middle fingers will develop;

2. The use of medial pectoralis nerve has no side effects and will be explained in the following section.

Operative technique

In the first stage, a 6-cm horizontal incision of the skin is made below the clavicle of the healthy side. The pectoralis major muscle is dissected from about 1 cm below the lower border of the clavicle. The pectoralis nerve can be observed entering the deep aspect of the muscle. It can be checked with an electrical stimulator, and then transected and prepared for grafting. It is best to mark its end with thin nylon, so that it remains easily accessible.

The entire length of the sural nerve is harvested, and its distal end is sutured to the medial pectoralis nerve with a few stitches of 10–0 nylon. The entire nerve is guided under the skin to the other side, until it reaches the proximal part of the arm region. There it is marked with colored nylon and is left under the skin. Usually after 1 year a small neuroma is observed at this end of the nerve, which indicates nerve growth.

At the second stage, which is usually 1 year later, the gracilis muscle is transferred to the arm. The gracilis muscle is located in the medial aspect of the leg, and extends from the pubis bone to the tibial tuberosity. It is about 42 cm long in adults, and the distal 10 cm is tendon. Its nerve is the anterior branch of the obturator nerve, and is 8–10 cm in length. Its dominant vessel pedicle, a branch of the deep femoral vessel, is about 6 cm long. This pedicle, together with the nerve, usually enters the muscle 9 cm below the proximal end of the muscle, and is capable of nourishing the entire muscle (Manktelow 1986).

For harvesting of the gracilis muscle, the skin incision starts from the insertion of the adductor longus tendon into the adductor tubercle and ends at the tibial tubercle. After the skin incision the adductor longus muscle can be recognized, and the vessel pedicle is between this muscle and the gracilis muscle. The entire vessel pedicle can be easily observed on lifting of the adductor longus muscle. There are two veins accompanying the artery. These vessels are dissected to the end and the artery and the veins are marked differently and harvested along with the muscle and its nerve for the transfer to the arm (Figures 2–4).

Simultaneously, a second surgical team prepares a suitable vein and artery in the proximal arm region for anastomosis. The end of the sural nerve, which has been transferred in the first stage, is also found and prepared for anastomosis. The proximal end of the gracilis muscle is fixed to the coracoid, and its distal end to the biceps muscle tendon just where the tendon joins the radius bone. The tension of the muscle is adjusted so as to keep the elbow in 45° flexion. Anastomosis of the vessels and nerve is then performed using 10–0 nylon and a microscope. The arm is fixed at 90° of elbow flexion for 5 weeks.

The following points should be noted:

1. It is better to harvest part of the skin along with the muscle; this can then be used as a monitoring device for checking the blood flow to the muscle postoperatively;
2. After recovery of elbow flexion with sufficient strength, finger flexion can be regenerated by transferring the distal end of the muscle to the profondus digital flexor tendons. This transfer is accomplished using the fasciae of the tensor fasciae latae muscle;
3. It is possible to try to generate elbow and digital flexion in one procedure. Since the muscle is about 42 cm long, it might be possible to fix the proximal end of the muscle to the coracoid and its distal part directly to the profondus digital flexor tendons. When this is not possible, the position of the proximal end of the muscle can be adjusted so that its distal end is sutured directly to the finger flexor tendons. In order to do this, the proximal end of the muscle is fixed to the proximal part of the humerus bone at the region of the insertion of the pectoralis major muscle tendon.

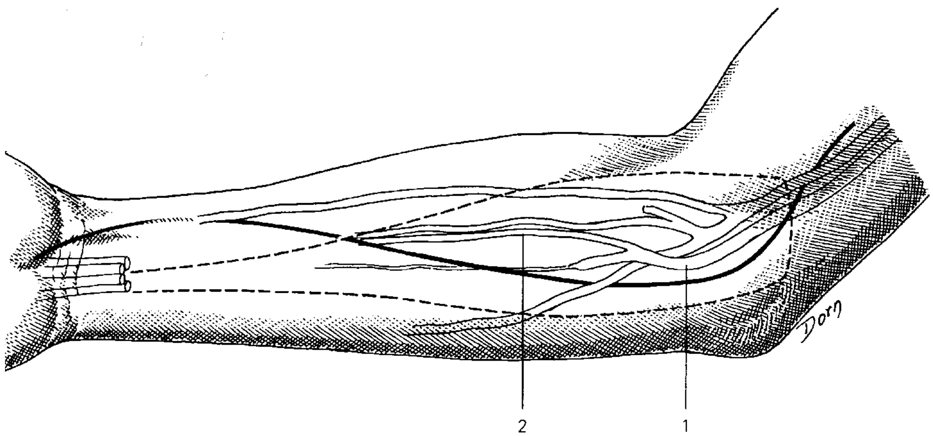

Figure 2

The long incision on the forearm allows the placement of the muscle

1 Median nerve;
2 Anterior interosseous muscle.

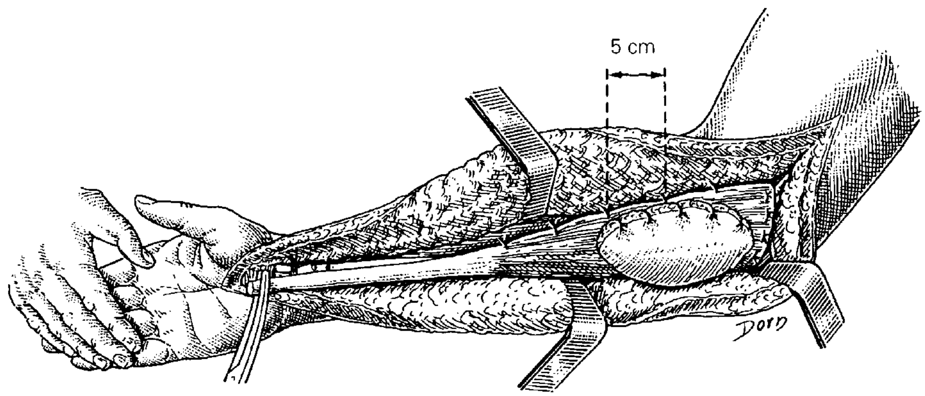

Figure 3

The muscle is placed in the forearm. The proximal tendon is fixed on the medial epicondyle. The length of the muscle is restored by using the 5-cm intervals between the sutures.

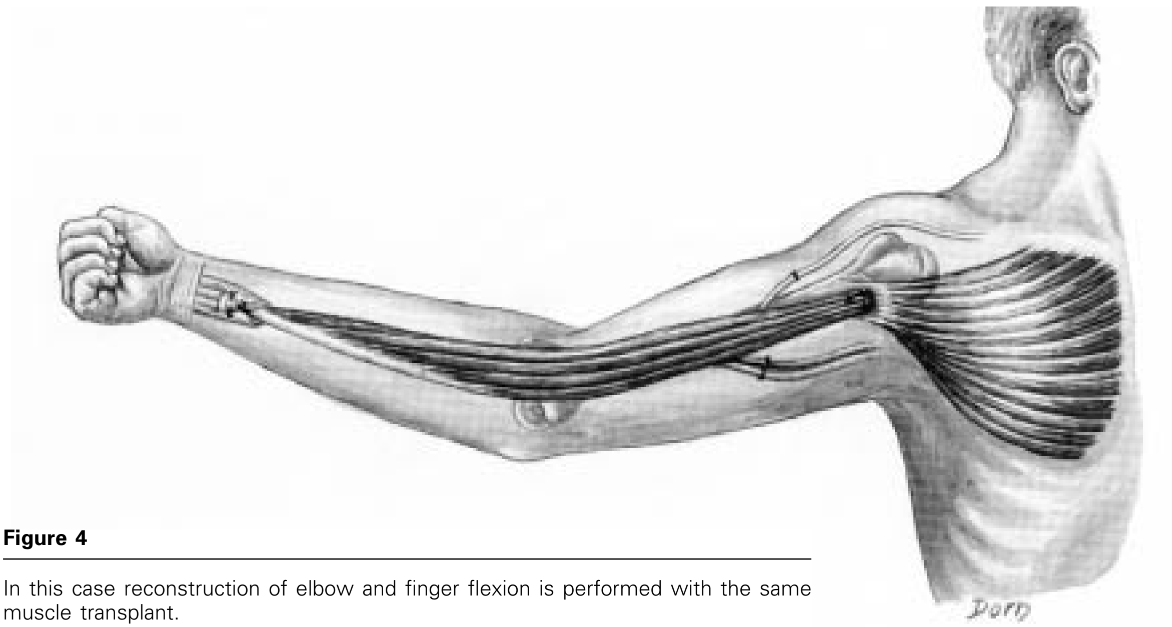

Figure 4

In this case reconstruction of elbow and finger flexion is performed with the same muscle transplant.

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15 Palliative surgery: free muscle transfers

Kazuteru Doi

The restoration of prehension after complete avulsion of the brachial plexus has been the focus of recent interest in reconstruction of the upper limb following brachial plexus injuries. The nerve cross-over technique, similar to transfer of the intercostal nerves to the median nerve to restore finger function (Millesi 1987, Narakas 1987), has failed for several reasons. The distance is too great between the site of nerve anastomosis and the neuromuscular junction of the forearm musculature. More than 1.5–2 years is needed for the regenerating axon to reach the target muscle and by this time atrophy of the muscle has ensued. Regenerating axons are also misdirected frequently and further contribute to the compromised result. Hence, simple nerve transfer should not be attempted to restore finger function following brachial plexus injuries. It can be used to achieve shoulder stability and active elbow flexion (Nagano et al 1989).

Re-innervated free-muscle transplantation has allowed recovery of motor function in cases of severely injured extremities, such as Volkmann's contracture and traumatic muscle loss (Manktelow et al 1978, 1984, Doi et al 1993). It can also be used to provide reliable and powerful recovery of motor function following brachial plexus injury. Classically, free muscle transfer has been used for reconstruction of elbow flexion in non-acute cases with flail upper limb secondary to brachial plexus injury. It has also become possible to regain finger and wrist function following complete avulsion of C5 to T1 roots using free muscle transfer. Inadequate recovery of power did not allow use of the upper extremity for activities of daily living. Recently, attempts have been made to restore more function than simple elbow flexion in cases of total avulsion injury of the brachial plexus.

Free muscle transfer can provide reliable and powerful motor recovery for finger function. The neuromotor units of the free muscle are in the upper arm nearer to the donor nerve, and the nerve to the muscle is purely motor. Following brachial plexus injury, free muscle transfer combined with multiple nerve transfers of the spinal accessory nerve and intercostal nerves can be used to restore prehensile function.

Prehension is a basic function of the human hand. A patient with complete avulsion of the brachial plexus has a normal contralateral upper limb. He or she can perform most of the activities of daily living with the unaffected upper limb. Few activities require the use of both hands, such as lifting a heavy box or holding a bottle while opening its cap. These actions need a powerful grip, independent of the contralateral limb. Hence, direct activation of finger flexion is imperative for a powerful grip (Doi et al 1991).

Several surgical approaches have been developed to restore prehension following complete brachial plexus avulsion (Berger et al 1990, Akasaka et al 1991, Doi et al 1995). To restore pinch (key grip), the Moberg type of simple handgrip reconstruction by activating radial wrist extensors has been attempted in the past (Moberg 1976). This technique along with simple nerve crossing failed to achieve independent activation of forearm muscles. Some investigators incorporated free muscle transfer to overcome these difficulties (Berger et al 1990, Akasaka et al 1991). Although the transferred muscle functioned well, finger flexion was weak, as flexion was achieved indirectly by synergistic action. Patients with brachial plexus injury avoid using the hand reconstructed by this synergistic action, as the contralateral normal hand can easily perform simple pinch.

Grasp release is also essential for prehension. This can be achieved by secondary tenodesis of the finger extensor tendons in a Moberg-type reconstruction. With this type of reconstruction, finger extension is assisted by gravity-aided wrist flexion and release can only be achieved with the elbow in flexed position. This cannot be accomplished with the elbow in extended position, making it difficult for the patient to use the reconstructed hand for everyday activities. Hence voluntary finger extension independent of elbow position is another prerequisite for reconstruction.

Stability of the shoulder and elbow joints is peremptory to use the transferred muscle efficiently. Re-innervated, transferred free muscles and triceps and shoulder girdle muscle provide stability to shoulder joint. If instability persists glenohumeral arthrodesis should be considered. Most authors (Berger et al 1990, Akasaka et al 1991) denied the significance of elbow stabilization, maybe because of its technical difficulty, and failed to provide some form of stabilization. Subsequently, even if their patients regained powerful wrist extension or finger flexion, they were not able to use the fingers optimally in daily activities because the elbow was unstable. All transferred muscles act simultaneously to cause elbow flexion and finger extension or finger flexion. Action is similar to the transferred brachioradialis muscle in cases of spinal cord injury. In such situations, the patients stabilize the unstable elbow by the contralateral hand because of non-functioning elbow extensors. Patients find it too inconvenient and avoid using the reconstructed upper extremity. Ultimately atrophy of transferred muscles ensues and the limb becomes useless for everyday activities. Reconstruction of the elbow extension is imperative whenever prehension is being reconstructed by the transfer of one muscle that moves multiple joints simultaneously (Doi et al 1997).

Basic sensory functions such as protective sensation and position sense should be restored when the motor function is reconstructed for the severely paralysed limb (Ihara et al 1996).

Limited numbers of motor nerves are available for reconstruction in brachial plexus injury. We have preferred to use the spinal accessory and the third to sixth intercostal nerves. Other available donor nerves are the phrenic nerve and contralateral C7 nerve root (Chung et al 1993, Gu et al 1998). However, we chose not to use these nerves because of possible adverse risk. The limited number of the available motor nerves forced us to explore the possibility of one muscle transfer for a two-function concept and to do reconstruction with double free muscle transfer to achieve prehension in a flail limb in brachial plexus injury.

The most useful functions in everyday activities for these patients are powerful grip, even if it is hook grip, flexion and extension of the elbow, and stability and rotation of the shoulder joint. While planning reconstruction, priority should be given to these factors.

The operative technique and long-term results of the double free-muscle transfer procedure for reconstruction of prehension following complete avulsion of the brachial plexus are described in this chapter (Doi et al 1995, Doi et al 1999, Doi et al 2000).

Indications

Patient selection

Based on the authors' experiences, the most important prerequisites for this procedure are the patient's motivation and financial support to continue the postoperative rehabilitation for at least one year, the interval between injury and operation, and the patient's age. A motivated patient without financial worries about the treatment will be able to concentrate more on the rehabilitation programme, which will greatly assist a better recovery. Elbow stability is imperative to obtain a satisfactory result and is usually achieved by the re-innervated triceps brachi muscle. When this procedure was done later than one year after injury, severe atrophy of the muscle resulted. No useful prehension for the patient was restored, because of incomplete recovery of the triceps brachi which produced loss of elbow stability. This procedure should be performed at least within 6 months following the injury. Poor re-innervation of the transferred muscles and other problems such as joint contracture and causalgia may result in inadequate recovery in older patients.

This procedure should not be performed in the presence of subclavian artery injury. The recipient vessels for anastomoses to the nutrient vessels of the transferred muscle might have been injured and development of thrombosis in the anastomosed vessels is more likely to occur. Other important prerequisites for this transfer are finger and elbow joint mobility, the presence of undamaged tendons in the hand and forearm, and good skin coverage in the arm and forearm.

Donor muscle selection

During the initial period in this series, the latissimus dorsi, gracilis and rectus femoris muscles were used as the donor muscle. However, long-term results with the latissimus dorsi and rectus femoris were not satisfactory. The latissimus dorsi failed to provide satisfactory finger function because of adhesion of the muscle to the reconstructed pulley system and rupture of its tendon due to ischaemic necrosis of the portion distal to the pulley. Because of the shorter fascicle length, the rectus femoris muscle had less excursion, resulting in poor finger function. The gracilis is the choice of donor muscle.

Donor nerves selection

Only a limited number of motor nerves are available for reconstruction in brachial plexus injury. Simultaneous reconstruction of two functions can be achieved by transfer of a single muscle. This at times may resolve the discrepancy between the number of available motor nerves and the number of basic functions that needed restoring. The spinal accessory and the third to sixth intercostal nerves are commonly used for transfer for motor and sensory reconstruction. Elbow flexion and finger extension are restored by using a single free muscle transfer innervated by the spinal accessory nerve. Finger flexion is restored by a second free muscle neurotized by the fifth and sixth intercostal nerves. The third and fourth intercostal nerves are anastomosed to the motor branch of the triceps brachi muscle to restore elbow extension and to stabilize the elbow, for negating the tendency of elbow flexion that may occur when the fingers are extended.

For sensory reconstruction of the hand, the intercostal nerves showed better recovery than the supraclavicular nerves (Ihara et al 1996).

Technique

This consists of six established reconstructive procedures:

1. Exploration of the brachial plexus, intraoperative monitoring of spinal evoked potential and sensory action potential and repair of the ruptured motor nerves if possible;
2. The first free muscle transfer for elbow flexion and finger extension – neurotization of transferred muscle by the spinal accessory nerve;
3. The second free muscle transfer for finger flexion – neurotization of the transferred muscle by the fifth and sixth intercostal nerves;
4. A nerve-crossing procedure to achieve elbow extension – the motor branch of the triceps brachi muscle is neurotized by using the third and fourth intercostal nerves. This is done simultaneously with the second muscle transfer;
5. The intercostal sensory rami is coapted to the medial cord of the brachial plexus to restore sensibility of the hand;
6. Secondary reconstruction – arthrodesis of the glenohumeral joint, carpometacarpal joint of the thumb and wrist joint, to increase stability; if indicated, tendon transfer of re-innervated infraspinatus muscle to stabilize the elbow joint if triceps brachi muscle recovery is not adequate; and tenolysis of the transferred muscle and tendons.

Timing of the various reconstructive procedures is important and is guided by several criteria. Procedures (1) and (2) are performed at the first stage operation. Procedures (3), (4) and (5) are done at the second stage operation, usually two or three months after the first. Operations mentioned in procedure (6) are done depending on the condition of recovery, around one and a half years after the first stage operation.

Brachial plexus exploration

Surgical exploration of the brachial plexus was carried out in all the patients. Spinal-evoked potentials and sensory nerve action potentials were recorded intraoperatively to confirm the diagnosis (Fuchigami et al 1994) and to define the pattern and level of injury. Reconstruction was undertaken only after confirming complete brachial plexus palsy secondary to avulsion of the C5 to T1 nerve roots. If, during the exploration, rupture (post-ganglionic injury) of the C5 nerve root was observed, nerve grafting between the proximal remnant of the C5 root and the suprascapular nerve was done to restore shoulder function.

First muscle transfer

The first stage was to reconstruct simultaneous elbow flexion and finger extension with a free muscle transfer using the spinal accessory nerve as the motor nerve (Fig. 1).

Gracilis muscle harvesting

The donor gracilis muscle from the contralateral thigh was selected, as the orientation of its neurovascular bundle matched the donor vessels. The length of the gracilis muscle, from its pubic bone origin to its tibial insertion was measured. (The length of muscle should be sufficient to span the distance between the acromion and midforearm without tension.) The donor muscle was then harvested from its proximal origin to the distal attachment. Gracilis muscle harvesting by the conventional technique leaves a long and unacceptable scar at the donor site. To minimize the length of scar, endoscopic harvesting of the gracilis muscle is recommended (Doi et al 1997). Correct muscle tension is critical for good postoperative function. Prior to detaching the muscle, the resting length of the muscle was recorded by placing black silk ligatures on the surface of the muscle at every 5 cm, as described by Manktelow et al (1984).

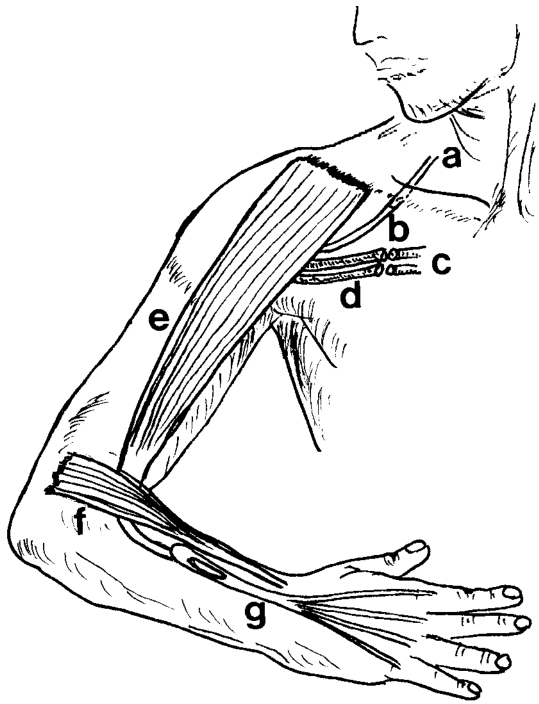

Figure 1

The first free muscle to restore finger extension and elbow flexion simultaneously is transferred in the anterior surface of the upper arm. The nutrient vessels of the muscle are anastomosed to the thoracoacromial artery and cephalic vein, and the motor nerve is connected to the spinal accessory nerve. The muscle origin was sutured to the acromion and latera clavicle proximally, passed underneath the pulley of the brachioradialis and wrist extensors in the anterior elbow and the distal tendinous portion of the muscle was sutured to the extensor comminus tendons distally in the forearm. (a) Accessory nerve; (b) motor branch of the muscle transplant; (c) thoracoacromial artery and branches of the cephalic vein; (d) nutrient artery and veins of the muscle transplant; (e) muscle transplant; (f) the brachioradialis and wrist extensors serving as a pulley; (g) extensor digitorum communis tendon. Reproduced with permission from Doi et al 2000.

Selection of donor nerve and recipient vessels

The distal portion of the spinal accessory nerve was used for neurotizing the transferred muscle. Sparing the upper branch preserved the motor fibres to the superior fibres of the trapezius muscle. The distal portion of the spinal accessory nerve was dissected, divided, and transferred. The middle and distal branches of the spinal accessory nerve were coapted to the motor nerve of the transferred muscle, which was passed underneath the clavicle. The nutrient vessels of the muscle transplant were then anastomosed to the thoracoacromial artery and vein, or the cephalic vein.

Position of the transferred muscle

A simple and straight route for the free muscle was created from its new origin, the acromion to its final insertion in the forearm to maximize the force of contraction. It was placed on the anterior portion of the deltoid muscle, the lateral aspect of the upper arm and dorsal surface of the forearm; deep to the brachioradialis and radial wrist extensor muscles, just distal to the elbow to prevent bowstringing. This position is optimal for elbow flexion and finger extension, although the grip may weaken when the elbow is flexed. The origin of the transferred muscle was sutured to the acromion. The distal tendon of the transferred muscle was coapted to the extensor digitorum communis tendons.

Adjustment of muscle tension

For optimal function, it is essential that the correct muscle tension be reproduced in the upper limb before final suturing of the muscle to the finger extensors. The muscle was stretched to restore the original length, until the distance between markers was once again 5 cm. While adjusting the tension, the elbow was kept in minus 30° of extension; wrist in neutral and the fingers were in fully extended position. The position of the stumps of the extensor digitorum communis tendons on the donor muscle tendon was noted and marked and the extensor digitorum communis tendons were coapted to the muscle transplant. The elbow was then flexed to 90° and with the fingers fully flexed and the wrist in a neutral position, tenorrhaphy was done at the previously marked sites. The biomechanics were examined.

Second free muscle transfer

The second free muscle transfer for reconstruction of finger flexion was done 2–3 months after the first operation (Fig. 2). By this time postoperative contracture of the elbow and finger joints had improved. The third to sixth intercostal nerves were dissected up to the mid-clavicular line and transferred to the axillary region. The second gracilis muscle was harvested from the ipsilateral thigh, making sure that it would span the distance from the second rib to the mid-forearm. The proximal end of the gracilis muscle was sutured to the second and third ribs near the mid-axillary line. For fixation, holes were drilled in the ribs and the muscle was anchored with non-absorbable sutures passed through these holes. The muscle was placed on the medial aspect of the upper arm and forearm so as not to be a secondary elbow flexor.

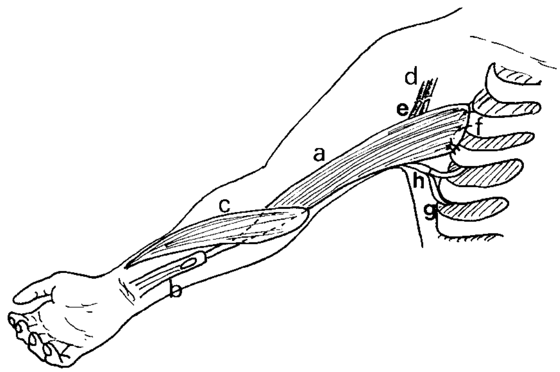

Figure 2

The second free muscle to restore finger flexion is transferred in the medial surface of the upper arm, and the nutrient vessels of the muscle are anastomosed to the thoracodorsal artery and vein individually. The motor nerve of the muscle is connected to the fifth and sixth intercostal nerves. The muscle is sutured to the second and third rib proximally, and the distal tendinous portion of the tendon is sutured to the flexor digitorum profundus tendons distally in the forearm, following passing the muscle underneath the pulley of the pronator teres and wrist flexors. (a) muscle transplant; (b) long finger flexor tendons. (c) pronator teres and wrist flexors serving as a pulley; (d) thoracodorsal artery and vein; (e) nutrient artery and veins of the muscle transplant; (f) the second and third ribs; (g) the fifith and sixth intercostal nerves; (h) motor branch of the muscle transplant. Reproduced with permission from Doi et al 2000.

In the forearm, just distal to elbow, the tendinous part of gracilis was passed under the pronator teres and long wrist flexors. The distal portion of the gracilis muscle being tendinous and thin passed easily through the small hiatus deep to the muscles and was coapted to the flexor digitorum profundus. Muscle tension was determined using principles as described above. The nutrient vessels were anastomosed to the thoracodorsal artery and vein. In the axilla, the fifth and sixth intercostal nerves were anastomosed without tension to the motor nerve of the second muscle transplant.

Nerve-crossing to the motor branch of the triceps brachi muscle

The third and fourth intercostal nerves were connected to the motor branch of the triceps brachi muscle, to activate the elbow extensors. This was done prior to the detachment of the second muscle from the thigh (Fig. 3).

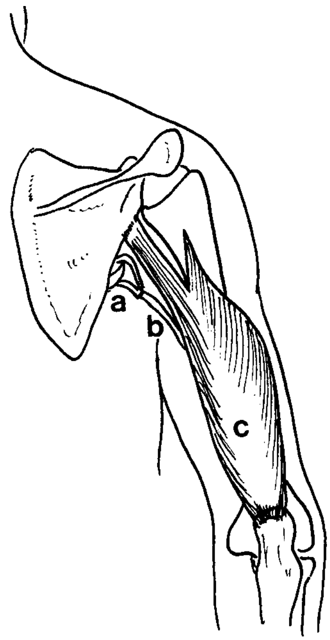

Figure 3

Nerve-crossing of the third and fourth intercostal nerves to the motor branch of the triceps brachi muscle to restore elbow extension and stabilization following complete brachial plexus avulsion is also done at the second free muscle transfer. (a) the third and fourth intercostal nerves; (b) motor branch of the triceps brachi muscle; (c) triceps brachi muscle. Reproduced with permission from Doi et al 2000.

Sensory reconstruction

The sensory rami of intercostal nerves were sutured to the medial cord of the brachial plexus at the second operation to restore hand sensibility.

Postoperative management

The upper limb was immobilized without tension on the transferred muscles, motor nerves and nutrients vessels for 4 weeks postoperatively and then the rehabilitation programmes were started as described below.

Rehabilitation

Initial stage: before electromyographic re-innervation of transferred muscles

The use of electrical stimulation for the transferred muscles and nerve-repaired muscles is still controversial. However, the authors prefer the electrical stimulation of the paralysed target muscles, such as the two transferred gracilis muscles, the triceps brachi, and the supraspinatus, and infraspinatus if the suprascapular nerve was repaired. The low-intensity electrical stimulation of the muscle was started from the third postoperative week and continued until electromyographic re-innervation was detected in the muscles.

At this stage, functional orthosis was used to immobilize the reconstructed upper limb. The authors preferred the air-bag type orthosis (Nakamura brace, Shimane, Japan) to immobilize the shoulder and elbow joints and a plaster-of-Paris long-arm cast was used for immobilization of the wrist and finger joints. Four weeks following operation, the long-arm cast was removed and only passive flexion of the elbow joint was commenced. During the early postoperative period, a plastic static splint was used to maintain the wrist in a neutral position and the proximal and distal interphalangeal joints in extension to allow these joints to contract in this position. At the sixth postoperative week, while protecting the muscle–tendon suture site of the transferred muscle from over-tension by keeping the wrist joint in extension following the first free muscle transfer or in flexion following the second free muscle transfer, passive extension of the elbow was started.

Only the metacarpophalangeal joints were moved passively, since the transferred muscles intended to move the single joint action to decrease the effect of claw finger deformity. At the ninth postoperative week, the air-bag orthosis was discontinued and the elbow sling-type orthosis was applied to prevent subluxation of the shoulder.

Late stage: after re-innervation

Following electromyographic documentation of re-innervation of the transferred muscle, usually between three and eight months postoperative, electromyographic biofeedback techniques were started to train the transferred muscles to move the elbow and fingers. Muscular facilitation or re-education is indicated when patients display minimal active contraction with an identified muscle or muscle group. The initial goal of re-education is for patients to reactivate voluntary control of the muscle. When the patient is working with a weak muscle, initially the intensity of the motor unit activity and the frequency of the muscle contraction are emphasized. Treatment sessions should be short and end when fatigue is noted by a decreasing ability of the patient to achieve the set goal level.

Independent finger flexion and extension training using electromyographic biofeedback techniques commenced following recovery of active motion of the elbow and fingers. Patients also practised skilled activities, such as lifting, holding, carrying, and pinching. All patients should follow the rehabilitation programme every day for 6 months postoperatively. And after the patients have mastered activation of the transferred muscle, the home programmes consisting of power-up exercise, individual activation of the transferred muscles, and daily-use practice should be detailed and recommended to the patients to be performed by themselves. The authors recommend the patients to continue the rehabilitation programme at least for 3 years postoperatively, as functional recovery will be expected to occur even after this period.

Secondary reconstruction

Elbow extension (dynamic stability)

Inadequate recovery of triceps muscle following intercostal nerve neurotization resulted in elbow instability. This ruined prehension function, even if the power strength of re-innervated transferred muscles was enough to move the fingers. Elbow stability could be provided by supplemental reinforcement of elbow extension by transferring the re-innervated infraspinatus to the triceps. Tenodesis of the triceps brachi when the infraspinatus recovery is not enough for transfer, is another optional procedure to provide stability of the elbow (Doi et al 1997).

Tenolysis

One-third of our 34 cases with double free muscle transfer resulted in sliding insufficiency of the transferred muscle in spite of satisfactory contraction of the muscle, which needed tenolysis. Under local anesthesia, tenolysis of the transferred gracilis and distal tendons was performed to allow full evaluation from the proximal musculotendinous junction of the gracilis to the distal insertion of the tendon. (Care should be taken when releasing adhesions underneath the pulley system.)

Carpometacarpal arthrodesis of the thumb

After significant recovery of the active finger motion, the carpometacarpal fusion of the thumb with intentional contracture of the metacar-

a

b

Figure 4

A 25-year-old man sustained complete avulsion of his left brachial plexus and underwent the double free muscle procedure. Finger flexion (a) and extension (b) with the elbow in extension; finger flexion (c) and extension (d) with the elbow in flexion; unscrewing a bottle cap with both hands (e); and lifting a 5-kg box with both hands (f) 36 months postoperatively. Reproduced with permission from Doi et al 2000.

c

d

e

f

pophalangeal joint and interphalangeal joint of the thumb and proximal and distal interphalangeal joints of the fingers provides stable pinch function.

Glenohumeral arthrodesis

If the instability of shoulder joint persists, arthrodesis of the glenohumeral joint may be performed at a later stage, following re-innervation of the transferred muscle. Arthrodesis of the glenohumeral joint will allow the scapulothoracic joint to be moved by the remnant of the trapezius muscle for patients with an unstable shoulder joint. This permits control of the upper limb and prevents dispersion of power of the transferred muscles. Glenohumeral arthrodesis should be done as a final stage in the reconstructive programme, since it makes the reconstructive procedures difficult to perform in the position of shoulder adduction.

Complications

Vascular compromise

The accompanying skin flap helps to monitor circulation of the transferred muscle, which may develop vascular insufficiency due to thrombosis in the anastomosed vessels. In case of vascular problems, prompt exploration of the anastomosed vessels is imperative for survival of the transferred muscle. After revision of the anastomosed vessel, not only fresh bleeding from the muscle, but also muscle contraction to electrical stimulation should be present. Otherwise, the muscle will develop ischemic necrosis and another free muscle transfer may be needed.

Delayed or failed re-innervation of the transferred muscles, and triceps brachi muscle

Electromyographic evidence of re-innervation of the transferred muscle was detected between 3 and 10 months after surgery, depending on the donor motor nerve used. Re-innervation was detected much earlier in muscles where the spinal accessory nerve was used (mean 3.9 months) than those re-innervated by the intercostal nerve (mean 4.8 months). Voluntary contraction was detected about 2 months after electromyographic documentation of re-innervation. Re-innervation of the triceps muscle occurred even much later than those of the transferred muscles re-innervated by the intercostal nerve (mean 8.2 months).

Delayed re-innervation later than the time described above or no re-innervation at all indicates a poor functional prognosis. Delayed and failed re-innervation will result in muscle atrophy. Atrophied muscle will not be able to activate joint motion. In such situations, further reconstructive plans should be abandoned.

Adhesion of the transferred muscle

Adhesion of the transferred muscle to the surrounding tissue occurred more or less in all the cases. One-third of the cases underwent tenolysis. Tenolysis was indicated when active finger function was not achieved despite strong contraction of the transferred muscle. All the transfers done with the gracilis muscle resulted in improved range of finger motions postoperatively; however, the latissimus dorsi had recurrence of adhesions.

Instability of the proximal joints

The transferred double free muscle moved multiple joints simultaneously. The first free muscle was for both elbow flexion and finger extension. The second free muscle was for finger flexion and for this reason it was not placed in the flexion–extension plane of the elbow. This muscle was not intended for elbow flexion. However, this also caused finger flexion and elbow flexion simultaneously. Hence, simultaneous elbow flexion occurred with finger movement as long as the antagonist of elbow flexion did not recover. The third and fourth intercostal nerves were anastomosed to the motor branch of the triceps brachi muscle to restore elbow extension and to stabilize the elbow, negating the tendency of elbow flexion with finger movement. Even if the power of the triceps brachi was weak, it could contribute to stability of the elbow with the aid of gravity. If re-innervation of the triceps brachi has failed, re-innervated infraspinatus transfer to the triceps brachi or tenodesis of the triceps brachi is recommended to restore elbow stability.

The re-innervated free muscle, triceps brachi and shoulder girdle muscles without arthrodesis can achieve stability of the glenohumeral joint. During exploration of the brachial plexus, if the C5 nerve root is available, it should be crossed to the suprascapular nerve using nerve graft, not only to improve shoulder function, but also to re-innervate paralysed muscles for use as possible donor muscles for transfer, if the triceps brachi did not recover. If the glenohumeral joint remains unstable even after recovery of these muscles, glenohumeral arthrodesis can be done, although this will limit several activities, for example, turning over during sleep may become difficult. Care must be taken to prevent fracture of the proximal humerus.

Sensibility of the hand

Restoration of basic modalities, e.g. protective sensation and position sense, is imperative when prehensile function is reconstructed for irreparable brachial plexus injury. Half of the patients achieved sensitivity of the palm better than S2 (Highet's grading system) and adequate position sense. None of the patients achieved sensitivity over the finger tips. Even so, protective sensation did not recover over the ulnar side of the hand and finger. Patients tended to sustain minor injury and burned their hands over the ulnar side of the hand.

Pain syndrome

Unlike reports in the literature, none of our patients had severe causalgia that could not be controlled using the usual analgesics.

General functional outcome

Of patients reconstructed by the double free muscle procedure and followed-up longer than 24 months after the second free muscle transfer (mean follow-up, 40 months) 26 out of 32 were assessed for long-term outcome of universal prehension, including motion and stability of the shoulder and elbow, voluntary and independent motion of the fingers, sensibility and ADL functions. Functional outcome of prehension according to the authors' classification (Doi et al 1995) was excellent in 4 patients (which implies restoration of more than 90° elbow flexion, dynamic stability of elbow, while moving fingers and more than 60° of total active motion of fingers; TAM) (Fig. 4), good in 10 (same as excellent, except TAM 30–60°) fair in 2 (TAM < 30°) poor in 9 and bad in 1. Satisfactory results, better than good, were obtained in 14 out of 26 patients (54 per cent) who obtained more than 90° elbow flexion, dynamic stability of elbow, voluntary finger motion at any position of elbow, more than 30° of total active motion of fingers, and daily use of their reconstructed hand for both-hands activities, such as holding a bottle while opening a cap or lifting a heavy object. These satisfactory results were obtained only from patients:

- of age younger than 32 years;
- with an interval between injury and surgery shorter than 8 months;
- with a longer follow-up than 55 months;
- without serious accompanied injuries of subclavicular artery, spinal accessory nerve and spinal cord;
- for whom the bilateral gracilis muscles were selected as donor muscle;
- with successful restoration of elbow stability with nerve-crossing or secondary tendon transfer.

Satisfying these prerequisites, the double free muscle procedure should provide reliable and useful prehensile function to the patient with complete avulsion of the brachial plexus to enable the use of their otherwise useless limb (Doi et al 2000).

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Obstetrical Paralysis

16
Aetiology

JM Hans Ubachs and Albert (Bart) CJ Slooff

History

The aetiology of the obstetric brachial plexus injuries has an interesting history. As early as 1764, Smellie suggested the obstetric origin of a paralysis of the arm in children. But only in 1872, in the third edition of his book *De l'électrisation localisée et de son application à la pathologie et à la thérapeutique*, Duchenne de Boulogne described four children with an upper brachial plexus lesion as a result of an effort to deliver the shoulder. The classical description by Erb in 1874 concerned the upper brachial plexus paralysis in adults, with the same characteristics as those described by Duchenne de Boulogne. Using electric stimulation, he found in healthy persons a distinct point on the skin in the suprascapular region, just anterior to the trapezius muscle, where the same muscle groups could be contracted as those affected in his patients. It is the spot where the fifth and sixth cervical roots unite, and where they are optimally accessible to electric current by virtue of their superficial position. Pressure on this 'point of Erb', caused either by fingers by traction on the armpits, by forceps applied too deep, or by a haematoma were for Erb, and many obstetricians after him, the only possible cause of the lesion.

But not everybody accepted the compression theory. Poliomyelitis and toxic causes were mentioned. Some even pointed to the possibility of an epiphysiolysis of the humerus, caused by congenital lues, and consequently a paralysis of the arm. Doubts about the pressure theory, however, were raised as a result of observation of Horner's syndrome, indicating damage of the sympathical nerve, together with an injury of the lower plexus. Augusta Klumpke, the first female intern in Paris, explained in 1885 Horner's sign in the brachial plexus lesion by avulsions of the roots C8–T1 and involvement of the homolateral cervical sympathic nervous system (Klumpke 1885). Klumpke later married Dejerine, and therefore the lower plexus palsy is sometimes called the Dejerine–Klumpke paralysis, as opposed to the upper plexus palsy, which is named the Erb–Duchenne paralysis. Thornburn (1903) was one of the first to assume that the injury was the

Figure 1

Engelhard's photograph demonstrating the result of excessive stretching during the delivery (Engelhard 1906).

result of rupture or excessive stretching of the brachial plexus during the delivery.

Pathogenesis

To test Thornburn's assumption, Engelhard investigated the influence of different positions and assisted deliveries on a dead fetus, in which the brachial plexus was dissected. In his doctoral thesis he demonstrated in 1906, with for that period excellent photographs, that the pressure theory was highly improbable (Fig. 1). Obstetric injury of the brachial plexus could only be the result of excessive stretching of that plexus during the delivery. In particular, he warned against strong downward traction of the fetal head developing the anterior shoulder in cephalic deliveries, and extensive lateral movement of the body in breech extractions. And his words still have their validity. More recently, Metaizeau et al (1979) repeated these studies and explained the differences in injury. The results of these investigations have been confirmed by our clinical and surgical observations (Ubachs et al 1995, Slooff 1997). Shoulder dystocia occurs mostly unexpected, and it is one of the more serious obstetric emergencies. The shoulder is impacted behind the symphysis pubis, and although there is a long list of manoeuvres to disimpact the shoulder, not one is perfect. Excessive dorsal traction, the first reaction in that situation, bears the danger of overstretching with consequent damage of the brachial plexus (Fig. 2). In breech presentation, even of small infants, the injury is caused by difficulties in delivering the extended and entrapped arm and therefore a combination of forceful traction with too much lateral movement of the body.

Reconstructive neurosurgery of the obstetric brachial plexus lesion, together with neurophysiological and radiological investigation, gives the opportunity to gain a clear understanding of the relationship between the anatomical findings during operation and the obstetric trauma. The injury may be localized in the upper or lower part of the brachial plexus, resulting in different phenotypes. Erb's palsy results from an injury of the spinal nerves C5–C6 and sometimes C7. It consists of a paralysis of the shoulder muscles, resulting in a hanging upper arm in endorotation, a paralysis of the elbow flexors and consequently an extended elbow in pronating position, caused by the paralysis of the supinators. Combination with a lesion of C7 results in a paralysis of the wrist and finger extensors and the hand assumes the so-called waiter's tip position. The total palsy, often incorrectly called Klumpke's palsy, is caused by a severe lesion of the lower spinal nerves (C7–T1) but is always associated with an upper spinal nerve lesion of varying severity. The impairment mainly includes a paralysis of the muscles in forearm and hand, sometimes causing a characteristic clawhand deformity, and sensory loss of the hand and the adjacent forearm. Involvement of T1 is frequently paralleled by cervical sympathetic nerve damage, an injury that will give rise to Horner's syndrome.

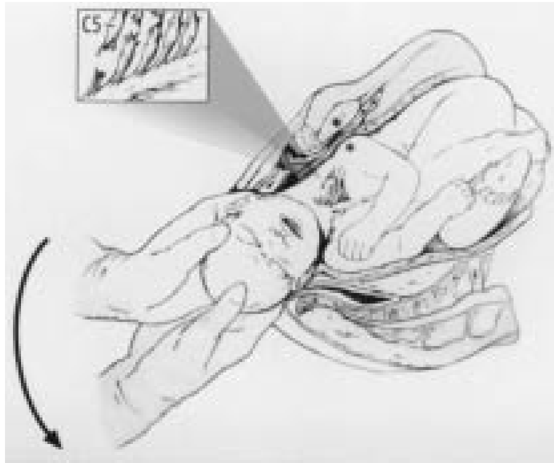

Figure 2

Excessive dorsal traction in shoulder dystocia with consequent damage of the brachial plexus. (From Ubachs et al 1995.)

Furthermore, stretching of the brachial plexus may result in two anatomically different lesions with different morbidities. The lesions are easily distinguished during surgery. Either the nerve is partially or totally ruptured beyond the vertebral foramen, causing a neuroma from expanding axons and Schwann's cells at the damaged site, or the rootlets of the spinal nerve are torn from the spinal cord, a phenomenon called an avulsion.

Table 1 Demographic and obstetric characteristics of the two obstetric brachial plexus lesion (OBPL) populations in relation to their respective reference populations. Values are given as percentages (From Ubachs et al 1995)

Characteristics	*Cephalic delivery*			*Breech delivery*		
	OBPL (n = 102)	*Control (n = 138 702)*	*P*	*OBPL (n = 102)*	*Control (n = 7926)*	*P*
Proportion						
Multipara	75	56	< 0.05	39	44	NS
Males	50	52	NS	46	46	NS
Incidence						
Pre-term birth*	7	14	NS	21	33	NS
Post-term birth	7	5	NS	7	3	NS
Small for dates (≤ 10%)**	0	10	< 0.001	14	18	NS
Large for dates (≥ 90%)**	71	10	< 0.0001	4	6	NS
Birth asphyxia (Apgar score ≤ 6)	65	1	< 0.0001	86	4	< 0.0001
Caesarean birth*	0	7	< 0.01	0	38	< 0.001
Forceps/vacuum birth	49	11	< 0.001	0	1	NS

*In the breech reference group the incidence of preterm deliveries and that of Caesarean sections was higher than in the cephalic reference group ($P < 0.05$, χ^2 test). **According to Dutch intrauterine growth curves (Kloosterman 1970). NS, not significant.

Patients

Study of the first 130 patients, operated on from April 1986 to January 1994 in De Wever Hospital (today the Atrium Medical Centre) in Heerlen, The Netherlands, offered the opportunity to prove Engelhard's assersion in 1906. Moreover, it was interesting to determine whether the presentation of the fetus during the preceding delivery – breech or cephalic – contributed to the localization and anatomical severity of the lesion. The results of that study, the first where the anatomical site of the damage was compared with the preceding obstetric events, were published in 1995. The indication for neurosurgical intervention was based on the criteria from Gilbert et al (1987). The obstetric history was traced by analysis of the obstetric records made at the delivery and compared much later with the anatomical findings at surgery. Demographic and obstetric data regarding a large proportion (146 533) of the 196 700 deliveries in The Netherlands in 1992 were obtained from The Foundation of Perinatal Epidemiology in The Netherlands (PEN) and the Dutch Health Care Information Centre (SIG). These data were used to identify specific features in the study population (Table 1).

Of the operated infants with obstetrics brachial plexus lesions (OBPLs), 102 were born in cephalic and 28 in breech position. Patients who had been delivered in cephalic presentation were born more frequently from a multiparous mother, were more frequently macrosomic, experienced intrapartum asphyxia more often and required instrumental delivery more often. Patients born in breech differed from the reference population by a higher incidence of intrapartum asphyxia. The gestational age at birth did not differ significantly.

In one-third (40/130) of the OBPL population, the preceding pregnancy had been complicated by treated gestational diabetes, the suspicion of idiopathic macrosomia (percentile of birth weight for gestation ≥ 90), obesity and even the explicit wish to give birth in a standing position, a strategy which tends to aggravate mechanical problems encountered during the second stage. Two-thirds (87/130) of the infants with OBPLs were delivered by multiparous mothers and, in almost half of them (39/87) macrosomia, instrumental delivery and/or other potentially traumatic manipulations had complicated the second stage of labour. Whereas the cephalic group was characterized by a disproportionate number of macrosomic infants, the distribution of the percentile of birth weight for gestation in the breech group did not differ significantly (Table 1 and Fig. 3). The mean neonatal weight of the children born in the cephalic position was 4334 g with a range from 2550 to 6000 g. Infants born by breech weighed a mean 3050 g with a range from 1230 to 4000 g. In spite of this marked weight difference, the incidence of mechanical problems during passage of the birth

Table 2 Traumatic birth and intrapartum asphyxia in the two birth groups. Values are given as *n* (%). Differences (*P*) not significant

	Cephalic (n = 102)	*Breech (n = 28)*
Complicated 2nd stage*	92 (90)	22 (79)
Intrapartum asphyxia	66 (65)	24 (86)

*Shoulder dystocia or difficult breech extraction.

Table 3 Incidence of the left- and right-side lesions: cephalic birth (*n* = 102) and breech (*n* = 28). Values are given as *n* (%)

Birth group	*Left side*	*Right side*	*P*
Cephalic	37 (36)	65 (64)	< 0.01
Breech*	10 (36)	18 (64)	NS

*Several of these infants had a bilateral OBPL. The operated lesion is mentioned. NS: not significant.

canal and that of intrapartum asphyxia (1 min Apgar score ≤ 6) was similar in the two groups (Table 2). It is uncertain whether the asphyxia was caused by the difficulty in delivery, or if it was one of the factors in the nerve damage by causing muscular hypotonia. Obviously, excess macrosomia in the cephalic group explains the high incidence of shoulder dystocia. It is interesting that twice as many right- than left-sided injuries were observed in the children delivered in vertex presentation. This is most likely to be a direct consequence of fetal preference for a position with the back to the left side, and hence a vertex descent in a left occipital anterior presentation (Hoogland and de Haan 1980). The preference for the right side was also noted for the breech group. However, this was not significant, possibly because of the smaller group size (Table 3).

An unexpected finding was the difference in clinical and anatomical type of lesion between the children born in breech and cephalic presentations (Table 4 and Fig. 4). Mechanically, a difficult breech delivery with often brusque manipulation to deliver the first arm, together with excessive traction on the entire neck was expected to predispose towards more extensive damage reflected in the Erb's type C5–C7 or the total C5–T1 lesions. Similarly, overstretching by traction and abduction in an attempt to deliver the first shoulder was expected to predispose for C5–C6 damage. To our surprise, two-thirds (19/28) of the injuries after breech delivery consisted of pure Erb palsies (C5–C6) caused, in the majority of cases (16/19), by a partial or complete avulsion of one or both spinal nerves. Total lesions were rare in the breech group. Conversely, the most common lesion after

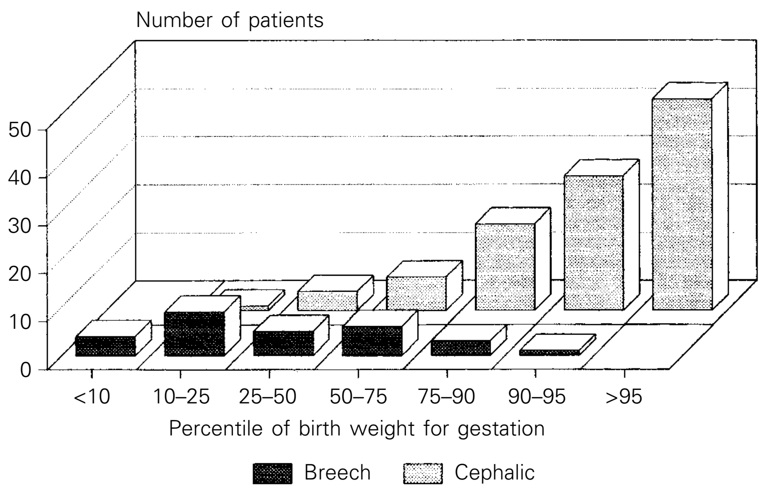

Figure 3

The weight at birth of 130 children with OBPLs.

Table 4 Effect of presentation at birth on type and severity of the OBPL birth groups. Values are given as percentages (From Ubachs et al 1995)

Type of lesion	*Cephalic (n = 102)*	*Breech (n = 28)*	*P*
Erb C5–C6			
Avulsion*	2	57	< 0.0005
Rupture	5	11	NS
Total:	7	68	< 0.0005
Erb C5–C7			
Avulsion*	8	18	NS
Rupture	43	7	< 0.0005
Total:	51	25	< 0.05
Total lesion C5–T1			
Avulsion*	20	4	< 0.05
Rupture	22	3	< 0.05
Total:	42	7	< 0.005
Any lesion			
Avulsion*	29	79	< 0.0005
Rupture	71	21	< 0.0005

*At least one spinal nerve.
NS: not significant.

cephalic birth was the more extensive Erb's palsy (C5–C7) usually resulting from an extraforaminal partial or complete nerve rupture, closely followed by the total palsy. In fact, a total palsy was an almost exclusive complication (43/45) of cephalic delivery, with nerve rupture and nerve avulsion seen equally frequently. Interestingly, if in this group the lesion was not total (C5–T1), the damage was always more severe as indicated by the incidence of nerve rupture. Apparently, unilateral overstretching of the angle of neck and shoulder in the cephalic group led to a more extensive damage, including the lower spinal nerves of the plexus.

An explanation of this phenomenon might be sought in tight attachment of the spinal nerves C5 and C6 to the transverse processes of the cervical vertebrae (Sunderland, 1991). As a result of that, unilateral overstretching in shoulder dystocia preferentially leads to an extraforaminal lesion of the upper spinal nerves and often to an avulsion of the lower spinal nerves C8–T1 from the spinal cord. A different causal mechanism, however, should be considered in difficult breech deliveries (Slooff and Blaauw, 1996). Hyperextension of the cervical spine and consequently a forced hyperextensive moment or elongation of the spinal cord in such a delivery, combined with the relatively strong attachment of the spinal nerves C5 and C6 to their transverse processes, might cause an avulsion by acting directly on the nerve roots between their attachment to the cord and their fixed entry in the intervertebral foramen. Sunderland calls this the 'central mechanism' of an avulsion (Sunderland 1991, Fig. 18.7, p. 157).

Associated lesions were frequent. Fractures of the clavicle or the humerus were evenly

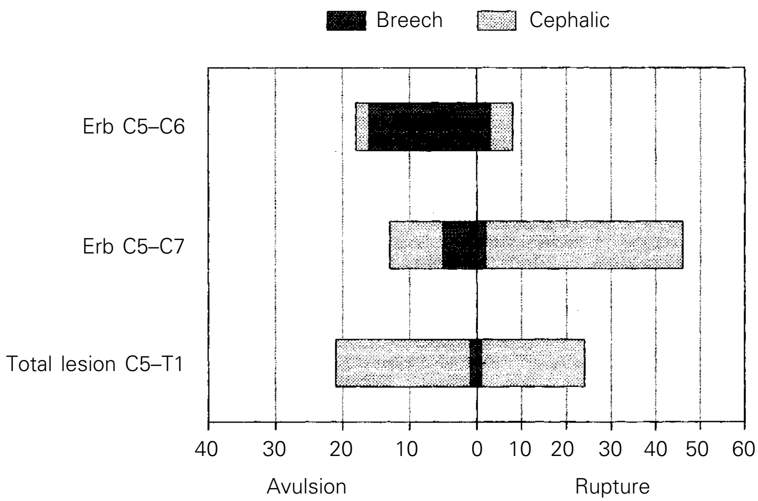

Figure 4

Presentation at birth, morbidity and type of lesion in 130 children. (From Ubachs et al 1995)

Table 5 Incidence of associated lesions in the two birth groups. None of the children had a spinal cord or facial nerve lesion. Values are given as *n* (%) (From Ubachs et al 1995)

Associated lesions	*Cephalic (n = 102)*	*Breech (n = 28)*	*P*
Sternocleidomastoid	9 (8)	5 (18)	NS
Fracture			
Clavicle	9 (9)	3 (11)	NS
Humerus	6 (6)	2 (7)	NS
Phrenic nerve lesion	3 (3)	10 (36)	< 0.0005
Bilateral OBPL	0 (0)	7 (25)	< 0.0005

NS: not significant.

distributed over the two groups, whereas persistent paralysis of the phrenic nerve was noted more frequently in infants born by breech and bilateral OBPL was seen exclusively after a breech delivery (Table 5).

Intrauterine maladaptation was never suspected, as no infant in these series was born by Caesarean section and all vaginal deliveries were either operative or were complicated by other potentially traumatic manipulations. A Caesarean section, for that matter, is not always safe and atraumatic: especially in malpositions, a Caesarean delivery can be extremely difficult. As early as 1980, Koenigsberger found in neonates with plexus injuries whose deliveries were uncomplicated, in the first days of life electromyographic changes characteristic of muscle denervation, which, in adults, take at least 10 days to develop. In neonates denervation activity is found much earlier, in our experience already after 4–5 days (see Chapter 4). It is therefore dificult to prove intrauterine maladaptation as a cause of nerve injury. This would demand electromyographic investigation within the first days after the delivery. Study of the aetiology, and the anatomic injury as its consequence, should teach a lesson. As already said, shoulder dystocia is not always predictable. Estimation of the child's birth weight is inaccurate. The average difference between the estimated weight before delivery and the birth weight is, independent of the method used, about 15–20 per cent. But even assuming a 100 per cent precision in predicting a birth weight of > 4500 g estimations are that from 58 to 1026 Caesarean deliveries would be necessary to prevent a single, permanent brachial plexus injury (Sacks and Chen 2000). There are many obstetric measures and manoeuvres described to overcome a shoulder dystocia. However, the crucial factor is that every midwife or obstetrician should have a well-conceived plan of action, which can be executed rapidly. Computer techniques to measure the forces used in shoulder dystocia have been developed (Allen et al 1994). In future, they might be used as a model for obstetricians in training to teach the handling of such a difficult and frequently unexpected problem.

The realization of the risk of birth trauma in breech presentation (and its legal consequences)

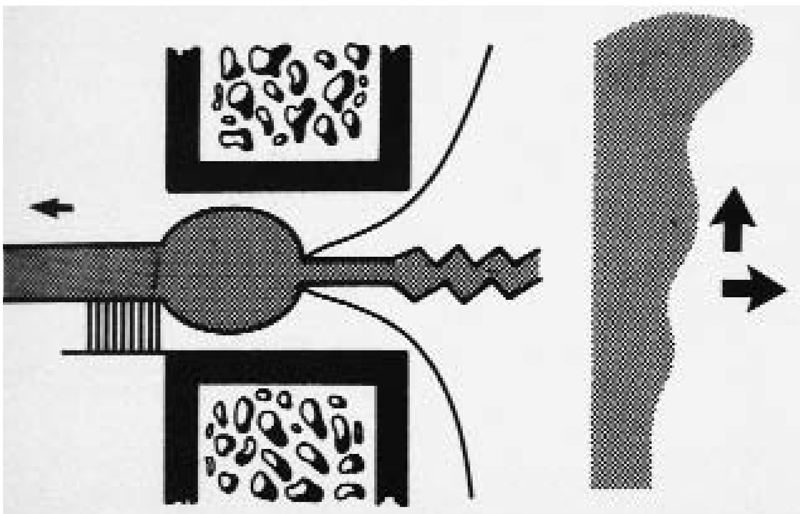

Figure 5

The 'central mechanism' of an avulsion (Sunderland 1991).

has made the number of Caesarean sections for that position in the Netherlands rise from 28.4 per cent in 1990 to 46.2 per cent in 1997. This number undoubtedly will increase inversely to the consequential lack of experience of the obstetrician.

The recent international study by Hannah et al (2000), involving 2083 women in 26 countries, confirmed that planned Caesarean section for the term fetus in breech presentation is better than planned vaginal birth, with similar maternal complications between the two groups.

Conclusion

The high number of abnormal preceding pregnancies or deliveries in the group of multiparous women suggests the risk of recurrence. Consequently, a multiparous woman with a history of mechanical problems during a previous delivery and with her current pregnancy complicated by even the suggestion of fetal macrosomia should alert the obstetrician to recurrent mechanical complications during delivery. If the fetus is in a cephalic presentation, a vaginal birth can be anticipated, although abdominal delivery should be considered if any delay develops in the first stage. On the other hand, if the fetus is in breech presentation, a primary Caesarean section seems recommendable to circumvent the markedly elevated risk for mechanical injury during vaginal birth.

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17
Examination and prognosis

Howard M Clarke and Christine G Curtis

Introduction

It is self-evident that the child with a suspected brachial plexus lesion should be examined as early as possible in order to make a definitive diagnosis, to begin recording the natural progression of recovery and to initiate education and support for the family. For example, problems such as positional torticollis can be treated effectively if early intervention, including appropriate positioning, is undertaken.

In order to illustrate our approach to these infants, the methods for and timing of examination of brachial plexus lesions in newborns, the prognosis regarding primary surgical intervention and the assessment of surgical outcomes will be discussed.

Initial evaluation

History

A careful obstetrical history should be obtained. Parents are routinely questioned about previous pregnancies and deliveries, the history of the current pregnancy including diabetes and toxaemia, the duration of labour and method of delivery. Further enquiries outline the early postnatal period including respiratory difficulties, evidence of fractures or Horner's syndrome and the extent of the paralysis seen in the first few days of life. Often the most difficult data to retrieve concern the mechanism of the delivery itself. This information is sometimes sketchy and may not be reliable in attempting to reconstruct the birth history.

The parents can, in some cases, give an extremely detailed account of the early recovery of movement in the limb. This information provides the introduction to a detailed examination of the infant.

Physical examination

Physical examination of the newborn should be thorough in order to rule out other diagnoses and determine the full extent of possible birth trauma. Observation of the position of the head, neck and arms gives useful clues to underlying pathology (Fig. 1). The sternocleidomastoid

Figure 1

The typical posture of a 6-week-old infant with a right upper trunk (Erb's) palsy. The extremity is held adducted at the side with the elbow straight. The wrist, fingers and thumb are flexed, and the infant often looks away from the affected side. (From Clarke and Curtis 1995, with permission.)

Figure 2

In a 6-month-old patient with a total plexus lesion from birth, the signs of denervation of the hand are seen with an intrinsic minus claw hand. No active extension of the fingers or thumb was seen, but flexion was full. (From Clarke and Curtis 1995, with permission.)

muscles are palpated to determine if a pseudotumour is present or if a muscle is shortened. Many have noted the tendency for infants with brachial plexopathy to turn the head away from the involved arm. If left unchecked this can lead to a contracture of the shortened sternocleidomastoid muscle and a true torticollis can develop.

Careful attention should be given to the position of the affected arm of the child. The classic position of Erb's palsy resulting from involvement of the upper roots is adduction and internal rotation of the shoulder, extension of the elbow, pronation of the forearm and flexion of the wrist and fingers. This typical posture may also occur in the absence of elbow extension since gravity holds the arm at the side of the supine infant. Total palsy is characterized by complete atonia of the extremity (Fig. 2). The fingers may rest in a flexed posture, which is the result of the tenodesis effect at the wrist rather than true power in the long flexors. Sensation may be absent, although this is difficult to test in an infant. Some arm movement may occur as a result of shoulder elevation, and this should not be confused with true shoulder joint movement. Klumpke's paralysis is extremely rare in obstetrical injuries (Al-Qattan et al 1995), but would be diagnosed when paralysis of the hand is observed in the presence of normal shoulder and elbow movement.

Palpation of the clavicles, humeri and ribs for fractures is part of a thorough examination. These fractures can produce a pseudoparalysis similar in initial presentation to a true brachial plexus lesion. Pseudoparalysis is caused by compression of the brachial plexus by the fractured bone, by swelling around the plexus, or by involuntary splinting of the arm in the presence of pain but in the absence of direct injury to the plexus itself. Characteristically, pseudoparalysis resolves more rapidly than a true obstetrical lesion of the plexus. Plain X-rays may be indicated to rule out fractures. Dislocation of the shoulder has also been associated with true obstetrical brachial plexus palsy (Stojčević-Polovina 1986, Eng 1971).

Observation of the abdomen for symmetrical diaphragmatic movement may help to indicate whether phrenic nerve paralysis has occurred. Fluoroscopy is probably the best single test to assess diaphragmatic function. Formal investigation of the position of the diaphragm should always be undertaken prior to surgery in case the patient develops respiratory difficulties following surgery, typically an increased frequency and severity of upper respiratory tract infections the next winter. A paralysed hemidiaphragm predating surgery may require plication to improve function. If the diaphragm was of normal excursion before surgery and is paralysed postoperatively, it may recover by the next winter season, sparing the child the need for plication.

The eyes are inspected for the signs of Horner's syndrome, especially in the presence of total paralysis. The four signs seen in Horner's syndrome are ptosis, myosis, enophthalmos and anhydrosis on the ipsilateral face. These findings are taken as indications of proximal injury (usually avulsion) of the lower trunk, as originally described by Klumpke in adult injuries (Klumpke 1885). She found that the Horner's resulted from avulsion of T1, which disrupts the communicating branch supplying sympathetics to the stellate ganglion.

Assessment of motor function

The most challenging aspect of the assessment of the newborn infant with paralysis of the

Table 1 Medical Research Council Muscle Grading System

Observation	*Muscle grade*
No contraction	0
Flicker or trace of contraction	1
Active movement, with gravity eliminated	2
Active movement against gravity	3
Active movement against gravity and resistance	4
Normal power	5

Data from *Aids to the Investigation of Peripheral Nerve Injuries* (British Medical Research Council 1943).

Table 2 Gilbert and Tassin Muscle Grading System

Observation	*Muscle grade*
No contraction	M0
Contraction without movement	M1
Slight or complete movement with weight eliminated	M2
Complete movement against the weight of the corresponding segment of extremity	M3

Data from Gilbert and Tassin (1987).

upper extremity is to determine a practical and reliable method for quantitating motor function. The infant cannot cooperate, the range of motor movement normally seen in young infants does not match that of the adult, and the power of even a normal infant limb is dwarfed by that of the adult examiner. In addition, we have need of an assessment tool that readily discriminates between scores that indicate the possibility for useful function and those which suggest that the function achieved by spontaneous recovery will be of little value to the child.

In 1943, the British Medical Research Council (MRC) suggested a system of recording power in patients with peripheral nerve lesions (*Aids to the Investigation of Peripheral Nerve Injuries*, 1943) (Table 1). The administration of this test was dependent on the patient understanding the nature and object of the examination. The system as originally described failed to distinguish whether active movement was through a full or partial range of motion. In current usage this test is often modified to require that full range of movement be obtained to score Grades 2 through 5.

Although some authors (Boome and Kaye 1988, Laurent and Lee 1994) utilize the MRC scale for assessment of motor power in infants with brachial plexus lesions, others have recognized the limitations of evaluating young patients with this system. Infants will only rarely use full power when being examined. Gilbert and Tassin suggested a modified British Medical Research Council classification, shown in Table 2, simplifying it to account for the difficulties of examining infants (Gilbert and Tassin 1987). M2 in this scale covers a wide range of active movements, beginning with slight movement with gravity eliminated and progressing to near full range of motion against gravity. This makes the scale difficult to use in assessing outcomes since most results typically fall in the M2 category and substantial improvements may not be documented.

Like Gilbert and Tassin, we have found it difficult to administer the MRC scale in infants, who cannot be expected to cooperate in demonstrating full voluntary power of individual muscles. In our experience, the M0–M3 scale does not accurately reflect the improvements in motor recovery seen in these children. For these reasons we have developed our own scale for assessing active movement in the upper extremities of infants and young children with brachial plexus lesions. The Active Movement Scale (Table 3) is an eight-point scale designed to capture subtle and significant

Table 3 Hospital for Sick Children Muscle Grading System

Observation	*Muscle grade*
Gravity eliminated	
No contraction	0
Contraction, no motion	1
Motion ≤ ½ range	2
Motion > ½ range	3
Full motion	4
Against gravity	
Motion ≤ ½ range	5
Motion > ½ range	6
Full motion	7

Full active range of motion with gravity eliminated (Muscle Grade 4) must be achieved before active range against gravity is scored (Muscle Grades 5–7). (From Clarke and Curtis 1995, with permission.)

changes in movement in the arm. A full score of 7 does not necessarily reflect full muscle strength, as the scale represents active movement only. To our knowledge, no reliable method of testing true muscle power or resistance in infants exists.

There are a number of advantages in using the Active Movement Scale. It can be used to grade movement in infants and young children, and does not require the child to perform tasks on command. Overall joint movements are evaluated in contrast to individual muscle testing, which may be difficult to perform in infants. Smaller changes in movement can be detected, and it can be used as a preoperative as well as postoperative evaluation tool.

We have developed the following guidelines in an effort to standardize the use of the Active Movement Scale:

1. A score of 4 must be achieved (full range of motion with gravity eliminated) before a higher score can be assigned. This clarifies scoring when limited movement is present both with gravity eliminated and against gravity;
2. Movement grades are assigned within the available range of passive motion. For example, if a flexion contracture is present at the elbow, full range of extension is scored if the elbow can be extended to the limits of the contracture;
3. Movement grades are assessed within the age-appropriate range of motion as assessed in the contralateral limb. For example, newborn infants normally do not flex the shoulder a full 90° above the horizontal. The uninvolved limb should be used as a control to estimate the extent of available normal range (Fig. 3);
4. Extension of the digits is assessed at the metacarpophalangeal joints. Flexion of the digits is evaluated by observing the distance at rest between the finger tips and the palm and then observing the active motion as a fraction of that distance both without and against gravity;
5. Digital flexion or extension is given a single grade by using the movement score of the best digit. For example, if the index finger scores a grade of 7 for flexion and the other digits score 2, then the finger flexion score is 7.

Figure 3

By presenting the same stimulus to both the normal and abnormal sides (though not of necessity simultaneously as shown here), a direct comparison can be made of the range of motion obtained. Here supination to neutral is seen on the affected right side and no finger or thumb extension. (From Clarke and Curtis 1995, with permission.)

Assessment using the Active Movement Scale is performed with the upper body and arms of the infant exposed. Ideally, the child is placed on a flat, firm surface where he can move or roll. A variety of toys to stimulate movement should be available (Fig. 4). Gravity-eliminated movements are assessed first to determine if higher scores can then be assigned. For example, to grade shoulder flexion the child is placed in the gravity-eliminated position of side-lying with the affected arm uppermost. A toy is placed within the child's view and moved in a way to attract attention. Tactile stimulation of the arm using the toy followed by movement of the toy in a forward direction draws attention to the arm and encourages flexion of the shoulder. The anterior deltoid region of the shoulder is palpated to detect flickers of movement if minimal active movement is seen. If less than full range of available passive movement is obtained compared to the normal side, then a score of 3 or lower is given. If full range of forward flexion is obtained (giving a score of 4), the child is placed in a supported sitting position to view movement against gravity. Again the child is encouraged to reach forward for an object. An against-gravity score of 5 or more is assigned

Figure 4

Bright toys with rattles and bells were used to attract the attention of this 5-month-old infant to the affected side. Stroking the forearm or hand with the toy will often elicit a motor response. (From Clarke and Curtis 1995, with permission.)

depending on the greatest range of motion observed. In this way, all joint movements are scored after observation in gravity-eliminated and against-gravity positions. Parents may also participate in encouraging movement if a child is especially anxious with strangers. With practice, all joint movements can be graded by observation of play in three positions: supine, side-lying and sitting.

Scores are given for the following joint movements: shoulder flexion, abduction, adduction, internal rotation and external rotation; elbow flexion and extension; pronation and supination of the forearm; wrist flexion and extension; finger flexion and extension; and thumb flexion and extension. These scores are recorded at the initial assessment and at 3-monthly intervals in the first year of life or until surgery intervenes. They are also used postoperatively to evaluate the results of surgery. The advantage of this system is that a small amount of movement against gravity is not sufficient to yield a high score in situations where it may be of limited functional value. The disadvantages are the time and practice required to carry out this technique successfully and the difficulty in determining the effect of gravity on such motions as finger flexion.

Curtis has demonstrated the reliability of the Active Movement Scale in a two-part study (Curtis 2000). Part A was an inter-rater reliability study in which two physiotherapists, experienced in using the scale, separately assessed 63 infants with obstetrical brachial plexus palsy. Part B examined the dispersion of Active Movement Scale scores of infants with obstetrical brachial plexus palsy as evaluated by physiotherapists with varying levels of prior experience after a single training session. Overall quadratic weighted kappa analysis in Part A demonstrated that the raters' scores were at the highest level of agreement ($K_{quad} = 0.89$). Part B established that the variability of scores due to rater factors, was low compared with patient factors, and that the variation in scores due to rater experience was minimal. The Active Movement Scale is a reliable tool for the evaluation of infants up to 1 year of age with obstetrical brachial plexus palsy when raters are trained in the use of the scale.

Another approach to the evaluation of children with brachial plexus lesions is to assess global movement of the extremity and look at patterns of movement that may be either functional or maladaptive. Such a grading scale has been established by Mallet (Mallet 1972) (Fig. 5), and is commonly used. The disadvantage of this system is that it is practicable only with children of 3–4 years of age, who can reliably perform voluntary movements on command. Recording the natural history of recovery in infant patients with this system is difficult.

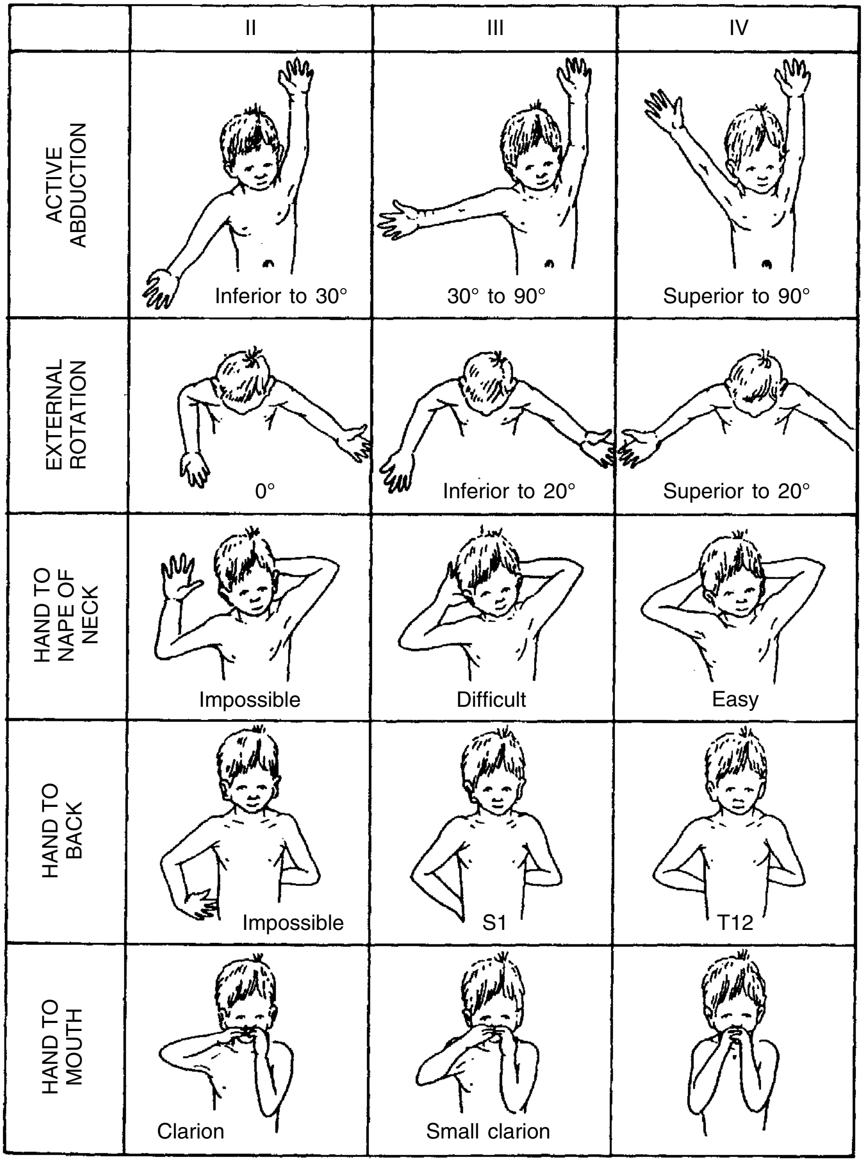

Figure 5

Mallet's classification of function in obstetrical brachial plexus palsy. Grade 0 (not shown) is no movement in the desired plane and Grade V (not shown) is full movement. (From Gilbert 1993, with permission.)

Assessment of sensory function

The assessment of sensation in infants is extremely difficult. In many cases it is only possible to determine if the child responds to painful stimuli and to examine for the signs of self-mutilation, which in children can indicate decreased sensory awareness. Narakas has classified the sensory response in infants into four grades which can be used to collect descriptive data (Narakas 1987) (Table 4). Narakas qualifies the scale by stating that the recovery of sensation is capricious and that the sensory scale may not consistently indicate the clinical progress of the lesion. Distinguishing between S1 and S2 can be difficult. In a completely paralysed limb, only the reaction to painful stimuli (S1) can be usefully evaluated.

Table 4 Narakas Sensory Grading System

Observation	*Sensory grade*
No reaction to painful or other stimuli	S0
Reaction to painful stimuli, none to touch	S1
Reaction to touch, not to light touch	S2
Apparently normal sensation	S3

(Adapted from Narakas 1987, with permission.)

Classification

The most complete anatomical classification for brachial plexus injuries includes the following categories: *upper plexus palsy (Erb's)* involving C5, C6 ± C7 (Erb 1874); *intermediate plexus palsy* involving C7 ± C8, T1 (Al-Qattan and Clarke 1994); *lower plexus palsy (Klumpke's)* involving C8, T1 (Klumpke 1885) and *total plexus palsy* involving C5, C6, C7, C8 ± T1 (Terzis et al 1986). In infants with obstetrical injuries, Gilbert found that two clinical appearances predominated in 1000 babies examined 48 hours after birth; paralysis of the upper roots and complete paralysis. Klumpke's paralysis with isolated involvement of the distal roots was not seen (Gilbert et al 1991).

Narakas has graded infants with obstetrical brachial plexus palsy based on the clinical course during the first 8 weeks of life (Narakas 1986) (Table 5). The classification is not anatomical but grades the overall severity of the lesion and implies a progressive degree of injury with increasing force applied at the time of delivery. Clinical types are assigned as follows. *Type I* is mild and heals in a few weeks. *Type II* shows an unpredictable prognosis in the first few weeks. Usually the shoulder does not recover but the elbow functions satisfactorily. Some of these patients do not recover wrist and finger extension and require tendon transfers. *Type III* involves the upper trunk, has avulsion of C7 and a stretch injury of the lower trunk. These may appear complete at birth with temporary Horner's syndrome. *Type IV* includes avulsion of C8 and T1 and persisting Horner's syndrome. Significant recovery of C5 and C6 function may occur, however. *Type V* shows severe injury involving all nerve roots. The Horner's sign is permanent, which, along with paralysis of the rhomboids, levator scapulae and serratus anterior, is a sign of a poor prognosis. Narakas classification is

Table 5 Narakas Classification of Obstetrical Brachial Plexus Palsy

	Clinical picture	*Pathology grades (Sunderland 1951)*	*Recovery*
Type I	C5–C6	1 & 2	Complete or almost in 1–8 weeks
Type II	C5–C6	Mixed 2 & 3	Elbow flexion: 1–4 weeks
			Elbow extension: 1–8 weeks
	C7	Mixed 1 & 2	Limited shoulder: 6–30 weeks
Type III	C5–C6	4 or 5	Poor shoulder: 10–40 weeks
			Elbow flexion: 16–40 weeks
	C7	2 or 3	Elbow extension: 16–20 weeks
			Wrist: 40–60 weeks
	C8–T1	1	Hand complete: 1–3 weeks
	(No Horner's sign)		
Type IV	C5–C7	4 and/or 5	Poor shoulder: 10–40 weeks
			Elbow flexion: 16–40 weeks
	C8	Mixed 2–3	Elbow extension incomplete, poor: 20–60 weeks or nil
	T1	1 and 2	Wrist: 40–60 weeks
	(Temporary Horner's sign)		Hand complete: 20–60 weeks
Type V	C5–C7	5	Shoulder and elbow as above
	C7	or avulsed	
	C8	3 or avulsed	Wrist poor or only extension: poor flexion or none
	T1	2 and 3	
	C8–T1	Avulsed	Very poor hand with no or weak
	(Horner's sign usually present)		flexors and extensors; no intrinsics

(From Narakas 1986, with permission.)

extremely valuable in providing clues to prognosis in the first 2 months of life. A further study using statistical methods to verify these prognostic factors would be highly informative.

Prognosis for recovery

Although many infants with plexopathy recover with minor or no residual functional deficits, a number of children do not regain sufficient limb function and subsequently develop functional limitations, bony deformities and joint contractures. In a thorough study by Bager, half of 52 consecutive patients had normalized hand function on clinical assessment at 6 months of age but half had identifiable residual impairments at 15 months of age (Bager 1997). Furthermore, Bellew et al have found that children with brachial plexus palsy, regardless of severity, showed more behavioural problems than normative data would suggest (Bellew et al 2000). The children with more severe palsies had even more behavioural problems and scored less well on developmental assessment. Determining which infants may develop such sequelae is of obvious importance in planning therapy.

Opinion varies widely on the spontaneous recovery of children with obstetrical brachial plexus palsy. Nonetheless, the majority of patients do well and do not require primary surgical intervention (Greenwald et al 1984, Jackson et al 1988, Piatt 1991, Michelow et al 1994). The lack of a uniform system for comparing outcome makes comparison of published studies difficult.

While all of the factors discussed above provide useful insights, our real need is to understand the natural history of this condition sufficiently to predict, at a few months of age, the probable outcome and the need for surgery. Ultimately, a large series of patients studied in a statistically sound manner will be necessary to provide secure points of reference. In our own attempt to understand these factors we have reviewed the records of the Brachial Plexus Clinic at the Hospital for Sick Children (Michelow et al 1994). Included were 28 patients (42 per cent) with upper plexus involvement and 38 (58 per cent) with total plexopathy. Sixty-one patients (92 per cent) recovered spontaneously and five patients (8 per cent)

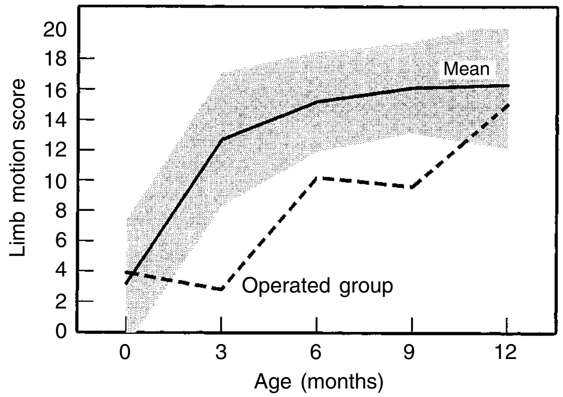

Figure 6

The natural history of obstetrical brachial plexus palsy as evaluated by Limb Motion Scores is depicted (solid line) for patients recovering spontaneously in their first year of life ($n = 66$). The shaded area represents ± 1 SD of variation from the mean score. Early improvement in limb movement is seen in patients who recovered spontaneously. The mean score for the operated patients has been plotted separately (dashed line) and shows a slower, less remarkable improvement. (From Michelow et al 1994, with permission.)

required primary brachial plexus exploration and reconstruction. Observations of shoulder abduction and adduction, as well as flexion and extension at the elbow, wrist, thumb and fingers, were recorded at or close to 3, 6, 9 and 12 months of age. A record of the natural history of obstetrical brachial plexus palsy from birth to 12 months of age was generated (Fig. 6). Inspection of the graph demonstrated an early improvement in limb movement in the patients who recovered spontaneously in contrast to patients with severe plexopathy requiring surgery.

Adapting the classification of Narakas, poor recovery was defined as elbow flexion of half or less than half the normal range and shoulder abduction of less than half the normal range (Narakas 1985). Recovery was otherwise considered to be good. Each patient was then classified into either a good recovery group or poor recovery group, based on their scores at 12 months of age. The assignment was made based on spontaneous recovery alone and not on whether surgery was undertaken.

Stepwise discriminant analysis (SAS: PROC STEPDISC with stepwise option (*SAS User's Guide: Statistics* 1985)) was used to study which

Table 6 Individual discriminants of recovery

Parameter	*p*
Elbow flexion	0.0004*
Elbow extension	0.018*
Wrist extension	0.0042*
Thumb extension	0.023*
Finger extension	0.0069†

*$n = 39$, †$n = 38$. (From Michelow et al 1994, with permission.)

Table 7 Discriminants of recovery

Parameter	*Rate of incorrect prediction (%)*
Elbow flexion (3 months)	12.8*
Elbow flexion (3 months) + finger flexion (birth)	7.1*
Elbow flexion + finger extension (3 months)	5.2†
Elbow flexion + elbow, wrist, thumb and finger extension (3 months)	5.2†

*$n = 39$, †$n = 38$. (From Michelow et al 1994, with permission.)

parameters at birth and 3 months were useful predictors of the two recovery groups at 12 months. The significant parameters were then analyzed using discriminant analysis (SAS: PROC DISCRIM (*SAS User's Guide: Statistics* 1985)).

The analysis demonstrated that a number of parameters were highly significant in their ability at 3 months to predict subsequent recovery at 12 months (Table 6). Elbow flexion at 3 months incorrectly predicted recovery in 12.8 per cent of cases (Table 7, Fig. 7). When appropriate parameters were combined, particularly elbow flexion with elbow, wrist, thumb and finger extension; recovery was incorrectly predicted in only 5.2 per cent of cases (Table 7, Fig. 8).

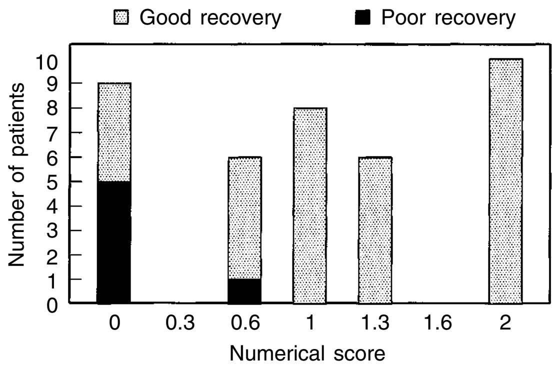

Figure 7

All patients, irrespective of whether primary plexus surgery was or was not performed, were classified into good and poor recovery groups based on their elbow flexion and shoulder abduction at 12 months of age ($n = 39$). The groups were then evaluated retrospectively with respect to elbow flexion at 3 months. A score of 0 at 3 months was seen with almost equal frequency in both groups indicating the poor discriminating ability of elbow flexion as a predictor. (From Michelow et al 1994, with permission.)

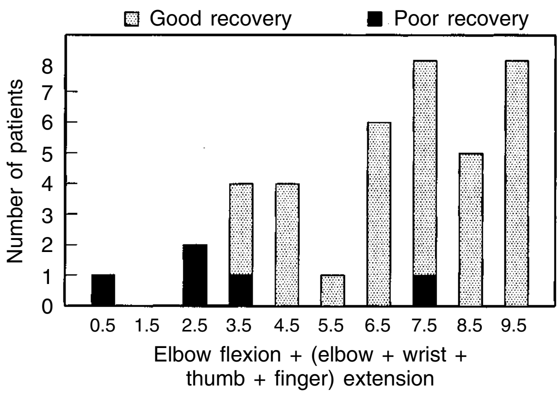

Figure 8

Based on elbow flexion and shoulder abduction scores at 12 months of age, patients were classified into good and poor recovery groups ($n = 38$). The Test Score of elbow flexion plus elbow, wrist, thumb and finger extension at 3 months is shown. A score of 3.5 out of 10 was the watershed between the groups. All patients with scores below 3.5 were in the poor recovery group and all patients in the good recovery group scored 3.5 or better. (From Michelow et al 1994, with permission.)

Indications for surgery

Many authors agree that attempts to avoid permanent sequelae necessitate intervention early in the first year of life in appropriate cases (Terzis et al 1986, Kawabata et al 1987, Alanen et al 1990). Is it possible, therefore, to predict by 3 months of age whether or not a child will spontaneously recover sufficiently to avoid unnecessary primary plexus surgery? While clinical examination is the best single method for determining the need for surgery (Yılmaz et al 1999), what does the examiner evaluate?

Gilbert and Tassin relied on spontaneous recovery of the biceps as the indication for surgery (Gilbert and Tassin 1984). If the recovery of the biceps had not begun at 3 months of age, the functional prognosis was poor and surgical repair of the plexus was warranted. More specifically, they suggested that surgery was indicated when there was a total palsy with a flail arm after 1 month and Horner's syndrome, when infants with complete C5–C6 palsy after breech delivery showed no signs of recovery by the third month, and when biceps was completely absent by the third month in infants with C5–C6 palsies. Because of the necessities of scheduling and for safety of anesthesia, surgery is performed in the third month (Gilbert et al 1988). These guidelines are widely used in many centres and are probably the most common indications in current use.

Narakas divided patients into three groups (Narakas 1985). Those patients who started recovering within 3 weeks would recover completely and would not require surgical measures. Patients who started to recover after the third week and continued to improve would often require secondary surgical procedures. Finally, those patients who did not start to recover after the second month of life would do poorly and were explored as soon as possible.

In the Waters' series, 66 patients followed from less than 3 months of age were divided into groups depending on the month of life in which biceps strength recovered (Waters 1999). In this carefully performed study, analysis of variance was used to demonstrate statistically that the earlier the biceps recovers, the better the final result for the patient. He concluded that patients with total lesions at 3 months of age (flail arm plus Horner's syndrome) and patients who had no recovery of the biceps muscle by 5 months of age should be offered surgery.

Some authors (Berger et al 1997, Grossman et al 1997, Chuang et al 1998, McGuiness and Kay 1999, Yılmaz et al 1999, Basheer et al 2000) feel, however, that the evaluation of elbow flexion alone is not sufficient to distinguish all patients who are suitable candidates for surgery. It has been our experience that a number of patients with absent elbow flexion at 3 months of age improved sufficiently by 9 months of age to obtain functionally useful elbow flexion of greater than half range against gravity (Michelow et al 1994), Grade 6 or 7 on the Active Movement Scale. Indeed, almost half of the patients in our natural history study with no elbow flexion at 3 months of age went on to have good extremity function according to Narakas' criteria (Narakas 1985) (Fig. 7).

Using the data from the natural history study outlined above (Michelow et al 1994), a Test Score was developed to determine the likelihood of a good outcome without surgery. The Test Score developed was based on a grading system that has since been supplanted in our clinic by the Active Movement Scale. In order to convert current scores on the Active Movement Scale (Table 3) to former numerical scores for testing purposes a conversion system is used (Table 8). A Test Score (x, range 0–10) can then be assigned to any patient at 3 months of age by summing the former numerical score (range 0–2) for the clinical grade for the following joint motions:

$$x = \text{elbow flexion} + \text{elbow extension} + \text{wrist extension} + \text{thumb extension} + \text{finger extension}$$

The linear discriminant function for this Test Score was:

$$y = 3.3 - 0.94x$$

If $y < 0$, good recovery is predicted. If $y \geq 0$, a poor outcome is expected. Solving the equation for $y = 0$ suggests a good outcome for cases with $x > 3.5$.

In practice, at 3 months of age the Muscle Grade (Table 3) of five selected joint movements (elbow flexion and elbow, wrist, thumb and

Table 8 Conversion from Current Muscle Grading System to Former Numerical Scores*

Current Muscle Grade	*Former Numerical Score*
0	0
1	0.3
2	0.3
3	0.6
4	0.6
5	0.6
6	1.3
7	2.0

*These conversions were required to utilize the previously published Test Score. (From Clarke and Curtis 1995, with permission.)

finger extension) are converted into numerical scores (Table 8). The five numerical scores are added to give a Test Score out of 10. Infants with a Test Score of ≤ 3.5 are booked for surgical exploration of the brachial plexus. If the Test Score is > 3.5, the infant continues to be followed in the clinic. Clearly the conversion of scales makes this evaluation method cumbersome. A new analysis of data obtained using the current Active Movement Scale is underway.

The above system is useful in identifying patients with total palsy who require early surgery. Supporting evidence indicating surgery in some total palsy patients can be deduced from the fact that none of the patients with Horner's syndrome in our series of 48 total plexus palsy patients went on to satisfactory spontaneous recovery (Al-Qattan et al 2000).

Some patients with upper trunk lesions who show good early recovery and have Test Scores > 3.5 may still not develop adequate elbow flexion by the end of the first year of life and may have poor shoulder function. Our present technique for selecting these patients for surgery is to continue to monitor the Active Movement Scores and if, at the age of 9 months, elbow flexion is less than Grade 6 (less than half range of motion against gravity), surgical exploration is offered.

To assess elbow flexion at 9 months of age we use what we have called the 'Cookie Test'. This test is performed with the child in a comfortable, sitting play situation. With the child's uninvolved hand occupied with a toy, the tester gently restrains the involved arm in a position of adduction against the child's trunk. The arm is restrained in this way to limit the compensatory shoulder abduction and internal rotation that children with upper root lesions characteristically use to bring the hand to the mouth (the trumpet sign). One half of an Arrowroot cookie is then offered to the involved hand and the child is encouraged to put it to the mouth. The cookie should be small to encourage full flexion of the elbow. The child passes the test, and is rejected as a surgical candidate, if the cookie is taken to the mouth by elbow flexion against gravity and with less than 45° of neck flexion (Fig. 9). If the cookie does not reach the mouth, or if marked flexion of the neck is required to reach the cookie, the child fails the test and surgery is considered (Fig. 10).

Figure 9

The 'Cookie Test' is administered with the child sitting comfortably. The elbow of the affected side is held gently at the side of the body and the child is encouraged to put the cookie to the mouth. If less than 45° of neck flexion is required in addition to active elbow flexion to get the cookie to the mouth, the test is passed. In this case the 9-month-old child passes the test and primary surgery to the plexus is not necessary. (From Clarke and Curtis 1995, with permission.)

Many of the concepts presented above are summarized in the treatment algorithm proposed by Berger et al. (1997). Total plexus lesions are recognized and operated upon early, but moderate lesions may be followed at multiple visits before a final evaluation of ongoing recovery is made.

In our clinic at the Hospital for Sick Children we use the Test Score at 3 months of age to

Figure 10

In this 9-month-old infant elbow flexion against gravity was limited although full flexion with gravity eliminated was present. The cookie did not even approach the mouth leaving the child visibly upset. The Cookie Test was failed and surgery was recommended. (From Clarke and Curtis 1995, with permission.)

select patients with severe and usually total plexus lesions for primary surgery. The unequivocal presence of Horner's syndrome is an absolute indication for surgery. The Cookie Test of elbow flexion is used at 9 months of age to distinguish additional patients, usually with upper trunk lesions, who have not recovered sufficiently and require surgery. The selected patients are offered surgical intervention at the earliest available opportunity once the decision to operate has been made.

Assessment of surgical results

Narakas originally believed there was no adequate classification to demonstrate the results of brachial plexus reconstruction because of the complexity of the lesions and of the repair (Narakas 1985). Nonetheless Narakas did provide us with some practical categories (Narakas 1985) (Table 9) as follows: *Good* results demonstrated abduction and flexion of the shoulder to 90°; external rotation to at least neutral; elbow flexion of 120° with MRC Grade 4 or better; elbow extension lag of not more than 20° with MRC Grade 3 or better; extension of the wrist to at least neutral; flexion of the wrist with MRC Grade 3 or better and a hand that could grasp an object the size of an egg and appreciate at least light touch. Fair results showed abduction of the shoulder to 50°–85°; external rotation with the elbow flexed and the forearm against the chest to at least 30°; elbow flexion to 90°–115° with a MRC Grade 3 or

Table 9 Narakas' Grading System for outcome in obstetrical brachial plexus palsy

	Good		*Fair*	
	Range	*MRC*	*Range*	*MRC*
Shoulder abduction and flexion	90°		50°–85°	
Shoulder external rotation	≥ Neutral		≥ 30°	
Elbow flexion	120°	≥ 4	90°–115°	≥ 3
Elbow extension	Lag ≤ 20°	≥ 3	Lag 35°–50°	
Wrist flexion		≥ 3		
Wrist extension	Neutral			
Hand	Grasp egg, light touch		Weak grasp, protective sensation	

MRC = Medical Research Council Muscle Grade (Table 1). Poor and nil were considered self-explanatory. (Data from Narakas 1985, with permission.)

Table 10 Raimondi's Grading System for outcome of hand function in obstetrical brachial plexus palsy

Observation	*Hand Grade*
Complete paralysis or slight finger flexion of no use; useless thumb with no pinch – no or some sensation	0
Limited active flexion of fingers; no extension of wrist or fingers; possible lateral pinch of thumb; supinated forearm	I
Active extension of wrist gives passive flexion of fingers (by tenodesis); passive lateral pinch of thumb; pronated forearm	II
Complete active flexion of wrist and fingers; mobile thumb with partial abduction and opposition; some intrinsic balance; no active supination – good sensation – good possibilities for secondary surgery	III
Complete active flexion of wrist and fingers; active wrist extension; weak or absent finger extension; good thumb opposition with active intrinsics; partial active pronation and supination	IV
Grade IV plus active finger extension and near complete pronation and supination	V

Hand Grades of III or better are considered to be useful functional outcomes. (From Clarke and Curtis 1995, with permission.)

better; a passive or active extension lag at the elbow of 35°–50°; a hand with a weak grip with some fingers capable of holding a light object and protective sensation at least in the median nerve territory. *Poor* results failed to achieve the above criteria. *Nil* results were self-evident.

A detailed, updated classification system for the assessment of hand function in operated patients with obstetrical lesions has been proposed by Raimondi (Clarke and Curtis 1995) (Table 10). This scale incorporates evaluation of both sensation and movement and attempts to distinguish useful from functionless results. The grading system has been simplified to make it easier to use. This system addresses the functional deficits seen in these patients. Grade III and above are considered useful outcomes.

We feel that two considerations are important in evaluating patients following primary surgery to the brachial plexus. The first is that the same system of recording should be applied both before and after surgery to allow direct comparison of paired data and facilitate statistical analysis. Secondly, it would be extremely valuable if all centers engaged in this surgery could form a consensus grading scale to be validated in a multi-center inter-rater reliability study. Our current approach to the evaluation of surgical results at the Hospital for Sick Children is to use the Active Movement Scale (Table 3) because it is reliable, readily used both in infants and young children, and allows statistical analysis of both the natural history and the results of surgical intervention.

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18
Conservative treatment of obstetrical brachial plexus palsy (OBPP) and rehabilitation

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Introduction

It is essential to be aware of the natural history of OBPP and the possible sequelae of this birth injury in order to be able to consider which kind of treatment is most opportune. Conservative treatment and surgery, whether a primary neurosurgical reconstruction or secondary surgery, should not be regarded as alternatives, but rather as complementary. Everyone involved in the conservative treatment of OBPP should, therefore, also be aware of the surgical indications. Knowledge of the natural history and possibilities of conservative treatment of OBPP can help with selecting those patients who will benefit from primary neurosurgical reconstruction or secondary surgery. It is not realistic to talk about conservative treatment of OBPP without also considering when neurosurgery and secondary surgery may be required.

Natural history

There is a real need to understand the natural history of OBPP in order to be able to predict the probable outcome and the need for surgery at an early stage. Naturally the parents of a baby with OBPP, having been confronted with an unexpected complication during the delivery of their child, are longing for information regarding the prognosis. It is, however, not possible to predict with complete certainty the ultimate consequences of this injury immediately after diagnosis.

A large number of children with OBPP experience a degree of paralysis in the affected arm for only a few days. Some have complete paralysis of the whole arm, but show rapid recovery of the distal muscles. If there is persistent complete paralysis 6 weeks after birth, the prognosis will be poor. External rotation of the shoulder and supination in the lower arm usually recover relatively late. Wrist and finger extension are often more troublesome than flexion. Eventually, some degree of biceps function will always develop. It is remarkable that despite poor hand function, good recovery of the sensation in the hand can occur. Return of motor function can continue until 2½ years of age, and sensory function beyond 3 years.

Eng et al (1996) performed electrodiagnostic studies which showed that reinnervation of the biceps occurs by 4–6 months of age, but active elbow flexion may not be apparent until 3–4 weeks later; forearm muscle reinnervation occurs at 7–8 months of age, and reinnervation of the hand muscles by 12–14 months. The value of EMG findings in predicting the recovery of OBPP can be considered dubious.

Gilbert et al (1988) noted that, throughout the last century, a question frequently posed by neurologists and surgeons was: ‘does the recovery of an Obstetrical Brachial Plexus Palsy (OBPP), which always exists but may well be incomplete, justify additional treatment, surgical or otherwise?’ Specht (1975) performed an extensive literature search concerning the prognosis of brachial plexus palsy in the newborn. He found that opinions varied from: ‘in the vast majority of infants the recovery of function begins within several days and paralysis clears promptly', to 'spontaneous recovery occurs to some degree in more than half the patients with paresis of the upper part of the plexus and is complete in only about 10 per cent'. Furthermore, he noted that, in general, neurologists, neurosurgeons and paediatricians were more optimistic than orthopaedic surgeons, who indicated a significantly higher incidence of incomplete recovery, possibly because the latter see these patients later because of the sequelae of OBPP. Another reason for this variation in opinions concerning the prognosis of OBPP could be that the term 'complete recovery' is poorly defined (Hoeksma et al 2000).

If complete recovery is defined as a child with OBPP who regains normal muscle strength together with normal sensation, Hoeksma found a complete recovery rate of 72.6 per cent. Different percentages may be found if complete recovery is defined in more functional terms, since remaining paresis may be accompanied by satisfactory function of the upper extremity. It might be expected that, if the classification of Narakas (1993) were followed, a much higher recovery rate score would be achieved: a 'poor outcome' by Narakas was defined as elbow flexion of 50 per cent or less of the normal range, and shoulder abduction of less than 50 per cent of the normal range. Otherwise the recovery, according to Narakas, was considered to be 'good'.

The conclusion must be that, due to the absence of a uniform assessment method and the fact that the groups of children with OBPP that have been followed-up are far from uniform, the results between the different outcomes cannot really be compared. This reinforces the view that the prediction of outcome is very difficult.

Neurosurgery

There have always been disputes about the effectiveness of neurosurgery on OBPP because, in the natural history of the condition, even the most severe lesions will show some degree of recovery. It also seems that recovery of active elbow flexion and of a certain degree of sensation is the rule. Kennedy (1903) reported the first surgical procedure for treating a brachial plexus injury. At that time, the results of this surgery were poor. Contrary to the general opinion nowadays, in 1955 Wickstrom et al stated that a neurosurgical reconstruction did not provide better results than non-operative treatment.

In his thesis, Tassin (1983) reviewed the records of 44 children who were not operated upon. His findings included the following:

1. When biceps and deltoid muscles began their recovery before 2 months of age, the result was a normal or nearly normal shoulder;
2. When biceps or deltoid muscle began to recover before the third month, the end result was good;
3. When biceps and deltoid muscles began their recovery after 3 months of age, the end result was average or poor.

Because of Tassin's findings, Gilbert et al (1988) started to explore the brachial plexus in every child with OBPP who did not have any biceps function by the age of 3 months. The biceps was considered to be the 'key muscle' because of the relation found between the time that the biceps showed clinical signs of reinnervation and the expected degree of recovery of shoulder function in particular.

Clarke and Curtis (1995) followed up 66 patients with OBPP, and found that 61 patients (92 per cent) recovered spontaneously and five patients (8 per cent) required primary exploration and reconstruction. It appeared that elbow flexion at 3 months incorrectly predicted recovery in 12.8 per cent of cases. When appropriate parameters (biceps together with triceps, wrist extension, finger extension) were combined, recovery was predicted incorrectly in only 5.2 per cent of cases.

Strömbeck et al (2000) studied functional outcome at the age of 5 years in 247 patients with OBPP. They compared the outcome in children with an upper lesion (C5–C6 and C5–C7) who had no early recovery, i.e. exhibited no muscle activity in their biceps or deltoid muscles at 3 months of age. It was found that shoulder function in C5–C6 palsies was significantly better in the operated group, but as far as other parameters were concerned there were no differences between the operated and non-operated group.

This difference was not statistically significant in the C5–C7 group.

These findings are in accordance with earlier reports by Gilbert and Tassin. In this series a substantial number of the non-operated patients showed good late recovery, and thus the writers suggest postponing the decision to operate in the C5–C7 lesion. It is remarkable that in the C5–C6 lesion group, decrease in grip strength and bimanual function was found. In this series, total lesions were generally treated early.

Basheer et al (2000) concluded in their study of 52 patients that the upper limb function gradually improved until the sixth month, after which there was no significant recovery. Although 90 per cent of the patients achieved their final score at the sixth month, there was no significant improvement between the third and sixth months. This result supports Gilbert's policy of performing early surgery at 3 months, rather than that of Zancolli and Zancolli (1988) who found that 75 per cent of their patients started recovering after the fifth month.

In his study of 66 patients with OBPP, Waters (1999) found that the results in the six patients with neurosurgical reconstruction were significantly better than of those in the 15 patients who were not operated on and had a biceps function recovery at the age of 5 months. The results in these six patients, however, were no better if they were compared with the results of the 11 patients in whom the biceps recovered at the age of 4 months.

This study confirms Gilbert's observation that it is very rare for children to have complete recovery if the biceps function returns after 3 months. There is, despite all these findings, no consensus concerning the indications for neurosurgery in OBPP. If the indication for neurosurgery, according to Gilbert's criteria, was reached on the basis of no biceps function at the age of 3 months, 39 of the 66 patients in Waters' study would have been operated, not just six.

Although there are no comparative outcome data concerning children who were treated neurosurgically and children who underwent conservative treatment, we agree with Birch et al (1998) that, in general, a child with severe damage to the brachial plexus will not be worse off if neurosurgical reconstruction is performed. There are some strong arguments in favour of neurosurgical treatment. Birch et al (1998) stated that: the palliative procedures of deformities secondary to the neurolesions are deeply unsatisfactory and the results of musculotendinous transfers in OBPP are far inferior to those following good nerve regeneration and on the whole they are inferior to those obtained for the treatment of poliomyelitis or simple peripheral nerve injuries. Reasons include: widespread weakness of muscle, which is at times not fully appreciated, inadequate cutaneous sensation and proprioception and later skeletal deformities'. Gilbert et al (1988) stated that: 'It is an advantage of operated cases that their musculotendon transfers are made possible by the larger recovery of shoulder muscles and the absence in most cases of the typical cocontractions that occur with spontaneous recovery. In most cases, therefore, the end result after surgical treatment will be better than spontaneous recovery. This surgical treatment includes the initial plexus repair and the subsequent operations: joint release and muscle tendon transfers, which need to be done at an early age'.

There is no doubt about the positive results of neurosurgery in selected cases of children with OBPP. There is, however, still no consensus, especially about when neurosurgical reconstruction should be performed.

The Brachial Plexus Work Group in Heerlen, The Netherlands, developed a flowchart as a general guideline on how and when to act if a child is born with a brachial plexus lesion (see Appendix 1). Of course not everyone will agree with the policy as described in this flowchart, but until there is a consensus it is important to have consistency in indications for intervention, to have an accepted and standardized method of assessment for evaluation and, if necessary, to adapt the indication parameters.

Conservative management

Range of motion (ROM) exercises should begin immediately to prevent the otherwise rapid development of contractures at the shoulder, elbow and wrist while waiting for the brachial plexus to recover. It should be remembered that the extent of the paralysis will sometimes regress, especially in the distal muscles of the affected arm. This does not exclude the possibility of a severe lesion in the upper roots.

Exercises must therefore be performed frequently, and should be aimed at maintaining full passive external rotation of the shoulder with the arms in adduction. To achieve this, both upper limbs must be exercised together. Attention should also be paid to maintaining the inferior and posterior scapulo-humeral angle. We, together with Birch et al (1998), believe that parents must be involved in the treatment of the child from the outset. The best physiotherapist is the mother or father. There is no scientific proof of the effectiveness of physical therapy in the prevention of joint contractures; however, we nevertheless believe that many fixed deformities can be prevented if the parents perform the appropriate exercises regularly during the day (for example, after every meal, after changing nappies etc) instead of waiting for the physiotherapist to come three times per week. On the other hand, severe fixed endorotation–adduction contractures have been seen in the shoulders of children whose parents faithfully performed the exercises as instructed.

It is believed that the development of shoulder contracture is due to motor imbalance and is dependent on the degree of neurological injury. Manipulation of the shoulder joint is probably not enough to prevent contractures completely if motor recovery in the deltoid and external rotators is insufficient to balance the internal rotators.

Posterior dislocation of the radial head with a gradual curving of the ulna can develop from the fourth month of age (Eng et al 1996). Forced supination of the pronated forearm may aggravate radial dislocation, and this radial head dislocation may be responsible for a progressive flexion contracture of the elbow. Since the biceps and brachialis at that age are often still paralysed, these muscles cannot be the cause of this contracture. Whenever there is a progressive flexion contracture of the elbow, splinting is recommended. Excellent results have been achieved with serial casting, provided this treatment is started in time. Splinting has otherwise generally been condemned, although some recommend the use of functional bracing in children, stating that it may be helpful in encouraging early hand use.

Although splinting is generally regarded as obsolete, Eng et al (1996) reported that all except mild cases were treated with a wrist/hand cock-up splint with the thumb in opposition. Later, a static elbow extension or dynamic elbow flexion or extension and supination splints were used as indicated. We recommend that redressing splints only be used at night. Usually this involves cock-up wrist splints, that also correct ulnar deviation in the wrist. If there is a weak extension of the wrist causing a ‘dropping hand’ and preventing the child from grasping, it is recommended that a cock-up splint only be used for a few hours during the day; we believe that this type of splint interferes with the sensation of the hand, and this could discourage the child from using the affected hand. Moreover, a cock-up splint may prevent the strength of the wrist extensors developing.

There is frequently a lack of active supination, and it seems that the biceps must reach normal strength before supination can be successfully accomplished. To perform supination of the elbow in extension, the supinator muscle itself must be strong or at least of normal strength (Eng et al 1996).

The thumb tends to become tight in flexion and adduction, and if this occurs the child can benefit from a nightly redressing splint, because a ‘thumb in palm deformation’ will limit hand function considerably.

The rate of recovery in OBPP can be very slow. It is therefore imperative to keep monitoring and if necessary treating the child during this period. Depending on the age of the child and the sequelae of the OBPP, the therapy should be adapted. As soon as the child is able to participate actively during therapy this should be encouraged. Passive exercises should only be performed if some functions, such as lateral/medial rotation of the shoulder or supination/pronation in the lower arm, are absent; however, even in this case the child should be stimulated to use the affected arm/hand for that particular function. The healthy unaffected arm can be used to support the affected side in performing active exercises: the child holds a stick with both hands supinated and the arms adducted, then the unaffected arm rotates externally and pulls the affected arm in medial rotation. When the unaffected arm is put in medial rotation, the affected arm is pushed into external rotation. Rotational exercises for the lower arm can be done in the same way. Special care should be taken when training the child to be independent as far as activities of daily life are concerned. Even if, for example, medial rotation is limited and doing up buttons is troublesome, the child should be encouraged to do it without too much support from the parents. Sporting activities such as swimming should be encouraged at a young age. It is, however, our experience that even with optimal conservative management some sequelae of the OBPP cannot be prevented. There is almost always some degree of scapular winging, lateralization of function to the unaffected other side, and some shortening of the affected side – the percentage of the shortening being dependent on the severity of the lesion.

Chuang et al (1998a) states that cross-innervation in the neuroma formation of the damaged nerves, muscular imbalance and growth are the three main causes of shoulder deformity in OBPP. Cross-innervation causes co-contractions of synergistic and antagonistic muscle groups. Muscular imbalance and co-contraction will lead to muscular contractures, which again are the main cause of development of shoulder and elbow deformities. Investigations are currently in progress regarding the use of botulinum toxin in children with cerebral palsy, and perhaps it will be possible in the future to use botulinum in children with OBPP and troublesome co-contractions. Berger and his colleagues in Hannover have started a trial with botulinum and have concluded in a very limited series that it might be an effective tool (Rollnick et al 2000).

Children with an OBPP are sometimes seen who hardly involve their affected hand in performing activities, despite the fact that doctors are convinced that there are no longer any serious neurological deficits. This kind of 'agnosia' should be related to initial disturbances in sensation and to a lack of creation of 'cerebral circuits' at a very early stage of life. Investigations are under way to see whether EMG-triggered myofeedback has an influence on these problems.

Sequelae of OBPP

Shoulder

The shoulder is by far the most frequently affected joint in OBPP. The medial rotation contracture with all its complications for the glenohumeral joint, is most common. Stimson first described a posterior dislocation of the shoulder in OBPP in 1888.

Fairbank (1913) expected that all children with OBPP with incomplete neurological recovery would develop a shoulder deformity, and suggested that this is in fact the only hindrance to complete recovery. Fairbank considered muscular imbalance to be the main cause of the posterior subluxation in the shoulder because he found it remarkable that no luxation was seen in complete paralysis.

L'Episcopo (1934) found that the disability resulting from obstetrical paralysis of the upper arm type is essentially due to internal rotation deformity of the humerus, which is a very poor functional position. The patient is unable to perform the necessary movements required when eating, combing the hair, putting on a collar and tie, dressing etc.

Green and Tachdjian (1963) reviewed all their OBPP cases between 1943 and 1961, and found the following to be the most common residual deformities requiring surgery:

- Fixed internal rotation deformity of the shoulder;
- Limited abduction of the shoulder and contractures of the adductors;
- An elongated coracoid;
- An elongated and downwards hooked acromion;
- Dislocation of the head of the radius.

Dunkerton (1989) noticed a loss of passive exorotation beyond neutral to be the main clinical symptom of a posterior dislocation. Troum et al (1993) considered that in young children (under 6 months of age) with a fixed medial adduction contracture, the birth trauma that caused the OBPP also causes the dislocation. It is indeed hard to imagine that a muscular imbalance at this age can lead to dislocation of the shoulder.

Birch and Chen (1996) reported that of 108 children requiring surgery because of severe limitation in passive external rotation of the shoulder, 45 had an uncomplicated medial rotation contracture, 56 had a posterior subluxation or dislocation of the head of the humerus, and seven had a dislocation complicated by overgrowth of the corocoid and acromion. In three cases, dislocation occurred at birth. In five biopsies of the subscapularis muscle, changes were seen that were consistent with post-ischaemic fibrosis. In all other cases progressive deformity was caused by muscular imbalance – the subscapularis and other medial rotators innervated by C7, C8 and T1 being unopposed by the lateral rotators innervated by C5.

Torode and Donnan (1998) calculated that the incidence of posterior luxation in OBPP is about 40 per cent.

Pearl and Edgerton (1998) found three consistent patterns of shoulder deformity in children with an apparently incomplete recovery of an OBPP:

1. Flattening of the glenoid;
2. A biconcave glenoid;
3. A pseudoglenoid with a posterior concavity distinct and separated from the remaining original articular surface.

All patients with a glenoid deformity had a passive lateral rotation of less than –10°. However, not every glenoid appeared deformed, even if there was a lateral rotation limitation. Both Zancolli and Zancolli (1988) and Pearl and Edgerton (1998) found that 28 per cent of patients had a normal glenoid despite having a fixed internal rotation contracture. Nonetheless, it is obvious that an internal rotation contracture secondary to OBPP has a high likelihood of being associated with glenoid deformity.

Birch et al (1998) produced a very useful classification of shoulder deformities in OBPP, describing four types with increasing severity caused by a medial rotation contracture:

1. The medial rotation contracture: the only abnormality is restriction of passive lateral rotation, which is diminished by 30–40°. Overgrowth of the coracoid was also described as an interesting cause of medial rotation contracture;
2. Posterior subluxation (simple): passive lateral rotation is restricted to about 10°. There is as yet no secondary deformity of the acromion, the coracoid or the glenoid;
3. Posterior dislocation (simple): the head of the humerus can be seen and palpated behind the glenoid. It may be possible to click the humeral head in and out of the glenoid. X-rays confirm displacement, and there is a characteristic windswept or curved appearance of the proximal humerus;
4. Complex subluxation/dislocation: in this final stage, marked skeletal abnormalities are apparent on clinical and radiological examination. These patients have pain, there is fixed flexion at the elbow with pronation of the forearm, and the compensatory thoracoscapular movement seen in many young children has disappeared.

Three skeletal abnormalities are significant:

1. An elongated coracoid;
2. An elongated and downwards hooked acromion;
3. A bifacetal appearance in the glenoid. The true glenoid lies above and anterior; the false glenoid lies below and posterior. In complex subluxation the articulation is between the head of the humerus and the false glenoid. In complex dislocation the articulation is between the lesser tuberosity and the false glenoid.

Hoeksma et al (2000) found that shoulder contracture occurred in at least one-third of the children with delayed recovery and at least two-thirds of the children with incomplete recovery. Delayed recovery was defined as recovery that took more than 3 weeks; complete recovery was defined as complete neurological recovery with normal muscle strength in all muscle groups together with normal sensibility. Even in the group with complete neurological recovery but a delayed recovery of more than 3 weeks, about 30 per cent developed a shoulder contracture. In the group of incomplete neurological recovery, the frequency of shoulder contracture was as high as 65 per cent.

Shoulder surgery

Sever stated as early as 1918 that if there is a fixed medial rotation contracture, conservative therapy is useless. He suggested a tenotomy of the pectoralis major and subscapularis. Gilbert et al (1991) advised that if external rotation drops progressively to below 20°, therapy is no longer efficacious. It is therefore appropriate to deliberate for some time on the surgical aspects of a fixed medial contracture when it appears that conservative management is unable to prevent this deformity, and we will concentrate here on such surgery. For all other shoulder surgery in OBPP, the reader is referred to the appropriate chapter of this book.

It is sometimes difficult to persuade physiotherapists and doctors who are treating children with an OBPP to allow them to undergo surgery, and the argument is often used that there is no need for an operation because the child does not show or complain of any disabilities and is still improving. This argument of the absence of disabilities and therefore the absence of indications for secondary surgery is misleading for two reasons:

1. A child born with a completely paralysed arm that persists will adapt and become entirely independent as far as activities of daily life are concerned; thus disabilities will not be obvious. Although in the case of adults consideration may be given to withdrawing treatment if there are no disabilities, this should not be done in the case of a child with an OBPP. A child will not miss a function he or she never had. It is, however, an obligation for everyone involved in the treatment of children with OBPP to do their utmost to create function in the affected arm that might be of invaluable benefit to the child.
2. Even if there are no disabilities at the time the operation is suggested, they might arise in the future if the suggested surgery is not performed. A fixed medial adduction contracture of the shoulder will generally not cause disability or pain to the child, but may become an insoluble problem because of irreversible shoulder deformities in the future adult. Gilbert et al (1991) formulates it very clearly: 'Contrary to traditional thinking, the surgeon should not wait to treat an internal rotation contracture. In the absence of surgical treatment recovery is limited, abduction is impossible, the extremity is dysfunctional, and, most important, osseous and articular deformity will occur. Posterior subluxation and deformity of the humeral head permanently worsens the prognoses. These anomalies, which have long been considered the result of obstetrical palsy, are in fact simply a consequence of untreated contractures'.

Subscapularis operations

Gilbert favours a posterior release of the subscapularis if the external rotation drops to 20°, but at the same time warns that soft tissue release of the internal rotation contracture should only be performed if the joint is congruent and the humeral head is round. Gilbert followed up 66 patients who had undergone posterior subscapularis release over more than 5 years. He found excellent results if the children were operated before the age of 2 years, but there was an 18 per cent failure rate if they were over 2 years, if there was an incorrect preoperative evaluation of articular deformities or if there was no postoperative physical therapy.

In Gilbert's opinion, posterior dislocation has disappeared with this aggressive treatment for medial rotation contracture of the shoulder. However, Birch found that children who were treated with a subscapularis slide/release developed bone deformities, even though the shoulder had been concentrically reduced. Hence, treatment with a subscapularis slide failed in the long term in one-third of the patients. He advises that in simple dislocation and subluxation the subscapularis tendon should be exposed and lengthened.

In Heerlen we follow Birch's policy and do not perform subscapularis releases because we believe that in most cases of a fixed medial adduction contracture there is already some degree of posterior subluxation.

Table 1 Comparing results of Gilbert and the Heerlen group on subscapularis operations

	Gilbert (release)	*Heerlen* (lengthening)
No. of patients	66	84
Prior neurosurgical reconstruction	28	40
Age at operation < 2 years	44	27
Age at operation 2–4 years	14	30
Age at operation > 4 years	8	27
Active exorotation after operation	31 (47%)	27 (32%)
Failures	18%	23%
Relapse requiring second lengthening		7
Exorotation contracture		12

Children have been known to lose the ability to actively medially rotate following a subscapularis tenotomy. It is therefore very important not to perform a subscapular tenotomy, but a lengthening of the subscapular tendon.

In Heerlen in the period 1995–2000, 84 children underwent an anterior subscapularis lengthening, 26 in combination with a resection of the coracoid. Twenty-seven (32 per cent) developed active external rotation within 4 months of lengthening, and therefore this procedure is no longer combined with a muscle transfer for exorotation. Our results with subscapular lengthening are comparable with the results achieved in the 66 children on whom Gilbert performed a subscapular release (see Table 1).

Gilbert does not specify what he considers to be a failure. Of course this is arbitrary and requires discussion. At Heerlen, a recurrence of the fixed medial adduction contracture was considered to be a failure. Zancolli and Zancolli (1988) warned against a soft tissue procedure on a medial adduction contracture with joint deformity because of the risk of creating an exorotation contracture, which in fact produces much more disability than a medial rotation contracture. Therefore, an exorotation contracture was also scored as a failure.

In fact, every time progression of shoulder deformity is not prevented, despite a subscapular release or lengthening, this should be considered a failure. To our knowledge, however, these results have not yet been reported.

It is noteworthy that after release *or* lengthening of the subscapularis without any kind of additional treatment, active external rotation developed in about of 30 per cent of the operated children.

Chuang et al (1998b) measure active external rotation with the arm in abduction. The arm of the patient is held in 90° abduction and 90° flexion of the elbow, and the patient is then asked to perform external rotation of the shoulder. If the hand cannot be raised above the chest (exorotation less then 60°), a poor result is scored. If the hand can reach the ear (exorotation 60–90°), the score is good. If the hand can reach the occiput (shoulder exorotation more then 90°), the result is excellent.

We assess active exorotation according to the Mallet score with the arm in adduction and the arm in 90° of flexion. It is striking that some children, despite good recovery of the infraspinatus on EMG, are not able to actively rotate the arm if it is held in adduction, but can actively externally rotate the arm if in abduction. There is no apparent explanation for this phenomenon, and this again shows the need for consensus on the method of assessment in order to compare results.

Following the Sixth International Workshop on OBPP held in Heerlen in November 2000, we decided to apply the following rules if a fixed medial contracture is found in a patient:

1. A fixed medial rotation contracture should be treated surgically if there is a persisting limitation of the passive external rotation of < 30;
2. If there is no posterior displacement of the head of the humerus, a subscapular slide will be performed;
3. If there is posterior displacement of the head of the humerus, an anterior approach with subscapular lengthening will be carried out; if there is an elongated coracoid, this will be shortened;
4. If there is a relapse of a fixed medial rotation contracture, subscapular lengthening will be carried out together with a muscle transfer to create active external rotation;
5. If the infraspinous muscle does not show signs of reinnervation by the age of 2 years and there is a fixed medial rotation contracture, subscapular lengthening will be performed together with a muscle transfer to create active external rotation;
6. If there is a fixed medial rotation contracture and a posterior luxation of the head of the humerus with deformities of the glenoid (bifacetal, retroversion), subscapular lengthening together with a derotational osteotomy of the humerus should be considered, because of the risk of creating a fixed external rotation contracture if repositioning of the head of the humerus is achieved by subscapular lengthening.

In Heerlen CT scan arthrography of the shoulder is performed preoperatively to obtain more information about the glenohumeral joint. In children older than 5 years, a CT scan without arthrography will suffice.

Following subscapular slide, the operated arm is immobilized in maximal lateral rotation for 3 weeks. After subscapular lengthening, the immobilization is for a period of 6 weeks.

Osteotomy of the humerus

As early as 1955, Wickstrom et al stated that all surgery around the shoulder should aim at an increase in the lateral rotation and abduction. His policy was as follows:

- If there is no shoulder deformity, this goal can be reached by simple tenotomy/release of contracted medial rotators. This should only be performed in combination with muscle transfers to strengthen the lateral rotators;
- If there is a dislocation or incongruency of the glenohumeral joint, no release or muscle transfer should be carried out. An open reduction should be performed in combination with an osteotomy of the humerus.

Most authors nowadays agree with Wickstrom, although not everyone advocates the combination of release with muscle transfers. Zancolli and Zancolli (1988) consider it a serious error to think that reduction of a posterior subluxation can be established if there is a deformity of the joint. An exorotation osteotomy is indicated in these cases, even if there is only a slight deformity of the head of the humerus, and usually after the age of 3–4 years.

Kirkos and Papadopoulos' (1998) indications for rotation osteotomy are:

- Patients at least 4 years of age, with a fixed medial rotation contracture and decreased strength of the teres major and latissimus dorsi, dislocation of a deformed humerus head, and relapse of deformity/medial rotation contracture after a soft tissue procedure;
- Patient over 8 years of age with a fixed medial rotation contracture or a limitation of the active rotation of the arm.

Following up a series of 22 cases, they found an increase in active abduction and in the arc of rotation. Intensive physiotherapy was not needed. This made it easier to manage younger patients because a high level of co-operation and compliance is not necessary, as it is after soft tissue surgery, especially tendon transfers.

Soft tissue procedures are recommended for young children who are under 6 years old and who have a severe internal rotation contracture without osseous changes in the humeral head. Release of the soft tissue contracture improves the cosmetic appearance but produces only slight functional improvement. There is an increase in external rotation without an increase in abduction, and there is also a risk of anterior dislocation of the shoulder. In addition, the range of rotational movement that is achieved decreases with time and with recurrence of the fixed internal rotation deformity.

Elbow/wrist/hand

If elbow flexion remained insufficient a Steindler procedure was used at Heerlen, transposing the pronator/flexor group from its insertion at the medial epicondyl to a more proximal site on the humerus, provided that the wrist extensors were strong enough to stabilize the wrist when the patient was using the wrist flexors to produce flexion of the elbow. Unfortunately, on several occasions there was a serious deformity of the elbow a few years after the Steindler procedure, and this became very unstable because transferring the flexor–pronator group had caused a growth disturbance of the medial epicondyl. It is therefore understandable that a latissimus dorsi transfer for active elbow flexion might be preferred to a Steindler procedure.

Zancolli and Zancolli (1988) mentioned the problem of a supination contracture, and this should be corrected before a 'fixed deformity' develops. The deformity causes an inner rotation of the lower arm bones with a volar subluxation of the distal ulna, and sometimes this is accompanied by a luxation of the head of the radius. A supination contracture causes serious disabilities in daily life. Activities of daily life request elbow flexion and pronation. Zancolli and Zancolli performed a re-routing of the biceps tendon to restore active pronation. The results at Heerlen with this procedure, especially in fixed deformities with a contracted interosseous membrane, are disappointing. Recently, functional improvements have been observed in children with a supination contracture who had undergone a pronation osteotomy of the radius. The hand is preferably placed in a position of 30° pronation. Birch et al (1998) warn that this operation may have to be repeated as the child grows.

Another disabling deformity is that in which the thumb lies in the ulnar deviated hand. In this situation, the extensor carpi ulnaris (ECU) can be transferred to the abductor pollicis longus if wrist extension is adequate. If wrist extension is poor, it might be better to transfer the ECU to the extensor carpi radialis brevis. Generally, however, the results of transfers in the hand are disappointing. As Birch et al (1998) mentioned: 'The results of tendon transfers in the hand are unpredictable and on the whole they are worse than those for any other neurological disorder'.

Developmental and behavioural outcome

There is always a danger of becoming too preoccupied with one aspect of the very complicated problems of OBPP and forgeting that 'life is more' for children with OBPP than just their affected arm. This may be the reason why relatively little research has been carried out into general developmental aspects in OBPP. In 1984, Greenwald et al suggested that psychological testing has not revealed any differences between normal individuals and those who sustained brachial plexus birth palsy. However, Bellew et al (2000) assessed children with OBPP with regard to both developmental attainment and behavioural problems, and found a high level of the latter. The children whose initial plexus injury was so severe that it required nerve surgery were found to have significantly poorer development than those whose injury did not require surgery, and the developmental delay was global. This study suggests that children with OBPP, particularly those with more severe injuries, may be at risk of developmental problems previously not identified. Because these developmental and behavioural problems have not previously been identified, the children have not had appropriate recognition or support for them. Whereas psychosocial risk factors became more prominent with increasing age and were related to poorer outcomes in children in all areas of functioning (motor, cognitive and social emotional development), organic risk decreased in influence.

Assessment

One of the biggest problems is to compare the results of the different treatment policies because of lack of consensus about the method of assessment and how to use the various scoring systems. This of course makes it very complicated to compare, for example, the results of a more conservative attitude in treating OBPP with a more aggressive surgical approach. The Brachial Plexus Work Group in Heerlen uses several assessment methods (see Appendix 2).

The Mallet scoring system is not really suitable for children under the age of 3 years. The children are asked to perform some movements to assess the function of the shoulder and the elbow. Determining the Mallet score is, however, not a complete assessment. It provides no information about the hand function or the passive ROM. Another problem is that some score 'active exorotation' with the arm in abduction, while Mallet scored active exorotation with the arm adducted to the trunk. The results differ in different positions of the arm. In Heerlen, grades I to V are used. Birch uses only three grades, and adds the five different scores to obtain a maximal score of 15. There should be a consensus about what is considered a good, fair or poor result: 15 will of course be a good result, but what should be considered a fair result? Any score between 8 and 13?

The passive ROM should be examined. The exorotation, measured with the arm adducted to the trunk, is particularly important in setting policy. A passive exorotation of less than 30° that does not improve with exercise should be treated surgically. The choice of surgery depends on the patient's age, degree of shoulder deformity and activity of lateral rotators (infraspinous muscle).

The shoulder joint should be examined carefully. The coracoid and acromion should be palpated and compared with the unaffected healthy side. The presence of a posterior or anterior displacement of the head of the humerus should be established.

The Gilbert/Raimondi score for shoulder, elbow and hand function is a very useful addition in assessment of the function of the arm and hand in children with OBPP. However, determining the correct scoring grade is frequently difficult. For example, if a child shows full active exorotation in the shoulder but less than 90° abduction, what should the stage be according to the scoring system of Gilbert and Raimondi? It is not possible to score a stage V or a stage II. In Heerlen, in this particular case a score of stage II plus would be allocated, but others might score a stage V minus. There are comparable problems in scoring hand function with this system.

It is essential to reach agreement about which assessment methods should be used and how. Another problem is agreement on interpreting the scores: which scores should be interpreted as good, fair or poor? Also, what exactly is meant by a good, fair or poor result – does this apply to the neurological state of recovery, or to the level of functional abilities? The latter could very well be good, while at the same time the neurological state of recovery might be poor.

Conclusions

OBPP is a very complicated, multi-faceted disorder. Conservative and surgical treatments cannot be separated, but should be used in conjunction. A multidisciplinary approach involving the parents, physiotherapists, occupational therapists, neurosurgeons, plastic surgeons, orthopaedic surgeons, rehabilitation specialists and psychologists is probably the way to achieve optimal results in treating children with OBPP. However, 'prevention' is better than 'cure', and therefore the final word in this chapter goes to Narakas (1987): 'Prevention may solve the problems of obstetrical palsy, as it has done for acute poliomyelitis.'

Appendix 1 Flow diagram – guidelines for action in OBPP (see next page)

Notes

What to do if you encounter a child with a neonatal palsy of the brachial plexus?

1. *Diagnosis:*
   - History of pregnancy and delivery – number of weeks, child no., presentation, cephalic/breech;
   - Difficulties, shoulder dystocia;
   - Reanimation, Apgar score;
   - Birth weight;
   - Help of nurse/specialist.
2. *Neurological examination:*
   - Look at the posture of the limb, the spontaneous movements;
   - Stimulate, sensory and motor testing, take time and be patient.
3. *Differential diagnosis:*
   - Clavicle fracture;
   - An obstetric lesion after vaginal delivery, cephalic/breech;
   - An obstetric lesion after Caesarean section;
   - Intra-uterine compression, maladaptation;
   - Congenital anomaly of the plexus;
   - Hereditary plexopathy;
   - Intra-uterine infection.
4. *Tests:*
   - Electromyography within the first days if an intra-uterine lesion is suspected;
   - Radiological examinations of thorax, clavicle, humerus if a phrenic paralysis is suspected, and/or a fracture;
   - Look for associated lesions: haematoma, fractures, phrenic-, spinal cord-, bilateral lesion, tracheal lesion or lesions of nerves VII, XI and XII.
5. *Therapy:* 3 weeks in a rest position, arm in front of the chest; no splints!

Encourage early presentation and control visits to augment the knowledge on the natural evolution of the lesion and to be sure that the exercises/physiotherapy proceed correctly.

Physical therapy is a continuing activity, in which parents play an important role, in order to stimulate muscle activity, and sensory function, and to mobilize the joints to prevent contractures.

If after 6 weeks a (nearly) totally flail limb still persists, further investigations such as electromyography and myelography will be necessary and surgical intervention will be unavoidable.

For other cases, with a more limited lesion to the upper plexus, a decision to intervene surgi-

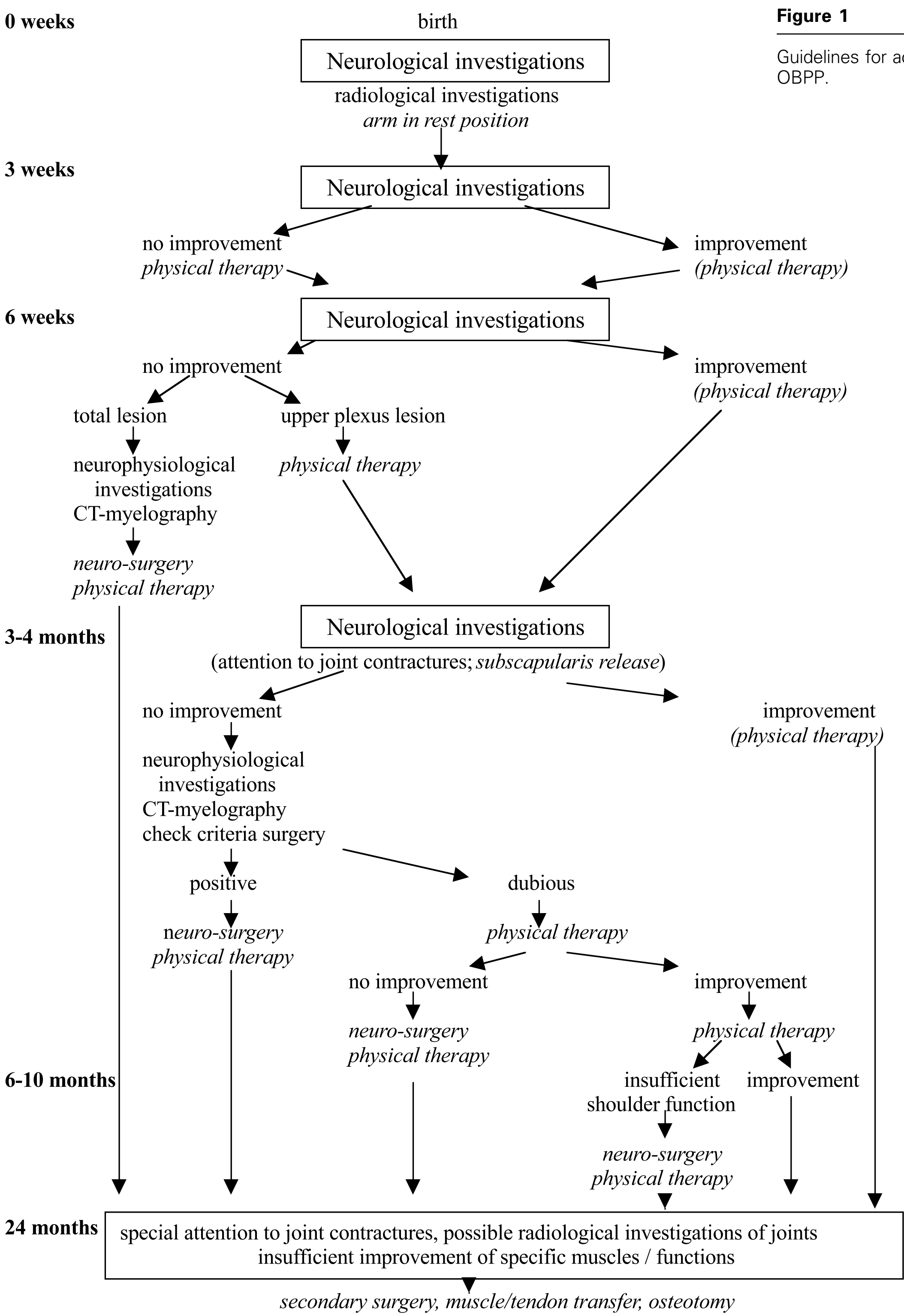

Figure 1

Guidelines for action in OBPP.

cally has to be made in the third or fourth month; supplementary investigations are scheduled. Check the criteria for neurosurgical treatment.

It is far more difficult to make a decision later, when some, but insufficient, shoulder function recovers.

In premature children and in children without or with poor physical therapeutic help and/or with severe contractures, the recovery of functions will be slower and incomplete. Contractures need special attention.

Criteria for neurosurgical treatment

- Biceps function M0 after 3 months, eventually combined with insufficient recovery of extensor muscles of elbow, wrist and fingers;
- Evidence of a severe lesion: Horner's syndrome, persisting hypotonic paralysis, persisting phrenic paralysis, severe sensory disturbances;
- EMG: persisting denervation with no action potentials;
- CT-myelography: meningocele formation outside the vertebral foramen.

Timing of neurosurgical intervention

- Generally at the age of 3–4 months;
- In severe (sub)total lesions and/or avulsions, as soon as possible;
- In doubtful cases of upper plexus lesions, not later than the age of 1.5–2 years(?);
- In late (sub)total lesions, until the age of 2 years or even later.

Appendix 2 Assessment of OBPP

Mallet Score

Active exorotation with arm abducted:
Hand–stomach reach:
Lat. dorsi:
Passive ROM:
Exorotation with arm adducted:
Endorotation:
Inf. GH angle:
Post. GH angle:
Elbow extension:
Supination:
Pronation:
Shoulder examination:
Elongated coracoid:
Aromion enlarged:
Posterior displacement:
Anterior displacement:

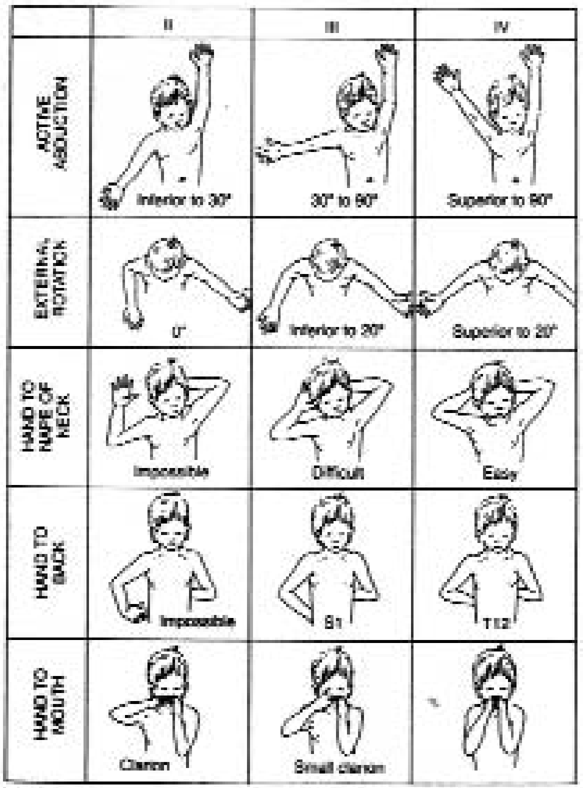

Figure 2

Mallet score (Gilbert modification) (from Gilbert 1993 with permission).

Gilbert/Raimondi assessment

Stage	*Shoulder assessment Gilbert/Raimondi:*	*Elbow assessment Gilbert/Raimondi:*	*Stage*
0:	Complete flail shoulder	Flexion: nil, some contraction	1
I:	Abduction = 45°, no active exorotation	Incomplete flexion	2
		Complete flexion	3
II:	Abduction < 90°, no exorotation	No extension	0
III:	Abduction 90°, weak exorotation	Weak extension	1
IV:	Abduction < 120°, incomplete exorotation	Good extension	2
		Ext. deficit: 0°–30°	0
V:	Abduction > 120°, active exorotation	Deficit 30°–50°	–1
		> 50°	–2

Hand-assessment Gilbert/Raimondi

Complete paralysis or slight finger flexion of no use; useless thumb – no pinch; some or no sensation	0
Limited active flexion of fingers; no extension of wrist or fingers; possibility of thumb lateral pinch	I
Active extension of wrist with passive flexion of fingers (tenodesis), passive lateral pinch of thumb (pronation)	II
Active complete flexion of wrist and fingers – mobile thumb with partial abduction–opposition; intrinsic balance – no active supination; no wrist extension; possibilities for palliative surgery	III
Active complete flexion of wrist and fingers; active wrist extension, weak or absent finger extension. Good thumb opposition with active intrinsic. Partial pro- and supination	IV
Hand IV with finger extension and almost complete pro- and supination	V

Rotation lower arm (Brachial Plexus Work Group Heerlen)

Pronation		*Supination*	
Absent	0	Absent	0
0°–45°	1	0°–45°	1
> 45°	2	> 45°	2
Complete	3	Complete	3

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19 Surgical technique

Jose L Borrero

The neural lesion in obstetrical brachial plexus palsy is one of traction or stretch. It should be clear that when a nerve is stretched the resulting injury is very variable. For the most simple of situations, such as when a single peripheral nerve is stretched, opinions differ as to the proper treatment (surgery or wait?). Differences in opinions continue even after deciding that the treatment is to be surgical (neurolysis or neuroma resection and grafts?).

Controversies are enormous when instead of a single nerve the highly variable stretch injury involves multiple nerves, located in a poorly accessible or understood part of the body, in proximity to vital structures, and do not follow a precise, constant pattern. Such is the situation with traction injuries to the brachial plexus. The situation is further complicated when the patient is a baby. Objective, precise evaluation is difficult if not impossible in the young pediatric patient. In addition, these patients create unavoidable emotions, which lead to unrealistic hopes of superior regenerative powers or exaggerated fears of patient brittleness.

It should be no surprise to recognize the subject of surgical treatment for obstetrical brachial plexus palsy as one sensitive, difficult, poorly understood and even feared matter. It is a subject full of controversies. This chapter summarizes the author's personal opinions and approach based on over 15 years of experience, which includes visiting and participating in surgery with surgeons in Europe and America as well as being the primary surgeon in 82 cases.

Anesthesia

Risk

Patients undergoing brachial plexus exploration and reconstruction are usually 3–8 months of age. Statistics show that the risk of general anesthesia is highest during the first month of life (Cohen et al 1990). Neonates therefore have the highest incidence of intraoperative adverse events. After the first month the risk of anesthesia decreases. In fact, adverse events during anesthesia are less frequent for ages 1–12 months than for ages 1–5 years (Cohen et al 1990). Accurate assessment of age and relationship to risk calls for calculation of both gestational age and postconceptual age. Both ages are defined as the time from fertilization to birth.

For our purposes the most common and important risk factor relates to the respiratory system and the occurrence of postoperative apnea. Apnea (absence of breathing for 20 seconds or longer) can be central (absence of respiratory effort) or obstructive. Central apnea is associated with prematurity. Preterm infants (having a gestational age of less than 37 weeks) have a higher risk of postoperative apnea up to 50 or 60 weeks postconceptual age (Cote 1993). Obstructive apnea is associated with upper respiratory tract infections (URI). During the first year of life a baby has an average of six URIs or about one every two months. Each of these episodes may take longer than two weeks to completely clear up and not be a factor leading to obstructive apnea. (Tate and Knight 1987). Thus, optimal conditions allowing elective surgery without additional risk are not always found during the second or third months of life. If optimal conditions are met (40 weeks gestational age, completely cleared URI, appropriate hospital, experienced anaesthesiologist), surgery during the second or third month should not represent an added risk. Yet no one knows with complete certainty which patients have less anesthesia risk and at what postconceptual or gestational age (Cote 1993). Delaying surgery on a healthy, normal baby after the second or third month is based on the 'level of comfort' of the anesthesiologist as well as convenience for the surgeon and not on measurable anesthesia risk for the patient.

Temperature

Hypothermia is a factor to consider in this patient group. Besides decreased ability to generate heat, the larger ratio of body surface to body weight in babies allows for faster heat loss than in adults. Hypothermia causes hypoxia, hypercapnea, acidosis and hypoglycemia. Babies also increase their oxygen consumption with lower temperatures. Effort must be made to prevent heat loss. The room temperature should be raised to maintain the infant's temperature. Heat lamps and warming blankets are also useful in preventing thermal stress. The core temperature should be monitored during surgery.

Fluids

Given that the operation involves one upper extremity and as both lower extremities are to be used as graft sources, access to peripheral veins is limited to only one arm. With anticipation the anesthesiologist should know that only the non-injured upper extremity is available for intravenous fluid administration. Experience in placing a reliable intravenous line is important. The inexperienced may find this difficult, cause unnecessary delays, may rely on inadequate scalp veins, or need to request additional help for jugular or subclavian catheter placement.

Infants, having a faster metabolic rate and a larger body surface to weight ratio than adults, become dehydrated more easily. An average 6 hours fasting period is generally accepted, although several studies have shown no difference in gastric residual volume or pH in children allowed to ingest unlimited clear liquids up until 2 or 3 hours prior to anesthetic induction (Schreiner et al 1990, Splinter and Schaefer 1990, Cote 1993). The deficit created by fasting for a patient under 10 kg is estimated as 4 ml/kg times the number of hours fasting (Savarese 1991). Fifty per cent of this total is to be administered in the first hour. Insensible losses resulting from evaporation depend on the incision size and site, the viscera exposed and respiration. These losses are small during brachial plexus surgery.

Maintenance fluid requirements for a baby under 10 kg are estimated as 4 ml/kg/h. Because these operations may take a long time, unrecognized hypoglycemia is of particular concern, thus dextrose is included in the maintenance solution (5 per cent dextrose in 0.45 per cent normal saline). A balanced salt solution (lactated Ringer's) is used to replace deficits.

Monitoring

For patients between 3 and 8 months old, the average weight is between 6 and 8 kg. For this group, the average respiratory rate, heart rate, blood pressure and blood volume are 20–40 breaths per minute, 110–180 bpm 60–110 mmHg systolic pressure, and about 80 ml/kg, respectively (Savarese 1991). In this group, urine output is expected as 0.5–1.5 ml/kg/h. Inhalation anesthesia, hypoperfusion and hyperthermia are causes of decreased urine output (McGowan and Chlebowski 1991).

Surgery

Position

A small folded towel along the posterior midline brings the chest forward and allows the shoulders to fall back in retraction. The head is slightly turned to the non-injured side with mild neck extension. Localized areas of pressure against the scalp should be prevented. The prep includes both lower legs to the groin, the injured arm and hand, and the axilla, anterior chest wall, supraclavicular fossa, and neck on the affected side. Heat loss during this preparation should be minimized. Recording electrodes are not placed because in my experience intraoperative recording has not been fruitful for key decision making. I recognize opinions differ in this regard (Fig. 1).

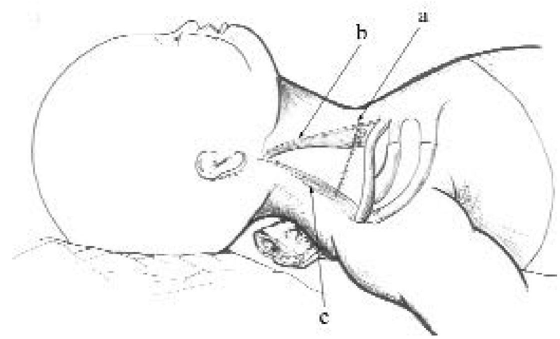


Figure 1

Position and incision. A small towel roll is placed between shoulder blades. The head is slightly turned with mild neck extension. The incision (a) is 2 cm above the clavicle from the lateral or posterior border of the sternocleidomastoid muscle (b) to the anterior border of the trapezius muscle (c). It follows skin lines.

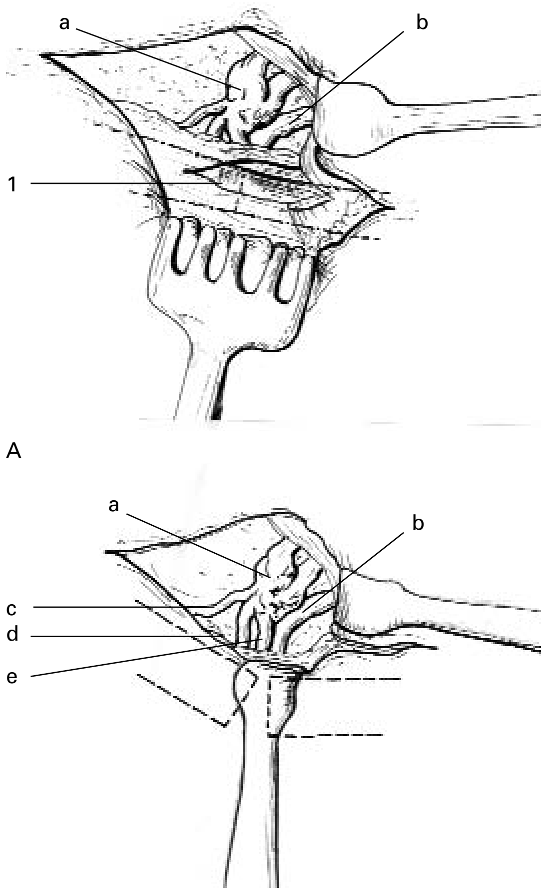


Figure 2

Exposure of distal upper and middle trunks. (A) Skin and tissue over clavicle is reflected inferiorly. Longitudinal incision on clavicular periosteum allows exposure of bare clavicle (1), which is cut transversely. (B) Retracting split clavicle inferiorly allows additional exposure of distal upper and middle trunks. (a) Neuroma in upper trunk, (b) middle trunk, (c) suprascapular nerve, (d) posterior division upper trunk, (e) anterior division upper trunk.

Magnification

Although naked eye dissection of the plexus is both possible and practical, magnification using loupes offers undisputed advantages, leading to a more delicate and precise dissection. At least ×2.5 magnification is recommended for the general dissection of the brachial plexus. For precise dissection of the roots at the foramen, often the operating microscope is best suited.

Incision

For all upper plexus cases and for most total plexus cases a transverse supraclavicular incision has been my preference for the past 10 years. This incision, 2 cm above the clavicle, extends from the lateral border of the sternocleidomastoid muscle to the anterior border of the trapezius muscle (Fig. 1). This incision allows dissection of the spinal accessory nerve and access to the vertebral foramen of plexus roots C5, C6, C7, and C8. It also permits exposure of the clavicle and all structures within the supraclavicular fossa. If further exposure is needed, the superior border of the clavicle is exposed. A longitudinal incision is made along the clavicular periosteum exposing a small central area of bare clavicle. The clavicle is cut transversely at this point. Inferior retraction produces inferior angulation of the clavicle and provides an additional centimeter of access to the distal portions of upper and middle trunks retroclavicularly (Fig. 2). Realignment of the clavicle with a

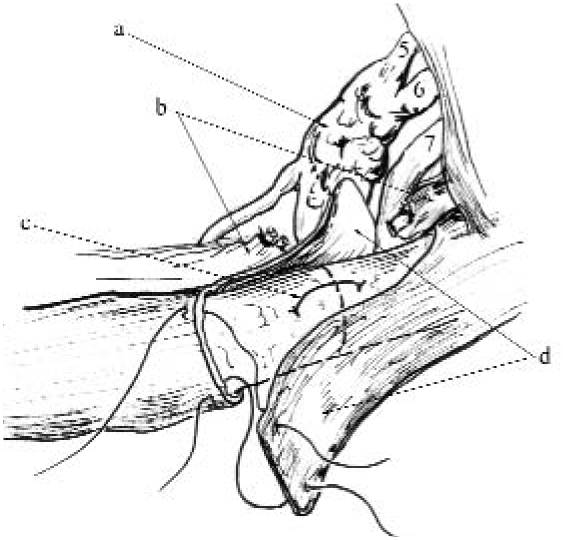


Figure 3

Splitting of the clavicle for complete exposure of the plexus. After exposing the clavicle, two opposing, u-shaped periosteal flaps (d) are elevated revealing the bare clavicle which is cut transversely. At closure, the clavicle is approximated with a tight absorbable suture (c) and the periosteal flaps are sutured back anatomically. (a) Neuroma, upper trunk, (b) suprascapular tissue containing suprascapular artery (ligated).

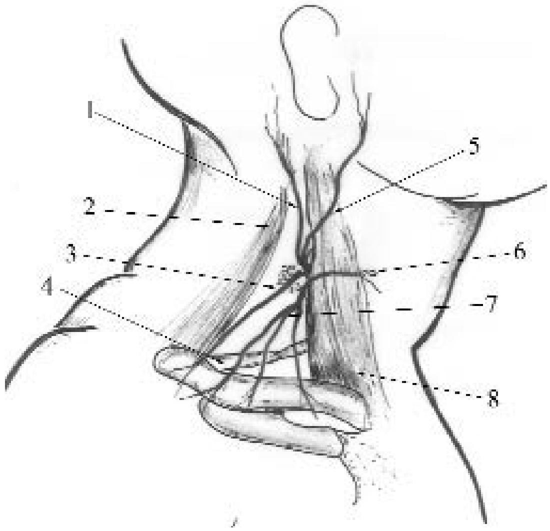


Figure 4

Surface anatomy. The posterior triangle is formed by: sternocleidomastoid (8), trapezius (2), and clavicle. The omohyoid (4) divides the posterior triangle into two smaller triangles. The accessory nerve (3) travels obliquely accompanied by lymph nodes. Branches from the cervical plexus are superficial and contain mostly sensory fibers: lesser occipital (1), greater auricular (5), cervical cutaneous (6) and suprascapular (7) which further divides into anterior middle and posterior branches.

simple but tight suture through the bone and repair of the periosteum are sufficient closure for complete bone healing.

In total plexus cases a complete clavicular osteotomy and mobilization is necessary when: (a) the subclavian artetry is found 'high' (almost superior to the superior border of the clavicle), or covering C8: (b) roots C8 ,T1 need complete exposure, particularly if one is *not* avulsed: (c) the infraclavicular plexus and branches need to be clearly defined.

In these cases, the posterior end of the skin incision is extended obliquely to below the clavicle. The pectoralis major is detached from its clavicular border exposing the inferior border of the clavicle allowing circumferential dissection. All soft tissue over the superior border of the clavicle, and the subclavius muscle inferiorly is divided, remembering that the suprascapular artery travels in this vicinity. Opposing periosteal flaps are created and elevated and the bare clavicle is exposed at its mid-portion (Fig. 3). The clavicle is cut transversely and reflected as necessary for complete exposure of the plexus and access to the subclavian artery.

When closing, clavicular approximation and alignment are maintained with a tight figure-of-eight suture passing through small drill holes near the divided ends of the clavicle. Periostal flaps are sutured back over the clavicle restoring normal anatomy.

Surface anatomy

The posterior triangle is bordered by the clavicle, the lateral (or posterior) border of the sternocleidomastoid muscle and the anterior border of the trapezius muscle. This triangle is further divided into two triangles by the omohyoid muscle. The larger superior triangle contains nerves of the *cervical plexus* and the *spinal accessory nerve*. These nerves enter the floor of the triangle at the mid-portion of the lateral border of the sternocleidomastoid muscle. Abundant lymph nodes surround the spinal accessory nerve at this point. That is why injury to this nerve can occur during node biopsy. The much smaller inferior triangle contains the *upper plexus trunk* and *transverse cervical vessels*. In this triangle the *external jugular vein* which travels superficially, parallel to the lateral border of the sternocleidomastoid, dives under the corner where the sternocleidomastoid meets the clavicle to join the *internal jugular vein*. On the left side, the *thoracic duct* ends at the angle between the internal jugular and subclavian veins. The sternocleidomastoid muscle may fan into a broad, flat attachment to the clavicle (clavicular portion) (Fig. 4).

Procedure

The transverse incision is deepened through the platysma. An effort is made to undermine the skin at the subplatysmal plane, both superiorly and to reach the level of the clavicle inferiorly. This facilitates exposure of the clavicle and later on closure by allowing identification and approximation of the platysmal layer.

Bleeding is controlled with the bipolar cautery. Instead of subcutaneous injection of epinephrine solution, which only helps while making the incision, gauze moistened with epinephrine solution is used throughout the procedure. This is particularly helpful in controlling bothersome oozing when operating through the microscope. The solution is made by diluting 1 ml of epinephrine 1:1000 in 100 ml of normal saline.

The lateral border of the sternocleidomastoid is identified and mobilized from its clavicular attachment. This insertion is divided at the clavicle using the cautery, yet leaving a periosteal cuff for repair when closing. External and internal jugular veins (and *thoracic duct on the left side*) lie underneath this insertion. The lateral border of the sternocleidomastoid is dissected exposing nerves of the cervical plexus (superficial or cutaneous branches) as they drape over this muscle at its mid-portion. These nerves correspond to the *cervical cutaneous*, traveling anteriorly, towards the midline, the *greater auricular* going superiorly in front of the ear and the *lesser occipital*, going superiorly behind the ear. At this same level but traveling towards the clavicle the superficial sensory *supraclavicular nerves* are seen (anterior, middle, posterior). These nerves should be preserved for they can also serve as nerve grafts. The *spinal accessory* nerve can be found at this same level traveling obliquely in a posterior direction. It lies slightly deeper and posterior, in the vicinity of lymphatic nodes that bleed with ease. Its presence is verified with the nerve stimulator. A long suture loop is used as a marker anticipating it being needed for neurotization later on. I find that for this nerve, at this early stage in surgery, small silicone rubber loops (vessel loops) are too big and get in the way.

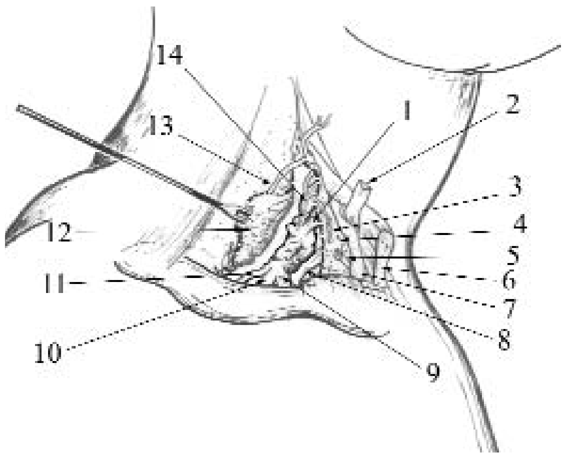


Figure 5

Dissection, upper trunk neuroma. Underneath the omohyoid, fatty tissue rich in lymphatics (12) is mobilized as a flap hinging posteriorly exposing the plexus.

1 – C6 plexus root
2 – Omohyoid, cut and reflected
3 – Phrenic over anterior scalene
4 – Anterior scalene
5 – Transverse cervical vessels, ligated
6 – Clavicular attachment of sternocleidomastoid, cut and reflected
7 – Internal jugular vein
8 – Middle trunk
9 – Anterior division, upper trunk
10 – Posterior division, upper trunk
11 – Suprascapular nerve
12 – Fat pad and lymphatics, retracted by hook retractor
13 – Supraclavicular nerve
14 – C5 plexus root

Next, the *omohyoid muscle* is identified, dissected and either divided or pushed to the side. Underneath this muscle, fatty tissue rich in lymphatics covering the supraclavicular fossa is first separated from the lateral border of the sternocleidomastoid and anterior scalene muscle. This tissue is mobilized as a flap, hinging posteriorly. The plexus lies directly underneath. During closure this tissue is laid back over the reconstructed plexus serving as useful protective cover. The *transverse cervical artery* and vein are contained in this fatty tissue. To facilitate dissection they can be divided and ligated (Fig. 5).

Fibrous portions of the *anterior scalene* are dissected from the usual neuroma comprising the upper trunk. The *phrenic nerve* may be adhered to this neuroma. Normally this nerve is attached to the upper trunk or to C5 plexus root by a small branch and travels over the anterior scalene muscle. Stimulation verifies its presence (Fig. 5).

The *C5 plexus root* is dissected as far proximal into the foramen as possible. Small vessels within the foramen cause bothersome oozing when disrupted. They can be controlled with epinephrine soaked sponges and bipolar electrocautery. The operating microscope may be needed to obtain a clear, precise dissection of the root as it exits the foramen. Reflecting the anterior scalene muscle medially while protecting the phrenic nerve allows anterior or medial dissection of the *upper trunk* and exposes *C6 and C7 plexus roots*. These roots are also dissected to their foramina and circled with silicone loops.

The *middle scalene* is found when dissecting the upper trunk posteriorly. It may also be fibrotic and scarred. Important branches forming the *long thoracic nerve* usually run through the middle scalene at this level. A normal *serratus muscle* response, noted when stimulating these nerves, indicates proximal root continuity with the spinal cord and that the injury is distal to these branches. These nerves should be dissected to their origin from C5, C6 and C7 plexus roots and protected.

The *middle trunk* may be matted against the upper trunk as one large neuroma. No attempt is made to separate these trunks proximally. Instead attention is given distally to the branching of the upper trunk. Posteriorly and just above the clavicle these branches are the *suprascapular nerve, the posterior division* and the *anterior division*. The posterior division is usually in closest proximity to the suprascapular nerve. The divisions continue underneath the clavicle. Therefore, if an inferior or retroclavicular exposure is necessary to visualize the divisions of the upper trunk and the terminal portion of the middle trunk, the clavicle should be exposed and if necessary divided as described earlier under 'incision'. The middle trunk branching into its anterior and posterior divisions occurs retroclavicularly. The middle trunk may have two anterior divisions, one merging with the anterior division of the upper trunk to form the lateral cord and one merging with the anterior division of the lower trunk to form the medial cord.

When separating the middle trunk from *C8 plexus root*, one must consider the *dorsal scapular artery*. This vessel can be a branch of the *thyrocervical trunk* or can originate directly from the *subclavian artery*. This dorsal scapular artery may lie *over* C8 and the middle trunk but *under* the upper trunk (Huelke 1990) (Fig. 6). It is best to expose, divide and ligate this vessel.

If C8 plexus root lies completely behind the *subclavian artery*, safe exposure calls for splitting the clavicle with inferior retraction of the soft tissues. When dissecting soft tissues surrounding the clavicle and dividing the *subclavius muscle*, it is necessary to remember that the *suprascapular artery* (branch of the thyrocervical trunk) is in close proximity. It is best to ligate and divide it (Fig. 3). After gentle mobilization of the subclavian artery, C8 plexus root can be clearly defined. *T1 plexus root* is often found inferior and anterior to C8. It is more transverse in orientation and maybe much smaller than C8. As a rule, T1 and C8 merge to form the *lower trunk*. This merging is usually retroclavicular, thus the lower trunk as such may not be seen in supraclavicular dissections or unless the clavicle is divided. The lower trunk then splits into anterior and posterior divisions. The *posterior division* joins to form the *posterior cord*. This merge can be quite distal and variable. Sometimes this posterior division originates directly from C8 (still retroclavicularly). In this situation the posterior cord does not receive contributing fibers from T1 (Bonnel et al 1980, Bonnel and Rabischong 1981, Bonnel and Canovas 1996).

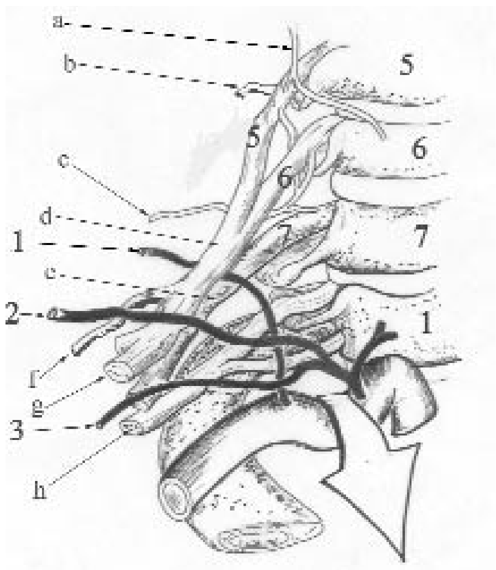


Figure 6

Arteries in the supraclavicular fossa involved in the dissection of the brachial plexus. The dorsal scapular artery (1) crosses *over* the C8 plexus root. It may continue *under* the middle trunk or as illustrated *over* the middle trunk and *under* the upper trunk. Its origin may be from the subclavian artery directly (illustrated) or from the thyrocervical trunk. Transverse cervical (2), and suprascapular arteries (3) usually arise from the thyrocervical trunk (Huelke 1990).
a – Phrenic nerve
b – Dorsal scapular nerve
c – Long thoracic nerve (Bell)
d – Upper trunk
e – Middle trunk
f – Suprascapular nerve
g – Anterior division of upper trunk
h – Lower trunk

Reconstruction and decision making

Meticulous exploration allows for definition of the anatomical location of the injury. Once the exact location of the injury is determined, precise definition of the severity or extent of this stretch injury is difficult if not impossible. (The physiological deficit may not correlate with the anatomical distortion). Even under the most favorable of conditions and availability of resources, prediction as to expected regeneration and recovery is only an educated guess. Reconstruction should be individualized, for no two cases are identical. That is why reports analysing results after surgery are often inaccurate unless they include specific comparable cases.

Neuroma appraisal: neurolysis

Most commonly, a neuroma with some physical continuity is encountered. The surgeon now faces the first major dilemma. *Should the neuroma be resected or a neurolysis conducted?*

Neurolysis is, of course, appealing but the sad reality is that it is usually not the best choice. Precise prediction of the regenerative capacity of the nerve fibers within a neuroma in continuity requires exact quantitative and qualitative analysis of those nerve fibers within the neuroma. This is not possible today in supraclavicular plexus injuries in babies.

Most surgeons with experience agree that the results after neurolysis are discouraging. Neuroma resection and grafting is preferred for it gives the best results (Kawabata et al 1985, Sloof 1995, 1997, Gilbert 1996, Birch 2000). My personal experience has been the same. After encouraging intraoperative studies, neurolysis alone (no neuroma resection) was carried out in two cases of C5, C6 rupture. Shoulder function in these two patients was inferior to the 17 cases of C5, C6 rupture treated by neuroma resection and grafting. I believe, however, that in cases of C5, C6 injury one should inspect and consider neurolysis of C7. Likewise, microneurolysis of C8 should be considered in cases of upper and middle trunk neuroma (C5, C6, and C7 injury).

Proximal root stump appraisal: histology

After the neuroma is resected, the surgeon faces the second major dilemma. *Is the proximal plexus root stump a satisfactory source of nerve fibers suitable for grafting?*

Correct appraisal of the proximal stump during plexus surgery is of critical importance. Connecting nerve grafts to an unsuitable proximal root will lead to a poor result. In appraising the proximal root stump the surgeon considers these criteria:

1. The combined preoperative evaluation (radiologic findings, electrodiagnostic studies, physical examination);
2. The gross examination of the root involved (appearance, palpation, how it feels on dissection, how it cuts);
3. The intraoperative muscle response to direct nerve stimulation;
4. Special nerve studies during surgery (evoked potentials, intraoperative nerve conduction studies);
5. Histological appraisal of the root.

Intraoperative frozen sections usually mean delays and added strain for the surgeon. If appropriate rapport and communication are established with members of the pathology department, frozen histological sampling can be obtained in a reliable, efficient manner, in less than 10 minutes. For the last 7 years histological appraisal of the extent of fibrosis (H & E stain), and myelin content (trichrome stain) has been obtained as a routine in our hospital (Florida hospital Medical Center, Orlando Florida) (Meyer and Claussen 1995, Malessy et al 1999). This, has allowed certain conclusions:

1. Histological sampling is not needed in every case, but it is helpful when there is doubt as to the quality of the proximal stump;
2. Histological sampling is a direct and objective method of defining proximal root suitability;
3. Presence of ganglion cells defines avulsion. The root distal to this avulsion may appear histologically normal. This root is unsuitable and should not be used;
4. It is best to dissect and transect the plexus root as far proximal into the foramen as possible.

Grafting

The gap created after neuroma resection is bridged with nerve grafts, which establish nerve continuity. Segments of sural nerve are most commonly used. Portions of the cervical plexus (supraclavicular nerves) and cutaneous nerves of the arm and forearm can also serve as grafts. These are autologous nerve grafts. Sadly, as of yet, a reliable substitute is not available.

Sural nerve grafts are obtained with a longitudinal, posterior, midline incision from the popliteal fossa to the lateral malleolus. A tourniquet is not used. Epinephrine soaked sponges and bipolar cautery provides minimal blood loss. Usually, 10–12 cm of sural nerve is obtained per leg in a 6–8 kg baby. On the average, graft length for supraclavicular plexus reconstruction is 2–3 cm each. Graft orientation is maintained by placing a dot in the distal end of the sural nerve with the marking pencil. (The dot is distal.)

Grafts can be coapted individually or as a cable made by grouping several nerve segments held together with fibrin glue. These cables can be further organized to match the resected portion of the plexus. This is easier done in a separate surface and then transferred as a unit to the patient where distal and proximal ends are glued or sutured. This method calls for great precision in orientation and in estimating graft length and relative diameter of both proximal and distal ends so that a near perfect fit is obtained. Experts like Gilbert can perform this maneuver with great precision and efficiency.

When grafts are sutured individually, I prefer to lay the entire sural nerve within sight in the neck wound. This maintains the graft moist and very accessible. Segments of nerve are measured and cut as needed without referring to the back table. Suction should be used with extreme caution or avoided completely. The awful empty feeling that accompanies watching nerve grafts being swallowed into the suction tubing will stay with you forever. Coaptation is completed with a single microsuture of 9–0 or 10–0 nylon. It makes sense to anchor deeper grafts first and more superficial grafts last. It is possible to maintain root fascicular orientation and to coapt grafts to specific fascicular groups within the plexus root. The merit gained by this effort is speculative.

Conventional suturing calls for passing the needle through both root and graft epineuron in independent throws. I find it efficient instead to bring the graft into the needle that is held in its position after it passes half-way through the proximal plexus root epineuron.

Fibrin glue

It is known that the combination of cryoprecipitate thrombin and calcium results in a substance that can be used as a sealant or adhesive. The usual proportions call for one unit of cryoprecipitate, 10 000 units of thrombin and 5 ml of 10 per cent calcium chloride.

Cryoprecipitate does not contain red or white cells. It contains antibodies and some coagulating factors. One unit of cryoprecipitate contains a minimum of 150 units of fibrinogen and 80 units of factor VIII (Florida Hospital 1999). Cryoprecipitate is obtained from pooled blood and needs to be cross-matched with the recipient. The sealant or adhesive properties result when fibrinogen is converted to an insoluble fibrin matrix. Thrombin, calcium and factor VIII catalyze this reaction (Malessy et al 1999).

Commercially available adhesive and sealant combine the same elements (fibrinogen, thrombin and calcium) in higher concentrations and more precise proportions. This results in improved rheological properties (elasticity, tensile strength, and adhesiveness). In addition, some products contain a substance called aprotinin, which retards the process of fibrinolysis, prolonging the adhesive property.

During plexus surgery, the tissue adhesive is used when bonding several grafts together along side to form a polyfascicular nerve trunk, which is then used to bridge the plexus gap created by resecting the neuroma. Some surgeons rely solely on this adhesive to maintain end-to-end coaptation. Others prefer a combination of one anchoring suture and fibrin adhesive. It has been shown that the presence of this fibrin matrix is not a barrier and does not interfere with the passage of regenerating axons (Romano et al 1991, Palazzi et al 1995).

Neurotization

In its broadest sense neurotization is defined as nerve regeneration after its division. For the brachial plexus surgeon, it is synonymous with nerve transfer or nerve crossing. It is to be used when the proximal end of a divided nerve is not available.

Nerve transferring requires a donor or proximal nerve source and a recipient or distal nerve. The proximal source can be from nerves outside the plexus (extraplexual), i.e. the spinal accessory serving the suprascapular nerve, or within the plexus itself (intraplexual), i.e. the C5 plexus root serving the lower trunk. A direct nerve transfer is not always possible. In many instances a nerve graft is needed to bridge the gap between the donor and recipient nerve. It should be obvious that these variables defining the nerve transfer will affect results. Anatomical and physiological disparities between donor and recipient nerves also create variables inherent to the specific transfer. The number and type of fibers in the donor and recipient nerves must have some similarity (Bonnel et al 1979, Bonnel and Canovas 1996).

The most commonly used *extraplexual* transfer is the spinal accessory to the suprascapular (Kawabata et al 1994). This transfer can be made direct, without a graft and without tension while preserving the proximal branches to the trapezius. Both nerves are about equal in caliber and fiber content. Useful infra- and supraspinatus muscle function can be obtained with this transfer. Other extraplexual sources for transferring include the *phrenic nerve*, the *hypoglossus nerve*, the *cervical plexus, intercostal nerves* and the *contralateral C7 root*. The deficit created as well as the expected useful muscle function gained is to be carefully considered prior to carrying out any of these transfers (Brunelli 1984, Kawabata and Shimada 1995, Narakas 1987, Sloof 1995, 1997).

Intraplexual transfer dictates using nerve grafts. This is the most accepted method of reconstructing the lower plexus with favorable results. Of course transferring one proximal donor source, like C5 plexus root to multiple distal elements such as the lower trunk and the upper trunk introduces the problem of fiber dilution or dispersion. It should be obvious that one proximal root alone is not sufficient or adequate to fulfill all the needs of upper and lower trunks. Available proximal roots used during reconstruction must be known in order to properly analyse and compare results after reconstruction.

Reconstruction strategy

Reconstruction is dictated by findings at the time of surgery. Each case needs to be individualized recognizing that variations in the number of roots affected, as well as, the location and extent of their injury are enormous. *Ruptures* or extra foraminal injuries can be repaired by resection and grafting assuming both ends are suitable. *Avulsion* or intraforaminal injuries are truly spinal cord injuries and cannot be repaired. In these cases, reconstruction is accomplished by directing nerve fibers from another source into the injured distal plexus (neurotization).

Based on injury location, two major categories exist: Injuries affecting the upper plexus; and injuries affecting the plexus totally. The upper plexus category is further divided into two types: those affecting roots C5, C6, and those affecting roots C5, C6 and C7.

According to Gilbert, the most common injury is one involving two upper roots (C5, C6). He reports that out of 436 operated cases, 48 per cent involved C5, C6 roots, 29 per cent involved C5, C6, C7 roots and 23 per cent were considered complete (Gilbert and Tassin 1987, Gilbert 1995, 1996). My personal experience differs from that observation. From a total of 82 cases, 40 (48 per cent) involved C5, C6 and C7, 19 (24 per cent) involved C5 and C6, and 23 (28 per cent) were considered total (involving more than the three upper roots).

Fortunately, the more common upper plexus injuries are also more commonly extraforaminal ruptures, thus repairable. Avulsions are more common in central roots (C6, C7 and C8). Isolated upper roots (C5, C6) injuries are frequent. I have not seen an isolated lower root (C8, T1) injury.

Recognizing the hand as most important for a useful limb, the order of preference during reconstruction should be *(1) hand, (2) elbow flexion, and (3) shoulder.* Guidelines for repair of specific injuries are included.

1. *C5, C6 injury: ruptures.* Dissect and transect roots as far proximally as possible into the foramen. Protect and check response after stimulating root branches to the serratus muscle (long thoracic nerve) and rhomboid muscles (dorsal scapular nerve). Expect near normal functional results (Mallet IV or better) when grafts bridge suitable healthy proximal stump and a neuroma free distal upper trunk. If there is doubt as to the quality of the distal upper trunk one must not hesitate to transect further distally and coapt grafts individually to the suprascapular nerve and to upper trunk divisions. Fibrosis in the distal upper trunk and its branches should alert the surgeon to dissect and inspect C7 plexus root (Fig. 7a).
2. *C5, C6 injury: one root ruptured the other avulsed.* Since C5 commonly contains less fibers than C6, avulsion of C6 with rupture of C5 leaves the smaller of the two roots as proximal source of axons. This is the less favorable situation. C6 is also considered to contribute more to biceps than to deltoid. The contrary holds for C5 (Birch 2000). Reconstruction calls for direct neurotization with distal spinal accessory to the suprascapular nerve and grafts from the ruptured proximal root to anterior and posterior divisions of the upper trunk. It seems reasonable to direct the best proximal fascicle to the anterior division of the upper trunk, so providing the most favorable situation for elbow flexion. If the proximal root stump is a suitable source of fibers, results will be quite good. I believe that C7 and the middle trunk should be inspected and neurolysis carried out unless noted perfectly normal (Fig. 7b).
3. *C5, C6 injury: both roots avulsed*. This uncommon plexus injury is seen after breech delivery, where it can occur bilaterally affecting babies that are not large (Geutjens et al 1996). At surgery if the avulsed roots have remained intraforaminally the diagnosis of avulsion is not evident as one sees root continuity into the foramen. In addition there may be little neuroma or fibrosis present. The operative findings, therefore, do not correlate with the profound loss in elbow flexion and shoulder function noted preoperatively. To make matters worse, if one decides to cut the root that does not look so bad, histology of an avulsed plexus root will reveal minimal fibrosis and near normal myelinization, an observation for which I personally have not yet found an explanation.

In C5, C6 root avulsion injuries there are no available proximal nerve fibers for plexus reconstruction. Neurotization is the only hope. Since the hand is normal in a C5, C6 injury, priorities should be *elbow flexion*, then *shoulder function*, in that order. For elbow flexion, I favor spinal accessory extended with a graft to the musculocutaneous nerve. I use a separate infraclavicular incision which separates the clavicular attachment of the

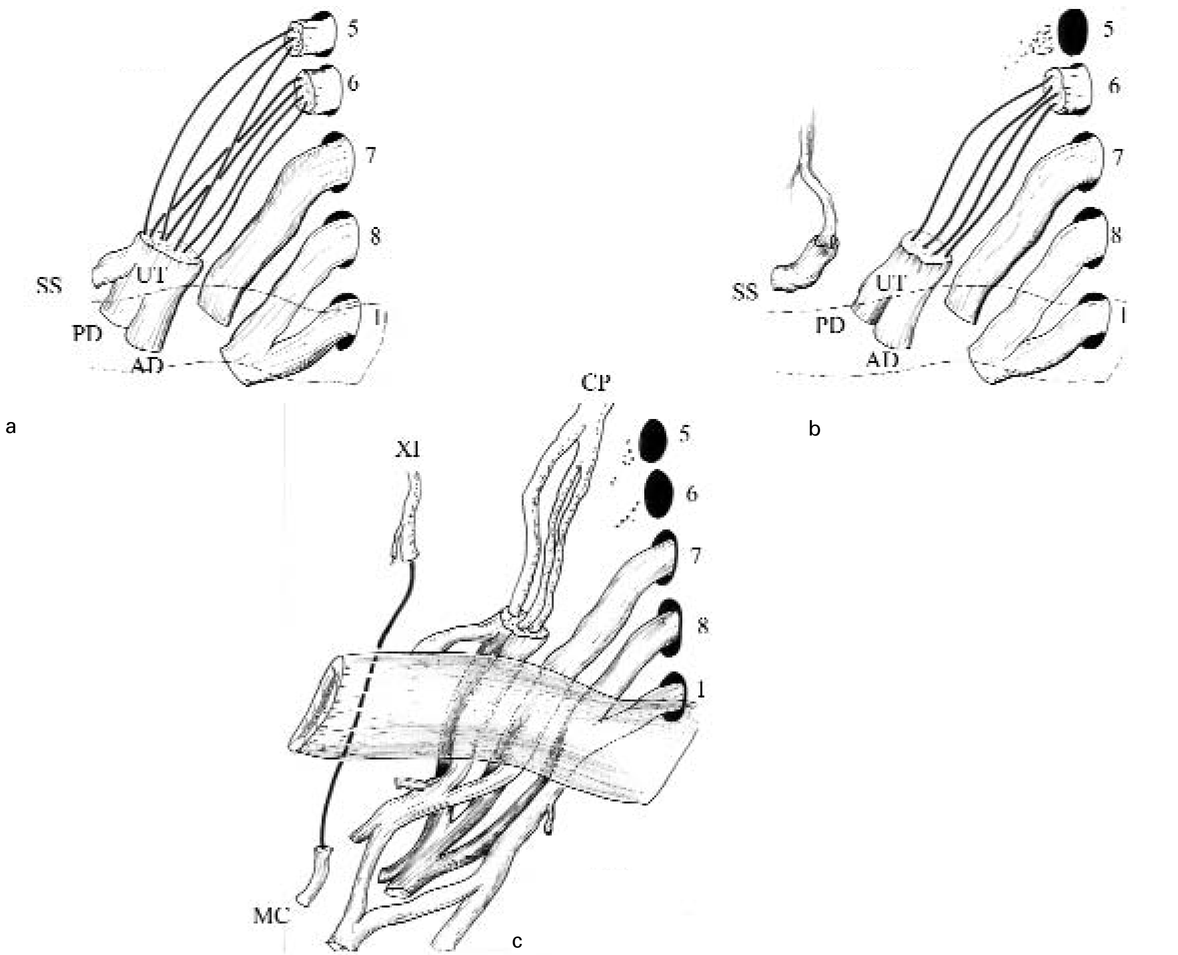


Figure 7

(a) C5, C6 injury: rupture. Both proximal root stumps are suitable for grafting. Distal upper trunk with little fibrosis and good fascicular organization. 7 grafts, 2–3 cm in length. All supraclavicular. Expect an excellent, near normal result. SS, suprascapular; PD, posterior division upper trunk; AD, anterior division upper trunk; UT, upper trunk. (b) C5, C6 injury, one root ruptured, the other one avulsed. Theoretically, prognosis is best if the smaller C5 root is avulsed and if C6 root stump is healthy and normal. Four nerve grafts to upper trunk are shown. Consider neurotization, distal spinal accessory to suprascapular. Results should be very good. (c) C5, C6 Injury, both roots avulsed. Assuming C7 is perfect and hand is normal, priorities should be elbow flexion and shoulder function. The problem is not having a proximal source of nerve fibers. Neurotization, spinal accessory to musculocutaneous (with a graft under clavicle), and cervical plexus to upper trunk. Other options described in text. Poor shoulder function is expected. XI, Spinal accessory; CP, cervical plexus; MC, musculocutaneous nerve.

pectoralis major allowing its inferior and medial mobilization and exposes the *pectoralis minor* which is reflected to either side or detached from its insertion at the coracoid process. Other surgeons prefer extending the original incision, detaching the pectoralis major from the clavicle and exposing the pectoralis minor. Without splitting the clavicle, tunneling is necessary to pass the graft in both circumstances.

Shoulder function will be poor but hopefully the intact medial pectoral nerve provides for useful pectoral muscle function, resulting in shoulder stability although with excessive unopposed internal rotation. Branches of the cervical plexus (sensory supraclavicular) are transferred to the upper trunk (mostly the anterior division) without needing a graft (Fig. 7c). I do not have enough experience to prove this as worthwhile, although a reasonably good result (able to reach mouth with supinated palm of hand, Mallet III) has been obtained in one case.

In an effort to obtain useful elbow flexion, others have considered transferring the spinal accessory to the anterior division, or the medial pectoral or intercostal to the musculocutaneous nerve (Gilbert and Tassin 1987, Gilbert et al 1991, Slooff 1997). Transferring a portion of the ulnar nerve to the musculocutaneous nerve at the upper arm level is also an alternative (Oberlin et al 1994, Sloof 1997, Leechavengvongs et al 1998). Precise data comparing these alternatives and their results does not exist. Gains from these efforts may be modest, yet important, considering the enormous incapacity that results from zero shoulder abduction and zero elbow flexion if left untreated.

Another alternative is to utilize C7 as a source of fibers with end to side grafts leading into the upper trunk. This concept is still experimental.

In one case I have transferred a large fascicle from the uninjured middle trunk directly into the upper trunk. A deficit resulting from dividing portions of a normal middle trunk was not observed post operatively. Results are expected to be favorable for this surgical procedure.

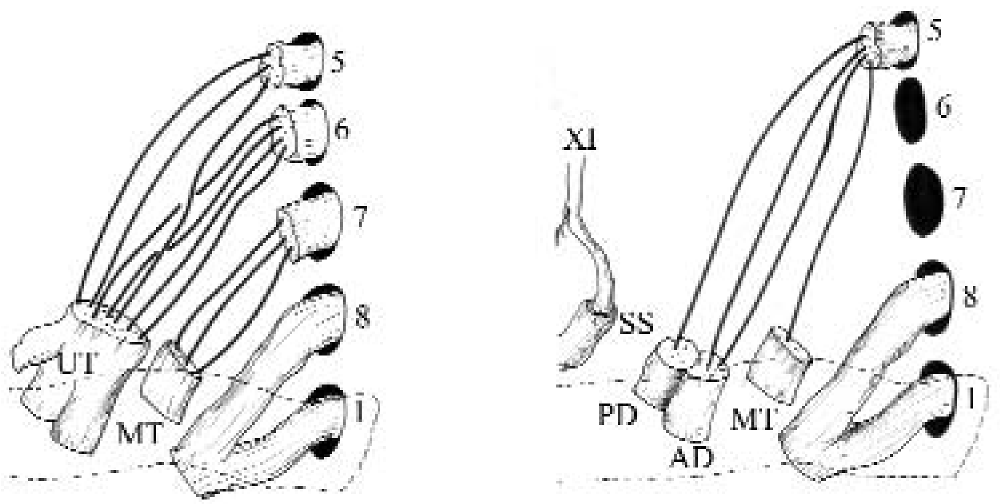
4. *C5, C6, C7 combined rupture and avulsion*. In these cases as in all upper plexus problems, hand function is quite good with normal finger and thumb flexion and normal or weak extension. Priorities should be elbow flexion, shoulder control and wrist extension. In agreement with Gilbert, I have observed that the most commonly avulsed root noted in this, three root, upper plexus injury is C7, particularly if the neuroma involves the divisions of the upper trunk (Gilbert and Tassin 1987). Often this root remains partially within the foramen. With gentle dissection and tugging, the root separates from the foramen and the ganglion becomes evident thus defining the injury as a C7 avulsion.

If three proximal roots are available, multiple grafts are used for plexus to plexus repair. It is common not to have enough graft material even after using both surals. Portions of the cervical plexus and the median antebrachial cutaneous nerve serve as additional grafts. The connection with the distal middle trunk may be retroclavicular and the clavicle may need to be divided and retracted inferiorly as described under ‘incision’. Inspect C8 and the lower trunk and consider neurolysis if there is any fibrosis (Fig. 8a).

If two or one proximal root is available as a source of fibers, my preference is transferring the spinal accessory to the suprascapular. nerve. Grafts from the healthiest looking proximal fascicle are directed to the anterior division of the upper trunk. Other grafts are then directed to the posterior division and to the middle trunk. I do not know if being so selective is worthwhile.

If only one proximal root is available, the problem is not having enough proximal source of nerve fibers. It is not possible to adequately supply the upper and middle trunks with one plexus root, especially the smaller C5. In theory, directing grafts from one proximal root to all distal recipients results in dilution or dispersion of the motor fibers. Muscles may be partially re-innervated with limited useful function.

I have directed all grafts from one healthy root into the upper trunk ignoring the middle trunk completely. The resulting strong elbow flexion with poor shoulder control, weak triceps and virtually no radial nerve function (zero wrist, thumb or finger extension) was disappointing. But, why was the shoulder and radial nerve function so poor? For unknown reasons, regenerating fibers traveled to the anterior division of the upper trunk and ignored the suprascapular nerve and posterior division of the upper trunk. Anatomical variations of the posterior cord is another explanation. In other words, the ignored middle trunk may have been the predominant contributor to the posterior cord and the



a b

Figure 8

(a) C5, C6, C7 ruptured, all proximal stumps suitable, distal upper and middle trunks with little fibrosis. Multiple grafts used for plexus to plexus repair. In this example 10 grafts (2–3 cm each) are shown. The problem is not having enough grafts. Expect good results if all proximal stumps are healthy and suitable and distal upper and middle trunk show minimal fibrosis supraclavicularly. UT, upper trunk; MT, middle trunk. (b) C5, C6 C7 injury: two roots avulsed, one root ruptured. Neurotization spinal accessory to suprascapular (extraplexual), grafts from available root to divisions of upper trunk and to middle trunk. Dilution of proximal nerve fibers is significant. Distal upper or middle trunk fibrosis calls for a more distal transection, thus longer grafts to anterior and posterior division of upper trunk and to distal middle trunk will be needed. This distal connection may be retroclavicular (may need to split the clavicle). The problem may be not having enough proximal fibers. In this example, two grafts are directed to the anterior division to illustrate priority for elbow flexion. XI, spinal accessory; SS, suprascapular; PD, posterior division upper trunk; AD, anterior division upper trunk; MT, middle trunk.

radial nerve, which becomes even more important when C5 and C6 are missing. A third explanation is unsuspected fibrosis at the distal upper trunk. The neuroma resection was not carried out distally enough. Or, maybe the proximal root was truly not that 'healthy'. Finally, maybe nerve regeneration through a graft simply did not progress as expected. The point is that sometimes results (good or bad) cannot be explained.

When only one proximal root is available, my preference today is to directly transfer the spinal accessory to the suprascapular and to graft the healthiest proximal group fascicle to the anterior division of the upper trunk. All remaining grafts to the remaining upper trunk and to the middle trunk. There is no choice but to accept dilution or dispersion of fibers. This seems better than directing long grafts into specific target nerves (Fig. 8b).

5. *Total plexus injury: C5, C6, C7 rupture, and avulsion of C8 and/or T1*. Priorities should be hand (wrist and fingers), elbow flexion and shoulder function. The spinal accessory is transferred to the suprascapular nerve. Grafts from the healthiest proximal fascicle are directed to the lower trunk and next to the anterior division of the upper trunk. Other grafts if available are directed to the posterior division of the upper trunk and to the middle trunk. Portions of the cervical plexus are coapted without a graft to the middle trunk. It is difficult to explain to parents and non-surgeon clinicians that results will be poor for some muscle groups, yet overall superior to no treatment at all (spontaneous recovery) (Fig. 9).

A similar strategy is followed when two or even one proximal root is available as a source of nerve fibers. Results of course, will be inferior in these severe total plexus injuries.

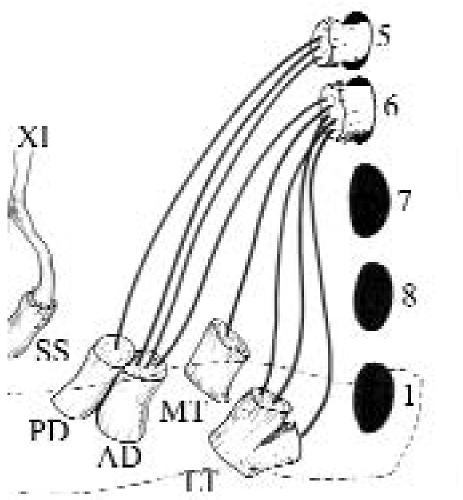


Figure 9

Total plexus injury: C5, C6 rupture, C7, C8, T1 avulsion. In this example two proximal roots allowing 8 grafts are available for reconstructing the entire plexus. Priorities should be hand, elbow flexion and shoulder function. Best proximal sources provide grafts to lower trunk and to anterior division of upper trunk. Neurotization of spinal accessory to suprascapular. Consider neurotization: Cervical plexus to middle trunk (without a graft). In total plexus injuries, as in all plexus injuries, reconstruction strategy is variable depending on what is available. Graft shortage and not enough proximal source of fibers are serious problems. Results will vary and major deficit will remain. Still these patients are better off than if not treated (spontaneous recovery). XI, Spinal accessory; SS, suprascapular; PD, posterior division, upper trunk; AD, anterior division, upper trunk; MT, middle trunk; LT, lower trunk.

Postoperative

The baby is immobilized to prevent disruption of the grafts. This calls for maintaining the affected arm in a sling and avoiding the angle between head and shoulder to exceed 90° on the affected side. It is best to have a splint or custom 'baby holder' brace made prior to surgery. This also helps parents understand what to expect and how to care for the baby after surgery. A minimum of 3 weeks immobilization is necessary. Babies older than 5 months do not tolerate this period as well as younger ones. This intolerance and excessive movement can adversely affect results in those operated on late.

Routine postoperative care includes an observation period of at least 24 hours. During this time IV fluids are reduced as diet progresses to normal. Pain and restlessness are addressed. Monitoring of O_2 saturations may be necessary.

Complications

In modern day, complications are few. Morbidity is rather low for such a delicate and complex procedure. Presumed injury to the phrenic nerve results in transient paralysis of the diaphragm and low O_2 saturations post operatively. I have had a baby with respiratory insufficiency, secondary to presumed aspiration, necessitating ventilatory support for 4 days. Another child was noted to have localized hair loss, presumably the result of localized pressure to the scalp either during surgery or postoperatively while in the 'baby holder splint'.

Conclusions

Brachial plexus surgery in the newborn reopens and expands the frontier of peripheral nerve microneurosurgery. Surgery calls for precise delicate technique with a solid knowledge of the anatomy. The surgeon must have a preconceived operative plan as well as understand reconstructive priorities and expected results. These are stressful, delicate operations that call for enormous sense of integrity and discipline in order not to yield to the easiest, fastest surgical solution including unjustified delays. In spite of such efforts, important factors affecting results are not known or controlled by the operating surgeon.

Acknowledgement

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20
Indications and strategy

Alain Gilbert

The basis of the indications for brachial plexus repair is correct assessment. There is no valid decision without a precise and detailed examination of the patient. Although EMG, CT scan and MRI may be of use in the exact determination of the lesion, I strongly believe that the surgical decision should be taken on clinical grounds.

The interpretation of the EMG is not easy and very different from that of an adult, where signs of recovery will usually mean a favorable outcome. In the baby, these signs mean only that a few fibers have crossed the neuroma and reached the muscle, but not that this muscle will have a controlled activity.

Examination of the baby and spontaneous recovery

The examination should be done with the baby lying down and then sitting, if he or she is old enough. The individual assessment of muscles is rarely possible; it is usually more correct to speak of functions: abduction, forward elevation, external rotation etc. (Figs 1 and 2). Some of these movements are difficult to provoke, and to effect them requires a very good knowledge of the child's reflexes. However, these tests should be simple enough for a pediatrician, physiotherapist or surgeon to do, and need not be limited to specialized centers.

In his thesis, Tassin (1984) followed the development of 44 patients from birth to the end of recovery. In these non-operated patients he was able to trace the relationships between recovery of individual muscles or functions and the end result. He demonstrated that if a patient had some sort of contraction of the biceps before the end of the third month, the end result would be good enough to avoid direct surgery (Mallet Grade IV). On the contrary all the patients who had not demonstrated any biceps recovery at 3 months were likely to have an incomplete result (Grade III or less). Based on this study we have

Figure 1

The typical presentation of an upper root lesion.

Figure 2

A complete lesion with flail arm and hand.

used these criteria for more than 20 years to decide on the need for surgical exploration of the plexus and we have since proved that operated patients are largely improved by surgical repair (Gilbert 1984, 1995, 1998). Several other test muscles were studied by Tassin but only the biceps and deltoid were found to be useful. The deltoid, however, cannot be used because its three components often recover separately and their examination is difficult as other muscles may provoke the movements (pectoralis major, external rotators, etc.). This was the reason for our exclusive choice of the biceps.

In the baby, the muscles cannot be studied on the same scale as the adult (M0 to M5). The voluntary movements are not reproducible in the young child and we have therefore been using a much simpler scale:

M0: no movement, no contraction
M1: contracting, no or very limited movement
M2: weak movement, incomplete range
M3: complete range of motion

Indications for surgical exploration

In 1903, Kennedy thought that the absence of recovery at 3 months after birth justified an exploration and a surgical repair. Two decades ago we found, based on the studies of Tassin (1980) that this indication was justified and we have been using it satisfactorily for the past 20 years. However, discussions have arisen from different surgical teams on the timing of the operation and the criteria used for the decision.

Many authors (Kawabata et al 1987, Terzis et al 1986) have adopted the 3 month deadline; others prefer to wait longer (4–6 months after birth), either for practical reasons if the child is referred late (Petrolati et al 1994), or for philosophical reasons (Clarke, 1995, Grossman 2000). Although recovery of the biceps is the main test adopted by most authors, some, after Clarke (1995), prefer to use a more complex test, giving numbers to each function and, in particular, giving great importance to the wrist extension. Clarke (1995) claims that by waiting and using his grading system, predictability for outcome is 7 per cent better than by the simple biceps test. However, there are drawbacks to the utilization of this system;

- It is complex and time consuming, and needs a specialized physiotherapist;
- Some patients will start a biceps recovery at 4 or 5 months, leading to a poor shoulder result if not operated on;
- At 6 months, a family may not accept the loss of already-acquired function of the upper limb and therefore refuse operation.

In Mediterranean or Middle-eastern environments this latter point can lead to many children escaping treatment. The precision for indications that is gained by waiting is balanced by the psychological difficulties with the decision whether or not to operate.

In patients with complete paralysis the situation is different and the aim is no longer biceps

Figure 3

Horner's syndrome.

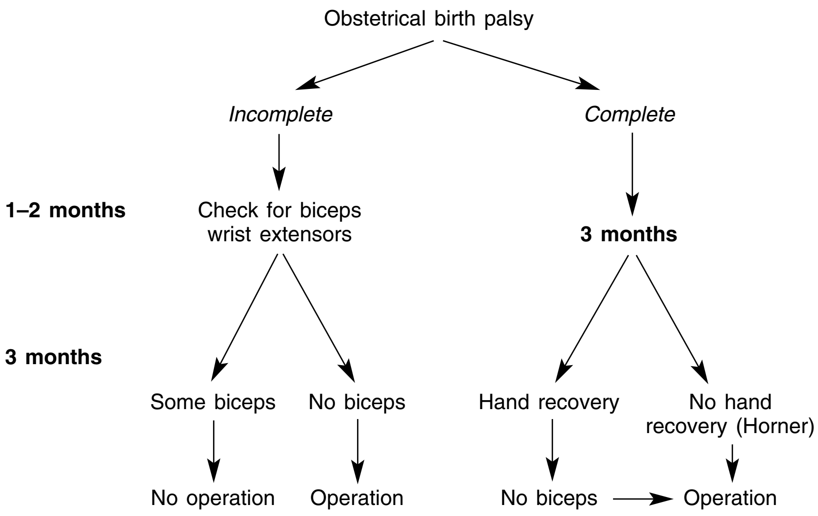

Figure 4

Indications for surgical repair. A patient who has not a recovered biceps (even a contraction) at 3 months is a candidate for surgical exploration and repair. With complete paralysis, repair will be necessary, even if the biceps is recovering, as long as the hand has not recovered and/or Horner's syndrome is present.

recovery but hand recovery. There are cases where the shoulder and elbow recover rapidly and extensively without hand function. In these cases one must be prepared to sacrifice some of the already recovered upper limb functions in order to obtain a better hand.

The presence of Horner's syndrome at the first examination will almost certainly lead to surgical repair (Fig. 3). Horner's syndrome is pathognomonic and there are very few exceptions. Al Qattan has shown that in his experience no patient with Horner's syndrome had any satisfactory spontaneous recovery (Al Qattan et al 1998). Chuang et al, reviewing older, non-operated patients, states that an overweight baby (more than 4.5 kg) with Horner's syndrome will show a poor recovery. On the contrary, Horner's syndrome is not so indicative in a baby of less than 4 kg at birth (Chuang et al 1998). The indications of surgical approach are summarized in Fig. 4.

Special cases

Late exploration

In some cases the child is seen much later, up to several years, having a flail arm or a poor recovery with or without co-contractions (Fig. 5).

The most common feature is a child seen at the age of 3 or 4 years, who had a complete palsy: the shoulder and elbow have recovered sufficiently but the hand is flail or extremely weak.

The situation is very difficult as, in order to obtain a good chance of recovery in the hand, it would be necessary to sacrifice some of the upper nerve roots. The use of extraplexual neurotization will never allow a good recovery in the hand. The decision is totally dependent on the family. The surgeon must assess the parents and judge whether they will accept the temporary (or even definitive) loss of some function in order to give the child a chance of recovery in the hand. This is one of the most difficult surgical decisions. If the whole arm is flail, the problem is not so acute. Then the time limit will be determined by the survival of the muscles (checked by EMG) and the brain adaptability. In obstetrical palsy, if there is no avulsion, the muscles may stay alive for many years as some fibers manage to cross the neuroma. However, even if the muscle can be reinnervated after several years, the child may never use it, as the brain cannot adapt to this new situation.

Of course, in any of these late cases, the choice will be weighed against the possibilities of muscle and tendon transfers, which might give a sufficient function without the risks of nerve

a b c

Figure 5

(a) A 9-year-old non-operated child with no elbow function. (b) A 25 cm graft is done between C5 and the musculocutaneous nerve. (c) Flexion of the elbow after 18 months.

surgery. This is true for shoulder and elbow but rarely of the hand.

Breech presentation

In breech presentation, the average birth weight is much lower than usual (Geutjens et al 1996, Slooff 1997). The specificity of the lesion is due to the high percentage of avulsion injuries of the upper root. When a baby of small weight, born by breech presentation, is seen with a severe upper palsy, extensive lesions should be expected. The shoulder is usually flail and the EMG shows absence of response in the C5–C6 muscles.

A myelograph CT scan may show meningoceles in the upper roots (Fig. 6). The difficulty is the repair. Often in these localizations, exploration shows the roots *in situ*. They are soft, whitish and do not respond to stimulation. The decision is not easy as we know that these partial avulsions recover in 50 per cent of cases (Gilbert). It is then best to leave the roots in place and close the wound. After 6 months a decision will be taken according to the recovery. If there is no or weak recovery, another exploration will allow repair by either neurotization or end-to-side suture (or both) (Fig. 7).

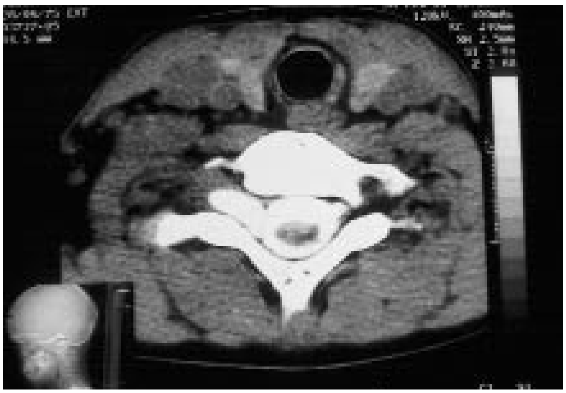

Figure 6

A CT-myelogram which can show a meningocele.

a

b

Figure 7

(a) Breech presentation. A myelogram shows two upper meningoceles. (b) Intraoperative view showing the roots in continents and no neuroma.

Conclusions

There is no strategy applicable in all cases of obstetrical palsy. In some clear-cut cases of complete C5–C6 or C5–C7 lesions with no signs of recovery at 3 months, or in a case of complete paralysis with no hand function and Horner's syndrome at 3 months, the decision for surgical exploration is easy and well understood by the child's family. However, sometimes it will not be so easy: at 3 months the surgeon may find no biceps function but there is some elbow flexion due to the brachioradialis; the hand has very weak movements but the elbow flexes. In such cases it is difficult to convince the family of the desirability for surgical intervention and no operation should be done on the child under these circumstances. It is even worse when the child is older and a surgical decision and repair will necessarily mean the loss of some recovered function.

This situation is often made more difficult by comments made by doctors, ignorant of the problem and usually giving negative advice. However, patient support groups often counterbalance this information.

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21
Results of repair to the obstetrical plexus

Alain Gilbert

Evaluation and grading of results

To evaluate the results of obstetrical plexus repair, the use of a clear system of grading is essential. This is the reason why, with Piero Raimondi, we have worked for several years on the definition of methods of assessment of outcome after repair of the plexus.

The evaluation of brachial plexus repair has always been very difficult as it encompasses many muscles and joints and several functions. Some authors (Narakas 1993) have proposed the use of a purely functional scale. Two difficulties arise: the need for voluntary, well controlled, active movement which is not possible in the young child; and the establishment of a hierarchy of movements. Others (Clarke and Curtis 1995) have been using functions to which numerical values have been allotted. This allows one to give with one number the overall value of the upper limb. However, we find again the difficulty of comparing different functions: does an upper extremity with an excellent shoulder abduction and rotation, a perfect flexion and extension of the elbow have any value if the hand is flail? In this case, the sum of all the numbers will give an overall result which seems acceptable. Individual testing is not possible in the baby for every muscle, owing to absence of voluntary movements. The use of reflex movements is limited to some rare muscles.

After looking into various systems, evaluating them, we found that the only possibility was to evaluate synergic groups of muscles, assess them in detail but give independent results for each joint. This does not solve completely the overall evaluation of the arm but allows precise comparison of each joint before and after operation.

We are, then, studying the shoulder, the elbow and the hand independently. The follow-up is another crucial factor. Not only must the child be examined at regular intervals (every 3 months, then 6, then 12), but check-ups should continue until the end of growth. We know too well the deleterious effect of growth on some results (size of the limb, joint abnormality, loss of abduction) to accept results which have not withstood the long-term evaluation. This puts us in a difficult position: can we publish results of evaluation before the end of growth? That means a minimum of 13 to 14 years follow-up. It would be the ideal situation but, as it is a relatively recent technique, it would not enable us to exchange information. The compromise solution is to publish follow-up details as late as possible, letting the reader know that our results may still be modified later.

In order to facilitate comparison, we have divided the cases in these categories:

- upper root lesions (C5–C6);
- upper and middle root lesions (C5–C6–C7);
- complete lesions.

Results of upper root lesions

We had reviewed 103 patients operated on for C5–C6 lesions before 1996 (Gilbert 1995). These patients have been reviewed at 2 and 4 years

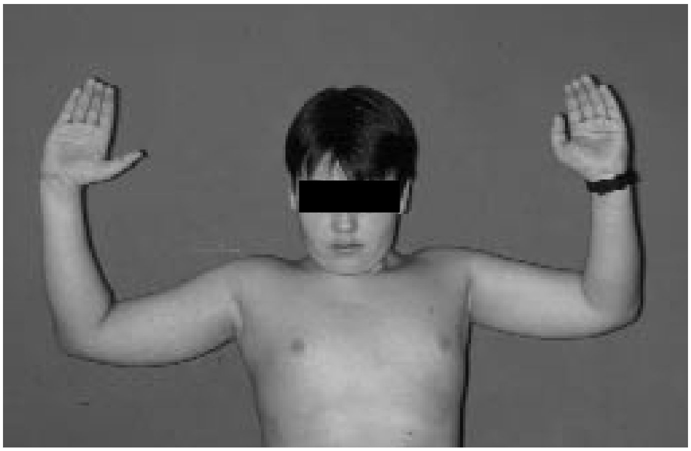
a

b

Figure 1

Left C5–C6 repair at 7 years postoperative. (a) Results on external rotation. (b) Results on abduction. In this case, the shortening is very limited.

a



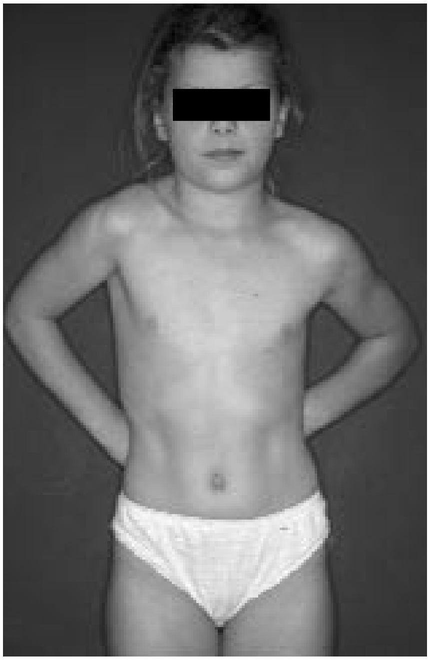
b

Figure 2

Left C5–C6 repair at 11 years. (a) Good abduction but marked shortening of the left arm. (b) Excellent external rotation.

post-operation (Figs 1, 2). We have used our grading system (see Chapter ••). At 2 years the results were:

- Grade IV–V (good or excellent) 52 per cent;
- Grade III (average) 40 per cent;
- Grade II or less (poor) 8 per cent.



a

b

Figure 3

Right C5–C6–C7 repair at 9 years. (a) Slight limitation of medial rotation. (b) Shortening and limitation of external rotation.

Most of the patients with poor results had avulsion injury of the upper roots after breech delivery.

One-third of these C5–C6 patients had secondary surgery of the shoulder, either for release (13 subscapularis releases) or tendon transfers (33 latissimus dorsi and 6 trapezius transfers). At 4 years, the new evaluation showed:

- Grade IV–V 80 per cent;
- Grade III 20 per cent;
- Grade II or less 0 per cent.

Results of upper and middle root lesions

In C5–C6–C7 defects, the anatomical lesions are usually more severe with many associated ruptures and avulsions (Fig. 3). At 2 years, the results of 61 patients were:

- Grade IV–V 36 per cent;
- Grade III 46 per cent;
- Grade II or less 18 per cent.

During the following years, 7 patients had subscapularis release and 25 had tendon transfers (24 latissimus dorsi and 1 trapezius). The patients were evaluated again at 4 years:

- Grade IV–V 61 per cent;
- Grade III 29 per cent;
- Grade II 10 per cent.

Although these results are not as good as those for as the C5–C6 patients, they were largely improved by surgery.

Results of complete lesions

A series of 73 patients with complete paralysis has been reviewed with a minimum of 8 years follow-up (Gilbert and Haerle 2000). The patients were reviewed at 2-year intervals.

At 2 years, the results of recovery in the shoulder were very limited, with only 25 per cent with Grade III and IV recovery. The upper roots are usually ruptured but a large part is used to re-innervate the avulsed lower roots, thus weakening the scapular belt. During the following years some improvement occurs but the changes are due mostly to tendon transfers (Fig. 4). A review at 8 years resulted in 77 per cent of patients of Grades III, IV and V with 44 per cent of Grades IV and V.

During these years 46 secondary operations were done, either releases for joint stiffness or latissimus dorsi transfers.

The results for elbow flexion recovery were excellent: 68 per cent of good or excellent results at 2 years; 81 per cent at 8 years, after only 9 secondary operations.

Forearm supination contracture is very common after complete palsy. This contracture was important and needed treatment in 13 cases (6 biceps re-routing and 7 rotational osteotomies).

In the hand and wrist the early evaluation at 2 years was very poor (only 35 per cent of useful results 3–4–5) (Fig. 5).

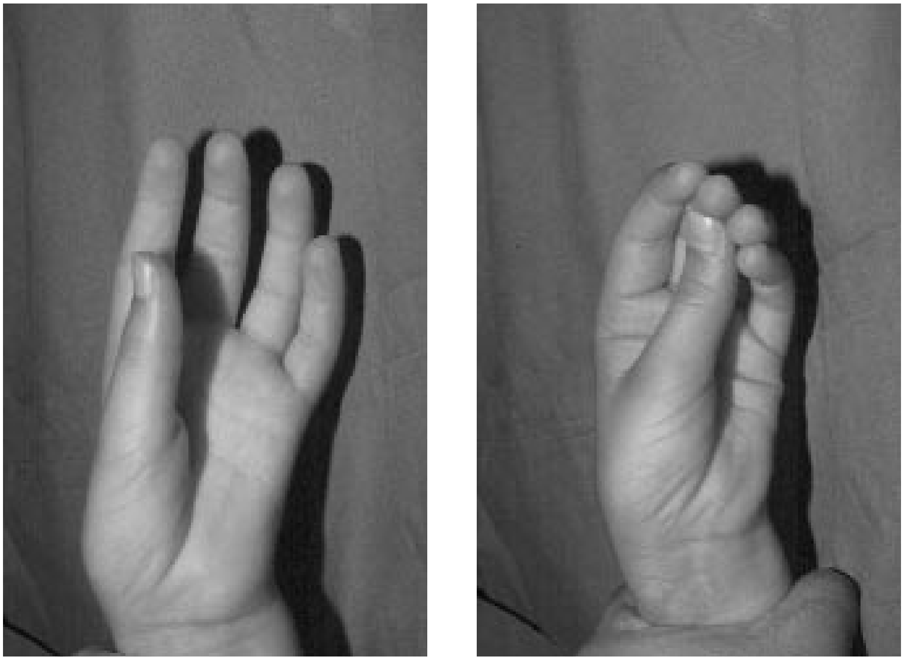
a

b

c

Figure 4

Complete right paralysis. Avulsion of C8–T1 repaired with upper roots. (a) Limited results on abduction. (b,c) Excellent function of the hand.



a b

Figure 5

Avulsion injury of C7–C8–T1 (a,b) Grade II hand – poor function.

During the following years, 22 transfers were done for wrist extension with only 14 valuable results. Very few transfers were done for the fingers.

At 8 years hand recovery had improved markedly, with 76 per cent of useful results. With avulsion injuries of the lower roots, intraplexus repairs using the upper roots give an acceptable result, justifying the surgical strategy of repairing the lower roots at any cost.

Conclusion

The long-term results of obstetrical brachial plexus repair confirm the advantages of surgical repair over spontaneous recovery. In upper root lesions, the results of shoulder recovery after surgical repair were far better than the results after spontaneous recovery in the same grade of patients.

In complete lesions, the intraplexual nerve transfers allow three-quarters of patients to recover a useful hand in cases of lower root avulsions who otherwise would have had a very poor and useless hand.

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22
Results of surgery after breech delivery

Gerhard Blaauw, Albert (Bart) CJ Slooff, and Robert S Muhlig

Patients

During the period January 1986 to January 2000, we examined 896 children with an obstetrical brachial plexus palsy in our outpatient department. We performed primary surgery 302 times in 299 patients. In 239 of these delivery followed cephalic presentation and in 60 the palsy occurred after breech delivery; one of these followed Caesarean section delivery of a breech presentation. Breech delivery is complicated, brachial plexus lesions occurring at a higher rate than in patients who are born after cephalic presentation (see Chapter 19 in this volume). In 57 patients, unilateral primary (nerve) surgery was performed. Although a bilateral brachial plexus palsy had occurred in 13 patients, bilateral primary surgery was only necessary in three of these. Thus in 60 patients, we performed primary surgery on 63 sides. Two-year follow-up was possible for 56 operations carried out on 54 patients (Table 1). We report the results of surgical treatment of 53 cases of upper brachial plexus lesions; complete lesions were not included because of the small number. In the latter cases the results of gain in hand function have until now been disappointing, and in one child the follow-up period was just over two years, thus distal results could yet be evaluated as recovery takes many years to develop.

Table 1 Data of 56 cases of surgery performed on 54 patients with obstetrical brachial plexus palsy after breech delivery

Gender:	
Female	22
Male	32
Birth weight (grams)	Range: 1230–4250 Mean: 3018 SD ± 684
Operated side:	
Right	31
Left	21
Bilateral	2
Concomitant lesions:	
local haematoma	8
phrenic paralysis	13
fracture of clavicle	5
fracture of humerus	3
bilateral brachial plexus palsy	13
Distribution:	
Upper palsy	
C5, C6	37
C5, C6, C7	16
(Sub)-total palsy	3
Age at operation (months)	Range: 3–21 Mean: 6.3 SD ± 3.9

Clinical presentation

The birth weight of the neonates in this series (Table 1) contrasts with our cases of brachial plexus palsy after cephalic presentation (Ubachs et al 1995). The latter cases are almost invariably macrosomic neonates.

In all children, it was noted directly after birth that there was a functional disturbance of the arm, although in some at first a fracture was suspected to be the cause. In fact a local haematoma pointed to the site of the trauma in eight cases (14 per cent). In five cases the clavicle was fractured (9 per cent), in three cases the humerus (5 per cent), and one child had a fracture of the femur.

Figure 1

Baby with palsy due to paralysis of C5, C6 and C7. Note waiter's tip position of hand and early muscle atrophy. (From Blauuw 1999)

Figure 2

Boy with a bilateral lesion. On the left side, the total lesion shows early proximal recovery. On that side there is also a phrenic palsy, which required plication of the diaphragm.

In 95 per cent of the cases ($n = 53$) there was paralysis of the upper roots: in 37 cases (66 per cent) of C5 and C6; in 16 (29 per cent) of C5, C6 and C7. In these babies the arm is internally rotated and pronated, and there is no active abduction or elbow flexion. If C7 is also damaged, the extensor muscles are paralysed, the elbow may lie slightly flexed and waiter's tip position of the hand is pronounced (Gilbert and Whitaker 1991). In 13 of these babies hemiphrenic nerve palsy was present (see below). Pectoralis major, finger and thumb flexors are usually active, but muscle atrophy often develops early (Fig. 1). In 13 babies, bilateral lesions were present (Fig. 2). Distal sensation and vasomotor control are usually unaffected. A complete palsy of upper and lower roots was present in only three cases. In one of these three cases, isolated early recovery of suprascapular function had occurred. Horner's syndrome was present; the phrenic nerve was normal.

Phrenic hemiparalysis

Phrenic hemiparalysis was present in 13 neonates. Most paediatric surgeons only consider surgical treatment (plication of the diaphragm) to be necessary in those neonates who have respiratory difficulties. This proved to be the case in seven patients; in six patients plication was performed before brachial plexus surgery. One patient who was refused plication prior to plexus surgery developed serious respiratory difficulties directly following plexus surgery. We regarded the cause to be the impact of prolonged surgery and immobilization in the cast. We are convinced that the indication for plication must not be too strict. In some children, hemiphrenic plication may prove to be a disadvantage; during thoracotomy required for plication, section of the latissimus dorsi may render this muscle unsuitable for later latissimus dorsi transfer. At present the indication for phrenic plication has been broadened because of the less invasive endoscopic technique now available. The added advantage is that no harm is done to the latissimus dorsi muscle.

Radiological findings

Radiologically, involvement of cervical dural sac and root sleeves was a frequent finding in this series. The myelogram was normal in only six patients, showing normal roots and root sleeves. In one patient we refrained from myelography because of the child's clinical condition. Hence the myelogram was abnormal in 47 patients. Traumatic arachnoid cysts (meningoceles), derived from torn root sleeves, often bilateral, seemed almost to be the rule in obstetric brachial plexus lesions after breech delivery. Rarely, the cyst reached outside the foraminal canal. In most cases arachnoid cysts were present on the upper roots only. Although myelography was performed in all but one case, the results in our early cases did not allow us to decide on the presence or absence of intradural rootlets, thus radiologically an accurate diagnosis of nerve root avulsion was usually not possible. The improvement in the quality of CT-myelography makes current assessments at present more reliable. The reader is referred to Chapter 3 in this volume.

Neurophysiology

The interpretation of the neurophysiological findings in brachial plexus lesions differs in neonates and adults, possibly due to anatomical differences. As mentioned previously, brachial plexus lesions following breech delivery have a significant degree of intradural root involvement; avulsions may be total or partial. In adult cases, the presence or absence of sensory nerve action potentials (SNAPs) differentiates between root lesions and extraforaminal lesions. In neonates, SNAPs are often difficult to measure owing to the small size of the fingers and hands and to the lack of cooperation. Also, special electrodes have to be used. For further information the reader is referred to Chapter 4 in this volume.

Indications for surgery

We follow Gilbert and Tassin's (Gilbert 1995) criteria, supplemented by those of Clarke and Curtis (1995), to operate when biceps function has not returned at the age of 3 months. Gilbert concluded that babies without a normal deltoid or biceps by the age of three months could not expect a good outcome, and so considered this to be the indication for surgical intervention. We consider this to also be the case when there is evidence of a severe lesion, such as a Horner's syndrome, persisting hypotonic paralysis, persisting phrenic paralysis, and severe sensory disturbances. The neurophysiological and radiological findings may add to the indication to operate but the decision is usually made on clinical grounds, because the radiological findings are sometimes difficult to interpret and neurophysiological changes may give a rosier picture than justified by the patient's final outcome (Gilbert and Whitaker 1991, Clarke and Curtis 1995, Slooff and Blaauw 1996a, Slooff 1997).

Most patients were operated before they had reached 6 months of age (Table 1), although 14 patients were older than 6 months at the time of operation: five were 7 months old, one was 8 months, and two were 9 months. Four underwent surgery at 10, 12, 14 and 16 months, respectively, and two at the age of 21 months. In two patients who had undergone bilateral surgery, the second operation was performed within one month of the first, well before the age of 6 months.

Surgical intervention

The surgical findings were grouped as shown in Table 2. We scored *certain avulsion* when there were one or several exteriorized root ganglia. In the extreme case the ganglion was without any contact with the foramen, but sometimes the motor and sensory roots had some anatomical connection with the foramen, although the

Table 2 Surgical findings

Certain avulsion	5
Probable avulsion	41
No avulsion	8
Neuroma spinal nerve C5	12
Neuroma spinal nerve C6	1
Neuroma upper trunck	10
Neuroma upper and middle trunk	1

Table 3 Surgical interventions

Intraplexal reconstruction	20
Accessory nerve to:	
Suprascapular nerve	39
Other nerve	5
Medial pectoral nerve to:	
Musculocutaneous nerve	19
Anterior division of upper trunk	2
Other nerve	3
Hypoglossal nerve	2
Intercostal nerves to musculocutaneous nerve	2
Other nerve transfer	1

ganglion was clearly visible. When we found one or several soft pale roots which could be traced up to the foramen, without a neuroma and without presentation of the ganglion, and which did not respond to stimulation, we scored *probable avulsion* (avulsion *in situ*), especially when this was supported by the radiological findings. When we found a neuroma, and when the roots responded to stimulation we scored: *no avulsion*; in eight patients there was no avulsion of any root. In eight other patients we found certain or probable avulsion of one or more roots in combination with a neuroma of another root or trunk (Fig. 3).

Table 3 presents the types of primary intervention. Often more than one type of intervention was performed in the same patient. Intraplexal reconstructions required resection of the neuroma and suralis nerve interposition and sometimes this was added with free transplants from supraclavicular nerves. Accessory nerve transfer was performed in 44 surgical cases, mainly to the suprascapular nerve ($n = 39$). In four cases the nerve was connected to the site of entry of spinal nerve C6 to the upper trunk, and in one case of complete avulsion of C6, the accessory nerve was connected to its motor root, and sensory nerves from the cervical plexus to its sensory root. Accessory nerve transfer was combined with transfer of medial pectoral nerves to the musculocutaneous nerve in 17 cases; in one patient motor nerves from the cervical plexus were added to the neurotization; in one, pectoral nerves were also sutured to the axillary nerve. In one patient a secondary nerve operation was performed which required the suturing of intercostal nerves to the musculocutaneous nerve,

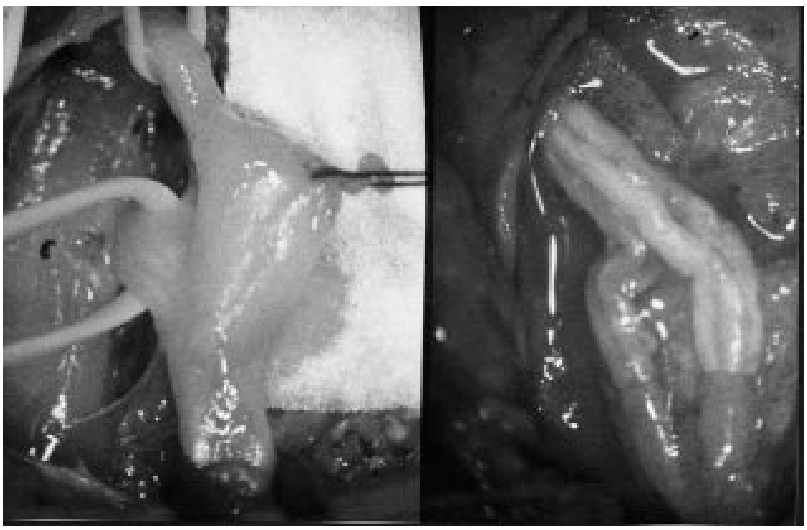

Figure 3

Intraoperative pictures. On the left side the figure shows a neuroma of C5 and a possible avulsion (avulsion *in situ)* of C6. The picture on the right shows the surgical result following resection of the neuroma, and grafting and suturing of C5 to the upper trunk and to the distal stump of C6. (From Blauuw 1999) because of failure of the primary transfer to the musculocutaneous nerve. Also, pectoral nerves were connected to the anterior division of the upper trunk in two cases, to the posterior division of the upper trunk in one case and to the entry of C5 into the upper trunk in another case. The hypoglossal nerve was used to neurotize (Slooff and Blaauw 1996b) the anterior division of the upper trunk twice in order to obtain elbow flexion and to enhance median nerve function. Intercostal nerve transfer was performed twice as stated above, in one case as a secondary procedure. We have added transfer of the cutaneous branch of the musculocutaneous nerve to neurotize the brachioradialis muscle in two patients, who had had a pectoral–musculocutaneous transfer, and this was successful at follow-up.

When a root was regarded as a probable avulsion, our usual attitude was to leave the root in place, so that spontaneous recovery could occur, because of the possibility of avulsion being partial. In these instances we still often performed nerve transfers for shoulder control and elbow flexion at the time of the first exploration. Gilbert (1995) found some kind of spontaneous recovery in 50 per cent of the cases with probable avulsion after breech delivery, ranging from recovery of one muscle to full recovery, supporting the presence of partial avulsion in these cases. When recovery did not take place, he performed a secondary intraplexal neurotization after 1 year.

Table 4 depicts the number and type of secondary surgical procedures. In many patients secondary surgery was not necessary ($n = 39$) due to a good result; in others more than one procedure was performed successively. Although subscapular release and shortening of the coracoid was noted in this table, these procedures are not strictly speaking secondary interventions. Also, re-Steindler should be omitted for similar reasons, so in fact 18 secondary surgical interventions were performed in 11 patients, and in 42 cases no secondary operations as such were necessary. The majority of secondary surgery was performed earlier in this series, possibly because neurotizations for shoulder control and elbow flexion have become standard in the last 7 years. In 10 cases one procedure was performed, in six cases, two procedures and in two cases, three or more. Remarkably in this series, subscapular release was only required in four cases and it is notable that joint contractures rarely occur in obstetrical palsy after breech delivery, especially in the presence of complete or partial avulsion.

Table 4 Secondary surgical intervention

Anterior subscapular release	4
Latissimus dorsi transfer	3
Double transfer	4
Steindler	9
Re-Steindler	3
Surgery for wrist extension	2
Shortening of coracoid	1

Results

For the assessment of postoperative results we used the Mallet scale (Gilbert 1993) (Fig. 4). This

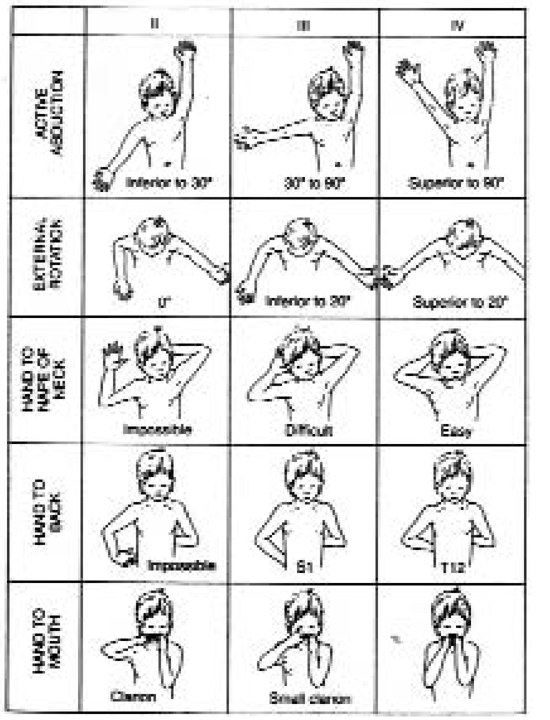

Figure 4

The Mallet scale.

is an assessment of global movement of the extremity, looking at patterns of movement that may be either functional or maladaptive. This scale can be applied in children aged 3–4 years, who can perform voluntary movements reliably on command, scoring shoulder functions as well as elbow flexion. It is particularly useful for assessing results of obstetrical brachial plexus palsy after breech delivery, as in these cases total lesions rarely occur and upper lesions are predominant: in the present series this was 95 per cent ($n = 53$). We used the original five-point scale with score 1 for no detectable function and score 5 when the function was normal, although a three-point scale (as used by Birch) may be more practical taking the original score 2 as score 1, and 4 as 3. In our experience, recovery of shoulder and other proximal muscle re-innervation is largely completed 2 years after nerve surgery. Thus, we report only on cases who have a minimum follow-up of 2 years. Only in the case of secondary surgery will the functions change at later follow-up.

The results of scoring following the Mallet scale are presented in Table 5, which shows that grade 3 was scored 70 times, and grade 4 was scored 155 times. A completely normal function (grade 5) was not scored in any instance and so grade 4 was the maximum score. If all cases had had a grade 4 recovery for the respective Mallet scale functions, the total number of grade 4 scores would have been 265 (5 × 53), hence we may conclude that only in slightly more than half of the cases were grade 4 scores given (58 per cent). In the earlier cases secondary procedures were performed more frequently; the Mallet scores of these are shown in Table 6. The results of the cases where only primary surgery was performed (Table 7) contrasts favourably with these cases.

Accessory nerves were used in 44 cases (83 per cent); in 39 the nerve was connected to the suprascapular nerve. In these patients shoulder abduction of 30–90° (Mallet 3) was found in 17 cases, and abduction of more than 90° (Mallet 4) in 19. Active shoulder external rotation 0–20° (Mallet 3) was present in four of these cases and external rotation of more than 20° (Mallet 4) in 26. This illustrates the effectiveness of accessory–suprascapular nerve transfer.

In the present series, where upper lesions were predominant, the medial pectoral nerve, a branch of the lower trunk, should be regarded as a good alternative for neurotizing the musculocutaneous nerve, and so intercostals were rarely used. According to Gilbert, we score good recovery (M3) when there is full range of active movement. Due to lack of cooperation in babies the MRC five-point scale cannot be used. Good recovery of biceps developed in 17 out of 19 cases having such neurotization. Good voluntary biceps function also occurred in two patients in whom the hypoglossal nerve was used for neurotization.

Table 8 shows the distribution of Mallet sum scores. Scores of 18 or more were regarded as

Table 5 Results of operations in 53 cases of upper brachial plexus palsy scored using the Mallet scale

Grade	*1*	*2*	*3*	*4*
Abduction	3	2	23	25
External rotation		11	7	35
Hand to nape of neck		8	15	30
Hand to back	2	7	11	33
Hand to mouth	2	5	14	32
Total:	7	33	70	155

Table 6 Results of operations in 11 cases of upper brachial plexus palsy scored following the Mallet scale, measuring results of both primary and secondary surgery.

Grade	*1*	*2*	*3*	*4*
Abduction	3	1	6	1
External rotation		3	2	6
Hand to nape of neck		7	4	
Hand to back	2	3	3	3
Hand to mouth	2	1	4	4
Total:	7	15	19	14

Table 7 Results of operations in 42 patients of upper brachial plexus palsy scored using the Mallet scale, measuring results of primary surgery only

Grade	*1*	*2*	*3*	*4*
Abduction		1	17	24
External rotation		8	5	29
Hand to nape of neck		1	11	30
Hand to back		4	8	30
Hand to mouth		4	10	28
Total:		18	51	141

Table 8 Mallet sum scores in 53 cases of upper brachial plexus palsy, measuring results of both primary and secondary surgery

Scores	9	10	12	13	14	15	16	17	18	19	20
Number	1	1	1	2	7	6	1	5	7	11	11

a good result, as was the case in 29 cases (54 per cent), and a fair result, of between 14 and 18 was present in 12 cases (23 per cent). When patients are not able to position their good hand in a good working position, this must be regarded as a poor result. Generally, this is the case when the score is less than 15, as found in 12 cases (23 per cent). The inability to externally rotate forms a major component in this group.

Discussion

Generally, the results of both primary and if necessary secondary operations in this series were rewarding with 54 per cent good results and 23 per cent fair results. In both these groups, most patients are able to position and use their more or less normal hand such that they can function normally, without serious impairment, according to the international classification. In the group that we classified as a poor result, many children were still able to function fairly well by compensating, making the number of cases which were judged as satisfying by parents still greater.

Our finding of the predominance of an upper brachial plexus lesion with a great number of myelographic abnormalities after breech delivery can be regarded as typical for this group. This finding is confirmed by earlier reports (Geutjens et al 1996).

In the present series at primary surgery, we aimed at recovery of externally rotate by neurotization of the suprascapular nerve in a large number of the cases. The figures show that we were successful in a great number of the cases. Also, the rate of recovery of shoulder abduction was significant. There is variability in the subjective appreciation of the functional result between the medical profession on the one hand and the parents and the patients on the other. Patients and parents are entheusiastically positive about the functional result to a greater extent than the medical profession might conclude from the Mallet scale. A reason for this variability may be that although the Mallet scale may show that some children actually do have impairments, these will often not cause children to suffer from disabilities.

The need for intercostal nerve transfer was not great in the present series, because of the successful use of the almost invariably well-functioning medial pectoral nerves, although intercostals can offer a good alternative. In this series intercostal nerves were only used twice. Also, due to the large number of cases of phrenic nerve palsy, we refrained from the use of intercostals, as in these cases intercostal nerve harvesting may increase the danger of respiratory difficulties.

The good results after accessory nerve transfer and pectoral nerve transfer support our attitude that this technique is a particularly useful method in cases of brachial plexus palsy after breech delivery. This is in accordance with an earlier study concerning an evaluation of 119 cases of accessory–suprascapular nerve transfer in obstetrical birth palsy after cephalic or breech presentation (Blaauw et al 1997). Because of these good results, we do not think it justified to use other, often more complicated, techniques for neurotization in obstetrical birth palsy after breech delivery.

Conclusion

Brachial plexus injuries after breech deliveries are associated with a different pattern of injury in comparison with birth palsies after cephalic presentation. The data from this series and from earlier publications (Geutjens et al 1996) show that obstetrical birth palsy after breech delivery is characterized by a high proportion of preganglionic injury (partial or complete avulsion) of the upper roots supplying the brachial plexus, illustrated by traumatic meningoceles in the preoperative myelogram. In our series, in the majority of these lesions, the damaged root had remained in the foramen (avulsion *in situ*). Following this pattern of injury, phrenic nerve lesions and bilateral brachial plexus lesions are almost characteristic complications of a breech delivery.

In this type of injury we found that the early application of selective nerve transfers is important and effective. The combination of accessory–suprascapular and pectoral–musculocutaneous nerve transfers proved particularly rewarding. In a minority of cases in this series, ruptures and neuromas were present, and classical intraplexal reconstruction with sural nerve transplants was necessary and effective, usually added by accessory–suprascapular nerve transfer. Remarkably, in this pattern of injury, development of joint contractures is rare.

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23
Palliative surgery: shoulder paralysis

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Introduction

Treatment of sequelae of shoulder paralysis varies depending on the degree of root involvement and, consequently, the severity of functional impairment.

First, as in all palliative surgery, the main goal is to treat a joint with minimal or no contractures or deformities. Therefore the first step is to treat any such capsular contracture or muscular retraction to make further muscular transfer easy.

In the pre-microsurgical era, the task was to treat spontaneously-recovered obstetric paralysis at an increased age where there was a significant amount of capsular contracture and muscular retraction and imbalance. The results were very seldom satisfactory due to the reduced range of passive movement of the shoulder joint and severe bone deformities. The more recent early microsurgical repairs, as shown by Gilbert (1995), Petrolati et al (1994) and Slooff (1995), allowed better functional results, especially regarding shoulder function, substantially reducing the need for palliative surgery. Nevertheless, the severity of plexus lesions in many cases (upper roots avulsion in breech presentation and total paralysis, in which the upper roots are mainly devoted to reconstructing the lower plexus (Raimondi et al 1998), with consequent partial reconstruction of the upper plexus) leads to the need for secondary surgery. In order to obtain better results, Gilbert and Dumontier (1991) suggested performing very early palliative surgery, either passive as in capsulotomy, muscle sliding or lengthening, or active as in muscle transfers.

Different clinical pictures can be described depending on different situations:

- Complete flail shoulder in breech presentation with C5–C6 avulsion in obstetric brachial plexus palsy (grade 0 shoulder following Gilbert's classification). In these cases there is significant articular instability of the thoracoscapular joint with insufficiency of the muscular couples (flexion–extension and elevation–descent); these facts, together with a complete lack of intrinsic (rotator cuff) and extrinsic muscles (deltoid system), lead to lack of elevation of the arm. These cases do not develop joint or bone deformities;
- Incomplete reinnervation (either spontaneous or following microsurgical repair) but a complete deficit due to extrinsic and intrinsic muscular imbalance and articular deformities. This category can be assumed as grade 0 (Gilbert's classification);
- Incomplete spontaneous recovery with the typical intrarotated arm and different degrees of shoulder abduction, with more or less complete lack of external rotation. The degree of functional impairment varies depending on the degree of recovery of the different muscular groups; thus clinical pictures also vary and it is not always easy to classify them;
- Incomplete recovery following early microsurgical repair (with different degree of deficit; the most frequent deficit is external rotation rather than shoulder abduction).

Although it is not our task here to study the biomechanics of the shoulder joint we must remember the prominent role of the rotator cuff system, which allows the glenohumeral joint to achieve intrinsic stability, complete elevation and external rotation (Celli et al 1985, Comtet et al 1989). This muscular complex, and particularly the supraspinatus muscle, constitutes a functional system that must be reconstructed (Howell et al 1986). This explains the interest in levator scapulae transfer to the supraspinatus in shoulder grade 0 or functionally grade 0 in order to allow the trapezius to deltoid transfer to work better and achieve good abduction in the scapular plane (Saha 1967, 1971).

We know that the latissimus dorsi muscle represents the first-choice transfer as a glenohumeral intrinsic stabilizer. The problem arises in the absence of a strong latissimus dorsi, and in these cases we utilize the levator scapulae muscle as an intrinsic stabilizer.

Joint contracture release

Before undertaking any surgery it is fundamental to treat the internal rotation contracture of the shoulder (Birch et al 1998) that very often appears due to the imbalance in muscular recovery (external rotators generally recover partially or do not recover at all, while internal rotators are usually stronger).

The predominance of internal rotator muscles combined with the absence of deltoid and external rotator muscles produces, with time, posterior subluxation and articular deformity of the humeral head, hypoplastic glenoid fossa retroversion, posterior and inferior traction of the acromion (especially in cases with partial recovery of the deltoid) and lateral and inferior traction of the coracoid process; this will constitute a block to the repositioning of the humeral head into the glenoid fossa and limit the external rotation due to contracture of the coracohumeral ligament. This retracted ligament together with the predominant function of the subscapular, pectoral major and teres major muscles will limit the external glenohumeral rotation.

To avoid all these severe joint deformities, which generally develop after 3–4 years of age, it is essential to treat them early. Gilbert and Dumontier (1991) recommended not waiting for osseous and articular deformities to occur, but rather treating the lack of passive external rotation when it becomes less than 20°. MRI or CT arthrograms are very useful for evaluating the condition of the joint and of the articular surface of the humeral head. It is obvious that if we expect to release the contracture later (at 7–10 years of age or later), when bone deformities have developed, we will not have a good chance of success. In the past Sever's operation (1927) was very popular, but with long-term follow-up we realized that there was a constant and significant lack of internal rotation. Even in lengthening the subscapular tendon, which we performed in the past together with the latissimus dorsi transfer, we could not constantly obtain sufficient external rotation due to the frequent capsular adhesions at the level of the tendon lengthening. Moreover, the reduction or complete lack of internal rotation occurfed very frequently. In the last 8 years we have performed the subscapular release as described by Carlioz and Brahimi (1971) and popularized by Gilbert et al (1988), and (Gilbert and Dumontier 1991), who recommend a very early operation when indicated – that is when the joint is normal and the humeral head is not flattened.

Subscapular release: surgical technique

The baby is positioned in a lateral position on the operating table, with the shoulder elevated by a pillow and the scapula completely free to be moved during the operation. The skin incision follows the external border of the scapula from the posterior pillar of the axilla to the tip of the scapula, while the shoulder is maintained in abduction by an assistant. The latissimus dorsi is then moved posteriorly and the border of the scapula exposed. Gilbert suggests transfixing the tip of the scapula by a strong suture, which can easily allow tension of the bone during the release. The subscapular muscle is then detached from the scapula, starting from the lateral border and by blunt dissection from all the anterior surface of the scapula (Fig. 1). If the muscle is not detached entirely from the scapula, the desired external rotation release will not be obtained; for this reason special care must be taken in detaching it both from the inner border and the angle of the scapula, remembering that at the superior border injury to the suprascapular nerve at the notch must be avoided. We then try to externally rotate the shoulder; sometimes this can be achieved only after progressive and relatively forced maneuvers, which finally release the possible associated capsular contractures. This is generally the case in older patients with more fixed capsular contractures.

Figure 1

Under the retractor the lateral border of the scapula is visible, from where the subscapular muscle has been detached.

One or two suction drains are recommended as a certain degree of bleeding often occurs from the periosteal vessels, which cannot be electrocoagulated, especially in the inner or upper part of the muscular detachment.

The arm is then immobilized in external rotation with the shoulder adducted for 3 weeks.

Once complete passive external rotation has been obtained, a spontaneous recovery of active external rotation due to the reinforcement of weak external rotator muscles will be observed over a period of a few months. This occurs in at least 30–40 per cent of cases, and is the reason why we never perform subscapular release and tendon transfer in the early cases. In late cases (at 4 years or more), where recovery of the external rotators cannot be expected, the two operations can be performed at the same time.

Regarding muscle transfer, two main different situations can occur as already mentioned: a transfer in a complete flail shoulder where no capsular contractures are present, or transfer in an incomplete shoulder recovery; in the former a double muscular transfer will be necessary, while in the latter often a subscapular release first and, in a second stage, a latissimus dorsi transfer will be required.

Transfers in grade 0 shoulders

The role of the scapulothoracic joint

As already mentioned, this type of reconstruction is performed either following breech presentation outcomes (total flail shoulder) or in shoulders in which, despite a certain degree of reinnervation, the functional results correspond to grade 0 in Gilbert's classification. The only difference is that in flail shoulder neither bone deformity nor capsular contracture are present while in the second group they are always present to some degree.

Correct function of the thoracoscapular joint is fundamental, as it allows correct orientation and thus greater mechanical advantage in the glenoid fossa. The combined movements of scapular bascule are based on a muscular couple constituted by the serratus inferior and rhomboid; scapular suspension is based on the couple levator scapulae and lower trapezius; thoracoscapular cohesion in protraction–retraction movements controlled by the couple constituted by the middle trapezius and middle serratus allows adequate positioning of the glenoid fossa during the movement of elevation of the arm, projecting the superior external angle of the scapula forward, upward and laterally. This reorientation places the intrinsically unstable articular scapulohumeral surfaces in a position of maximal congruency and mechanical advantage, allowing the glenohumeral stabilizing action of the rotator cuff.

The normal function of the thoracoscapular joint depends on the integrity of the cervical plexus responsible for innervation of the levator scapulae, the dorsal scapular nerve for innervation of the rhomboids, and Bell's nerve for innervation of the serratus anterior muscle.

A full clinical examination of the thoracoscapular muscles helps us to assess the possible outcome of secondary reconstructive surgery of the glenohumeral complex in cases without deltoid and rotator cuff function.

In sequelae of obstetric brachial plexus palsy, either with partial or absent spontaneous recovery and in early operated cases with poor recovery, a scapulohumeral rhythm at a cortical level has never been integrated by the patient. If we assume this, the transfer of the upper trapezius to the deltoid will never manage to supply this complicated functional system: it only pretends to put this primitive elevation mechanism acquired by the patient himself in a more favourable distal insertion. Transferring the acromial insertion of the upper trapezius as near as possible to the original insertion of the deltoid to the humerus converts this muscle from a thoracoscapular muscle to a thoracohumeral one, thus jumping two joints.

Consequently in cases in which the inferior scapular angle and the inner border of the scapula are not under the control of the serratus-rhomboid system (which happens in complete flail shoulder for upper roots avulsion), the action of the transfer will have repercussions on the scapuloglenoid system in such a way that, during the superior translation of the humeral head, it will project the head against the acromion, elevating the superior external scapular angle. As a consequence of this concept of functional anatomy of the shoulder, we can understand why the possibilities offered by secondary reconstructive surgery are limited. The presence of structural deformities which still preserve a passive range between 110° and 120° of elevation may not influence the results of palliative surgery. Limitations of passive range of external rotation may be an influence in those patients in which the transfer allows an elevation of 90°. When they reach 90° of abduction, the great tuberosity is in conflict with the acromion, blocking the progression of the elevation movement.

Levator scapulae transfer

The levator scapulae muscle arises from the transverse processes of the atlas and the axis and the posterior tubercles of the transverse processes of the third and fourth cervical vertebrae by means of four independent tendons. The first tendon is usually the biggest, and covers the others. These insertions are usually fused with the longissimus capitis and splenius cervicis tendons posteriorly, and with the middle scalene muscle anteriorly. The distal insertion of the levator scapulae is at the border of the upper angle of the scapula. This attachment is made up of short tendinous fibers, which overlap the costal surface of the serratus anterior fascia.

The blood supply of the muscle is multisegmentary. The upper part is vascularized by the ascendent cervical artery (terminal branch of the thyreo-cervical trunk), and sometimes by branches of the vertebral artery. The middle part of the muscle is supplied by the transverse cervical artery, posterior scapular or deep transverse cervical arteries (a collateral of the subclavian artery). The lower part of the levator scapulae is vascularized by the inferior scapular artery, and the anastomotic system with the posterior scapular artery.

The nerve supply is also multisegmentary. The cervical plexus provides from one to four motor branches and two to four anastomotic loops. The cervical branches arise from beneath the posterior border of the sternocleidomastoid muscle following a craniocaudal direction (downward). The dorsal scapular nerve had branches to the muscle in less than 50 per cent of the specimens in our cadaveric study.

Due to its very proximal innervation, the levator scapulae muscle always functions, even in very severe total plexus lesions. This fact allows us to utilize this transfer as a glenohumeral intrinsic stabilizer when no latissimus dorsi is available.

Surgical technique

With the patient in lateral decubitus, the surgical approach is through a vertical incision parallel to the inner border of the scapula, continuing with an incision following the scapular spine to the deltoid region. Detaching the trapezius to allow its simultaneous transfer to the deltoid allows exposure of the upper part of the vertebral border of the scapula and consequently, the scapular insertion of the levator scapulae muscle. The levator scapulae is detached from the scapula with a long strip of periosteum along the inner border of the scapula (until the inferior angle) in order to obtain a long tendon for its distal reattachment to the greater tuberosity. It is important to be careful of the nerves and vessels for the rhomboid, which lie in a deeper and more medial plane compared to the levator scapulae; the surgical plane between the levator scapulae and the rhomboid is a very safe plane as nerves and vessels for the levator scapulae reach the muscle anteriorly. Special care must be taken when detaching the muscle at its distal insertion to the upper medial angle of the scapula; it is important to try to maintain a sufficiently strong continuity between the muscle and its prolongation through the periosteal strip. After detaching the levator scapulae from the scapular angle with its periosteal prolongation, it is sufficient to free it proximally no more than 2–3 cm until we can see that the direction of the transplant is completely straight and in line with the greater tuberosity.

The distal insertion to the greater tuberosity in children is done using 3-0 or 4-0 nylon, while in adults a bone-to-bone fixation is used for a stronger insertion, harvesting a piece of bone from the scapula at the end of a periosteal strip so that it can be fixed with a screw to the greater tuberosity.

After detaching the periosteal strip from the scapula, the rhomboid must be reinserted to the scapula in order to preserve its function (remember that rhomboid, together with serratus, is responsible for bascule movements of the scapulo-thoracic joint).

Trapezius transfer: surgical technique

As the trapezius transfer is normally performed in conjunction with levator scapulae transfer, the previously described incision following the scapular spine is used, continuing in a straight line following the middle deltoid to the region of its insertion to the humerus. In this way the proximal insertion of the deltoid to the acromion and the distal insertion of the trapezius are exposed.

The trapezius is detached from the overlying skin using electrocautery, as there may be bleeding from the numerous cutaneous vascular branches.

The trapezius is detached from the spine of the scapula, taking care to spare the spinal nerve for the middle and lower trapezius, which lies 2 cm medially to the scapula border in the muscular mass of the trapezius; this nerve can easily be damaged by traction and coagulation. Different opinions have been expressed regarding the distal bone detaching from the acromion. If the acromion is to be preserved, complete detachment of the superior trapezius is necessary in order to project the distal insertion as distally as possible.

Saha has described transfer of the trapezius in poliomyelitis patients, in which the acromion was sectioned with the external extremity of the clavicle, sparing the insertion of the coracoclavicular ligaments. A piece from the bone of scapular spine and acromion sufficiently wide to allow a strong and safe distal insertion are thus obtained. After detaching it from the acromion and from the scapular spine, the trapezius is submitted to gentle traction in order to detach it from the underlying supraspinatus muscle and free it completely. The deltoid, previously detached from its proximal insertion, is retracted, and the trochiter is exposed. At approximately 2 cm distal to the trochiter the bone cortex is rasped for 2 mm in depth in order to prepare for reinsertion of the piece of acromion included in the trapezius transfer. This piece of acromion has to be decorticated on its lower surface (articular surface). The distal insertion may be performed with two screws (in adults) or with non-absorbable suture, e.g. nylon, in children. The point of insertion may vary depending on circumstances and need; if anteversion (external rotation) is required the distal insertion will be located in a more anterolateral position; if more internal rotation is required (a very rare situation) the insertion will be more posterolateral. Throughout this time the arm must be maintained in abduction to avoid stretching of the trapezius muscle fibers. When the trapezius transfer has been completed over the previous transfer of the levator scapulae, the deltoid is reinserted over the trapezius transfer to re-establish a better profile of the shoulder, improving the cosmetic aspect.

Two drainage tubes are positioned, one in the lower angle of the scapula and the other under the trapezius, and the subcutaneous and skin suturing is completed.

Immobilization in a plaster cast with shoulder abduction of 90–100° and in external rotation of 50–60° is maintained for five weeks.

Comments

Despite different techniques of tunneling and reinforced insertion, the insertion of the trapezius to the humerus in some cases undergoes dehiscence requiring re-operation. Moreover, the sparing of the acromion together with the long period of postoperative immobilization favors the development of adhesions, which in some instances lead to the need for reintervention. On the other hand, the preservation of the acromion prevents cranial translation and subluxation of the humeral head, favoring a pulley which improves the axis of traction of the levator scapulae after its transposition to the supraspinatus. Nowadays we detach only a piece of acromial bone, sparing the acromial vault.

In some cases early results showed 110–120° of elevation of the arm, which later stabilized at 80–90°; in other cases after growth, augmentation of weight and lack of a correct and ongoing rehabilitation program, there was a significant loss of abduction to 60°.

In the situation of performing the transfer of the upper trapezius following Saha's technique with no stable scapulothoracic joint, transposition of the levator scapulae will not produce a centering action of the humeral head, but it will produce traction of the humeral head with a conjoint movement of rotation of the glenohumeral joint and elevation of the upper external scapular angle.

The synergy of function between the upper trapezius and the levator scapulae makes their conjoint action easy, strengthening the action of elevation of the shoulder and contralateral spine lateralization, which is normally cortically integrated very well by these patients.

In obstetric brachial plexus palsy, we could never obtain the same results as Saha (1967, 1971) showed in his polio patients in terms of abduction and external rotation. Nevertheless, a grade 0 shoulder that can reach an average elevation of 80–90° with a tenodesic external rotation of 20–30° has been considered satisfactory.

In a second operation, we can adjoin the latissimus dorsi transfer to the infraspinatus in order to obtain a degree of active external rotation. This transfer is done through a posterior approach to the rotator cuff, as will be described later.

Palliative surgery in a partially functioning shoulder (shoulder grade II–III)

The following transfers are indicated in patients with grade II or III shoulders (Gilbert's classification); that is, in patients with partial recovery of abduction and partial or absent recovery of external rotation. Schulze-Berge (1917) was the first to suggest a transfer of the latissimus dorsi as an external rotator, but it is thanks to L'Episcopo (1934) that the technique has been popularized, associated with a section of both subscapular and pectoralis major muscles as suggested by Sever. Hoffer et al (1978) modified the distal insertion of the transfer of the conjoint tendon of both latissimus dorsi and teres major to the rotator cuff at the point of insertion of the teres minor muscle.

The ideal indication is in cases with a more or less good abduction having a deltoid of strength M4, but with a weak or absent external rotation. Of course the latissimus dorsi that is to be transferred must also be of sufficient strength.

It is evident that a capsular contracture or muscular retraction must be treated in order to avoid fixed deformity of the shoulder joint. Today it is easier to establish a correct algorithm with early treatment of articular deformity and to perform the transfer as a second stage. Frequently after an early subscapular release there is a substantial improvement in active external rotation thanks to the re-establishment of correct muscular balance, which allows reinforcement of a weak external rotator.

In some instances the patients present very late, after a spontaneous partial recovery and with a significant degree of fixed shoulder deformity. In these cases the treatment would be simultaneous tendon transfer and correction of the deformity by means of tendon lengthening or muscular release. This was our experience until the late 1980s; at that time the technique we utilized was transfer of the latissimus dorsi (through a unique anterior approach) with associated coracoid osteotomy and subscapular release if necessary (Morelli and Saporiti 1985).

Latissimus dorsi transfer

Anterior approach

The skin incision follows the deltopectoral groove, running in the axilla up to the lateral border of the scapula. Osteotomy of the coracoid process is performed and the three muscles inserted onto it are reflected. The subscapularis tendon is completely exposed. At the scapular border the subscapular muscle is detached subperiosteally from the anterior plane of the scapula, as already described. If this is insufficient and resistance to the passive external rotation continues to exist, the subscapular tendon is lengthened, taking care to avoid opening the glenohumeral joint and causing anterior luxation of the humeral head.

Once the problem of contractures is solved, we move on to the transfer. In the past we usually utilized the transfer with the conjoint tendon of latissimus dorsi and teres major; some authors prefer to separate the tendon of the teres major from that of the latissimus dorsi (Gilbert et al 1988, Gilbert and Dumontier 1991). Until the end of the 1980s we utilized the conjoint tendon, which was sectioned as near as possible to its bone insertion. The deltoid muscle is elevated, creating a passage for the tendon from behind up to the rotator cuff. The arm is internally rotated in order to reach the insertion point of the teres minor. The conjoint tendon of teres major and latissimus dorsi is then passed from behind under the deltoid, and is fixed with two stitches of 2-0 or 3-0 nylon to the point of insertion of the teres minor muscle to the rotator cuff. The stitches are secured with the arm in maximal internal rotation. If the coracoid has been detached, it is wired in its original position after having shortened 1–1.5 cm. A plaster cast immobilizes the arm in 100° of abduction and maximal external rotation with the elbow flexed at 90° for five weeks.

These associated static and dynamic operations in the past gave relatively good results, considering the associated longstanding deformity. Today this reconstructive strategy has changed thanks to a better algorithm with the early treatment of postural deformities.

The operation we prefer, when passive mobility of the shoulder allows it, is the isolated transfer of the latissimus dorsi to the external rotators.

Posterior approach

Nowadays we utilize only the posterior approach; the patient is positioned in lateral decubitus on the opposite, healthy side. The skin incision runs from the posterior border of the deltoid through the posterior pillar of the axilla and follows the inner border of the scapula. The latissimus dorsi tendon is detached from the humeral shaft and the muscles isolated for a few centimeters downwards, which allows better movement upwards to the new insertion (Figs 2 and 3). We prefer to isolate the neurovascular bundle in

Figure 2

The common tendon of the latissimus dorsi and the teres major has been divided and the difference in length of the two tendons is easily visible: the latissimus dorsi tendon can now reach a higher point than the teres major.

Figure 3

In this case the teres major tendon has been transferred to the infraspinatus and the latissimus dorsi passed beneath the posterior deltoid and transferred to the supraspinatus.

order to avoid possible tension or lesions. The humeral head and the rotator cuff are exposed through a transdeltoid incision following the muscle fiber direction. The tendon is passed under the posterior deltoid and then reinserted as high as possible onto the rotator cuff. The tension of the transplant has to be sufficient, while the arm is maintained in a 120° of abduction and maximal external rotation; the distal insertion is generally performed with a non-absorbable suture (generally a 3-0 nylon). As usual, a plaster cast is used for five weeks.

Regarding the utilization the isolated tendon of latissimus dorsi or the conjoint tendon of latissimus dorsi and teres major, we agree that the course of the two tendons is different (Fig. 2), and moreover the teres major is inserted onto the scapula and limits the ascent of the latissimus dorsi. This fact suggests separating the two tendons and utilizing the tendon of latissimus dorsi alone, sectioning the union with the teres major tendon. In some instances, when the latissimus dorsi does not seem too strong, it can be supported by the teres major: in this case the tendon is divided and, after gliding to re-establish the correct relationship lengthwise, the teres major tendon is fixed once again to the latissimus dorsi but at a lower point. This trick (suggested by Gilbert) allows joining of the two forces, avoiding elevation of the scapular angle.

Results

The results differ depending on the preoperative findings (Figs 4, 5, 6). In paralytic shoulder the real difficulty is not the surgical technique, but rather the correct clinical preoperative evaluation, and therefore the best surgical indication. We want to emphasize that there is no indication in severe bone and joint fixed deformities. In these cases the indication may be for a static operation such as an external rotation corrective humerus osteotomy.

To evaluate the results, we must differentiate the transfer for grade 0 shoulder or functionally grade 0 from the transfers for the shoulder with some function spared or recovered. We utilize Gilbert's scale rather than Mallet's scale because it appears that the functional evaluation is more strictly related to the shoulder function (abduction and external rotation).

Table 1 Results of transfer of the latissimus dorsi

Preoperative grade (patients)	*Postoperative grade (patients)*
I (9)	II (2)
	III (3)
	IV (4)
II (31)	III (14)
	IV (17)
III (3)	IV (3)

Personal experience with the transfer of the latissimus dorsi in 43 patients with different degrees of deficit ranging from grades I to III (Morelli and Saporiti 1985) gave the results shown in Table 1.

On the whole we obtained two grade shoulders II (4.6 per cent), 17 grade III shoulders (39.5 per cent) and 24 grade IV shoulders (55.8 per cent), which represents an important functional improvement as compared to the preoperative situation: nine cases of grade I shoulders (20.9 per cent), 31 grade II shoulders (72.1 per cent), and three grade III shoulders (7 per cent).

The first conclusion when looking at these results is that all the patients improved their function with surgery. Of course the results are related to the severity of the preoperative situation. Moreover, in this series published in 1985, 35 per cent of cases had significant joint deformities, mainly due to late surgical treatment. This can explain the relatively poor results obtained in the group shoulder grade I.

Another conclusion, made retrospectively, is that we operated only a few patients with a grade III shoulder: this means that, at least in the past, a grade III shoulder was considered sufficient from the functional point of view, and that parents were not so inclined to undergo a surgical operation with the possibility of only a limited functional upgrading. Nowadays of course we suggest transfers more often in these cases, as we are aware of the good results obtainable.

In a series of 44 patients operated using transfer of the latissimus dorsi alone and by a posterior approach, Gilbert et al (1988) achieved, in most cases, a considerable improvement in active external rotation; even grade IV shoulders (where we generally do not advise surgery) could

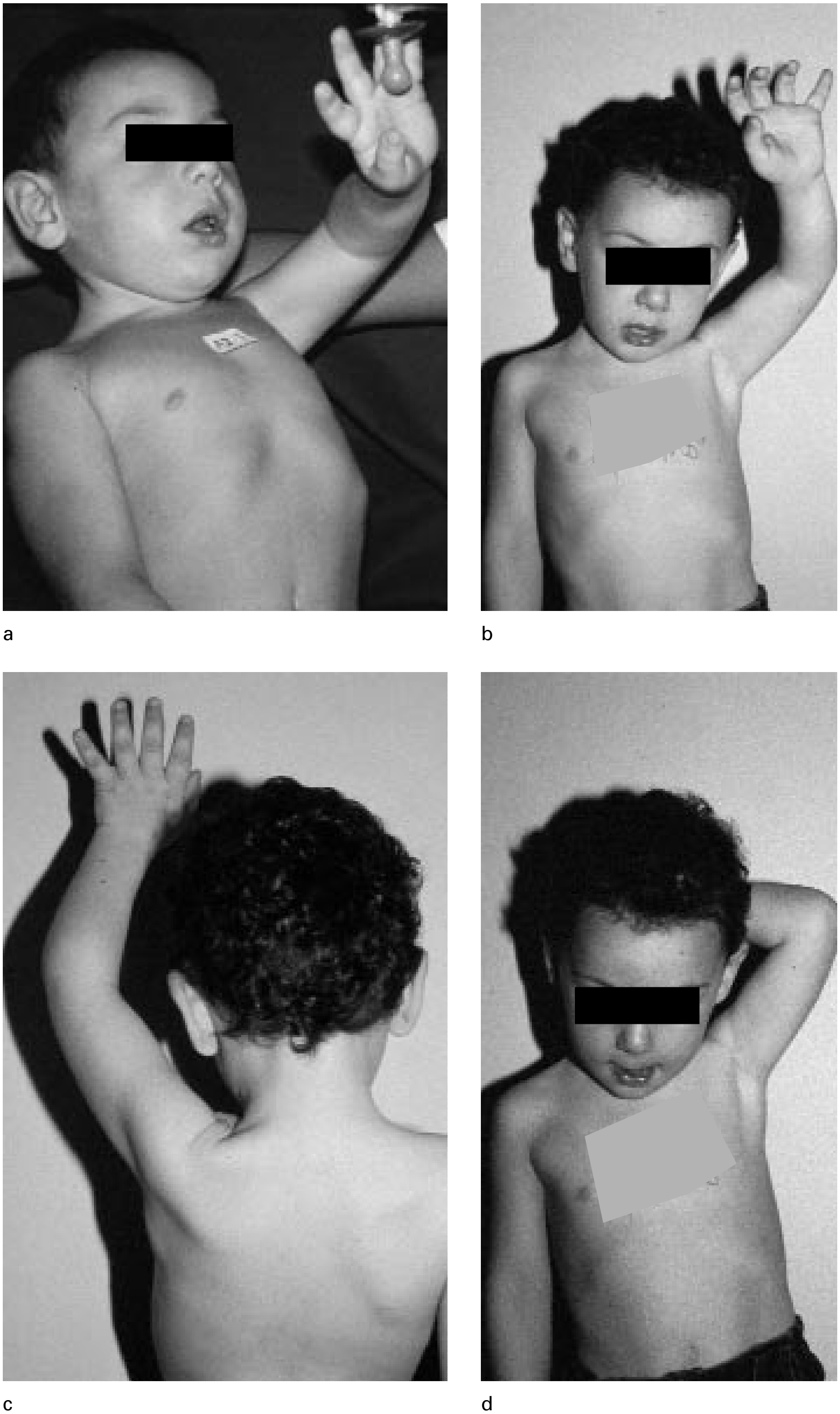

Figure 4

(a) An 18-month-old child with a spontaneously recovered OBPP with 95° of shoulder abduction and no external rotation, neither active nor passive due to a marked retraction of subscapular muscle and anterior capsular contracture (Gilbert grade III shoulder). A subscapular release and latissimus dorsi transfer to the rotator cuff have been performed with a single antero-lateral surgical approach. (b–d) The patient 2 years after surgery, with good recovery of active external rotation and a significant improvement in shoulder abduction. The scar is hardly visible at the lateral border of the scapula, the axilla and the deltopectoral groove.

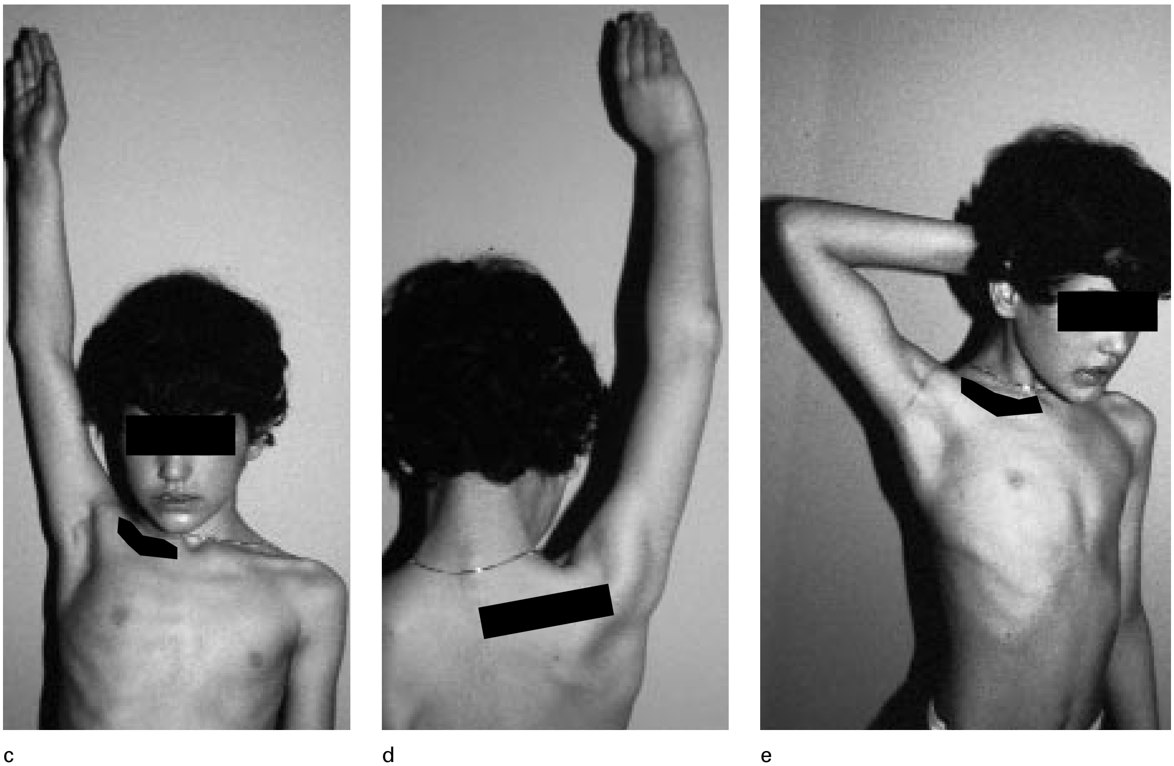

Figure 5

(a,b) An 8-year-old boy with a spontaneous recovered OBPP with 90° of shoulder abduction, no external rotation and severe capsular contracture and subscapular muscle retraction (Gilbert shoulder III). Through an antero-lateral approach a subscapular release from the scapula, a coracoid partial resection and latissimus dorsi + teres major muscle transfers to the rotator cuff have been performed. (c–e) Very good active external rotation and shoulder abduction 2 years after surgery.

Figure 6

(a,b) A 12-year-old boy with spontaneous evolution of a severe total OBPP with a shoulder grade 0. Shoulder palliative surgery had been indicated due to the presence of some function at the hand. A triple transfer has been performed: (c) The trapezius transfer is lifted up with a piece of acromion, while underneath the levator scapula has been harvested with a periosteal strip to reach the supraspinatus insertion; laterally, the latissimus dorsi has been prepared for transfer to the infraspinatus. (d–f) Functional result 1 year later. The patient can achieve 95° of abduction in the scapular plane, a satisfactory result if we consider that it has given an upgrade from a grade 0 shoulder to a grade III shoulder. The lack of elbow extension is now the main problem.

reach an average of 35° of external rotation. Of 23 cases of grade III shoulders, 13 could obtain an average of 45° improvement in shoulder external rotation (upgrading to grade IV shoulder) and four obtained an average improvement of 36°. Of five cases of grade II shoulders only two upgraded to grade III. In a more recent series, Gilbert and Haerle (in publication) have followed 122 cases with a minimum of 3.8 years follow-up and an average of 5.9 years. Of these 122 cases, 52 had been operated after C5C6 paralysis, 47 after C5C6C7 paralysis, 3 after C5C6C7C8 lesions, and 20 following complete paralysis. On average, the transfer had been done 3.2 years after the plexus repair. The average improvement in abduction was 29° after 1 year, 31° after 3 years, but only 15° after 5 years, showing the late deterioration of the result, probably due to disuse. The results regarding external rotation were almost constant, with an 83 per cent improvement at five years.

Results for grade 0 shoulders

A different situation is found in terms of results in the cases of transfer in grade 0 shoulders.

We studied a series of 27 patients with a grade 0 shoulder in which we performed the following type of secondary reconstruction:

Levator scapulae transfer	1 case
Trapezius + latissimus dorsi + levator scapulae	16 cases
Trapezius + levator scapulae	6 cases
Trapezius + teres major + latissimus dorsi + levator scapulae	4 cases

The following results were achieved.

Latissimus dorsi + trapezius + levator scapulae (16 cases)

Spontaneous recovery	*Cases*	*Results*	*Complications*
Good scapulo-thoracic	12	Gilbert grade III 11 cases	Myolisis 1 case
Deficit of scapulo-thoracic	0		

Post-microsurgery	*Cases*	*Results*	*Complications*
Good scapulo-thoracic	2	Gilbert grade III 2 cases	No
Deficit of scapulo-thoracic	2	Gilbert grade II 2 cases	No

Trapezius + levator scapulae (six cases)

Spontaneous recovery	*Cases*	*Results*	*Complications*
Deficit of scapulo-thoracic	6	Gilbert grade II 6 cases	No

Trapezius + latissimus dorsi + teres major + levator scapulae (four cases)

Spontaneous recovery	*Cases*	*Results*	*Complications*
Good scapulo-thoracic	3	Gilbert grade III 3 cases	No

Post-microsurgery	*Cases*	*Results*	*Complications*
Deficit of scapulo-thoracic	1	Gilbert grade II 1 case	No

Levator scapulae (1 case)

Post-microsurgery	*Cases*	*Results*	*Complications*
Good scapulo-thoracic	1	Gilbert grade III 1 case	No

It is evident that in this category of patients the results are less good than in the previous group; in the cases with the best results we managed to reach grade III of Gilbert's classification. The external rotation obtained is characteristic of a dynamic tenodesis effect and is approximately about 20°, and 30° as an integrated movement in the elevation of the arm in the scapular plane with a tendency to flexion in the sagittal plane. In the poorest cases the shoulder achieved good stability, which could help elbow flexion and shoulder abduction, with projection of the hand between 30° and 60° allowing a totally useless arm to be transformed into a useful support to the contralateral healthy arm.

The main problem is the progressive impairment of function with time that was observed in a certain number of cases. After surgery we normally immobilize the shoulder with plaster for five weeks, and the plaster or a splint is then maintained for at least three months and removed temporarily only for the rehabilitative active and passive exercises. Later on, following complete removal of the splint, the patients are submitted to a rehabilitative program, with special care not to force adduction and internal rotation, for one or two more months. We try in this way to avoid functional overcharge of this new muscular system, which can gradually return to its preoperative situation. During the immediate postoperative period and later on during the first months of the rehabilitation program there is a high risk of myolisis. In some cases we have been forced to reoperate the patient and start the rehabilitation program again.

The key to good, long lasting results is the presence of correct scapulo-thoracic motorization, which allows stabilization of the scapular suspension and bascule. This facilitates the combined action of these muscles, avoiding the overcharge provoked by the conjoined elevation of the humerus and of the superior external angle of the scapula due to the action of active mobilization of the inferior scapular vertex.

Conclusions

Palliative surgery in obstetric brachial plexus paralysis must not be considered as an obsolete treatment. We are aware that early microsurgical repair of the brachial plexus leads to substantial improvement in terms of functional results as compared to a spontaneous late recovery. Nevertheless, in many instances it is still necessary, especially for the shoulder area, to perform muscular transfers to improve the results further. This is especially true in avulsion lesions of upper roots or in total paralysis, in which the upper roots are mainly devoted to reconstruction of the lower plexus.

Generally the results are much better than those obtained in the past using palliative surgery alone.

What has changed is the global strategy in obstetric paralysis treatment: early microsurgical repair plays the most important role, as it gives the child the unique opportunity to recover to the best degree and especially in total paralysis, it gives the opportunity of recovering useful hand function. However, palliative surgery plays such an important role in the general reconstructive planning that the surgeon who performs microsurgery must already have in mind all the possible surgical steps and the correct timing to realize them.

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24
Palliative surgery: tendon transfers to the shoulder in children

Aydın Yücetürk

Introduction

The first description of obstetrical birth palsy was given by Smellie in 1764. Duchenne in 1872 and Erb in 1874 described upper brachial plexus palsy, and in 1885 Klumpke gave accounts of palsy, its lower part which includes C8 and T1, and of complete palsy. Twenty years later, Fieux questioned Erb's theory, believing that the lesion is caused by overstretching (Egloff et al 1995).

It is generally accepted that obstetrical brachial plexus palsy occurs as a result of extreme lateral traction on the head of the infant away from the shoulder during the last phase of the delivery. According to Metaizeau et al, a force of between 20 and 40 kg is necessary to produce a lesion (Clarke and Curtis 1995). Most of the these injuries resolve without operative intervention, and patients recover with minor or no residual functional deficits. Twenty-five per cent of estimated nerve fibres within the brachial plexus pass to the shoulder girdle (Birch 1995). Shoulder and scapular muscle innervations are shown in Tables 1 and 2.

Most infants who show signs of recovery in the first month generally have normal function, but if they do not recover in the first month of life they have a considerable risk of long-term limited strength and range of motion. As the delay in recovery extends, the risk increases proportionately (Waters 1997). A number need plexus repair. The clinical examination is important and EMG predictions frequently have no clinical correlation in infants. If recovery of the biceps has not begun at three months, the functional prognosis is poor and plexus repair is indicated (Gilbert et al 1991, Gilbert 1995, Yücetürk 1996, Waters 1997, Chen et al 1999).

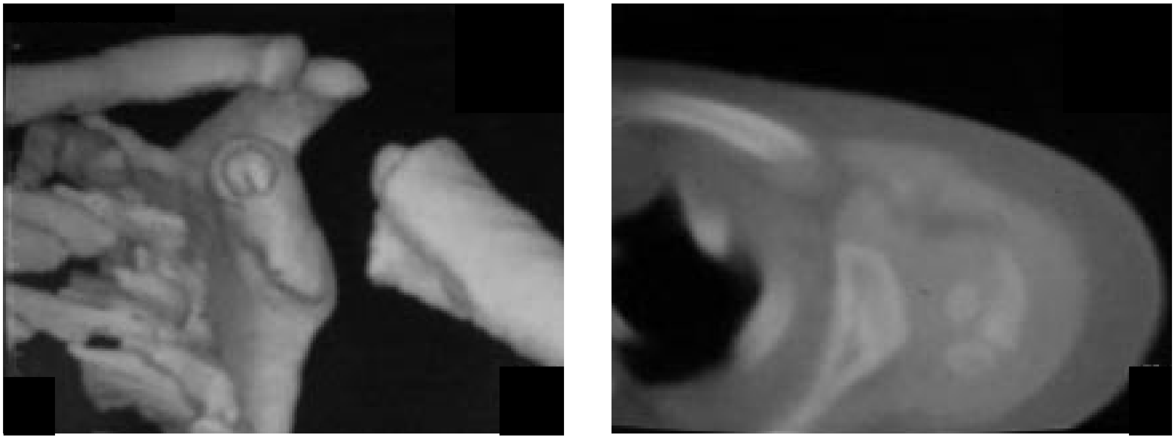
Table 1 Shoulder muscles and innervations (Kendall et al 1993)

Flexors: anterior deltoid (C5–6), biceps (C5–6), pectoralis major upper (C5–6–7), coracobrachialis (C6–7)
Abductors: deltoid (C5–6), supraspinatus (C5–6) biceps long head (C5–6)
Lateral rotators: infraspinatus (C5–6), teres minor (C5–6), posterior deltoid (C5–6)
Extensors: posterior deltoid (C5–6), teres major (C5–6–7), latissimus dorsi (C6–7–8), triceps long head (C6–7–8–T1)
Adductors: pectoralis major (C5–6–7), teres major (C5–6–7), latissimus dorsi (C6–7–8), triceps long head (C6–7–8–T1)

Table 2 Scapular muscles and innervations (Kendall et al 1993)

Abductor: full flexion: serratus anterior (C5–6–7–8)
Lateral rotators: serratus anterior (C5–6–7–8), trapezius (nerve XI – accessory) and ventral ramus (C2–3–4)
Adductor: full abduction: trapezius (nerve XI – accessory) and ventral ramus (C2–3–4)
Lateral rotators: trapezius (nerve XI – accessory) and ventral ramus (C2–3–4), serratus anterior (C5–6–7–8)
Adductors: medial rotators and elevators – full extension: rhomboids (C4–5), levator scapula (3–4–5)
Ant. tilt of scapula by: pectoralis minor (C6–7–8–T1)
Adductors: to side against resistance: rhomboids (C4–5), trapezius (nerve XI – accessory) and ventral ramus (C2–3–4)

The characteristic posture of the shoulder following upper type obstetrical birth palsy is one of internal rotation and limited abduction. The primary abductors, the supraspinatus and deltoid muscles are affected.The powerful external rotator infraspinatus, is also palsied or paralysed. The shoulder external rotator may be



a b

Figure 1

(a) 3D CT of the shoulder dislocation; (b) CT of the shoulder subluxation.

functioning but its force is not enough against the strong internal rotators and shoulder adductors such as the pectoralis major, subscapularis, teres major and latissimus dorsi (Hentz 1999, Waters and Peljovich 1999).

Motion about the shoulder requires the coordinated moment of four joints and over 20 muscles. Thirty-three per cent of shoulder elevation is from the scapulothoracic joint. Saha believed that good elevation requires prime mover (deltoid or pectoralis major), steering group (supraspinatus, infraspinatus and subscapularis) and depressor group (pectoral head of pectoralis major, latissimus dorsi, teres major and teres minor muscles) (Price and Grossman 1995).

Biceps recovery at later than three months generally needs secondary surgery (Gilbert et al 1991, Gilbert 1995). Waters documented the natural history of brachial plexus birth palsy in relation to the recovery of biceps function. Infants who had recovery of biceps function during the fourth, fifth or sixth months of life later had significantly worse function, according to the criteria described by Mallet, than those who had recovery in the first three months (Waters and Peljovich 1999, Waters 1999). According to Gilbert, after plexus repair one third of Erb's palsy patients need secondary surgery (Gilbert 1995).

Shoulder problems in obstetrical birth palsy

In 1913 Fairbank focused on the frequency of subluxation of the shoulder in obstetrical birth palsy. Moore, in 1939, noted that internal rotation contractures with external rotation palsy are often associated with a posterior dislocation (Egloff et al 1995; Fig. 1). Babbitt and Cassidy described anterior and inferior dislocation of the shoulder related to a dynamic phenomenon of muscular imbalance, and according to their observations dislocation took place during the first six months (Egloff et al 1995).

Table 3 Historical review of different techniques for shoulder tendon transfers

Pectoralis major transfer	Hildebrandt (1906)
Trapezius muscle transfer	Hoffa (1902) Bateman (with acromium and spina scapula bone bloc)
Short head of biceps	Ober (1944)
Latissimus dorsi	'Episcopo (1934), Hoffer (1978)
Multiple muscle transfers	Harman (1950)

Figure 2

Glenohumeral deformity black arrow: lengthened coracoid; white arrow: sometimes forceful external rotation results with air arthrogram.

Table 4 Shoulder paralysis (Gilbert grading system)

Stage 0	Complete flail shoulder
Stage 1	Abduction 45°, no external rotation
Stage 2	Abduction <90°, no external rotation
Stage 3	Abduction =90°, weak external rotation
Stage 4	Abduction <120°, incomplete external rotation
Stage 5	Abduction >120°, active external rotation

Table 5 Evaluation of external rotation

Negative:	Absent external rotation	–45°
Insufficient:	Weak active external rotation	–30°,–20°
Fair:	External rotation until neutral	0°
Good:	External rotation beyond neutral	+20°,+30°
Excellent:	Complete external rotation	+45°

Since the main problem of the shoulder in obstetrical birth palsy is muscle imbalance, a great number of techniques and modifications have been described (Table 3).

Shoulder abnormalities

Abnormalities in the shoulder after obstetrical birth palsy include: poorly formed and hypoplastic humeral head; a short, abnormally formed clavicle and a hypoplastic elevated scapula with a shallow glenoid fossa; an inferiorly directed coracoid process; an abnormally tapered acromium, and subluxated shoulders (Pollock and Reid 1989, Waters et al 1998, Ogawa et al 1999; Fig. 2). As in Figure 2 sometimes forceful external rotation results with air arthrogram.

Contractures and shoulder dislocation

Internal rotation and adduction contractures develop at the glenohumeral joint because of muscle imbalance. Shoulder paralysis (Gilbert grading system) and evaluation of external rotation are important for the treatment and follow-up (Tables 4 and 5). As time passes, progressive deformity occurs in the glenohumeral joint and sometimes dislocation of the joint can be seen (Egloff et al 1995, Waters et al 1998, Hentz 1999, Waters and Peljovich 1999). In 1905, Whitman described three origins of shoulder dislocations in infants: true congenital dislocation, traumatic dislocation during delivery, and dislocation secondary to the obstetrical birth palsy. Fairbank in 1913, focused on the frequency of shoulder subluxation in obstetrical palsy and described the pathophysiology (Egloff et al 1995, Pearl and Edgerton 1998) (Fig. 1).

Initially, paralysed subscapularis recovers more quickly than the external rotators and abductors. The anterior capsule is short because of the malposition of the humeral head. Posteriorly, the infraspinatus, teres minor and deltoid muscles cannot provide sufficient support. The muscles that are not paralysed (teres major, latissimus dorsi and subscapularis) pull the head down and backward (Egloff et al 1995).

The age for operation for contractures is generally 12–24 months (Bennett and Allan 1999). Adduction and internal rotation contractures are common, and the Carliotz operation (release of subscapularis origin from scapula anterior) can be performed once the child is over 8 months of age (Gilbert 1997). In late cases (over 2 years), of age subscapularis lengthening is preferable without opening the anterior shoulder capsule (Bennett and Allan 1999). Shoulder dislocations are treated by open reduction and muscle transfers and humeral osteotomy (Dunkerton 1989, Yücetürk 1999). Isolated abduction contracture is rare, and release of the deltoid muscle and sometimes lengthening of the supraspinatus is the treatment of choice (Bennett and Allan 1999). Abduction and external rotation contractures are another form of contracture; transfer of infraspinatus tendon to teres minor tendon and release or recession of infraspinatus and supraspinatus tendons with or without release of deltoid muscle is the treatment of choice (Bennett and Allan 1999).

Glenohumeral deformity

Progressive glenohumeral deformity occurs in obstetrical birth palsy due to muscle imbalance as the patient's age increases. According to Chuang et al, three main causes of shoulder deformity due to obstetrical birth palsy are: cross-innervation of the muscles (caused by misdirection of regenerated axons); muscular imbalance (caused by paresis or earlier recovery); and growth (Chuang et al 1998a, 1998b).

As time passes, incongruity of the glenohumeral joint, deformity of the humeral head and hypoplasia of the glenoid is seen. In the X-ray, ossification of the humeral head is limited compared to the unaffected side. Hernandez and Dias found CT useful in evaluation of the shoulder for proper placement of the humeral head in plaster or orthotic devices (Hernandez and Dias 1988) Waters et al evaluated 42 brachial plexus birth palsy patients' shoulders, using computerized tomography or magnetic resonance imaging. They found that the degree of retroversion of the glenoid on the affected side was –25.7° compared with –5.5° on the unaffected side. Sixty-two per cent of the 42 shoulders had evidence of posterior subluxation of the head (Waters et al 1988). Gudinchet et al studied five shoulders, using MRI, and blunt anterior and posterior labrum was seen (Gudinchet et al 1995).

Intraoperative arthrograms were performed by Pearl and Edgerton and showed that 72 per cent of the patients had a deformity of the posterior aspect of the glenoid. Of 18 patients, five had flattening of the posterior aspect of the glenoid, seven had biconcave glenoid with the humeral head articulating with the posterior of the two concavities, and six had a so-called pseudoglenoid. This deformity, which is the result of muscle balance and internal rotation contracture, is severely advanced by the time that the child is 2 years old (Pearl and Edgerton 1998).

Surgical procedures

The timing of surgery is important and depends upon the pathology and treatment choice (Table 6).

Tendon transfers

In obstetrical birth palsy, surgical procedures are performed to improve shoulder function (increase of shoulder abduction and external rotation). Various transfers are described in the literature (Table 1). Most of the authors selected one technique or combined or modified them. The L'Episcopo techique was, for example, modified by Covey et al, who transferred the latissimus dorsi and re-routed it from the axillary approach (Covey et al 1992). In the literature the results generally appear to be satisfactory

Table 6 Timing of the surgery

Algorithm of secondary procedures in obstetrical palsy			
Contractures 8–24 months	Shoulder dislocation immediately after diagnosis	Tendon transfers after 24 months	Bony procedures after 5 years of age

whichever technique is used. Preoperative physical examination and the power of the muscles are very important, and also techniques must not be standardized; and combined procedures must be used according to the preoperative planning and surgical findings.

Chuang et al described perioperative studies demonstrating the existence of muscle recovery by cross innervation, and a new strategy of muscle transposition to minimize the influence of cross innervation by releasing the antagonistic pectoralis major and teres major muscles and augmenting the paretic muscles. Augmentation was done by transferring teres major to the infraspinatus muscle and reinserting both ends of the clavicular part of the pectoralis major muscle laterally (Chuang et al 1998b).

Price and Grossman transferred the teres major and latissimus dorsi as one conjoined tendon to the posterior aspect of the greater tuberosity (Price and Grossman 1995). Gilbert believes that the excursion of the teres major and latissimus dorsi is different, and the latissimus dorsi must be transfered alone (Gilbert 1997). After trapezius transfer with the acromium in traumatic patients, Ruhmann et al were satisfied with the improvement in stability and function (Ruhmann et al 1998). In obstetrical cases, trapezius transfer is generally combined with other muscle transfers, especially in patient with weak deltoid and supraspinatus muscle functions.

L'Episcopo muscle tendon transfer also improves the functional outcome in adult traumatic brachial plexus lesions (Beauchamp et al 1998).

After Sever–L'Episcopo transfers transient and permanant axillary nerve palsies have been reported (Strecker et al 1990).

Humeral osteotomy

Restoration of lateral rotation at the shoulder can improve its function (Goddard and Fixsen 1984). Vulpius and Stoffel performed external humeral osteotomy to correct internal rotation contracture in 1913. Zancolli used the same osteotomy, and noted that osteotomy improves abduction as well (Egloff et al 1995).

Twenty-two patients between the ages of 4 and 17 who were unable to perform self-care activities were treated by Kirkos et al with rotational osteotomy of the proximal part of the humerus. All patients had decreased strength of the lateral rotator and abductor muscles and normal strength of the subscapularis and pectoralis major muscles. Osteotomy was performed between the insertions of the subscapularis and pectoralis major muscles. The average increase in active abduction was 27°, and the average increase in the arc of rotation was 25° (Kirkos and Papadapoulos 1998). Waters' studies indicate that both tendon transfer and humeral osteotomy can uniformly improve function in children with chronic brachial plexopathy according to their age and glenohumeral deformity (Waters and Peljovich 1999; Fig. 3).

Figure 3

Humeral osteotomy.

Scapula

Seventeen muscles are attached or take origin from the scapula. The most important muscles are the serratus anterior, trapezius, rhomboids and levator scapula. The muscles help the scapula to remain in position during the full range of motion of the shoulder.

The effects of scapular instability are functional (dynamic) and cosmetic. Functional effects include diminished arm abduction and external rotation. Cosmetic effects include shoulder asymmetry and impaired scapular growth.

In 1984, Hertzmark et al reattached the rhomboid muscle to the scapula. In 1989, Whitman et al used fasciat lata graft between the scapula and spinal processes, and in 1980 Ketencian et al used fascia lata graft between the scapula and the ribs for stabilization of the scapula. Tensor fascia lata graft was also used for the transfer of the pectoralis major to the inferior medial part of the scapula for scapular winging.

Surgical results

Between January 1994 and September 2000, the author operated on 116 patients for obstetrical birth palsy shoulder sequelae. Sixty-seven (57.8 per cent) were male and 49 (42.2 per cent) were female. In 62 patients (53.4 per cent) the right side was affected and in 54 patients (46.6 per cent) the left side was affected. The age at surgery was between 5 months and 22 years (average 7.2 years). Five families had two children with the same problem. Seventy-three patients (63 per cent) had combined elbow, forearm and hand problems. Generally all the problems are operated in one stage if the patient was over the age of 5 years.

Shoulder posterior dislocation

Five cases were operated after CT or MRI diagnosis; three were under the age of 1 year. A posterior approach was used for the latissimus dorsi and teres major transfer to the rotator cuff, and an anterior approach was used for subscapularis lengthening and pectoralis major transfer to the rotator cuff. In two cases, shoulder stiffness was seen. Shoulder stiffness was not seen in two cases which were operated after 1.5 years of age. Shoulder subluxation was seen in 18 cases and the same tendon transfers were performed.

Contractures

After 8 months of age, the Carliotz operation was performed (six cases). All had combined tendon transfer (latissimus dorsi and teres major transfer to rotator cuff, subscapularis lengthening and pectoralis major transfer to rotator cuff) after 2 years of age. The author did not achieve good results with the Carliotz operation.

For the abduction contracture, two patients had subscapularis lengthening. Eleven patients had infraspinatus and teres minor lengthening because of an internal rotation deficit and external rotation contracture.

Ninety-eight per cent of patients were operated for internal rotation and adduction contracture. Only two had humeral osteotomy alone. The posterior incision was made first, from 1 cm inferior to the posterior acromium to the axillary fold. The latissimus dorsi and teres major were transferred to the rotator cuff and sutured with non-absorbable sutures with the patient's arm resting on the trunk. If the patient had an internal rotation deficit, infraspinatus lengthening could be done at the same time. If the teres major was stiff and not mobile enough to reach the rotator cuff, tenotomy only was performed. According to Gilbert, the excursion of the two muscles is different and they must therefore not be transferred together.

In 25 cases, tenotomy of the teres major as performed. In this approach, it is important to protect the axillary nerve, posterior circumflex humeral artery, radial nerve just under the teres major and axillary nerve entrance to the deltoid muscle when suturing the tendon to the rotator.

A deltopectoral incision was made for the anterior approach. The cephalic vein was protected. The pectoralis major was cut at the insertion site and the pectoralis minor tendon was protected. The subscapularis tendon was isolated and lengthened. The anterior circumflex humeral artery, axillary nerve and anterior capsule were protected. External rotation was

a

b

c

Figure 4

(a) preoperative
(b) postoperative abduction
(c) postoperative external rotation.

examined. In Klumpke patients, if the pectoralis minor was contracted then lengthening was performed. When 20° of external rotation was maintained, the pectoralis major was transferred to the rotator cuff and sutured with non-absorbable sutures. After release, if there was still an external rotation deficit and if the patient was over 5 years of age, humeral osteotomy was performed just over the pectoralis major insertion to maintain 20° of external rotation and plate and screw fixation was used.

When the deltoid and suprascapularis muscles were weak, trapezius transfer with acromial bone block was performed in patients over 5 years of age. If the patient was under 5 years of age, only tendinous transfer was done. The levator scapula was not used in this series.

Incisions were closed with two layers of absorbable sutures. The skin was closed with absorbable subcuticular sutures. In the last 3 years, 3M Soft-Cast was used for immobilization in 90° abduction and neural rotation. The axillary region was augmented with six layers of Soft-Cast splint. Immobilization was for 6 weeks, and wounds were not opened during this time. Five days of antibiotic cover were given. After 6 weeks, the cast was removed with scissors; a cast-cutter was not necessary. Fifteen days after removal of the cast, physiotherapy began if possible.

Following the operation, if the shoulder elevation increases to more than 90° and the triceps muscle power is under 3 (antigravity weakness), the patient has a disability problem. The same problem can be seen after transferring triceps to biceps for elbow flexion, combined with shoulder tendon transfer. Almost all the patients' families were satisfied with the post-operative result (Fig. 4).

Glenohumeral deformity

If the patient had glenohumeral deformity, the approach was the same as above. The author does not immediately perform humeral osteotomy; for this, the patient must have enough internal rotation before surgery.

Shoulder arthrodesis

Only one case (15-year-old patient), which had weak shoulder muscles and bony atrophy, had shoulder arthrodesis and plate screws fixation.

Coracoid osteotomy

In some cases a lengthened coracoid was seen, especially in direct X-ray. During this series none of them blocked the external rotation, and nothing was done to the coracoid process.

Scapular winging

In one case the pectoralis major, lengthened with tensor fascia lata, was transferred to the medial border of the scapula and the result was good.

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25
Medial rotation contracture and posterior dislocation of the shoulder

Rolfe Birch

Introduction

Medial rotation contracture and posterior dislocation of the shoulder is the most common and most significant secondary deformity in obstetrical brachial plexus palsy (Birch et al 1998, Birch 2000). Surgery to correct the deformity proved necessary in more than one third of the 1200 children seen in our unit from 1982. Diagnosis is often delayed, and the untreated deformity has severe consequences for function within the upper limb as a whole. By late adolescence or early adult life, movements of the shoulder girdle are greatly restricted. The upper limb lies in fixed medial rotation; there is pain from the disorganized gleno-humeral joint; and there is flexion pronation posture of the elbow, often complicated by subluxation of the head of the radius (Fig. 1).

Most children with obstetrical brachial plexus palsy (OBPP) progress to good or at least useful neurological recovery, and it is the duty of orthopaedic surgeons to encourage this potential function by earlier detection and more appropriate treatment of this deformity (Fig. 2).

Historical background

The causation, course, skeletal consequences and methods of treatment were set out by workers

Figure 1

Posterior dislocation in a 21-year-old man. Movements of the gleno-humeral joint are restricted and painful. There is now a fixed flexion pronation posture at the elbow with secondary dislocation of the head of radius.

Figure 2

The typical posture of posterior subluxation in a 2-year-old boy. Note the flexion pronation posture of the forearm.

during the last century. It seems that their work has been neglected or misunderstood, in spite of the recent resurgence of interest in the neurological lesion itself. Whitman (1905) distinguished between congenital (rare) and acquired (common) subluxation, stating that acquired subluxation was caused by fibrosis and contractures during the period of paralysis: it was a consequence of the neurological lesion. Fairbank (1913) wrote: 'the muscle which is most affected and offers the strongest bar to outward rotation is the subscapularis'. He described the results of surgery in 18 cases where a technique was used in which the subscapularis tendon and capsule, and the coraco-humeral ligament, were divided. In three cases the coracoid was sectioned. The radiological features of the deformity were fully described by Sever in his analysis of a series of 1100 children with OBPP (Sever 1925). He recognized delayed ossification of the head of the humerus, progressive deformation of the glenoid and, in later stages, overgrowth of the acromion and 'marked elongation of the coracoid process, due probably to the pull of the contracted coracobrachialis muscle'. Sever was unable to demonstrate any case of epiphysis separation or of dislocation caused during delivery, but Putti, whose work was reported by Scaglietti (1938), thought that the deformity was caused by direct injury to the proximal humerus: 'the most constant and characteristic change is the deformation of the angle of declination' (i.e. of retroversion of the head of humerus upon the shaft). Controversy continues. Zancolli and Zancolli (1993) thought that damage to the growth plate (epiphysiolysis) was the major factor in causation of the deformity, but in the same volume Gilbert (1993) wrote that: 'posterior subluxation deformity of the humeral head permanently worsens the prognosis. These anomalies that have long been considered the result of obstetrical palsy are, in fact, in consequence of untreated contractures'. Goddard (1993) studied over 200 cases treated by Gilbert, and uncovered only two instances of injury to the growth plate. Tubiana (1993) commented on the reasons for these differences in interpretation, 'which actually correspond to two different patient groups'. Our experience suggests that both views are correct and represent important contributions.

We described our experience with 86 operations of subscapularis recession and 59 cases of subluxation or dislocation treated by the anterior approach in 1996 and in 1998 (Birch and Chen 1998, Birch et al 1998), noting a high incidence of recurrence of deformity in the former (29 cases) and substantial loss of medial rotation in the latter. These findings led to a significant change in our approach owing to better understanding of the deformity of the glenoid in advanced cases and the high incidence of retroversion of the head upon the shaft.

The present paper is based on analysis of 166 children operated for the deformity between 1992 and 1996. All these had at least useful neurological recovery, either spontaneously or after repair of the brachial plexus. The functional grades were at least Raimondi 4 for the hand and Gilbert and Raimondi 4 for the elbow, and the mean range of elevation at the shoulder was 150° at final review. In other words, all of these children had substantial recovery through all elements of the brachial plexus. We excluded from discussion 44 other children who were treated for the shoulder deformity, who had more severe neurological injuries and in whom the problem was one of paralysis. It is essential to distinguish between these two groups; the difficulties and methods of solution are quite different. In the 'paralytic' group with severe neurological injury, the priority is to improve innervation of the upper limb as far as possible. Muscle transfers are only of palliative value, but transfer of the latissimus dorsi to the lateral rotators may be necessary to improve lateral rotation and so restore the muscular balance at the shoulder. Such muscle transfers were not needed in the 166 children described, all of whom regained functional lateral rotation. In some the difficulty was restoration of adequate medial rotation. Of the 166 children, 28 had had previous subscapularis recession and 21 operations of anterior release, and the deformity had recurred in these 49 children. All of these 166 children fell into Groups I, II or III of the Narakas classification: none was delivered by breech.

Causation

In 40 children the deformity was detected at birth or shortly afterwards, and in 30 more it was recognized within the first year of life. One father gave a clear description of the mechanism of

Table 1 A clinical classification of shoulder deformity (based on observations by Dr Liang Chen, in Birch et al 1998)

Type	*Relation of head of humerus to glenoid*	*Clinical evidence*	*Radiological evidence*	*Supplementary investigations*
Medial rotation contracture	Congruent	Loss of passive lateral rotation of 30° or more	Normal: coracoid may be elongated	Ultrasound – congruent. MR scan may show retroversion of head upon shaft of humerus
Simple subluxation	Head of humerus in false glenoid	Lateral rotation to neutral. Head palpable posteriorly	Incongruent. No other skeletal abnormality	Ultrasound, CT and MR scans confirm incongruency: retroversion, and 'double facet' glenoid may be seen
Simple dislocation	Head of humerus posterior to glenoid	Fixed medial rotation contracture at about 30°. Head evidently lying behind glenoid	Head of humerus behind glenoid. No other skeletal deformity	Ultrasound, CT, MR scans confirm. Retroversion may be seen
Complex subluxation	Head of humerus in false glenoid. Secondary bone deformity	Lateral rotation to neutral or less. Overgrowth of coracoid and acromion palpable.	Extent of coracoid and acromion abnormality seen: 'double facet' of glenoid.	Confirm incongruency and skeletal abnormality but may mislead about glenoid shape
Complex dislocation	Head of humerus behind glenoid. Secondary bone deformity	Fixed medial rotation contracture of 30° or more, obvious secondary bone changes	Head of humerus behind glenoid: overgrowth of coracoid and acromion; abnormality of glenoid	Confirms dislocation and extent of skeletal abnormality

In all cases, a flexion pronation posture of elbow and forearm is seen. In advanced cases this deformity becomes fixed, and may be associated with dislocation of the head of radius
The extent of retroversion of head upon shaft of humerus cannot be measured accurately by any ancillary investigation, and it is best determined at operation of open reduction.

injury. During a difficult vertex delivery the afflicted arm was pulled into abduction and then across the chest, into forced flexion with medial rotation. In 13 cases the subscapularis muscle was densely fibrosed, which may represent a post ischaemic or compartment syndrome lesion analogous to that described in the adult case by Landi et al (1992). However, in 57 children the deformity developed or progressed whilst under observation, and in 20 the deformity occurred after repair of the upper trunk and progressed in spite of continuing observation and assiduous exercises. In 11 children recovery was so good that they were discharged from the clinic with normal or near-normal function, only to return later with established deformity! Birch and Chen (1996), in their analysis of the earlier 120 consecutive cases, made the alarming observation that in no less than 12 children, the shoulder awaiting treatment for uncomplicated medial rotation contracture had progressed to dislocation whilst awaiting admission. This suggests that the primary cause is, in most cases, the neurological lesion, which invariably afflicts C5 and C6 irrespective of whether the rest of the plexus is damaged or not. There is paralysis of the lateral rotator muscles, of infraspinatus and teres minor, innervated by the fifth cervical nerve. The medial rotators (most especially the subscapularis muscle) innervated by the seventh and eighth cervical nerves are never paralysed or are only weakened for a short time so that their action is unopposed. Muscular imbalance is potent cause of deformity in the growing limb, and the deformity of the shoulder is a reflection of this general principle. We have not encountered a single instance of anterior dislocation of the gleno-humeral joint.

Classification of the deformity

The rate of progression of the deformity varies from child to child, and is not necessarily related to age. Advanced secondary bone changes have been seen in children aged 3 years or less, whilst dislocation in the presence of only minor deformity has been seen in children aged 11 or 12 years. The deformity is progressive, and there is a spectrum from medial rotation contracture to complex dislocation of the shoulder (Table 1).

Diagnosis

The diagnosis is made by physical examination. For babies, the infant is placed supine and the examiner holds both upper limbs with the elbows flexed to 90°. The arms are held adducted against the chest and the upper limbs are gently rotated into lateral rotation. Any diminution in the range of passive lateral rotation in the afflicted upper limb is significant. Serious errors in diagnosis are caused by incorrect examination, and the practice of examining one limb in isolation or of estimating passive range for rotation within the arm in abduction is condemned. The examination is done gently, and if the infant protests then the examiner must suspect incongruity at the gleno-humeral joint. In older children, the posture of the upper limb is characteristic, lying in medial rotation with flexion and pronation at the elbow. The contour of the shoulder is abnormal, with head seen prominently behind the glenoid. Palpation reveals abnormalities of the coracoid and acromion. In nearly every case a clear impression of the extent of bone deformity can be formed from the physical examination supplemented by plain anteroposterior and axial radiographs. Arthrograms, CT and MR scans have been used in diagnosis (Waters et al 1998, Pearl et al 1998). Ultrasound examination is a suitable aid to diagnosis before the first 12 months of life in those cases where the clinician is suspicious about the congruity of the shoulder.

Classification of the secondary bone deformities is set out in Table 2. The changes in coracoid and acromion are best detected by clinical examination; the extent of retroversion at operation; and the changes of the head and of the glenoid by plain anteroposterior and axillary radiographs supplemented by inspection at operation. MR scans provide valuable information in the advanced case, but the findings from these, and from CT scans, must be interpreted with care; they must not be used in place of careful clinical examination (Figs. 3, 4).

Table 2 Summary of bone deformities

Coracoid	Normal	30
	Moderate	98
	Severe	38
Acromion	Normal	121
	Anterior spur	36
	Overgrowth of whole	9
Glenoid	Normal	38
	Double facet	99
	Planar	22
	Severe posterior defect	16
Head of Humerus	Normal	125
	Conoid or oval	25
	Flattened	9
	Trench or bifid defect	7
Retroversion	Less than 30°	83
	30–50°	20
	50–70°	36
	Over 70°	27

In the advanced case, the glenoid exhibits both planar and posterior defect.
Some of the deformities of head and glenoid were caused by earlier inappropriate treatment.

Recording shoulder function

Careful recording of clinical data is essential. Without such a record, comparison between different series is impossible and much clinical work is rendered valueless. We have followed the proposals of Gilbert and of Raimondi, and recommend that other clinicians use these systems, which are summarized below.

Three systems are used in our unit. Nearly all children aged 1 year or more willingly demonstrate these exercises using coloured crayons or small toys as encouragement. Observation of the infant gives useful information about the range of active movements, the passive range can be measured. Records are made at each clinic attendance, and the three systems, taken together, provide useful information about shoulder function.

The first method (Table 3) is derived from the system proposed by Alain Gilbert, and has been modified to record the presence of functional

Figure 3

Complex posterior dislocation in a 7-year-old boy. Although the true glenoid appeared to be reasonably well developed at operation, posterior bone block was necessary to secure the stabilization. This had to be done as a second operation. Final scores in this case: Gilbert 5+, Mallett 15.

Figure 4

AP radiograph of complex subluxation in a 7-year-old girl. There is overgrowth of the anterior acromion. Note the elongation of the coracoid.

Table 3 A method of staging shoulder function in OBPP (drawn from Gilbert 1993)

Stage 0	Flail shoulder
Stage I	Abduction or flexion to 45° No active lateral rotation
Stage II	Abduction < 90°, lateral rotation to neutral
Stage III	Abduction = 90°, weak lateral rotation
Stage IV	Abduction < 120° – incomplete lateral rotation
Stage V	Abduction > 120° – active lateral rotation
Stage VI	Normal

The suffix + is added to indicate sufficient medial rotation permitting the hand to come against the opposite shoulder. Our convention restricts children with no lateral rotation beyond neutral to Stage I, usually I+, because adequate medial rotation is maintained.

medial rotation. The child with fixed medial rotation contracture such that the passive range of lateral rotation is restricted to the neutral position or less is, by convention, given a grade of Stage 1 and no more. Mallet's system (Table 4) records five shoulder functions, according a maximum of three points to each. A child with 15 points has a good shoulder but by no means a normal one. Our system of recording the active and passive range of movements of the shoulder is set out in Table 5, and this includes measurement of the range of active prono-supination, which usually improves after successful relocation of a dislocated joint. This system recognizes

Table 4 The Mallet system of measuring function at the shoulder

Value of active = shoulder function	1	2	3
Global abduction 	<30°	30° to 90°	>90°
Global external rotation 	<0°	0°-20°	<20°
Hand to neck 	Not possible	Difficult	Easy
Hand to spine 	Not possible	S_1	T_{12}
Hand to mouth 	Marked trumpet sign	Partial trumpet	<40° of abduction

that loss of active range may arise from paralysis or weakness of muscles, but also from fixed contracture. Two specific measures merit description.

The inferior gleno-humeral angle

This is the angle between the axes of the humerus and the lateral border of the scapula with the arm in adduction. In the normal shoulder, this is at least 150°. In some children, contracture of the inferior capsule and of the latissimus dorsi and teres major is so tight that the active and the passive angle is diminished to 30–40°. Weakness of the abductor muscles of the shoulder is shown by substantial discrepancy between the passive and active ranges.

The posterior gleno-humeral contracture

This is measured as follows. The affected hand is placed onto the opposite shoulder, with the

Table 5

Page 2 (OBPP shoulder)

Range of Movement														
DATE	Forward flexions		Lat rotation		Inferior GH angle		Post GH angle		Abduction		Medical rotation		Rotation forearm	
	Active	Passive	Active	Passive	Active	Passive	Active	Passive	Active	Passive	Active	Passive	Active	Passive

Figure 5

Loss of active medial rotation in a child with a posterior gleno-humeral angle of no more than 10°. This was corrected by de-rotation osteotomy of the shaft of humerus.

axis of the humerus parallel to the ground. The angle between the axes of the humerus and of the blade of the scapula is measured. In a normal shoulder this should be 70°, whilst in a severe contracture it may be reduced to 0°. Some of this contracture arises from capsular tightness, and it can be overcome by firm depression of the scapula onto the chest wall whilst holding the arm in the position described. However, most of the contracture is caused by bone deformity (retroversion of the neck of the humerus), and it is commonly seen after successful relocation of dislocation. Treatment, which is straightforward enough, is outlined below (Fig. 5).

Treatment

Exercises

Obviously, the best treatment is prevention. It is possible to overcome an uncomplicated medial rotation contracture by assiduous but gentle stretching of both limbs into lateral rotation *with the arms adducted against the side.* It is for the clinician to teach the parents this exercise and to insist that physiotherapists perform the stretch correctly. Close monitoring is essential, and these children are reviewed at intervals not exceeding 6 weeks. The exercises are performed four or five times before every feed in the case of infants, and the arms are held in the position of lateral rotation for 4–5 seconds. If the exercise provokes pain, then the clinician should assume that the shoulder is incongruent. Forceful stretching, or persisting with these exercises when the shoulder is plainly incongruent, is damaging.

Surgery

Subscapularis recession was described by Carlioz and Brahimi in 1986. Gilbert (1993) emphasized that the operation should only be performed if the shoulder is congruent. The incidence of recurrence has already been mentioned. It is clear that those surgeons inclined to follow this operation must perform, meticulously, the indications and techniques of the originators: above all the operation must be done only *if the shoulder is congruent and if the lateral rotator muscles have recovered sufficiently to restore balance*. As in all work in obstetric brachial plexus palsy prolonged and careful clinical follow up is essential.

Lateral rotation osteotomy of the shaft of humerus has no place in the treatment of the deformity. It does nothing to secure congruent reduction of the head of the humerus into the true glenoid, it increases retroversion of the head upon the shaft of the humerus. Results have been singularly unimpressive in those cases when it was used as palliation for the irreducible shoulder.

Correction of deformity by the anterior approach is intended to secure congruent relocation of the head of the humerus into the true

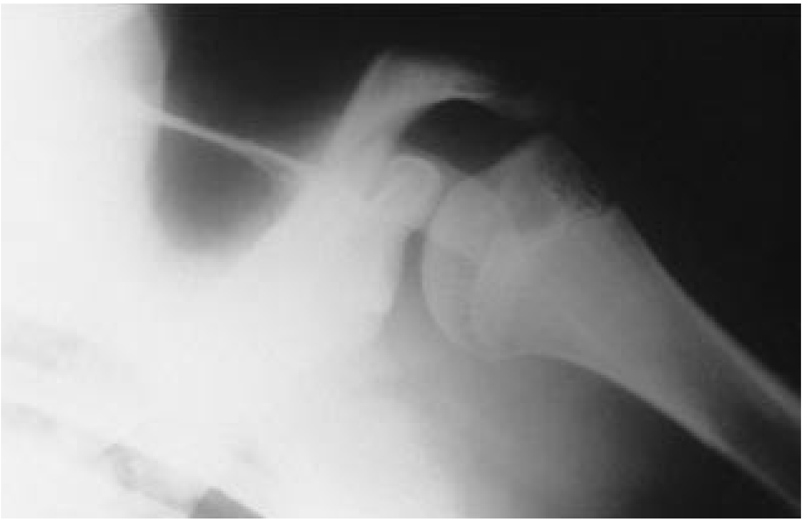

Figure 6

AP radiographs of complex subluxation in an 8-year-old girl.

glenoid. The obstacles to this reduction include overgrowth of the coracoid process, contracture of the coraco-humeral ligament, and contracture of the subscapularis muscles. Significant retroversion of the neck of the humerus must also be corrected. The technique of operation is fully described elsewhere (Birch 2001a, 2001b).

The record of the abnormalities displayed should include:

1. The condition of the deltoid and pectoralis muscles;
2. The length, breadth and inclination of the coracoid, and whether it abuts against the head of the humerus in attempted lateral rotation;
3. The contribution of the coraco-humeral ligament to the contracture;
4. The state of the subscapularis muscle;
5. The condition of the labrum;
6. The depth and breadth of the true glenoid;
7. The location of the false glenoid and the presence or absence of an intervening cartilaginous ridge between this and the true socket;
8. Overgrowth of the acromion;
9. Any abnormality of the anterior part of the head of the humerus;
10. The stability of reduction, between full lateral rotation and medial rotation. Re-dislocation of

Figure 7

Axial radiograph of complex subluxation in an 8-year-old girl.

Figure 8

Function in 3-year-old boy, 18 months after relocation of simple dislocation. Gilbert 5+, Mallett 15.

Figure 9

Axial radiograph of the case shown in Fig. 4 8 years later, showing a degree of remodelling of the head, although its enlargement suggests that there may have been a degree of avascular necrosis.

Figure 10

The clinical outcome in this girl, now aged 15. Gilbert score 5+, Mallett 15.

the head of the humerus into the false glenoid or behind it at neutral rotation or even in the inner range of lateral rotation is one indication of retroversion.

We estimate retroversion of the head upon the shaft of humerus by grasping the head of the humerus between the index finger and thumb of one hand, to define the coronal plane of the head, and grasping the epicondyles of the humerus with the finger and thumb of the other hand. The coronal plane of the head of humerus and the distal humerus are parallel in the normal infant shoulder. Retroversion of the head in excess of 30° is significant; retroversion in excess of 50° demands de rotation osteotomy. This was done in 55 of these children; where possible it should be done at the same operation, but the arm is too small in children under the age of 18 months. The shaft of the humerus is exposed between the pectoralis major and deltoid tendons.

Table 6 Mean Gilbert and Mallet scores before and after operation

		Gilbert		*Mallet*	
Deformity	*Cases*	*Pre-*	*Post-*	*Pre-*	*Post-*
Medial rotation	12	1.85	5.1	10.2	14.0
Simple subluxation and dislocation	42	1.50	4.3	9.2	13.3
Complex subluxation and dislocation	112	1.70	4.3	9.3	12.0

The low Gilbert scores recorded before operation are a reflection of our modification of this system (see Table 2).

A posterior bone block is indicated if there is a severe defect of the postero-inferior wall of the glenoid. It has now been done in 12 cases. The precise indication for this technique has yet to be clarified, but it is probably necessary in longstanding cases with marked abnormality of the posterior lip of the glenoid. In these cases, MR scanning has a place in defining glenoid morphology. Our experience with osteotomy of the glenoid has been very unsatisfactory.

Results

The children were followed for a minimum of 3 years, and the changes in the Gilbert and Mallet functional scores are summarized in Table 6. The changes in the mean ranges of active movements at the shoulder and of prono-supination before and after operation are summarized in Table 7. Some of the improvement recorded must inevitably reflect continuing neurological recovery. We point out that the low Gilbert score recorded before operation is a reflection of our modification of his system of measurement (see Table 2).

The long-term outcome from this intervention will not be known for a number of years. It is likely that later reconstructive operations will prove necessary in some of these children when they reach adult life, and it is hoped that, by improving the anatomical relation of the gleno-humeral joint, subsequent arthroplasty or even arthrodesis will be a practical proposition.

The improvement in function at the elbow and in the forearm is, at times, remarkable. In some children, improvement of active extension of the wrist was seen. The observations of parents and our functional assessments in these children suggest that successful relocation of the shoulder brings about marked improvement not only at the shoulder but also in function of the limb as a whole.

Acknowledgements

Mr George Bonney kindly gave permission for use of the photographs in this chapter, drawn from *'Surgical Disorders of the Peripheral Nerves'*. Mrs Margaret Taggart was responsible for collating all clinical records and for preparation of the manuscript.

Table 7 Means of ranges of active movements at shoulder before and after operation

Deformity	*Cases*	*Forward flexion*		*Abduction*		*Lateral rotation*		*Medial rotation*		*Prono-supination*	
		Pre-	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*
Medial rotation	12	124	153	136	156	– 6	65	94	86	104	152
Simple subluxation and simple dislocation	42	105	127	111	128	–17	55	90	81	105	156
Complex subluxation and simple dislocation	112	96	122	103	128	–17	42	90	76	87	142

There is no doubt that some of the improvement in flexion and abduction is a reflection of continuing neurological recovery.

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26
Palliative surgery: elbow paralysis

Vincent R Hentz

Introduction

Elbow deformity and dysfunction are frequent consequences of obstetrical brachial plexus palsy. In fact, lack of elbow flexion, along with poor shoulder movement may be the first recognized sign of a perinatal palsy immediately after birth. A variety of problems are recognized including paralysis or paresis of either elbow flexion or extension or both, or stiffness of the elbow. Stiffness is typically manifest as a flexion contracture of the elbow, and/or a supination or pronation contracture of the forearm. These sequelae of obstetrical brachial plexus palsy may be seen in infants and children who have recovered spontaneously, or in those who have undergone early neural reconstructive procedures.

In terms of incidence, the most common presentation is weakness of elbow flexion, followed by flexion contracture. Less common are supination contractures of the forearm. Pronation contractures are somewhat less common than supination contractures. Unlike the adult circumstances, it is exceeding rare to see a child with total paralysis of the biceps–brachialis muscle groups and total inability to flex the elbow, either after spontaneous recovery or surgery. This seems true whether the initial insult involved only the upper elements of the brachial plexus, as in Erb's palsy, or whether the injury was more global. In the last 10 years, we have seen only one child with total absence of elbow flexion among more than 200 children examined in our clinic (Fig. 1). Total absence of any elbow extension is also exceedingly unusual.

Figure 1

This child, born via breech delivery, is the only child in our series who regained absolutely no elbow flexion. His plexus was explored at 6 months of age. C5 and C6 roots appeared normal to observation but only small cortical responses could be measured. The roots were not reconstructed. By 18 months of age, no biceps activity could be observed, although EMG studies showed some electrical activity. He subsequently underwent ulnar motor to biceps branch crossover.

Anatomy and pathology

Paralysis and paresis

Flexion of the elbow is typically a product of active contraction of the prime elbow flexors, the biceps, and brachialis muscle groups. These are innervated in most instances by axons emanating from the anterior parts of the C5 and C6 nerve roots. These motor axons join at the superior trunk and then travel via the anterior division of this trunk as it contributes to formation of the lateral cord. They leave the lateral cord as the musculocutaneous nerve.

The elbow can be partially flexed by accessory elbow flexors, such as the post-axial brachioradialis and extensor carpi radialis longus muscles, and by pre-axial muscles that have origin above the elbow joint, such as the pronator teres and the flexor carpi ulnaris. All of these accessory muscles lie too close to the axis of rotation to do more than bring the forearm to slightly less than 90° and lack power at this range to perform really useful work. Moreover, in the case of the pre-axial muscles, the individual must recruit nearly all of the fibers of these muscles in order to initiate elbow flexion, and as they do so, the forearm pronates, the wrist flexes and the fingers clench. This posture and resultant initiation of weak elbow flexion is referred to as the 'Steindler effect' (Steindler 1946). The brachioradialis and extensor carpi radialis longus muscles are typically innervated by the C5 and C6 roots. The pronator teres and flexor carpi radialis are innervated by the C6 and C7 roots, and the flexor carpi ulnaris by the C7 and C8 roots.

It has been my experience that children with obstetrical brachial plexus palsy injuries affecting the upper roots are much less adept at utilizing this Steindler effect than adults who suffer upper root injuries. This may have more to do with the lack of children who persist in exhibiting complete paralysis of the biceps and brachialis muscles after obstetrical brachial plexus palsy, compared to adults who suffer traumatic obstetrical brachial plexus palsy.

The prime elbow extensor is the triceps muscle, innervated by motor axons from the C6, C7, and C8 roots. These axons travel via the posterior divisions of the upper, middle, and lower trunks, as part of the posterior cord and finally, the radial nerve. Therefore, the triceps remains innervated in the majority of children who suffer upper root injuries. Paralysis of elbow extension is thus seen only in more global obstetrical brachial plexus palsy injuries.

Elbow stiffness

The relatively high incidence of residual elbow flexion contracture is a subject of some conjecture. These children exhibit a flexion contracture of varying severity (Fig. 2). The development of an elbow flexion contracture in the context of a

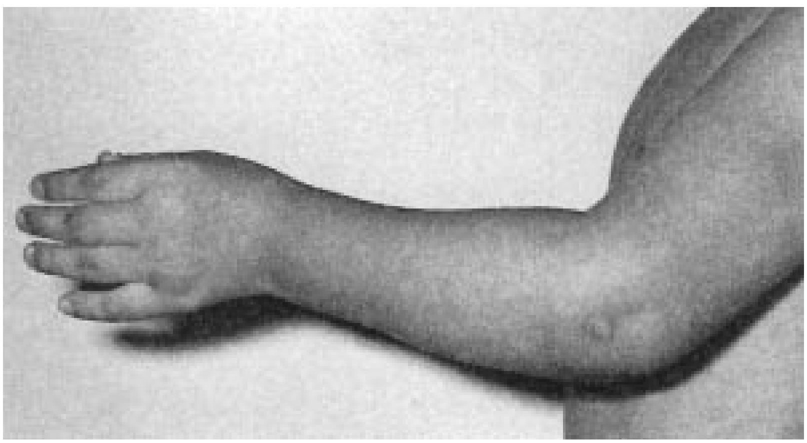


Figure 2

Example of an elbow flexion contracture in a previously unoperated child who suffered a C5–C6 (Erb's) perinatal brachial plexus palsy. (From Ballinger and Hoffer, 1994 with permission.)

weak biceps is somewhat paradoxical. The fact that this can appear relatively soon after birth has led to speculation that the same birth trauma that led to injury to the brachial plexus may cause a direct injury to upper limb muscles, including the deltoid and the biceps. This birth trauma may lead to unrecognized consequences, such as an unrecognized post-partum compartment-like state associated with death of muscle fibers. These necrotic muscle fascicles will be rapidly replaced by scar that may then undergo contraction, leading to elbow flexion contracture. This theory is somewhat reinforced by the great difficulty experienced in overcoming an elbow contracture by means of splinting. This resistance to conservative splinting mirrors that experienced in trying to open the contracted hand and wrist following Volkmann's contracture.

This seeming paradox of this frequently progressive deformity has been investigated by Aitken (1952) who recognized a common triad of deformity including proximal ulnar curvature, radial neck clubbing, and posterior subluxation of the radial head. The pathologic mechanisms responsible for this clinical presentation have not been clearly determined. Their consequences are well recognized however and treatment is very difficult, if not impossible.

Ballinger and Hoffer (1994) have documented the incidence of such contractures in their population. They studied 121 patients over the age of 3 years with Erb's C5–C6 palsies, eliminating other causes of elbow pathology such as radial head dislocation, and eliminating those with more global palsies. In 38 children, there was an average of 19° of contracture with a range from 0 to 40°. Only four of the 38 patients had no elbow contracture. Of the remaining 34 children, 29 had extension strength that averaged one grade higher than flexion strength. Seven patients had what was termed 'clinically significant' contracture, meaning greater than 30°. All seven had greater flexor than extensor power.

Ballinger and Hoffer (1994) offered three possible explanations including persistence of the fetal flexion posture into the early postnatal period. They posited that the presence of a flexion contracture might be beneficial to the infant with weak flexor strength, and therefore the flexed position might be maintained during the day. They also offered the possibility that the flexor may recover before the extensor and, by the time the extensor recovers, the contracture is already present.

Associated stiffness about the elbow may also be manifest as a supination or pronation contracture of the forearm. Enlargement of the bicipital tuberosity of the radius may occur as a consequence of biceps muscle pathology. As mentioned above, the proximal ulna may become curved. The consequence may be proximal radio-ulnar impingement.

Eberhard (1997) identified nine children who had suffered global obstetrical brachial plexus palsy injuries presenting with fixed supination deformity. Impingement of the bicipital tuberosity on the ulna was the main cause of the supination deformity in all nine children. All were improved by disinsertion and reinsertion of the biceps tendon on the bicipital tuberosity, a modification of Zancolli's (Zancolli and Mitre 1973) biceps re-routing procedure.

Functional pathology

Elbow flexion

Most children with weakness of elbow flexion after obstetrical brachial plexus palsy injury will have biceps–brachialis strength at the M2–M3 level. They may be able to lift the hand of the affected limb to their mouth but are unable to sustain this against resistance. As the opposite arm is typically of normal strength the child will have used this limb since infancy for tasks that require great strength. Unless these children are frequently tested, the weakness of elbow flexion may go unrecognized for some time because the child will perform most activities of daily living somewhat effectively even with weak unilateral elbow flexion.

As the elbow functions in concert with more proximal joints in positioning the hand, deformity and weakness of the shoulder will compound the functional consequences of elbow flexor weakness. The shoulder pathology may draw more attention than the elbow weakness, because shoulder deformity much more often results in an abnormal posture of the entire limb. For example, as the child begins to walk and then to run, his internally rotated limb begins to impinge against his body. Without sufficient external rotation at the shoulder, as the child flexes the elbow, the arm impinges against the body. The child learns quickly to abduct the shoulder so that the flexing arm can clear the body and be brought toward the mouth. This co-contracture of elbow flexion and shoulder abduction, termed the ‘trumpet’ sign, may be a consequence of misguided axonal regeneration, and thus co-innervation or a learned activity or some element of both may exist. Regardless of etiology, if the child cannot lift the arm easily because of the internal rotated humerus, the child is more likely to avoid flexing the elbow, and the biceps and brachialis muscles may become somewhat ignored, underutilized and underexercised. The consequence is persistent weakness. Correction of the pathologic shoulder may be necessary before one can adequately assess elbow function, particularly in the young child.

An additional functional problem occurs when re-innervation has been misguided and the child co-contracts elbow flexors and extensors. Whether the etiology is a consequence of misdirected regenerated motor axons, or central or peripheral ephaptic transmission, or aberrant muscle recruitment is not clearly determined. However, the functional consequences are clearly visible. The result is weakened elbow flexor power, typically seen when the child tries harder to flex the elbow.

Recently, Rollnik et al (2000) reported the application of botulinum toxin type A in six children with severe biceps–triceps co-contraction after spontaneous nerve regeneration following obstetrical brachial plexus palsy injury. The children ranged in age from 2 to 4 years. All were treated two to three times over a period of eight to 12 months with 40 units of botulinum toxin at two sites along their triceps muscle. In this small series, elbow range of motion increased from 0 to 25–50° to 0 to 25–100° and flexion strength from MRC classification of 1.7 to 3.7. Most interestingly, there was no recurrence after a one-year follow-up. These findings are preliminary but provide a degree of optimism. They strengthen the concept that neural plasticity plays an important role in the ultimate functional outcome. Weakening the overactive triceps may allow the child to begin using the arm more normally, thus reinforcing the creation of more appropriate neural pathways and permitting the regression of inappropriate ones.

Elbow extension

Weakness of elbow extension may be consequential as the infant and later the child strives to achieve developmental milestones. However, weakness in extending the elbow is usually felt to be less functionally disabling than weakness in flexion at the elbow. None the less, weakness of elbow extension interferes with the infant turning him or herself from side to side, and interferes with attempts to push up from a sitting to a standing position. Later in life, weakness in extending the elbow interferes with the efficiency of performing many tasks, such as straightening the arm to make it easy to put the arm through the shirt sleeve. Jones et al (1985) described the indications for surgically strengthening elbow extension in four children who had suffered obstetrical brachial plexus palsy injury. The average age at surgery was 10 years in these four patients.

Elbow stiffness

The consequences of an elbow with a fixed flexion contracture may be both esthetic and functional, especially when one considers that all these children exhibit some limb length discrepancy. The fixed flexed elbow exaggerates the appearance of a short limb and further decreases the reach and sphere of movement of the affected limb. As mentioned above, a contracture of greater than 30° is said to be clinically significant (Morrey et al 1981).

Treatment

Paralysis/paresis of elbow flexion

The functional goals for the child with absent or weak elbow flexion after obstetrical brachial plexus palsy injury are to provide increased strength of flexion and elbow control. Given that the function of the shoulder influences elbow function so significantly, problems of shoulder control strength and range of motion are typically addressed as well, either at an initial stage or simultaneously.

The conservative and surgical management of the brachial plexus injury itself is adequately discussed in preceding chapters of this volume. I will focus on the management of weak or absent elbow flexion in the child who has either been allowed to undergo spontaneous evolution of the injury or who has already undergone neurosurgical reconstruction.

Timing and indications

There are no clear guidelines regarding either timing or indications available in the medical literature. Most clinicians will elect to observe both the operated babies and those allowed to spontaneously evolve over many months, or even years, before considering introducing palliative measures. However, one should not restrict one's thinking to only classical palliative treatments such as muscle–tendon transfers, contracture release, or osteotomy. As referred to above, aggressive early treatment of recognizable functional problems, such as dysfunctional biceps–triceps co-contracture, may play an important role.

Early intervention

There is a clear role for secondary neurosurgical reconstruction with the goal of restoring elbow flexion. The most common circumstance involves an infant who has undergone primary plexus exploration and reconstruction which included procedures specifically designed to restore elbow flexion, but who has demonstrated no biceps recovery within the expected interval. One example is a child, now between six to nine months following nerve grafts from the C5 and C6 root to the anterior division of the superior trunk with no evidence of voluntary biceps contractions. One may consider obtaining an EMG in hopes of this providing some direction for further reconstructive decisions. However, it is clear that the EMG provides overly optimistic assessment and is not particularly indicative of functional outcome in obstetrical brachial plexus palsy injuries (Benaim et al 1999). Strong consideration should be given to going forward with surgical procedures that add to the motor axon population potentially able to re-innervate the biceps and brachialis. This might involve re-exploration of the original reconstructive site but more likely involves finding fresh sources of motor axons. Some clinicians have termed this as 'supercharging' the muscle.

Axonal supercharging

Several different methods have been described. All have as their goal, the achievement in a rapid fashion of growth of motor, as opposed to mixed motor and sensory axons into the target muscle. Both plexal and extraplexal axonal sources have been described.

The most popular today is some variation of the procedure introduced by Oberlin (Loy et al 1997), who described adjoining nearby expendable motor fascicles directly to the motor branches of the biceps and brachialis muscles. Oberlin suggested using motor elements of the ulnar nerve and recommended sacrificing those innervating the extrinsic forearm muscles rather than intrinsic muscles. Oberlin's cases were primarily adults who had suffered traumatic plexus injuries, but this philosophy has been and can be applied equally successfully to children who have suffered obstetrical brachial plexus palsy injury to the upper roots as opposed to those with a global palsy. For these globally injured babies, other extraplexal sources of motor axons must be sought.

Other clinicians have looked to other sources of motor axons, again describing the procedures primarily in adults. Gilbert (Dumontier and Gilbert 1990) utilized ipsilateral and even contralateral medial and lateral pectoral nerves. Motor elements of the median nerve, or the thoraco-dorsal nerve may be used to directly supply the biceps and brachialis to restore elbow flexion. Indeed, recovery of biceps function is such a high priority that one could even justify using a less expendable motor nerve to achieve this priority. One might argue that sacrificing a nerve such as the thoraco-dorsal nerve, and by doing so accepting sacrifice of the latissimus dorsi muscle, a muscle that is often used to restore elbow flexion through a secondary muscle–tendon transfer, may be cavalier.

The indications for such muscle 'supercharging' are not well defined as mentioned above. Neither is the duration of the window of opportunity to achieve some success. Anecdotal information indicates that the window of opportunity is of much greater duration if the muscle has been at least partially re-innervated by the original surgical procedure or through spontaneous evolution. A muscle that is completely denervated for more than one year, even in the child, will probably not respond in a systematic fashion to this supercharging procedure.

Some argue that this window of opportunity is too short and that children's muscles respond differently to nerve injuries. There is only anecdotal evidence to support this concept, but that is enough for some clinicians to propose even primary plexus repair or reconstruction on children even four years or more from birth.

The outcome of such procedures for this obstetrical brachial plexus palsy population cannot be determined from a review of the literature. Too few cases have been performed in this cohort.

Late intervention

Timing and indications

Late intervention relies primarily on classical muscle–tendon transfers and rarely on such procedures as microvascular functional free muscle transfers. Timing and indications for muscle transfers to restore elbow flexion are similar to those for most related procedures. They must typically await some level of psychological maturity on the part of the child. Most transfers benefit from a period of formal therapy as part of the re-education process. Children between ages 2 and 4 rarely exhibit the necessary maturity.

Once sufficient maturity has been achieved, it is possible to assess in a meaningful and reliable manner the strength of remaining muscles. Prior to this age, this assessment is difficult if not impossible.

The indications for muscle–tendon transfers to strengthen or restore elbow flexion in this population must be carefully individualized. Even weak flexion will be effective flexion for most activities. Reconstruction of elbow flexion requires surgery of far greater technical complexity than most other standard muscle–tendon transfers. Re-education of the most commonly used muscle resources, such as the triceps, latissimus dorsi, and pectoralis major is far more complex than that associated with other transfer procedures. One must carefully consider the risks and benefits in performing relative complex reconstructive surgery requiring sophisticated re-education maneuvers in a very young patient. Resources to restore elbow function are too scarce to waste through surgical misadventure.

Specific procedures

Steindler flexor-plasty (Steindler 1946)

There is insufficient information in the literature to allow one to determine which of the several common transfers is best for the pediatric post-obstetrical brachial plexus palsy injury population. From the standpoint of technical and re-education simplicity, the Steindler procedure must prevail over latissimus dorsi or pectoralis major transfer. One might consider transferring the pectoralis minor either in isolation or combined with the Steindler procedure, if one seeks a more modest boost to elbow flexion power. I have preferred this procedure in those pediatric patients who exhibit good wrist stability and active elbow that is flexion sufficient to allow them to initiate elbow flexion. In this case, one can attach the transfer under a little less tension and usually avoid extension loss while anticipating better power in the mid-range of elbow flexion. These patients need power in this range and not necessarily at the end range.

The Steindler procedure is best performed in patients who can exhibit the Steindler effect produced by pronating the forearm and flexing the wrist and at the same time swinging the arm at the elbow to overcome gravity. With this

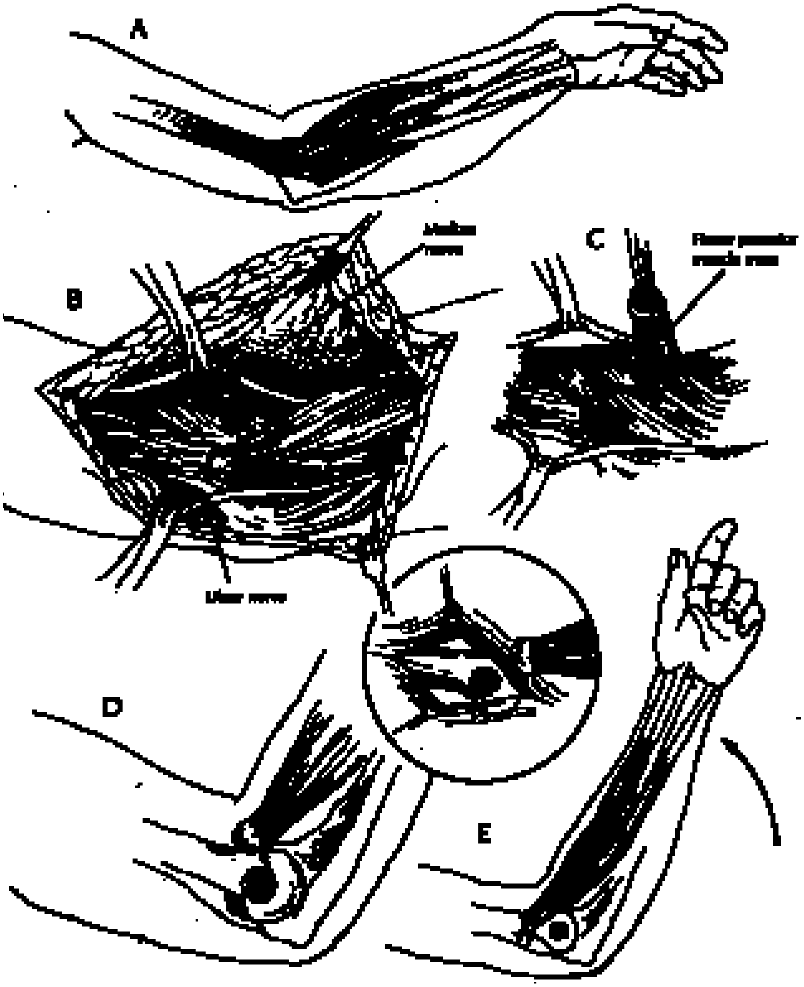


Figure 3

The operative steps of the Steindler flexor-plasty are illustrated. The flexor/pronator origin is detached along with a piece of the medial epicondyle (A,C). The ulnar nerve is protected and the median nerve is dissected to allow proximal migration of the branches to the pronator teres (B). The bony attachment of the muscle origins is moved proximally on the humerus and is placed on the mid-anterior surface of the humerus at a point comfortably reached by the muscle origin/epicondylar block with the elbow flexed 45 to 60° (D). The epicondyle may be fixed to the humerus with a wire or screw (E).

maneuver, they should be able to then maintain their arm somewhat flexed at the elbow against the force of gravity. Those patients lacking good wrist extension are poor candidates for this procedure, as it accentuates wrist flexor power.

Author's preferred technique

A curved incision is planned that is oriented longitudinally across the medial epicondylar area at the elbow and extends proximally and distally over sufficient length to expose the junction of the distal one-third and middle one-third of the humerus and the proximal one-half of the forearm flexor pronator muscle mass (Fig. 3, A). The incision is made through subcutaneous tissues with care being taken to preserve major cutaneous nerves. The medial epicondyle is exposed, and the ulnar nerve is located and cleared above the cubital tunnel behind the medial epicondyle. The nerve is gently elevated out of the cubital tunnel, preserving motor nerves coursing to the flexor carpi ulnaris (Fig. 3, B). The flexor carpi ulnaris is split distally from the point where the ulnar nerve penetrates it to allow free mobilization of the nerve and muscle. The subcutaneous dissection is carried distally over the pronator teres, which forms the radial border of the flexor pronator muscle mass.

The median nerve is best located at elbow level just ulnar to the biceps tendon and beneath the bicipital fascia (lacertus fibrosus) and adjacent to the brachial artery. The median nerve is elevated and dissected distally, special care being exercised to preserve motor branches to the pronator teres (Fig. 3, B).

The origin of the muscle mass from the medial epicondyle is identified, and one may judge where an osteotomy should be placed to elevate and move the entire conjoined origin of the muscles. With the median and ulnar nerves carefully protected, the epicondyle may be separated from the humerus, together with the muscle origins, by controlled osteotome osteotomy (Fig. 3, C). The muscle origins, along with the freed epicondyle, may then be reflected up, and the flexor pronator muscle mass may be dissected from the underlying joint capsule in a natural separation plane. The muscle group is stripped from the ulna distally, to the extent allowable by motor nerve branches from both the median and the ulnar sides. The flexor carpi ulnaris is split along the plane started by the penetration of the muscle by the ulnar nerve. With the elbow flexed to about 45°, one may reflect the freed epicondyle and muscles across the elbow to get an impression of how far proximally on the humerus the transferred mass will reach (Fig. 3, D). The anterior surface of the humerus is exposed at this level by splitting what remains of the atrophic biceps and brachialis muscles. With the median nerve reflected radially, the proper site for bone-to-bone epicondyle-to-humerus juncture is determined. It is placed on the mid-anterior surface of the humerus at a point comfortably reached by the muscle origin/epicondylar block with the elbow flexed 45 to 60°. The anterior cortex of the humerus is removed to receive the epicondyle. The epicondyle may be fixed in place with a large wire suture or by screws (Fig. 3, E). After initial fixation, the extent of elbow extension is gently tested with the forearm supinated and pronated. It should extend to 60 or 70° without undue tension. The lack of traction on and freedom of the median and ulnar nerves are checked, and the tourniquet is removed to achieve satisfactory hemostasis before closure of the skin wound.

The elbow is immobilized at about 60° of flexion in a dressing with an overlying splint. After 3 weeks of healing, gentle passive extension may be initiated, with progression to active and passive range-of-motion exercises over a period of 3 more weeks. Night splinting in progressive maximum extension is important. Some prefer a turnbuckle extension device for progressive night-time extension splinting. Many months of instructed and self-administered physical therapy prove rewarding to patients who have undergone this operation.

Latissimus dorsi transfer (Zancolli and Mitre 1973)

I prefer this technique for pediatric patients who have a strong latissimus and little elbow flexion power. Rehabilitation is difficult and biofeedback and functional muscle stimulation have proved helpful.

Author’s preferred technique – bipolar transfer

The three critical elements of the procedure are as follows:

1. Careful dissection of the neurovascular structures to allow proper re-positioning of the latissimus dorsi from posteriorly to anteriorly without the risk of kinking or torsioning the neurovascular pedicle;
2. Transfer of the normal tendinous insertion of the latissimus dorsi on the humerus to the coracoid process of the scapula to align the muscle properly as an elbow flexor;
3. Weaving of the cut end of the biceps insertion through the fibrous origin of the transferred latissimus dorsi so that the origin of the latissimus dorsi became its new insertion.

Function of the latissimus dorsi is first checked by palpating the posterior axillary fold and watching the muscle area on the back while the patient is asked to adduct and dorsally displace the arm (as in elbowing one’s way through a crowd). Tensing of the muscle is readily detected, and often the outline of the muscle may be seen on the back.

Knowing that the arc of rotation is close to the spine of the scapula along the axillary border, one may plan a skin island, if it is needed, so that it will be carried to an area of deficit upon the arc of rotation. An incision is made along the axillary surface of the muscle in order not to violate the island of skin but to allow exposure of the thoraco-dorsal neurovascular bundle. Once the bundle is noted, the island of skin, if needed, is circumscribed by a continuation of the incision, and the skin edges are tacked down to the epimysial fascia with temporary sutures. The rest of the superficial surface of the latissimus dorsi is exposed by dissecting the areolar plane superficial to the muscle fascia. A marking suture is placed proximally, close to the muscle origin, and another is placed distally, near the insertion site. The distance between these sutures is noted with the arm in adduction and then in abduction. The whole muscle may be dissected up along its deep surface, carefully avoiding inadvertent elevation of the serratus anterior muscle with the latissimus. The origin from fascia along the lumbosacral vertebrae and posterior iliac crest is cut, preserving enough fascia on the muscle from which to fashion a new tendon of insertion. Segmental vessels to the muscle along the medial origin constitute the minor blood supply to the muscle. They may be sectioned without concern for flap survival when the major thoraco-dorsal pedicle is preserved. The muscle is dissected to its humeral insertion, carefully preserving the pedicle, and the insertion itself is sectioned in preparation for the bipolar transfer.

The muscle may now swing through a wide arc, with the neurovascular pedicle as a pivot, and passes across the axilla. Final tension will be adjusted so that the original resting length of the latissimus dorsi is re-established. This is judged by placing marking sutures regularly along the muscle before its release from its original site. The muscle is tubed and tunneled between incisions made at the shoulder level and on the front of the distal arm, just proximal to the elbow. The distal end of the latissimus dorsi is attached to the biceps tendon by a weave technique (Fig. 4, A). The proximal end is attached to the coracoid process (Fig. 4, B). When the elbow is put through its range of flexion and extension with the arm abducted and adducted, the range should duplicate as closely as possible that noted when the muscle was in its original position.

After closure of the wound, the limb is splinted with the elbow flexed at 90°. After 6 weeks of

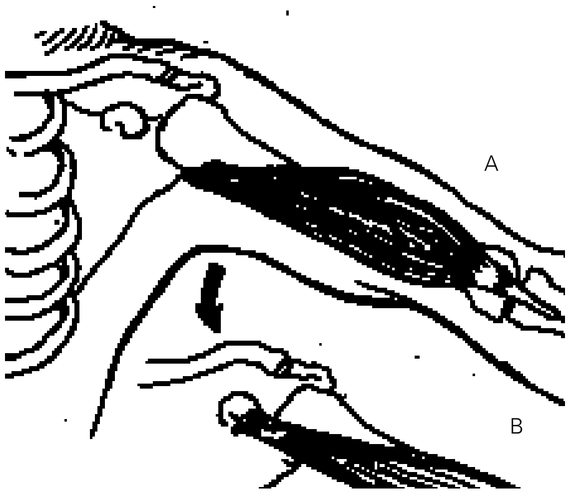


Figure 4

Operative steps in bipolar transfer (A, B) of the latissimus dorsi to restore elbow flexion. See text for details.

immobilization, active exercises are initiated, and the elbow is allowed to move gradually to its fully extended position in the following 3 weeks.

Re-training for elbow flexion can be difficult, as it often is with the latissimus dorsi transfer. Careful physical and occupational therapy and biofeedback exercises are helpful. The patient may be able to accelerate rehabilitation by coughing to stimulate the latissimus dorsi. Six months or more are usually required to achieve full strength and excursion of the transferred muscle.

Pectoralis major transfer

I have little experience with this procedure in the pediatric population. The scarring in this age group is significant and a source of parental concern.

Author's preferred technique (Carroll and Kleinman 1979)

Integrity of the pectoralis major muscle is assessed by grasping the anterior axillary fold and observing the anterior chest wall while the

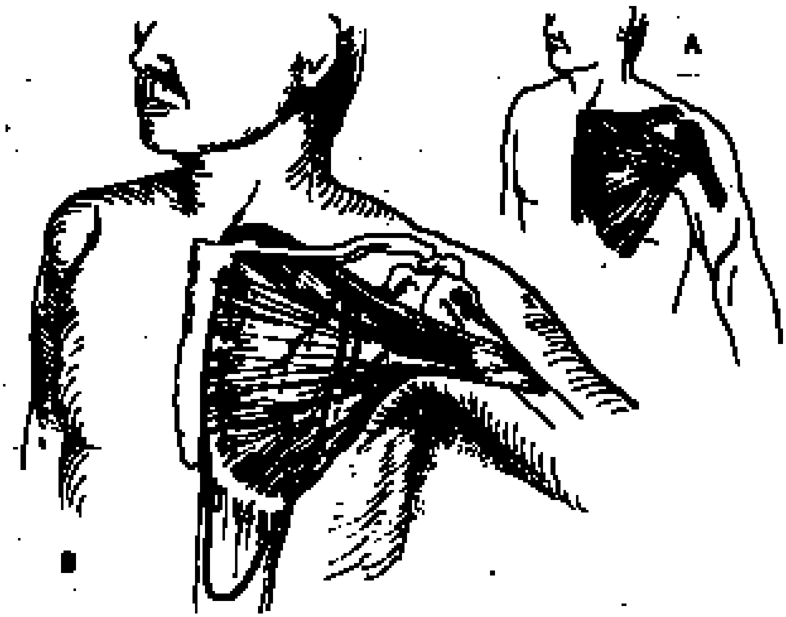
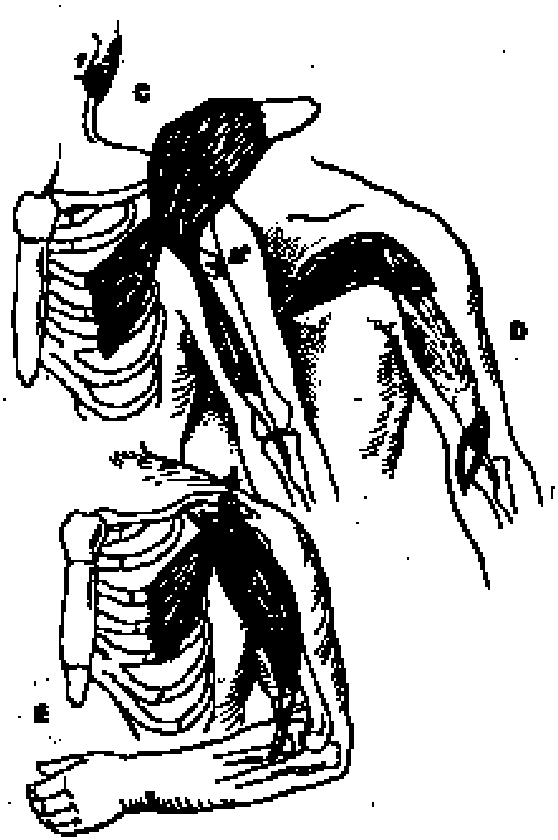


Figure 5

Operative steps for transfer of the pectoralis major to restore elbow flexion. See text for details.



patient adducts and internally routes the arm against resistance.

An incision is planned that will course along the muscle 2 cm below the superior insertion on the clavicle and 2 cm lateral to the sternal origin. The incision is carried down to the xyphoid area to expose the superior extent of the anterior rectus sheath (Fig. 5, A).

Laterally, the incision is extended along the deltipectoral groove marked by the cephalic vein. If skin is to be carried with the pectoralis muscle, the incision is designed to circumscribe an island of skin in a position appropriate to meet the need in the arm. The position is determined by designing it in relation to the pivotal pedicle in the recipient and then the donor position.

A second incision is planned in the antecubital fossa to expose the biceps tendon and its insertion into the biceps tuberosity of the radius.

The incision is initiated superiorly to expose the deltopectoral groove and cephalic vein. The groove is deepened, retracting the cephalic vein superiorly. The pectoralis minor insertion on the coracoid process is seen and cleared. The clavicular origin of the pectoralis is detached to expose the pectoral vessels and the medial and lateral pectoral nerves. Electrical stimulation helps identify the nerves. Once the neurovascular structures are identified, they are carefully protected as the dissection proceeds.

If an island of skin is to be carried, a circumscribing incision is made around it, and the skin is tacked down to the pectoral fascia with temporary sutures. The rest of the muscle is cleared in the extrafascial plane over its entire superficial surface.

Marking sutures may be placed, one at the junction of the muscle with the rectus sheath and a second close to the muscle's insertion on the humerus. Measurements of the distance between these two marking sutures with the arm abducted and externally rotated and then with the arm adducted and medially rotated are corded for later use.

A tongue of rectus fascia for use as a distal muscle attachment is outlined and elevated, leaving it attached to the pectoralis muscle (Fig. 5, B). The superior, medial, and inferior muscle attachments are severed, and the whole muscle is elevated, dissecting in the areolar subpectoral plane superficial to the pectoralis minor. Great care is exercised to avoid inadvertent injury to the primary neurovascular bundle. If the muscle is to be transferred as a bipolar transfer, the insertion of the pectoralis major on the humerus is sectioned close to bone (Fig. 5, C, large arrow).

A second incision is made across the antecubital fossa and is extended proximally on the medial side and distally on the lateral side to expose the tendon of the paralyzed biceps close to its insertion on the radial tuberosity (Fig. 5, D).

If the skin and subcutaneous tissue covering the arm are uninjured and sufficient, a tunnel is created by blunt and sharp dissection just superficial to the biceps fascia. The tunnel connects the proximal and distal incisions along the anterior (biceps) side of the arm. If skin is insufficient by virtue of loss or scarring, it is resected to good skin on all sides, and enough skin will be brought from the chest wall with the muscle to cover the transferred muscle without skin tension.

The pectoralis muscle is shifted to check for adequacy of the pedicle dissection. The medial inferior corner of the muscle with its rectus sheath tongue is swung distally to the biceps insertion, and the fascia end, previously inserted on the humerus, is swung upward to the acromion process beneath the retracted deltoid (Fig. 5E). The muscle is shifted proximally and distally to a position that will allow it to contract and relax with elbow flexion and extension and with the arm abducted, creating the least possible tension on the neurovascular structures. The muscle is rolled into a fusiform shape, and the junctures are made distally and proximally (Figs 5, D, E). The tension of the muscle is judged by setting the two insertion sites such that when the elbow is flexed and extended, the measurements between the marking sutures come closest to duplicating the range of contraction noted when the muscle was in its original bed.

Wounds are closed with or without the skin island according to indication, and the arm is immobilized on the anterior trunk with the elbow flexed during healing. Immobilization for 4–6 weeks is followed by progressive passive and then active range-of-motion exercises.

Other muscle–tendon transfers to restore elbow flexion

Triceps to biceps transfer: This transfer (Hoang et al 1989) has a long history and has proven to be effective in restoring a good range of motion, but at the expense of all active elbow extension. This transfer is probably best performed in circumstances where dysfunctional biceps–triceps co-contraction fails to respond to conservative treatment such as botulinum toxin injection, or where no other suitable local muscle is available.

Sternocleidomastoid to biceps transfer: This transfer is rarely performed today, primarily because of the significant cosmetic deformity that results. Kumar et al (1992) have described a modification of the standard technique that may reduce what is otherwise a strikingly altered appearance.

Advancement of the insertion of the biceps: Nemoto et al (1996) recommends moving the attachment of the biceps about 2 cm distal to its original insertion. He reported improved flexion power in six patients.

Functional free muscle transfers: The indications for the application of these procedures in the pediatric post-obstetrical brachial plexus palsy population are similar to those for the adult population. The sources available to innervate the transfer are similar to those discussed for the adult traumatic brachial plexus patient. This is discussed more completely in other chapters. One must be concerned about using several intercostal nerves to re-innervate the free muscle transfer in a young child who has a coexisting ipsilateral phrenic nerve palsy with evidence of reduced pulmonary function.

Results after muscle–tendon transfers to restore elbow flexion

Most of the literature dealing with reconstruction of elbow flexion describes global results and the patient population is primarily adult males who have suffered traumatic brachial plexus palsy. No series defines results in only pediatric cases. In these reports, there is no consensus on which donor muscle performs the best. Botte and Wood (1989) reviewed the Mayo Clinic series and found that latissimus and pectoralis transfer provided about the same arc of antigravity motion. Moneim and Omer (1986) found disappointing results on standardized daily living evaluations in his series of patients who had undergone latissimus transfer. Marshall et al (1988) reviewed London's St. Mary's Hospital experience and determined that latissimus and triceps performed best; Steindler procedures were adequate while the results of pectoralis transfers were disappointing. Liu et al (1993) reported 71 consecutive cases of Steindler flexorplasty including 13 patients who suffered obstetrical brachial plexus palsy. Seventy-nine per cent were judged to have good or excellent results. Dutton and Dawson (1981) reviewed 25 consecutive Steindler procedures. The mean arc of flexion was 95° with an average loss of extension of 36°. Brunelli et al (1995) reported good results with this procedure. Matory et al (1991) described modifications in the incisions for pectoralis transfer that reduce the scar effects. Hoang (1989) reviewed seven patients following triceps to biceps transfer, five of whom could bring their hand to their mouth.

It is difficult to extrapolate results obtained in adults to the pediatric population. Many adults who need these operations have flail shoulders and in many arthrodesis has been performed.

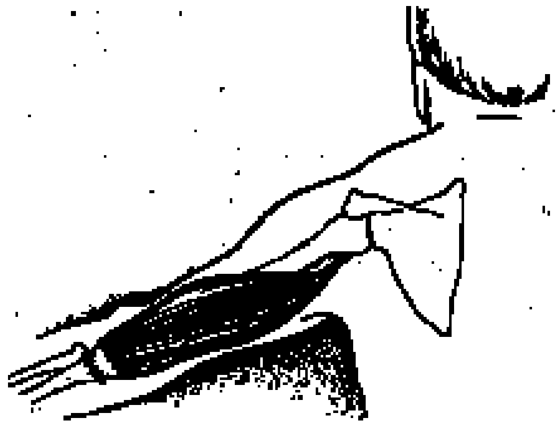


Figure 6

Use of the latissimus dorsi for elbow extension. A simpler monopolar transfer can be performed.

The salutary effects of shoulder arthrodesis on elbow flexion strength has long been recognized. Few obstetrical brachial plexus palsy patients undergo gleno-humeral arthrodesis.

Elbow extension

The methods to achieve improved elbow extension include such traditional muscle–tendon transfers as latissimus to triceps and posterior deltoid to triceps transfers (Moberg 1975). Jones (1985) reported on the outcome of latissimus to triceps transfers in four children after obstetrical brachial plexus palsy. The surgical technique is similar to that described for reconstruction of elbow flexion, differing only in that the transfer works well as a unipolar transfer (Fig. 6). Postoperatively, all demonstrated increased strength of elbow extension and improvements in activities of daily living.

Elbow stiffness

The treatment of the stiff elbow in the post-obstetrical brachial plexus palsy population has proved difficult. Once a contracture has developed it is very resistant to conservative treatment. Dynamic extension splinting has been minimally successful in restoring lost extension range but is effective in preventing progression of the deformity.

For significant deformity (greater than 30°) surgical release may be appropriate. Soft tissue contracture will account for some of the contracture and thus soft tissue release will be partly effective. This includes anterior capsular release and lengthening of the biceps, either as an intramuscular release or by formal Z-lengthening. Some fractional lengthening of the humeral origins of the pronator teres and flexor carpi radialis may be necessary.

Very severe contractures are rare and are probably best managed by some combination of soft tissue release and a dome osteotomy of the humerus at the supracondylar level.

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27

Palliative surgery: pronosupination in obstetrical palsy

Eduardo A Zancolli (II)

Obstetrical palsy of the upper limb represents a severe traumatic complication during delivery, which basically involves the brachial plexus and occasionally the osteoarticular structures of the shoulder and its deep periarticular muscles.

Our aim is the description and treatment of the relatively frequent obstetrical palsy sequela – consequent to extensive lesions of the brachial plexus – represented by *forearm supination deformity*, usually associated with *ulnar deviation*

a b

Figure 1

(A) Early flexible supination deformity in a 2-year-old girl after a whole-limb with partial recovery type of sequela. These initial flexible forearm deformities offer the opportunity to prevent the retraction of the interosseous membrane through the indication of early tendon transfers to rebalance the pronosupination function. (B) Very severe (180°) supination deformity of the forearm in a 15-year-old girl after a severe sequela of the distal type. A postoperative X-ray is seen in Fig. 11.

of the wrist and variable deficits of hand function. Forearm supination deformity tends to be progressive, culminating in severe retraction of the interosseous membrane and subluxation or dislocation of the distal radio-ulnar (DRU) joint and in a few advanced cases to dislocation of the radio-proximal radius head (Figs. 1b, 3, 4). Early recognition of this deformity is of paramount importance to prevent fixed deformities, which increase the hand deficit (Fig. 1a).

General considerations

Before dealing with the forearm supination deformity, we consider it of importance to mention some general concepts related to obstetrical palsy and its sequelae.

Sequelae of obstetrical palsy depend on three main initial lesions: (1) the brachial plexus, (2) the osteoarticular system, particularly at the proximal humeral level, and (3) direct damage to the deep periarticular muscles of the shoulder.

Brachial plexus injury manifests by different lesions of the motor, sensitive and sympathetic fibers: neuropraxia, axonotmesis and root avulsion. In axonotmesis the magnitude and time for recovery will depend on its degree of severity. Three main topographical initial brachial plexus lesions have been classically recognized: (1) *upper type* (Duchenne–Erb paralysis) (Duchenne 1872, Erb 1874), where the cervical nerves C5 and C6 are involved; (2) *upper and middle type*, with lesion of C5, C6 and C7 (C7 lesion can be total or partial), and (3) *total type* (Duchenne–Erb–Klumpke paralysis) with lesion of C5–T1. In our series we have not found isolated lesions of the C8–T1 (Klumpke's paralysis, Klumpke 1885). Occasionally the pattern of nerve lesions is irregular.

This classification of initial brachial plexus injuries differs from the classification we have adopted (Zancolli III et al 1979a,b,c, Zancolli II 1981, Zancolli II and Zancolli 1988, 2000), to group the diverse sequelae of the upper limb (see below).

The primary osteoarticular lesion of the proximal humerus (epiphysiolysis) was initially described by Kuestner (1885) and thoroughly studied by Putti (1932) and Scaglietti (1938). Primary epiphysiolysis was present in 32.5 per cent of our series (1979). We consider that the deep periarticular muscles of the shoulder joint can be affected by the initial obstetrical trauma. This explains early muscular fibrosis, such as the contracture of the subscapularis muscle a few months after birth. A similar interpretation for congenital torticolis by direct birth injury has been made by Suzuki et al (1984).

Other factors that contribute to increase the initial lesions are: incorrect or delayed initial treatment; forced manipulations with the intention to elongate severely retracted muscles, ligaments and capsules; plaster casts or braces for the shoulder in forced 'Statue of Liberty' position, and surgical pitfalls.

A delay in the rebalance of paralytic muscles or the prevention and correction of muscular contractures or ligament retractions usually allows progressiveness of deformities and joint subluxations or dislocations. A typical example is represented by the classical and common *supination deformity of the forearm* caused by the muscular imbalance created in distal brachial plexus lesions. In these cases the interosseous membrane begins to retract within a few years after birth (Fig. 1) and with time the DRU joint subluxates or dislocates. Another example is represented by early and severe internal contractures of the shoulder that frequently demand surgical release early on – usually after 6–8 months of life – to prevent deformity of the humeral epiphysis.

These examples indicate the importance of creating new muscular balances at different levels of the upper limb, particularly in those deformities that tend to be progressive, producing bone deformities and joint subluxation or dislocations.

Clinical material

Our clinical material to obtain a classification of sequelae of the upper limb in obstetrical palsy was represented by an initial study of 368 patients evaluated at the National Rehabilitation Center of Buenos Aires, Argentina (1979) (Zancolli et al 1979a,b,c). Of this series, 203 patients were operated on for sequelae of the shoulder and 93 patients received reconstructive surgery of the elbow, forearm and hand. An analysis of another series of 148 cases (Zancolli II and Zancolli III 1988) showed that 63 per cent of patients were female of whom 54 per cent were affected on their right upper limb and 4 per cent were affected on both sides. In this series a high birth weight (> 4 kg) was recorded in 92 per cent of cases. Breech presentation occurred in 12 per cent. Other pathologies observed at birth were: congenital dislocation of the hip (1.3 per cent), torticolis (2.7 per cent), and partial paralysis of the lower limb caused by a combined spinal cord lesion (1.2 per cent). All these percentages relate to a sample group of 148 patients.

Recovery of muscle paralysis was variable. The sooner after birth that the recovery begins, the better is the final result. Particularly good functional results are obtained from those cases where recovery begins before week 4–6; fair if it begins after week 6 and poor, with severe sequelae, if recovery does not begin before 6 months of age. In favorable cases spontaneous recovery can continue improving until 18–24 months. Our recent observations (Zancolli II and Zancolli III 1988, 2000) showed that biceps function begins to recover in 75 per cent of the cases after the fifth month. This indicated us that direct surgery of the upper plexus should not be undertaken before the fifth month, approximately. Some 18 per cent of our cases did not recover elbow flexion and this should be the case for direct reconstructive surgery of the upper brachial plexus (C5–C6 nerve tissue replacement in postganglionar lesions). Of our patients with middle-plexus injuries, 46 per cent had a definitive tricep paralysis. In total plexus lesions, 79 per cent recovered some finger function but 21 per cent had no recovery at all (complete hand paralysis). When the hand begins to recover before 3 months of age the final functional result will generally be acceptable. If hand active movements have not appeared at 6 months, the final function will be very poor or non-existent. Horner's syndrome was initially present in the cases with severe paralysis of the hand (21 per cent).

Classification of sequelae

Very little has been written relating to classification of the residual deformities of obstetrical paralysis of the upper limb. Typically, classifications have usually referred to the initial lesions of the brachial plexus, but not to its sequelae after the recovery period. Only the shoulder has received special attention (Steindler 1923, Gilbert et al 1988).

Table 1 Classification of obstetrical palsy sequelae

Type	*Clinical picture*	*Percentage*[a]
1	Proximal limb	53
2	Proximal middle-limb	10
3	Posterior cord	10
4	Whole-limb with partial recovery (forearm supination or pronation deformities)	25
5	Whole-limb with complete flaccid paralysis	2

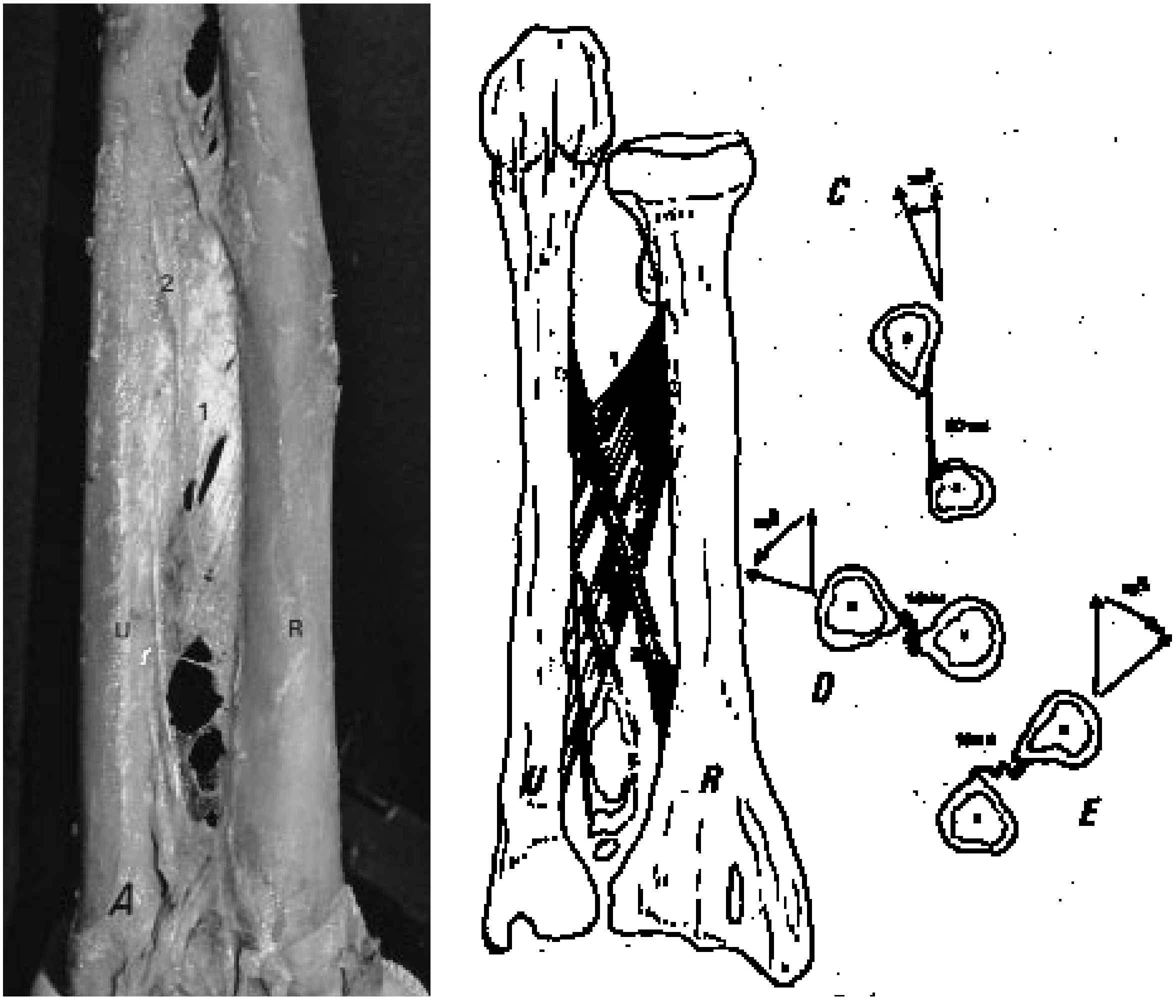
[a]Percentages referred to 148 patients evaluated (Zancolli II and Zancolli III, 1988, 2000).

Based on our clinical material we initially (Zancolli II et al 1979a,b,c) recognized three main types of sequelae: (1) proximal upper-limb, (2) predominant distal and (3) predominant whole-limb paralysis. Through subsequent evaluations (Zancolli II and Zancolli III 1988, 2000), we now recognize five types of sequelae that give us a better correlation with the selection of the peripheral reconstructive procedures (Table 1).

In the *proximal limb* (type 1) (53 per cent) the principal pathology is located in the shoulder and elbow and occasionally a moderate pronation contracture of the forearm can be demonstrated. The shoulder sequelae have been divided by us into two main groups: (1) joint contracture and (2) flaccid paralysis. Shoulder contractures are divided into five subgroups in relation to the local pathology and surgical treatment (Zancolli II 1984).

In the *proximal middle-limb* (type 2) (10 per cent), the affected proximal limb muscles are similar to type 1, with the addition of muscular paralysis depending on the C7 cervical nerve lesion, such as: triceps, pronator teres, extensors of the wrist and fingers and flexor carpi radialis. The latissimus dorsi is usually very weak and not suitable for transfer. If the triceps is very weak a paralytic flexion contracture of the elbow is frequently present. This group of patients may present a forearm supination deformity due to the muscle unbalance created between the pronosupination muscles.

The *posterior cord* (type 3) (10 per cent) is characterized by severe functional deficit present in shoulder abduction and elbow, wrist, fingers and thumb extension, due to the distal muscles being innervated by the nerves depending on the posterior cord of the brachial plexus.



a b

Figure 2

(a) Anatomy of the interosseous membrane. (Dorsal view of the forearm.) r, radius; u, ulna; 1, strong descending radio-ulnar fibers (DRUF); 2, weak descending ulno-radial fibers (DURF). (b) This drawing show the two types of fibers (dorsal view of the forearm). The DRUF (1) run between the anterior aspect of the interosseous border of the radius to the interosseous border and posterior aspect of the ulna. These fibers represent the principal part of the membrane. Their fibers are very thick and strong and retract very easily in the forearm supination deformity in obstetrical palsy. Dorsally to the DRUF are thin fibers, the DURF (2), that run distally, crossing the DRUF. The DRUF tense in supination and the DURF tense in pronation. (C) We have found in cadaveric investigations that the interosseous space widens at its maximum in a supination of 20° (20 mm) and that reduces to 14 mm in maximum supination (D) and to 10 mm in maximum pronation (E). (Investigation in an adult cadaveric specimen.)

In the *whole-limb with partial recovery* (type 4) (25 per cent) the entire upper limb is affected but partial recovery has been achieved. The principal deficit is at the distal part of the limb (forearm, wrist and hand). These are the patients who most frequently present with supination deformity of the forearm. In our series we have not found a single case of exclusive sequelae of the distal part of the upper limb, presenting normal shoulder and elbow. In our series of the limb of

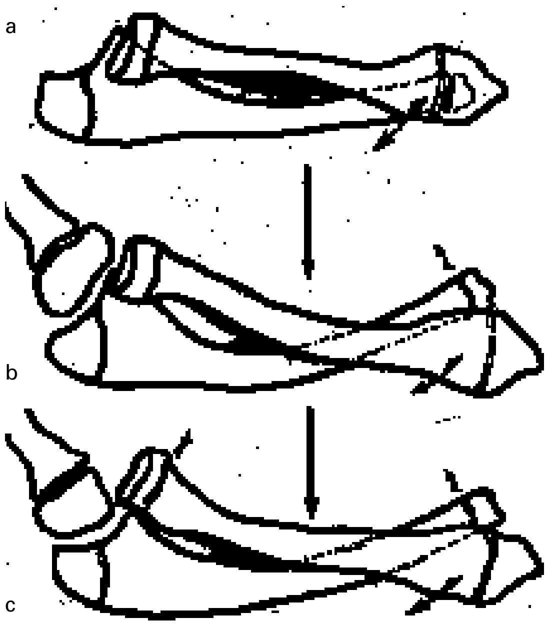


Figure 3

Progressiveness of the forearm supination deformity in obstetrical palsy. (A) Initial deformity with or without retraction of the interosseous membrane. The DRU joint is congruent. (B) Fixed deformity with retraction of the interosseous membrane and the dorsal structures of the DRU joint and volar dislocation of the distal ulna. (C) Volar dislocation of the distal ulna and the radius head (arrows).

type 4 sequelae has the following characteristics: (1) moderate internal rotation contracture of the shoulder and severe functional deficit to abduction; (2) flexion contracture of the elbow, (3) supination deformity of the forearm, frequently associated with ulnar deviation of the wrist (Fig. 8); (4) pronation contracture of the forearm (Fig. 12), and (5) different types of digital paralysis (Figs 1–3, 8, 12). At the end of the growing period the upper limb usually presents hypotrophy, with a considerable reduction of its length. Occasionally Horner's syndrome may persist.

Shoulder abduction was limited in our cases to an average of 56° – range between 10 and 90°. The Putti's sign was present in 27 per cent of the cases. Elbow flexion paralysis was present in 18 per cent and elbow extension paralysis in 46 per cent. Flexion contracture of the elbow was present in 62 per cent of the patients (average 30°). There were three cases with dislocation of the proximal end of the ulna and pronation deformities of the forearm (Fig. 12) and one case with osteonecrosis of the humeral trochlea.

In the *whole-limb with complete flaccid paralysis* (type 5) the entire upper limb is paralyzed, without joint deformities. The only active muscle controlling the limb is the trapezius. This is a very uncommon type of obstetrical sequela (2 per cent).

Forearm supination deformity associated with ulnar deviation of the wrist

Clinical picture

Very frequently, supination deformity of the forearm results from extensive paralysis of the lower part of the upper limb after obstetrical palsy. Very few papers have been written regarding its treatment (Grilli 1959, Owings et al 1971, Putti 1932, Steindler 1923, Zancolli II and Zancolli III 2000). According to our series the supination deformity of the forearm was particularly observed in the types 2 (proximal middle-limb) and 4 (whole-limb with partial recovery) of residual deformities. In both types of sequelae an imbalance is produced between the active supinator muscles (biceps and supinator) and the paralysed pronator muscles (pronator teres and pronator quadratus). Considering both types of sequelae, totalling 35 per cent of all the upper limb sequelae, the supination deformity was present in 69 per cent of the cases with persistent and extensive distal paralysis. Pronation contracture was present in 28 per cent of our series.

Initially, forearm supination deformity may be reduced passively (Fig. 3, 7). With time and growth – usually after 2 years of age – the interosseous membrane begins to retract and the deformity cannot be passively reduced. In the supination position of the forearm the interosseous membrane space of the forearm reduces and the interosseous becomes retracted in its strong descending radio-ulnar fibers (Fig. 1b, 2). Under these circumstances these fibers retract and pronation is blocked. The deformity

Table 2 Classification (stages) of obstetrical supination deformities of the forearm

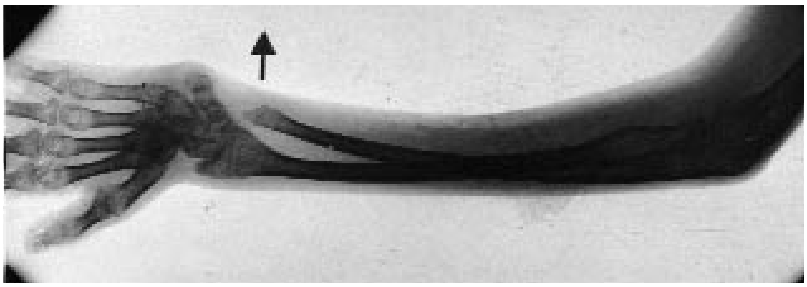
Stage I	Flexible deformity (congruent DRU joint)
	(a) active triceps
	(b) paralytic triceps
Stage II	Fixed deformity (contracture of the interosseous membrane)
	1. Congruent DRU joint
	(a) active triceps
	(b) paralytic triceps
	2. Incongruent DRU joint (subluxation or dislocation)
	3. Volar subluxation or dislocation of the distal ulna and radial head

becomes fixed very quickly and with time the deformity produces a curvature of the forearm bones, especially the radius (Figs 3, 7, 8), and volar subluxation and dislocation of the distal end of the ulna (Figs 3, 4, 8). In severe deformities the radial head dislocates volarly (Figs 3, 4b, 8). The dislocation of the distal end of the ulna is palpated over the volar aspect of the wrist with the forearm in supination (Fig. 8b).

Associated with forearm supination, the wrist hyperextends due to the paralysis of its volar flexors and the partial activity of the dorsi flexors tendons (Figs. 4b, 8a, b). With forearm in supination gravity increases wrist hyperextension and ulnar deviation. The frequent presence of an active extensor carpi ulnaris (ECU) muscle tends to accentuate the ulnar deviation of the dorsiflexed wrist. The power of the ECU is usually greater than that of the radial extensors of the wrist and flexor carpi ulnaris.

Supination contracture of the forearm is a very disabling deformity. Owing to its presence, many common activities in daily life, such as dressing, eating and writing, require elbow flexion and abduction plus internal rotation of the shoulder. With this deformity the patient is not motivated to use the hand and has a functional deficit out of proportion to the real muscular and hand sensory conditions. This indicates the importance of early correction of the deformity to improve hand function before bone deformities and joint dislocations occur (Fig. 1a).

Associated with forearm supination and deformity of the wrist (dorsiflexion and ulnar deviation) the fingers and thumb often show great weakness or paralysis, especially of their intrinsic muscles. Usually, the metacarpophalangeal joints of the fingers are stiff in extension due to contracture of their collateral ligaments. The



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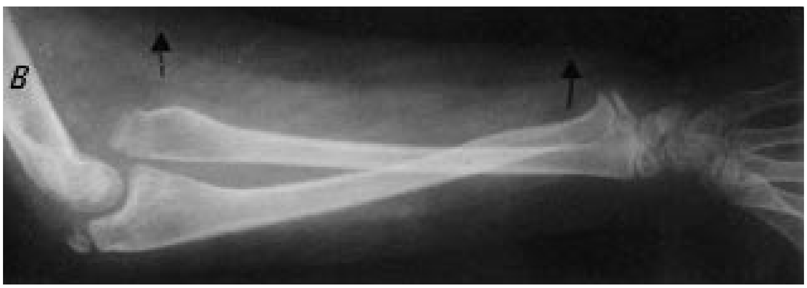


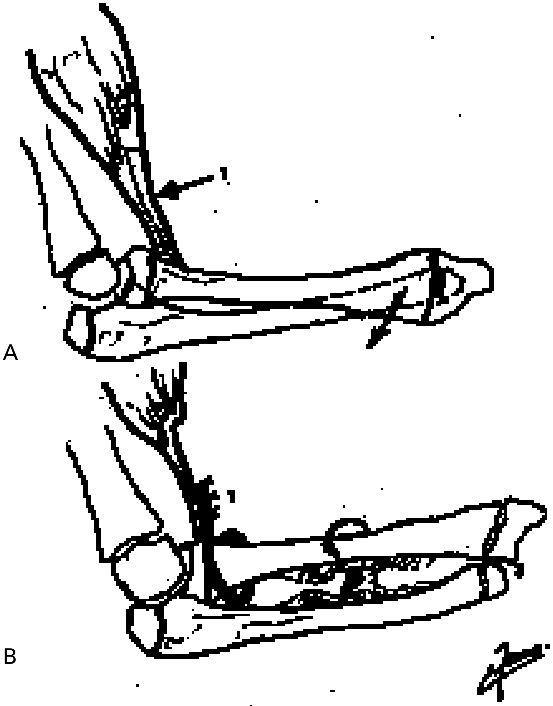
b

Figure 4

(A) X-ray in a supination deformity with incurvation of the forearm bones and volar dislocation of the distal ulnar head (arrow). Interosseous membrane retracted. (B) Very severe supination contracture with volar dislocation of the radial head and distal ulnar head (arrows).

thumb is usually paralysed and drawn in adduction. A flexion contracture of the elbow is frequently present due to the imbalance between a paralytic triceps and an active biceps.

The forearm supination deformity presents into two stages: (1) *flexible* (posture in supination) and (2) *fixed* (contracture). The latter can be mild (20°), moderate (20–60°) or severe (over 60°). In severe long-standing cases, the rotation of the forearm can reach up to 180°, as in two of our cases (Fig. 1B). Table 2 shows our clinical classification, which is closely related to the operative procedures (Table 3).



A

B

Figure 5

(A) Re-routing of the biceps tendon. The tendon is split in a Z fashion (1). It is exposed through a volar elbow incision. In a fixed supination deformity the interosseous membrane is initially released through a long longitudinal posterior incision. After this, a forceful manipulation in pronation is performed (Fig. 8f). This technique is indicated in a flexible deformity with a congruent DRU joint with a functioning triceps (stage I,a) and in a fix deformity with a congruent DRU joint and good triceps (stage II-1,a). (B) The part of the tendon attached to the radius is passed dorsally around the radius, from the ulnar to the radial side, deep to the supinator (1). With the forearm in 30° of pronation and with the elbow in 80° of flexion the two ends of the tendons are sutured side to side. A Kirschner wire can maintain the forearm in pronation during 5 weeks. A long posterior splint with the elbow in 90° is applied during the postoperative period.

Surgical treatment

Indications and timing

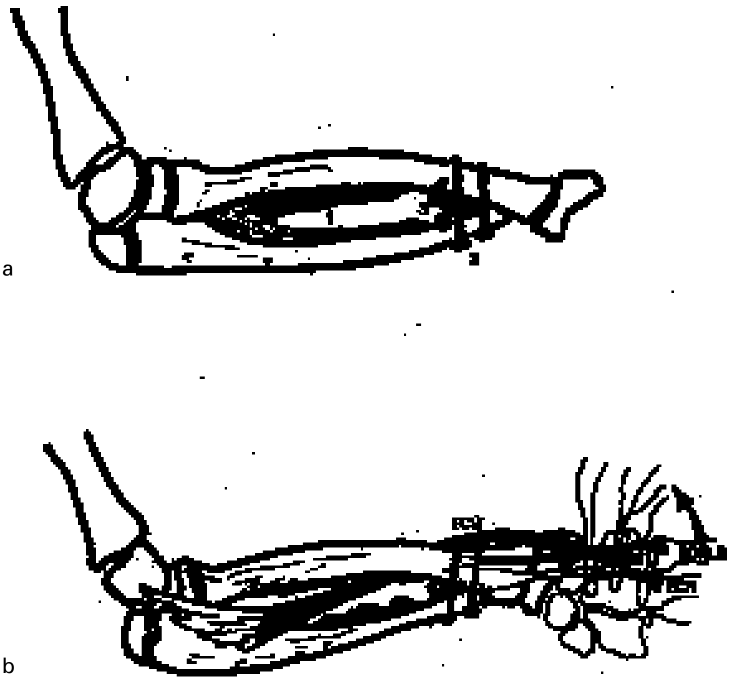
Surgical indications basically depend on the pathology of the interosseous membrane – flexible or retracted – and the condition of the distal radio-ulnar (DRU) joint and the triceps function. Other factors to be considered are: the deformities of the shoulder and elbow and the remnant function of the hand. In general, a severe shoulder deformity should be corrected first. A mild or moderate flexion contracture of the elbow is not a surgical contraindication to forearm surgery. The supination deformity and the dorsiflexed and ulnarly deviated wrist are corrected next. The reconstructive surgery of the hand should be the final step. Surgical techniques depend on the pathology of the involved soft tissues, joints and muscular condition. Surgery should be ideally indicated as soon as the supination deformity begins to increase (stage I) (Fig. 1,A). Conservative treatment (manipulations and splint) cannot prevent the contracture of the interosseous membrane and the progressiveness of the deformity. Correction of the supination deformity usually increases digital function.

Operative procedures

The author shall refer to the principal distal deformities of the upper limit after obstetrical palsy and to his prefered surgical procedures.

1. Forearm supination/wrist ulnar devication deformity

This is a complex deformity where two components are usually combined: (i) forearm supination and (ii) wrist dorsiflexion with ulnar deviation.



a

b

Figure 6

(A) Release of the interosseous membrane (1) and reduction of the deformity, with distal excision of the ulnar head and distal radio-ulnar fusion, fixed with two screws (2). Bone grafts are added (3). This technique can be indicated in the following conditions: flexible supination deformity without a functioning triceps (stage I,b); fixed deformity with a congruent DRU joint but a paralytic triceps (stage II-1,b); fixed deformity with an incongruent and DRU joint, with or without a functioning triceps (stage II-2), and in associated dislocation of the radius head (stage II-3). (B) Transfer of the ECU tendon through the forearm interosseous space. The tendon surrounds the radius volarly and is fixed to the extensor carpi radialis longus (ECRL) and brevis (ECRB) tendons. It is indicated in wrist dorsiflexion and ulnar deviation flexible deformities and usually is associated with biceps re-routing or distal radio-ulnar fusion.

(i) Forearm supination component

Different techniques to correct forearm supination deformity have been published. Blount (1940) introduced closed osteoclasis of the middle third of both bones of the forearm. Zaoussis (1963) indicated osteotomy of the proximal end of the radius. In 1967 we presented the results of treatment of 14 patients by release of the interosseous membrane and re-routing of the biceps tendon to obtain pronation (Zancolli II 1967). Release of the interosseous membrane was initially described by Putti (1940) and the re-routing of biceps by Grilli (1959). We have combined both procedures (Zancolli II 1967). Owings et al (1971) have presented their experience with biceps re-routing. Our surgical indications in recent years have been based in the classification presented in the Table 2. In our experience osteoclasis and osteotomies of the forearm bones will usually recur in time due to the persistence of the pronosupination muscular imbalance.

In the case of a *flexible supination deformity* (congruent DRU joint without contracture of the interosseous membrane) and with a good triceps (stage I,a) we *re-route the biceps tendon to produce pronation* (Figs 5, 7). The transfer is fixed with the forearm in 30° of pronation and with the elbow in 80° of flexion. The position obtained can be provisionally secured with on Kirschner wire between both forearm bones during 5 weeks (Table 3). Our results have been satisfactory: patients obtain some degree of pronation (Fig. 7).

Biceps tendon re-routing is contraindicated in flexible deformities with triceps paralysis (stage I,b). Under this condition the procedure will produce a postoperative flexion contracture of the elbow. In these cases, the flexor carpi ulnaris tendon – when active – is transferred deep to the flexor tendons of the forearm and the median nerve and fixed to the distal radius at the brachioradialis tendon insertion. This technique can produce partial active pronation. If the extensor carpi ulnaris (ECU) tendon is paralysed the deformity is corrected by a distal radio-ulnar fusion.

In *fixed supination deformities* (stage II) the surgical indication vary in relation to the local pathology. In a fixed deformity with a congruent DRU joint and good triceps (stage II–1,a) the

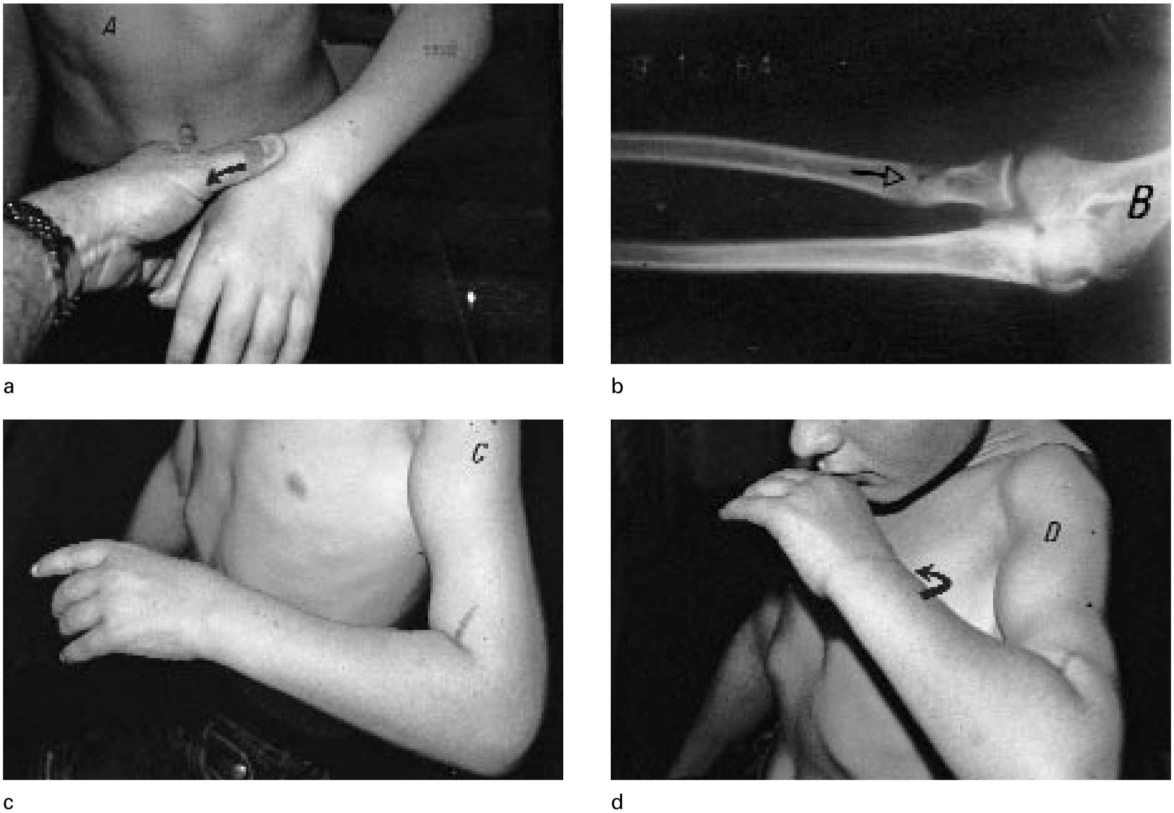


Figure 7

(A) A case of a flexible supination deformity with a congruent DRU joint in a 11-year-old boy. Through a passive maneuver it is possible to pronate the forearm. Triceps was active. A transfer of the biceps to pronate the forearm was indicated. (B) Reinsertion of the entire biceps tendon into the dorsal side of the radius neck to obtain pronation (arrow). This technique differs from that shown in Fig. 5. (C) A good position in pronation was obtained. (D) The patient reaches the face very easily.

Table 3 Surgical techniques most frequently indicated in forearm supination deformity. In all the cases a transfer of the ECU tendon may be indicated to correct ulnar deviation of the wrist and to maintain active wrist extension (Fig. 6b)

Stage	*Indication*
Flexible deformity	
Stage I-a (good triceps)	Biceps tendon re-routing to pronation
Stage I-b (bad triceps)	Transfer of the FCU or distal radio-ulnar fusion
Fixed deformity	
Stage II-1,a (good triceps)	Excision of the interosseous membrane and re-routing of biceps to pronation
Stage II-1,b (bad triceps)	Excision of the interosseous membrane with distal radio-ulnar fusion
Stage II-3	Excision of the radial head, release of the interosseous membrane and distal radio-ulnar fusion

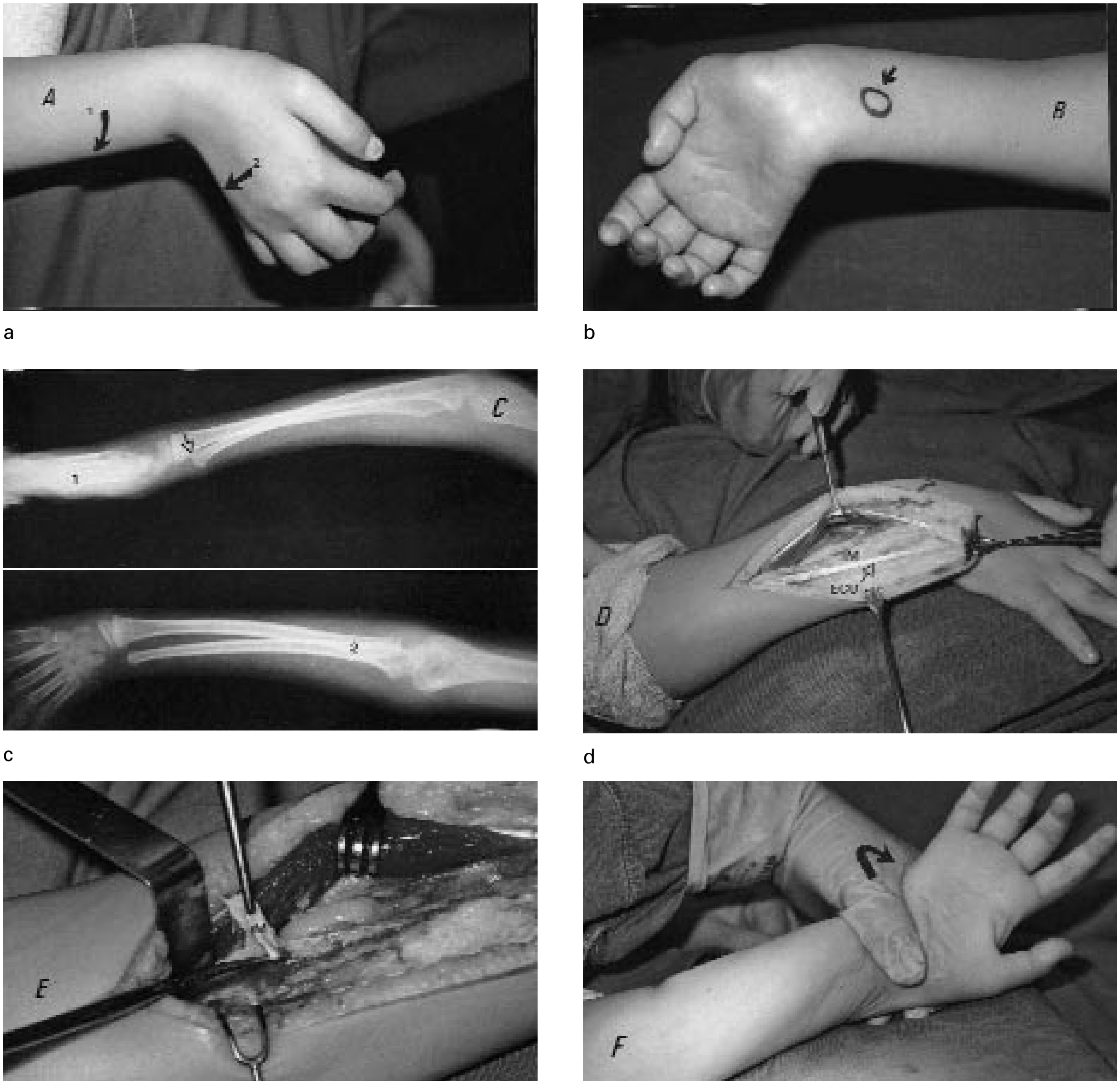


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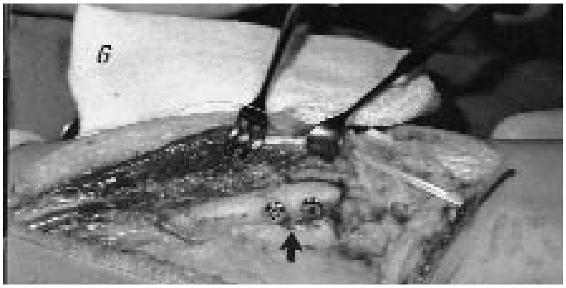
Figure 8

(A) A case of a fixed supination deformity (1) without functioning triceps in a 12-year-old girl. Ulnar deviation of the wrist (2). (B) The distal ulnar was palpated (dislocated) on the volar aspect of the wrist (arrow). (C) Volar dislocation of the distal ulna in lateral view (arrow) (1). In anteroposterior view a separation is seen at the DRU joint (2). Note incurvation of the forearm bones. (D) Long dorsal incision to expose the ECU tendon – usually active – and the interosseous membrane (IM). (E) Ample excision of all the retracted fibers of the interosseous membrane. (F) Intraoperative passive maneuver to obtain maximum pronation after the release of the interosseous membrane. (G) Radio-ulnar fusion in the desired angle of pronation (20°). Bone grafts are added. Fixation with two screws (arrow). The ECU tendon is retracted radially. (H) Radio-ulnar fusion proximally to the radius growing cartilage (arrow). The ulnar head has not been excised. (I) The ECU tendon is passed volarly to the radius (arrow). R, distal radius. (J) The ECU tendon has been passed through the interosseous space (1) and emerges close to the distal radius epiphysis (2). The ECRL and ECRB are exposed (3). (K) Final position of the forearm (20° pronation) and the wrist after the distal radio-ulnar fusion and transfer of the ECU tendon have been performed. (L) Fixation of the ECU tendon to the ECRL and ECRB tendons (arrows). (LL) Final result after five years from the operation. Active wrist extension was possible up to 60°. (M) Wrist flexion (30°) through the effect of gravity (arrow). The flexor tendons of the wrist were paralyzed. (N) Wrist position and alignment were maintained in all functions of the upper limb.



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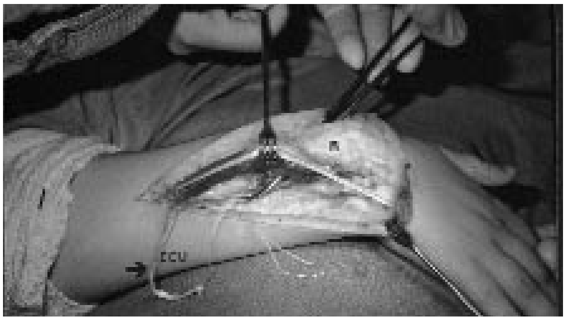

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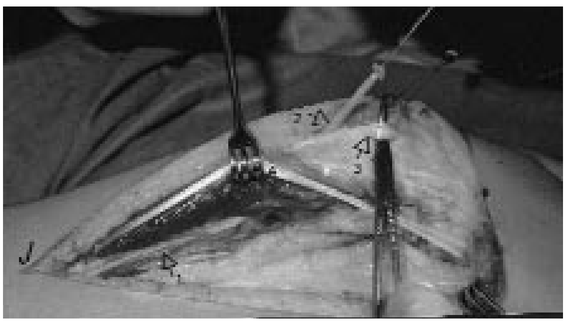

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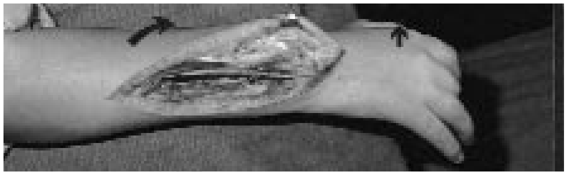

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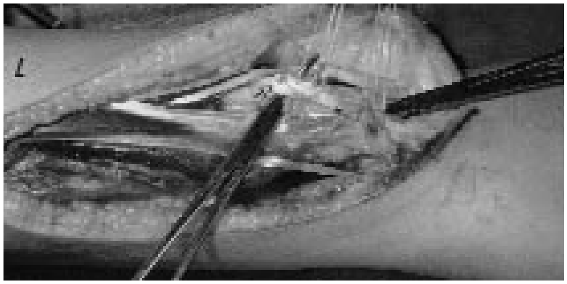

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Figure 9

(A) Distal radio-ulnar fusion in a fixed supination deformity in a 4-year-old girl. Synostosis is seen performed proximally to the radius growing cartilage (arrow). (B) Nine years after the operation the fusion moves proximally. The initial correction of the forearm was maintained. The growing cartilage was not affected.

deformity is corrected by an ample excision of the retracted interosseous membrane, followed by manipulation of the forearm towards pronation and re-routing of the biceps tendon to produce pronation. The interosseous membrane is particularly released at the middle third of the forearm where strong retracted fibers are present (descending radio-ulnar fibers) (Zancolli II and Cozzi 1992) (Fig. 2). Poitevin and Valente (1999) has described in detail the different fibers of the interosseous membrane.

Eighteen biceps re-routing operations were performed in obstetrical palsy patients. The patients' age at time of surgery ranged from 4 to 12 years – mean 10.5 years. In 12 patients a release of the interosseous membrane was indicated in the same surgical stage. None of the cases failed to correct the supination deformity. In three cases a flexion contracture of the elbow was produced. In these cases the triceps was paralyzed.

In a fixed deformity with congruent DRU joint and paralytic triceps) (stage II-1,b), and in a

Figure 10

In the case of this 10-year-old girl, the growing cartilage of the radius was injured during a distal radio-ulnar surgical synostosis. Two years later the cartilage was seen blocked into its ulnar side.

Figure 11

Distal radio-ulnar fusion (1) is combined to wrist fusion (2) in a 16-year-old girl with a severe supination deformity. The interosseous membrane was excised. Incurvation of both bones of the forearm is seen. (This postoperative X-ray is of the patient in Fig. 1B.)

flexible deformity I,b, biceps transfer to obtain muscular rebalance should not be attempted, otherwise a postoperative flexion contracture of the elbow is likely to result.

In our experience, the cases of fixed deformity with congruent DRU joint and paralytic triceps (stage II-1, b), or with subluxated or dislocated DRU joint, with or without triceps (stage II-2), the best indication consists of:

1. ample excision of the interosseous membrane through long dorso-ulnar incision, following the ECU tendon;
2. release of the dorsal capsule and ligaments of the DRU joint;
3. manipulation of the forearm to obtain maximum pronation;
4. excision of the distal end of the ulna;
5. radio-ulnar fusion proximal to the growth plate of the radius (Table 3) (Figs 6, 8).

The synostosis produced between the ulna and radius is fixed with two screws or crossed Kirschner wires. The forearm is fixed in 20° of pronation to compensate through gravity the lack of wrist flexors tendons when the arm is at the side of the body. Bone graft is added from the resected distal ulna.

We have indicated this technique in 32 patients between 1972 and 1998. Forearm

Figure 12

(A) Pronation deformity in a whole-type with partial recovery of an obstetrical palsy sequela, in a 20-year-old patient. The fingers were in a claw deformity. (b) Incongruent DRU joint and radius in curvation (anteroposterior view). (C) Dorsal dislocation of the distal ulna (lateral view). (D) Dislocation of the proximal end of the ulna. In this case a distal radio-ulnar fusion was performed after an ample excision of the interosseous membrane.

supination deformity was corrected in all the cases. We have not seen late deformation of the distal radius or its growing cartilage (Figs 8,H; 9), except in one case where this cartilage was violated during surgery (Fig. 10). This case involved a fall, 10 years after the surgical procedure, where a fracture at the bone fusion was produced (at the screws level). Associated with a re-routing of biceps or to a radio-ulnar fusion, a transfer of the ECU tendon can be indicated to correct ulnar deviation of the wrist (Fig 6, 8) (see below).

In very severe hand paralysis, after the growing period, the distal synovitis of the forearm can be combined with the wrist fusion (Fig. 11).

In a supination contracture with volar dislocation of the distal ulna and radial head (stage II-3) the supination contracture is corrected by the excision of the interosseous membrane and excision of the radial head followed by a distal radio-ulnar fusion, as described above.

(ii). Wrist dorsiflexion with ulnar deviation component

As mentioned, is usually orsiflexion position of the wrist with ulnar deviation can be associated with forearm supination (27 per cent) (Zancolli II and Zancolli III 1988). In the wrist deformity there exists usually a muscular imbalance where the great majority of the muscles that pass through the radial aspect of the wrist are paralysed (thumb extensors, extensor carpi radialis brevis and longus aNd flexor carpi radialis). Frequently the only active wrist muscle is the extensor carpi ulnaris.

The ulnar deviation is initially reducible and basically produced by the effect of gravity and the traction of an unopposed active ECU tendon. There are three possible treatments for this deformity: (1) a brace, (2) wrist arthrodesis after the growing period, or (3) tendon transfers. We prefer tendon transfers when treating a child during the growing period. As we have mentioned before this technique is ideally performed simultaneously with the correction of the supination contracture (biceps transfer of radio-ulnar fusion).

The ECU tendon is passed through the excised interosseous membrane towards the volar compartment of the forearm and then re-routed around the volar aspect of the radius (passing deep to the radial vascular bundle) and sutured to the extensor carpi radialis longus and brevis with a tension to maintain the wrist in 20° of dorsiflexion (Fig. 8). The route given to the tendon transfer is very effective to maintain the wrist in the axis of the radius.

This technique gives excellent results in correcting ulnar deviation and restores a good wrist dorsiflexion. It prevents a future fixed ulnar deviation of the wrist (Fig. 8) and eliminates the use of wrist splints in a growing child. The preservation of wrist extension through the activity of the transferred ECU tendon and wrist flexion by the gravity effect can be used to create tenodesic effects over the fingers and a thumb in very severe digital paralysis.

2. Forearm pronation deformity

Pronation contracture deformity of the forearm, as mentioned before, can be present in distal sequelae of obstetrical palsy. In this deformity the distal ulna dislocates opposite to the supination deformity, that is dorsally. The interosseous membrane retracts very easily. Our proposed surgical treatment when the DRU joint is incongruent, subluxated or dislocated, consists of an ample excision of the interosseous membrane, tenotomy of the retracted pronator muscles and distal radio-ulnar fusion in position (Fig. 12). Tendon transfers or wrist fusion can be associated.

3. Hand sequelae

The clinical presentation of hand function is variable depending on the degree of spontaneous recovery. Hand sequelae are difficult to classify, and consequently it is difficult to standardize surgical procedures. If tendons are available for transfers, hand function may be reconstructed. Generally muscles to transfer are weak and reconstruction of hand function is a challenge.

In most of the cases the surgeon has only one or two wrist motors available for transfers and these are used only after a wrist arthrodesis is performed (after the growing period).

An attempt was made to classify the different types of hand sequelae (Zancolli II and Zancolli III 1988, 2000).

The usual patterns of paralysis we have see are:

- radial-type (complete or dissociated) (30 per cent),
- median and ulnar-type (8 per cent),

- diffuse paresis (13 per cent),
- total paralysis (21 per cent),
- irregular distribution of paralysis (28 per cent).

The dissociated radial paralysis presents when there is a good wrist extensor and bad finger extensors, or vice versa. The diffuse paretic hand has only a few degrees of digital motion in flexion and extension (none of these muscles can be transferred). Tendon transfers employ only muscles of value 4 or 5. Total paralysis (21 per cent) is compatible with root avulsion of C7, C8, and T1. In these cases the combination of a distal radio-ulnar fusion to a wrist fusion can produce a good assistant limb (Fig. 11).

Conclusion

We have presented our preferred palliative surgical procedures to correct residual distal deformities of the upper limb after obstetrical palsy. We have studied, in particular, the supination deformity of the forearm usually associated with wrist dorsiflexion and ulnar deviation. The distal residual sequelae have been classified. This classification permits selection of the most appropriate reconstructive procedures. The surgical procedures here proposed have passed the test of time. Our aim has been to communicate our experience of this challenging and severe pathology.

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28
Palliative surgery: forearm and hand deformities

David C-C Chuang

Introduction

Clarke and Curtis (1995) classify birth palsy into four categories according to anatomy: (1) Erb's palsy, a palsy involving C5, C6 and sometimes C7, also called upper plexus palsy, which causes deformities mostly of the shoulder and elbow; (2) Intermediate plexus palsy involving C7 and sometimes C8, T1; (3) Klumpke's palsy, a palsy involving C8, T1, and (4) total plexus palsy, involving C5–C8 and sometimes T1. The last three types cause deformities mostly of forearm and hand. In their 3508 cases of obstetrical brachial plexus palsy (OBPP) evaluation, only 20 cases (0.6 per cent) were Klumpke's palsy.

Gilbert (Gilbert et al 1991), evaluating 1000 babies with birth palsy at 48 hours after birth, found that two types predominated in this population: paralysis in the upper roots; and complete paralysis. Isolated involvement of the distal roots, Klumpke's palsy, was not seen. Chuang et al (1998a) have classified OBPP into two types: (1) initial OBPP (or Infant OBPP, I-OBPP), some of whom required early nerve surgery; and (2) late OBPP with deformity, called sequelae OBPP (S-OBPP, or child OBPP), many of whom require surgical correction. As a result of evaluation of 121 S-OBPP children, Chuang created a 'score of 10' system for functional evaluation. 'Erb's score of 10' gives 10 points for upper plexus functions including shoulder abduction, shoulder external rotation, elbow flexion, elbow extension, forearm supination and pronation, and trumpet's sign. 'Klumpke's score of 10' gives 10 points for lower plexus functions including wrist extension, wrist flexion, metacarpophalangeal (MP) joint extension, interphalangeal (IP) joint extension, finger flexion, thumb adduction and thumb abduction. The author has found that hands in patients with S-OBPP fortunately tend to be functional. No one was found with complete hand palsy; some C8 or T1 function still remained (ie incomplete avulsion); or some C8–T1 function from the aberrant re-innervation from the upper plexus was found (ie avulsed C8–T1 is possibly connected to the disrupted upper trunk).

Forearm and hand reconstruction in S-OBPP with a poor Klumpke's score presents more difficulty in reconstruction than the shoulder or elbow. Few papers in the literature have discussed in detail forearm and hand reconstruction caused by OBPP (Zancolli 1967, 1981, 1988, Adler 1967, Doi 1996, Hoffer 1991, Lamb 1980). In this chapter, we present a retrospective review of our S-OBPP patients who had undergone palliative surgery for sequelae deformities of the forearm and hand.

Materials and methods

We treated sequelae deformities of forearm and hand in S-OBPP in nearly 100 cases between 1988 and 1997 (a nine-year period). Of these, 54 were followed-up more than two years. They all had deformities arising from spontaneous recovery without any prior nerve surgical intervention. There were 35 male patients and 19 female. The patients' average age based on the first time of surgical correction for deformity of forearm and/or hand was 10 years old, ranging from 3.5 to 21 years. The average age for shoulder or elbow reconstruction is 4–5 years old (Chuang et al, 1998b). Many of them might have undergone

a

b

c

d

Figure 1

(A,B) A 16-year-old girl of late obstetrical brachial plexus palsy with severe supination contracture of the left forearm and sensory disturbance of the hand. (C,D) After re-routing the biceps for forearm pronation in addition to separation of the

a

b

Figure 2

(a) An 8-year-old boy of late OBPP with deficits of the wrist and finger extension of the right upper limb. (b) At 5 months after multiple tendon transfer with pronator teres-to-ECRB, FCU-to-EDC and PL-to-EPL.

shoulder or elbow correction before. The affected limbs were 36 in the right and 18 in left upper limb.

The common sequelae deformities in the forearm and hand in S-OBPP include: (1) forearm supination contracture (Fig. 1a,b), or forearm pronation contracture, the former being of higher incidence than the latter; (2) weak or absent wrist extension, MP joint extension and/or IP joint extension (Fig. 2a); (3) weak or absent finger flexion (Fig. 3a); (4) wrist ulnar deviation; (5) thumb instability; and (6) sensory disturbance, especialy in ulnar 2 fingers.

The main surgical procedures performed for forearm and hand deformities in S-OBPP included: forearm flexor tendons transfer for extension of wrist, MP joint or IP joint or thumb (26 patients); re-routing of the tendon for forearm pronation (treatment of forearm supination contracture) (16 patients); re-routing of the tendon for radial deviation of the wrist (treatment of wrist ulnar deviation) (11 patients); functioning free muscle transplantation for extensor digitorum communis (EDC) and extensor pollicis longus (EPL), using the musculocutaneous nerve as a transformator (five patients); functioning free muscle transplantation for flexor digitorum profundus (FDP) (four patients); opponensplasty (six patients); plication of extensor tendon (six patients); distal advancement of central extensor mechanism for IP joint extension (five patients); wrist extensor tendon transfer for finger flexion (three patients); for MP joint extension (one patient); for lumbricales replacement (one patient); for MP joint flexion (A1 Lasso procedure) (one patient); bone fusion including wrist fusion, or thumb fusion (three patients); reduction of volar dislocation of the radial head (three patients) (see Table 1).

Multiples of the above surgical procedures for the deformity of forearm and hand were done on the same patient. Many of them might had the reconstructive procedures for the shoulder and/or elbow at the same time as forearm and hand reconstruction.

a

b

Figure 3

(a) A 6-year-old boy had left late-OBPP with weak finger flexion. There was no regional tendon available for transfer. After right contralateral C7 transfer with two sural nerve grafts (b), and a gracilis functioning free muscle transplantation for FDP replacement in a two stage procedure, he achieved finger flexion and can now hold an object with the help of an IP-extension dynamic splint (c,d).

c

d

Surgical techniques

A. Correcting MP joint drop (and/or wrist drop)

When forearm flexors are powerful

Powerful wrist or finger flexors and/or pronator teres are very important. Those muscles can be utilized for transfer for finger and/or thumb extension. Most late OBPP patients have more or less wrist extension, but drop the MP joint because of poor muscle strength of the extensor digitorum communis (EDC), associated with weak extensor pollicis longus (EPL) or weak abductor pollicis longus (APL). The incidence of flexor-to-extensor transfer was quite high in our series, 26/54 patients (48 per cent). The traditional technique of tendon transfer for radial nerve palsy (Tsuge 1989a, Schneider 1991, Green 1993, Wheeler 1996) can be applied here. Preoperatively, careful examination of each forearm volar muscle is critically important for a successful transfer. At least M4 muscle strength (against resistance to 3 kg) is available for transfer. The route of tendon transfer should also consider the deformity of wrist deviation. For example, in wrist ulnar deviation with weak wrist extension, FCU (flexor carpi ulnaris)-to-ECRL (extensor carpi radialis longus) transfer around the radial bone will be more effective than passing through the interosseous membrane. It not only corrects wrist extension but also corrects wrist ulnar deviation. FCU-to-APL around the ulnar bone will be better than PL (palmaris longus)-to-APL, which not only benefits thumb abduction but also corrects wrist ulnar deviation.

When forearm flexors are not powerful

There were four methods utilized individually for correcting MP joint drop (ie for EDC replacement):

1. *Utilizing the musculocutaneous nerve as a transformator.* The musculocutaneous nerve was found and isolated between biceps and coracobrachialis muscles in the upper arm and axilla. It was cut at the distal third of its length. The distal stump was re-innervated by direct coaptation to the deep central branch of the three intercostal nerves (usually T3–T5) (Chuang et al 1996). The proximal stump was then used as a recipient motor source to innervate a fresh free muscle for EDC replacement. Gracilis myocutaneous functioning free muscle transplantation was always the first choice. The proximal end of the transferred muscle was fixed to the upper third of the humerus, a space between the deltoid insertion posteriorly and biceps muscle anteriorly. The distal end was sutured to the EDC tendon by the end-to-side weaving method. A postoperative splint, allowing elbow flexion and wrist plus finger extension was applied for six weeks. Electrical stimulation of the muscle could start at three weeks postoperatively;
2. *ECRL-to-EDC transfer.* In pure but rare Klumpke's palsy, finger flexion and MP joint extension are quite commonly seen as absent or weak. Only one wrist flexor, FCR, and one wrist extensor, ECRL, are preserved. ECRL-to-EDC transfer (a concept of one muscle for two functions) was quite effective. The EDC's 4 tendons were moved out of (or superficial to) the dorsal transverse carpal ligament and sutured together. The ECRL was detached from its insertion and sutured to the EDC by the end-to-side weaving method. Postoperative splinting for 6 weeks was required;
3. *Plication of EDC (and/or APL).* We had 6 patients treated by this when there was no available tendon for transfer. We preferred shortening by segmental resection and tendon repair, instead of side-to-side plication which could easily become loose again. In side-to-side tendon plication, there is not cut tendon surface allowing tendons to adhere together;
4. *Wrist fusion plus correcting drop in the MP joint.* Three older S-OBPP patients (more than 15 years old) were treated by wrist fusion. Simultaneous tendon transfer with FCR-to-EDC (2 patients) or plication of EDC (1 patient) was performed.

B. Correcting finger flexion

In Klumpke's palsy or total plexus palsy, weakness or partial absence of finger flexion is commonly noted. When powerful wrist extensor

Table 1 Operative procedures for deformities of forearm and hand in 54 late obstetric brachial plexus palsy

Purpose	*Procedure*	*No. patients*	*Incidence**
Correcting MP joint and/or wrist drop			
When forearm flexors are powerful	Flexor-to-extensor transfer	26	48%
When forearm flexors are not powerful	Plication of EDC, APL or ECR	6	28%
	ECRL-to-EDC (one muscle for 2 functions)	1	
	Wrist fusion + tendon transfer or plication	3	
	Utilizing MCN as a transformator	5	
Correcting finger flexion	Extensor-to-flexor transfer	3	11%
	FFMT for FDP (ICN innervation)	2	
	Contralateral C7 + FFMT (a two-stage procedure)	1	
Thumb opposition (opponensplasty)	Using flexor transfer	4	11%
	Using extensor transfer	2	
Correcting forearm supination contracture	Re-route biceps	16	37%
	Re-route biceps + additional procedure	4	
Correcting forearm pronation contracture	Re-route pronator teres	3	5%
Correcting IP joint extension	Distal advancement of EDC to middle phalanx	5	15%
	Using dynamic splint	3	
Correcting wrist ulnar deviation	FCU-to-ECRL	2	20%
	ECU-to-ECRL	3	
	ECU-to-APL	2	
	Route ECRL	4	
Correcting proximal head dislocation			
Volar dislocation	Annuloplasty by distal biceps tendon	1	5%
	By triceps tendon	1	
Dorsal dislocation	Wedge osteotomy	1	

*A patient may have two or multiple procedures.
MCN, musculocutaneous nerve; FFMT, functioning free muscle transplantation; MPJ, metacarpophalangeal joint; IP joint, interphalangeal joint; ECRL, extensor carpi radialis longus; APL, abductor pollicis longus; EDC, extensor digitorum communis; FDP, flexor digitorum profundi; FCU, flexor carpi ulnaris; ECU, extensor carpi ulnaris.

are available, traditional extensor-to-flexor transfer is used as in treatment of high median and/or ulnar nerve palsy (Omer 1993; Burkhalter 1993; Tsuge 1989a). However, incidence of this transfer is low (possibly in only three of our patients) because of a high frequency of wrist extensor weakness. In cases where wrist extensor donors are unabilable, functioning free muscle transplantation for FDP replacement is preferred, either using intercostal donor nerves as a donor nerve (two patients), or contralateral C7 transfer followed by a free muscle transplantation in a two stage procedure (1 patient, Fig. 3c).

C. Opponensplasty

The use of forearm flexor transfer (four patients) is more common than extensor transfer (two patients) for thumb opponensplasty.

D. Correcting forearm supination contracture

Forearm supination contracture varied in severity for S-OBPP. In less severe cases (interosseous membrane is not yet fixed), re-routing the biceps as described by Zancolli (1988) is often enough for forearm pronation, as in 12 patients of our series requiring this treatment (16/54, 30 per cent). However, for severe supination contracture (90° or more, with a fixed interosseous membrane) additional procedures, such as detaching or re-routing the supinator to become a pronator (a technique similar to the Zancolli's procedure of re-routing the biceps), extensive separation of interosseous membrane including the distal radioulnar joint, and rotational osteotomy of the radius were also required for further enhancement of forearm pronation, in addition to re-routing of the biceps (four patients).

E. Correcting forearm pronation contracture

This was rarely necessary, and only performed when a patient was keen to acquire some supination for hand-to-mouth movement. Re-routing the pronator teres to simulate a supinator may help in enabling some hand-to-mouth movement (three patients).

F. Correcting IP joint extension

Intrinsic palsy of the hand in Klumpke's or total plexus palsy is one of the biggest challenges to the reconstructive surgeon. Some techniques were utilized:

1. *Distal advancement of the central limb of the extensor mechanism to the base of the middle phalanx (five patients).* This is only indicated in patients with positive MP joint extension but deficits in proximal interphalangeal (PIP) joint extension. Loosening of the central attachment of the EDC to the middle phalanx due to prolonged deficit of PIP joint extension is the main cause. Distal advancement of the central extensor mechanism to the base of middle phalanx is a feasible procedure for PIP joint extension (six patients). The surgical technique is similar to the correction of a Boutonniere deformity (Tsuge 1989b);
2. *Lumbricales reconstruction* by FDS transfer (one patient), or by ECRL transfer with tendon graft (one patient);
3. *Using IP-extension dynamic splint* (3 patients, Fig. 3b,c).

G. Correcting wrist ulnar deviation

Wrist ulnar deviation is quite commonly seen in S-OBPP, caused by muscle imbalance (10/54 patients, 18.5 per cent). Too strong FCU, ECU or EDC is the main cause. Surgical correction, mainly for cosmesis, included releasing wrist ulnar contracture, FCU transfer to the ECRL (2 patients), or ECU transfer to the ECRL (three patients), or ECU to the APL (two patients); or re-routing ECRL or APL. (After division of the ECRL or APL tendon, the proximal stump goes around the radial bone and sutures back to the distal stump: four patients.)

H. Correcting a proximal radial head dislocation

1. *In volar dislocation.* A long sling including part of the muscle was elevated from the distal biceps tendon (one patient) or from the triceps tendon (one patient), based on the distal insertion. The sling wraps around the radial neck and pulls the neck posteriorly. It was fixed to the posterior distal triceps tendon under tension. A temporary K-wire was fixed from radius to the ulna bone for four weeks of immobilization;
2. *In dorsal dislocation*. One patient received wedge osteotomy of the ulnar side of the radius to reduce the radial head into the normal position where it was fixed with a plate and screws. For complete dislocation of radius and ulna at the elbow, no surgery is advocated, as it will possibly cause elbow stiffness.

Results

The existence of powerful forearm flexors, especially wrist flexors, is very useful for reconstruction, and their transfer usually leads to good results (Fig. 3b). The success of FCR-to-EDC transfer is higher than FCU transfer (11/12, 92 per cent vs. 5/8, 62 per cent). Success of PL (palmaris longus) transfer to EPL (extensor pollicis longus) was around 70 per cent; and pronator teres (PT) transfer, usually to the ECRB, was 60 per cent. But FDS, usually the ring finger (fourth FDS), transfer for digits or thumb extension has more unpredictable results. Extensor tendon transfer by using BR (brachioradialis), ECRL, or ECU for finger flexion or thumb opposition usually gave unreliable and poor results.

Re-routing the biceps for forearm pronation is quite useful. It increases forearm pronation from average 24.5° (range, 0–80°) up to an average of 77.5° (range, 0–90°). But if the supination deformity is very severe (more than 90°), the procedure is not enough. Detachment of the supinator from the radius, separation of interosseous membrane, release of distal radio-ulnar joint, and rotational osteotomy of the radius or the humerus will be additionally required to get a good result (Fig. 1c,d).

Plication of the extensor tendon (ECR, APL or EDC) was only effective in half of the cases (6/12) and worked well only temporarily, ending in recurrence due to getting loose. Tenodesis of extensor tendon, EDC, to the radius in one case caused wrist and finger extension contracture due to growth, which eventually required release.

Distal advancement of the central extensor mechanism was an effective method to improve IP joint extension in six cases. Lumbricales reconstruction with ECRL and tendon graft in one patient, and with fourth FDS in another one patient were occasionally performed. Both patients showed also improvement of IP joint extension.

Using functioning free muscle transplantation to improve hand function is a more advanced and complex surgical procedure. We had five patients with the musculocutaneous nerve as a transformator. All five patients achieved improved EDC function by the free muscle transplantation. Recovery of elbow flexion, innervated by intercostal nerves, was fortunately as good as before. However, using an intercostal nerve to innervate a free muscle transplantation for finger flexion did not produce a good result in either of two patients. The muscle strength was only M2.

One child had contralateral C7 elongation with two sural nerve grafts which were embedded into the biceps muscle. One year later, a gracilis free muscle transplantation for FDP replacement was performed at the second stage. He finally achieved M3–M4 finger flexion strength. However, he still needs a dynamic splint for the finger IP extension (Fig. 3c,d).

Discussion

Leffert (1985) wrote a good review about the history, pathogenesis, clinical presentation, musculoskeletal changes and prognosis of obstetrical brachial plexus palsy (OBPP), although he misused the term 'congenital brachial palsy'. A wide divergence of opinion as to the best treatment remains. He concluded that the treatment of the paralytic hand due to OBPP must be highly individualized. Hentz (1991) has mentioned that palliative treatment of the sequelae of birth palsies is difficult, and the results are rarely totally satisfactory.

Questions related to the management of sequelae deformities of the forearm and hand of late OBPP include: (1) what is the best age for the later management or palliative reconstruction? (2) in triple deformities of shoulder, elbow and hand, what is the first priority for reconstruction? (3) is traditional tendon transfer or bone management enough for those deformities? and (4) is there any difference between younger and older late OBPP patients related to palliative reconstruction?

For reconstruction of the sequelae deformities in S-OBPP, most authors favor an age of 4 years or more as optimal (Leffert 1985, Gilbert et al 1991, Chuang et al 1998b) because of no severe contracture, active cooperation, easy clinical evaluation, better following order and performing the rehabilitation program. Preoperative examination of each functional muscle that is prepared for transfer is critically important for a successful transfer. Advising the children that they should undertake continual muscle strength exercises before the transfer takes place is also very important, which usually requires parental supervision and encouragement.

Shoulder and elbow muscles always recover earlier and more maturely than the forearm and hands. Patients with Erb's palsy are also more frequent than those with Klumpke's palsy. The muscles in the forearm or hand most show paresis (incomplete palsy with weak strength), paralysis (complete palsy with significant atrophy), or contracture due to muscle imbalance or aberrant re-innervation. Aberrant re-innervation is less seen in the forearm and hand except supinator muscles. The tendon transfer in the forearm and hand is no more based on the relationship between antagonist and agonist as seen as in the shoulder and elbow (due to aberrant re-innevation) (Chuang 1998). Therefore, although the treatment is highly individualized, shoulder and elbow reconstruction are usually performed before forearm and hand. In our experience, the optimum time for forearm and hand reconstruction is at school age 6–13 years old, while for shoulder and elbow reconstruction the optimum time is at pre-school age, 4–6 years old. There is usually a lack of powerful muscles in the forearm and hand for transfer in the late OBPP. Continuous physical therapy with rehabilitation program to increase the muscle strength in the forearm and hand are important for the later management.

From our results evaluation, traditional tendon transfer is usually not enough (either number or strength) for reconstruction of deformities of forearm and hand in S-OBPP. Powerful wrist and finger flexors felt by clinical examination are more reliable than extensors as potential candidates for transfer. A high failure rate was encountered when using wrist extensor transfer, either for opponensplasty or for FDP reconstruction. We usually required further complex techniques to overcome it, such as functioning free muscle transplantation (Doi 1996).

Utilizing intercostal nerves as a transformator is indeed a high-risk procedure, requiring an advanced microneurovascular anastomosis technique and surgical experience in intercostal nerve transfer and functioning free muscle transplantation. It is really beneficial for finger extension when there is lack of powerful regional tendons for transfer. Patients start to have ability to extend their fingers towards targets, and they really feel that the hand is useful. The transferred muscle for EDC replacement, innervated by the musculocutaneous nerve, is always stronger than free muscle transplantation innervated by an intercostal nerve or spinal accessory nerve, because more muscle belly locates and functions in the forearm. The other alternative for EDC reconstruction is possibly only the dynamic splint, which needs to be worn continuously and is inconvenient. Contralateral C7 transfer with long sural nerve graft embedded into the biceps muscle, followed by a functioning free muscle transplantation as a two-stage procedure is an another effective option for EDC reconstruction.

Tenodesis, such as ECR or EDC fixed to the radius, is absolutely no good as a procedure in growing children, as it ends in wrist or finger contracture. Elongation of ECRL to EDC out of dorsal transverse carpal ligament is an another effective option based on the concept of 'one muscle for two functions' (Doi 1996). The ECRL, of course, needs to be strong enough.

Arthrodesis is only indicated in older children, more than 15 years old, or when there is no more growing cartilage seen in the distal radius or ulna by X-ray radiography.

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29
Treatment of co-contraction

Robert Hierner and Alfred C Berger

Introduction

Between 1981 and 1999, 1714 patients with brachial plexus lesions were treated in our institution. There were 418 obstetrical brachial plexus patients. In order to optimize treatment and to enable a therapeutically relevant documentation, both as thorough as possible and internationally comparable, we have developed the so-called ‘Plexus evaluation system’ (PES) – an examination and documentation procedure for obstetrical (Hierner et al 1999) and adult (Hierner et al 2000) brachial plexus lesions.

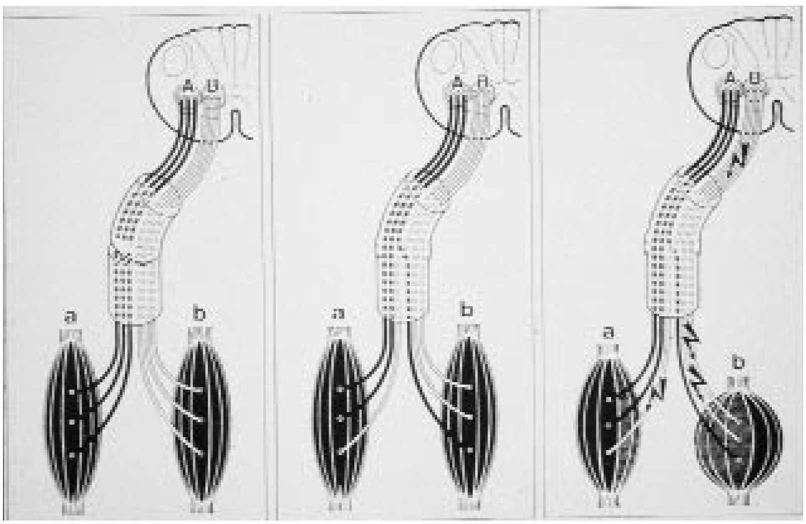
For the treatment of brachial plexus lesions we are using the so-called ‘integrated treatment concept’ (Berger et al 1991). Daily physical therapy is the basis of every treatment. Spontaneous or early surgical nerve repair is given the highest priority. Secondary procedures (tendon transfer, free functional muscle transplantation) alone or in combination with adjuvant procedures (joint releases, botulinum toxin, capsulodesis, splints, arthrodesis, derotation osteotomies) often can improve the overall result.

Epidemiology

Muscle co-contractions after nerve regeneration in proximal brachial plexus lesions, either spontaneously or postoperatively, occur in every patient with a higher degree (SUNDERLAND III–V) nerve lesion.

Pathophysiology

Co-contractions after brachial plexus injury are the result of an aberrant nerval re-innervation at the site of lesion (or repair), thus anatomically



a b c

Figure 1

(a–c) Pathophysiology of muscle co-contraction after regeneration of proximal brachial lesions. (From Schliack and Memmenthaler 1987.)

a

b

Figure 2

Treatment of severe deltoid/teres major co-contraction with repeated intramuscular injection of botulinum toxin type A: (a) pre-injection ('trumpet sign'); (b) 24 months post-injection (shoulder abduction with hand to ceiling movement 'big man-test').

defined (Mumenthaler et al 1998). Misled axons after spontaneous or postoperative nerve regeneration in brachial plexus lesions occasionally cause severe muscle co-contractions (Roth 1983, Mumenthaler et al 1998) (Fig. 1).

Those severe co-contractions may not allow basic movement functions like shoulder abduction, shoulder external rotation, elbow flexion, etc and/or hamper coordinated movements of the whole extremity, like hand-to-mouth. Moreover, motor development is delayed and secondary skeletal deformities will occur (Clarke and Curtis 1995, Lone 1966, Gordon et al 1973, Tassin 1983, Greenwald et al 1984, Tada et al 1984, Narakas 1986, Gilbert and Tassin 1987, Jackson and Hoffer 1988, Gilbert 1995, Sloof 1995, Berger et al 1997, Rollnik et al 2000 Hentz 1991, Michelow et al 1994).

Classification

For clinically relevant purposes muscle co-contractions can be classified according to their localization and severity. Co-contractions may occur over the whole extremity, with the most important being deltoid/teres major at the shoulder level (Fig. 2a,b) and triceps/biceps co-contractions at the upper arm level (Fig. 3a,b).

With regard to severity of co-contraction, a classification into mild, moderate, and severe turned out to be useful in clinical practice (Table 1).

Diagnosis

The leading symptom of muscular co-contraction is a contracting muscle without adequate motor function, although passive range-of-motion of the adjacent joint(s) is free or not significantly limited. Further specific clinical examination looks for co-contraction of the antagonistic muscle, either by palpation (moderate) or on inspection (severe). Further information can be obtained from an EMG (amplitude, traces). As severe muscular co-contraction leads to secondary deformities in the growing skeleton (joint deformities, length discrepancy), special attention must be given to its early detection and documentation.

Table 1 Classification of muscular co-contractions after brachial plexus lesions

Co-contraction	*EMG*	*Clinical examination*	*Treatment*
Mild	+	Not visible on clinical examination	None
Moderate	+	Visible on clinical examination No significant functional disturbance	Physical therapy (biofeedback)
Severe	+	Visible on clinical examination Significant functional disturbance	Physical therapy biofeedback botulinum toxin Palliative surgery

Treatment

Specific options for the treatment of muscular co-contractions can be classified into non-operative treatment and operative treatment. Non-surgical treatment options are physical therapy, biofeedback training, and intramuscular injection of botulinum toxin type A. Surgical treatment has a palliative character and comprises tenotomy and tendon transfer (Table 3).

Non-operative treatment

Physical therapy

The specific aim of physical therapy in muscle co-contraction treatment is to strengthen the agonist in order to overcome the co-contracting antagonist. However, low patient compliance in children and persistent co-contractions often lead to disappointing results.

Biofeedback training

Biofeedback training has proved of good value in the treatment of synkinesis after facial nerve repair. Preliminary results in post-traumatic adult brachial plexus lesions are promising.

Botulinum toxin type A

Botulinum toxin type A is a potent drug in the treatment of several diseases associated with increased muscle tone or muscle overactivity, such as torticollis spasmodicus, blepharospasm, limb dystonia, facial hemispasm, and spasticity (Scott et al 1985, Bernius et al 1999). Spasticity may reflect disabling muscle overactivity, including permanent activity in the absence of any stretch or volitional command, inappropriate responses to cutaneous or vegetative input, and unwanted antagonistic co-contractions (Heinen et al 1999). Since botulinum is effective in the treatment of the spasticity-associated co-contractions, it might be beneficial in postparalytic antagonistc movements after obstetrical brachial plexus lesions (Hierner and Berger 1998). Although there are no structural changes at the peripheral nerve, our results clearly indicate that repeated intramuscular injections of botulinum toxin type A into the co-contracting antagonist result in a lasting reduction of imbalance between antagonist and agonist activity, with the possibility of adequate function (M4 power) (Alfonso et al 1998, Hierner and Berger 1998, Schubert et al 1998, Hierner et al 1999). This functional change might be explained by: (1) local interaction at the motor plate; (2) structural changes of the injected muscle and its antagonist; (3) changes at the first and second motor neuron.

Botulinum toxin type A is an extremely potent agent acting presynaptically by blocking the release of acetylcholine at the neuromuscular junction. The neurotoxin is actively taken up into the nerve terminal. However, this ‘pharmacological denervation’ is temporary. Nevertheless, it should be taken into account that no recurrence of severe co-contractions has been observed up to now. These long-lasting effects cannot be explained by a simple temporary palsy of the co-contracting antagonistic muscle. They might be explained by effects at the muscle and spinal cord level and central effects like the so-called ‘cortical plasticity’ (Fujimoto et al 1992).

At the skeletal muscle level botulinum toxin injection leads to a temporary muscle atrophy, showing variable fiber diameter and an increasing number of type I fibers. Even after repeated injections, no muscle fibrosis or persistent muscle atrophy like that after nerve damage could be found (Heinen et al 1999). From studying spastic patients we have learned that agonist/antagonist co-contractions lead to functional impairment by reducing the joint excursion and the speed of the movement. Moreover, constantly increased muscle tone during growth leads primarily to reduction of muscle growth and secondarily to muscles and joint contractures. This in itself leads to secondary joint and skeletal deformities, thus a vicious circle with further functional impairment persists (Bernius et al 1999). It is essential for the success of botulinum toxin treatment that physical therapy is intensified concurrently. As 'pharmacological denervation' is temporary, the aim of physical therapy is: (1) strengthening of the agonist and stretching of the antagonist, which leads to an increased total amplitude of movement (TAM), thus preventing secondary joint and/or skeletal deformities; (2) to learn and/or stabilize new simple (elbow flexion) or complex (hand-to-mouth) movements, and (3) to teach the patient to coordinate those movements with weaker but still persistent co-contractions (Heinen et al 1999). Although experimental data show that botulinum toxin is transported to the central nervous system by the retrograde axonal transport mechanism, there is no clear evidence that it has direct impact on the central nervous system. Its mode of action seems to be restricted to the peripheral nerve system (Hambleton and Moore 1995).

Operative treatment

Palliative surgery is indicated if the non-operative treatment fails or does not lead to a satisfactory result. In each and every case donor site morbidity (= loss of function of the co-contracting antagonistic muscle) must be balanced against its benefit (increased active range-of-motion).

Tenotomy

The simplest palliative procedure is tenotomy of the co-contracting antagonistic muscle. However, by simple transsection of a tendon, movement potential is lost. Therefore, simple tenotomy is only indicated if no transfer is possible. This may be the case of a co-contracting teres major muscle in adult brachial plexus palsy.

Tendon transfer

If the co-contracting antagonistic muscle can be used to reinforce the action of the weak agonist, a tendon transfer is the treatment of choice. Without the possibility of shoulder abduction > 90° and lack of other possibilities to restore elbow flexion, triceps transfer is a good option in adults to restore the important elbow flexion, by giving up active elbow extension. Triceps tendon transfer (Carroll and Hill 1972, Marshall et al 1988) to the biceps is rarely indicated n children (Berger et al 1991, 1997) because of possible skeletal growth impairment by too early a tendon transfer.

Personal experience and results with botulinum toxin type A

From 1997 to 2000, 14 patients with severe co-contraction after brachial plexus injury were treated in cooperation with the neurological department. There were eight children (age 2–4 years) with severe triceps/biceps co-contraction, one child (age 8 years) with triceps/biceps co-contraction after spontaneous recovery and modified Steindler-transfer, two children (age 4 years) with severe deltoid/teres major co-contraction, and two adults with severe triceps/biceps co-contractions after early microsurgical brachial plexus repair.

Six children (aged 2–4 years, mean 3.2, SD - 1.0) presenting severe biceps/triceps co-contractions after nerve regeneration (three cases with spontaneous regeneration, three cases after early microsurgical repair at the age < 6 months) were treated by intramuscular injection of botulinum toxin type A into the triceps. We used botulinum toxin A (DYSPORT, Ispen Pharma) with a concentration of 25 Mouse Units (MU)/ml. An average of 39.2 MU (range: 25–50 MU, SD 8.0) was injected into the triceps muscle at two sites. EMG with surface electrodes (Viking II, Nicolet Instruments, Madison/Wisconsin, USA) was used to evaluate

Table 2 Personal experience and results after repeated intramuscular botulinum toxin type A injections for the treatment of triceps/biceps co-contractions

Patient's initials / *Criteria*	*1 HM*	*2 SJ*	*3 BT*	*4 SS*	*5 SC*	*6 NM*	*Total/ mean*
Age (years)	4	3	4	2	4	2	3.2
Nerve regeneration[a] microsurgical nerve repair	s	s	nr ½XI-SSC neurolysis (C5–C7)	nr 2 ½XI-SSC neurolysis 2 C5–(1x5) ax 4 C6-(4x5) FasLat	nr ½XI-SSC neurolysis (C5–C7)	s	s =3 nr = 3
Active ROM elbow pre-Botox (Neutral-0-Method)	0–20–40°	0–30–50°	0–20–40°	0–30–40°	0–30–50°	0–20–50°	0–25–50°
Elbow flexion power pre-Botox (MRC)	M2 (hand-to-mouth)	M2 (hand-to-mouth)	M2 (hand-to-mouth)	M1 (hand-to-mouth)	M1 (hand-to-mouth)	M2 (hand-to-mouth)	M1 = 2 M2 = 4 (hand-to-mouth 0/6)
Active ROM elbow post-Botox (Neutral-0-Method)	18 months 0–20–95° 24 months 0–10–100°	18 months 0–30–100° 24 months 0–10–100°	18 months 0–20–120° 24 months 0–10–120°	18 months 0–30–110° 24 months 0–20–110°	18 months 0–30–80° 24 months 0–10–95°	18 months 0–20–100° 24 months 0–20–110°	18 months 0–25–101° 24 months 0–13–106°
Elbow flexion power post-Botox (MRC) 18/24 months	M4/M4 (hand-to-mouth +)	M4/M4 (hand-to-mouth +)	M4/M4 (hand-to-mouth +)	M4/M4 (hand-to-mouth +)	M2 +/M4 (hand-to-mouth +)	M4/M4 (hand-to-mouth +)	18 months M2+ = 1 M4 = 5 (hand-to-mouth 5/6) 24 months M4 = 6 (hand-to-mouth 6/6)
Dose of botulinum toxin (Mouse Units)	40	40	40	40	50	25	39
Duration of triceps paralysis (weeks)	36	19	44	19	16	18	25.3
Number of injections	2	3	2	2	2	3	2.3
Complications	–	–	–	–	–	–	–
Recurrency	no	no	no	no	no	no	0/6

[a]S, spontaneous; nr, early microsurgical nerve repair. 21/2XI-SSC, direct neurotization of half spinal nerve onto suprascapular nerve; 3 C5–1×5) ax, intraplexual neurotization from C5 root with 1 nerve graft of 5 cm length onto axillary nerve. 4 C6–(4×5), intraplexual neurotization from C6 root with 4 nerve grafts of 5 cm length onto lateral fascicle.

a

b

c

Figure 3

Treatment of severe biceps/triceps co-contraction with repeated intramuscular injection of botulinum toxin type A. (a) pre-injection; (b) 24 months post-injection (elbow extension); (c) 24 months post-injection (elbow flexion with hand-to-mouth movement 'cookie-test').

biceps/triceps co-contractions before and after the treatment (Rossi et al 1982). All patients were followed-up at four-week intervals. Information about the onset of response and duration of botulinum toxin effects was obtained via the parents. Clinical testing (muscle power graded by the British Medical Research Council classification) and measurement of the active range of motion using the Neutral-0-Method (Fig. 3a–c) were performed prior and after injections. Possible complications, like systemic or local muscular paralysis (ptosis, strabismus, impairment of swolling, etc), and/or allergic responses to the toxin therapy were checked. Moreover, the duration of the temporary 'pharmacological denervation' (Erbguth and Claus 1996) and the number of injections were recorded (Table 2). The patients of all children had given written informed consent to the treatment (Hierner et al 2001).

Onset of response following the first injection was seen after an average of 8.5 days (range: 4–14 days; SD 4.4). Mean active elbow flexion prior to application was about 50° (range: 20–60°) and muscle power was graded M1 (2 cases) to M2 (4 cases). Hand-to-mouth movement was not possible in any of the patients. At 18 months after injection, mean elbow flexion was about 100° (range: 80–120°) and muscle power was graded M2+ in one case and M4 in five cases. Five out of six patients were able to perform adequate hand-to-mouth movement. Two years after the last injection elbow flexion power could be graded as M4 in all patients and hand-to-mouth movement ('cookie test') was possible in all patients. Moreover, a clear reduction in extension lag of the elbow could be seen. On EMG examination a clear reduction of triceps contractions during biceps activity was observed. Temporary paralysis of the triceps after injection persisted for 16–44 weeks with an average of 25.3 weeks. In order to achieve a stable elbow flexion at the M4 level the botulinum toxin Botox injection had to be repeated two or three times. The average time of treatment took 8–21 months. There was no recurrence of co-contraction in any of the patients at the 18 month follow-up point. Mild-to-moderate discomfort at the injection site was seen for several days after injection in two children. It has to be pointed out that no severe adverse events occurred, especially no bleeding, infection, extensive muscle weakness, or systemic complications (Table 2, Fig. 3a–c).

Table 3 Differential treatment 'muscle co-contraction' in obstetrical and adult brachial plexus lesions

Options	*Obstetrical*		*Adult*
	early	*late*	
Physical therapy	−	+	++
Biofeedback training	−	−	++
Botulinum toxin type A	++	+	+
Tenotomy	−	−	+
Tendon transfer	−	+	++

Discussion

There are specific differences in the treatment of muscle co-contraction in children and adults (Table 3). In babies and young children the aims of treatment are: (1) treatment of co-contraction, and (2) treatment of secondary skeletal deformities at their early stages. Programmed physical therapy and biofeedback training proved of low value, because of low patient compliance. In this age group the main aim is to provoke movement during daily playing or daily living activities of the child. In contrast, based on personal experience, repeated intramuscular injection of botulinum toxin type A proved of immense value for early treatment of co-contraction and thus prevention of secondary skeletal deformities. Moreover, when started at the age of 2–4 years with secondary skeletal deformities just beginning (ie elbow extension lag) it was surprising to see that those early deformities disappeared after treatment with growth. Tenotomies and tendon transfers are not indicated at this age (Table 3).

In older children a specific physical therapy program may be possible, as well as biofeedback training. Again, botulinum toxin A is an important tool in combination with physical therapy. In selected cases tendon transfers – especially at the shoulder level – may be indicated.

In the adult patient, physical therapy and biofeedback training proved of value. Botulinum toxin is an adjunct to make physical therapy more easy or effective by blocking the co-contracting antagonistic muscle. If the non-operative treatment fails or does not lead to a satisfactory result, tenotomies, and especially transfers of the cut tendon to the agonistic muscle, are the treatment of choice (Table 3).

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Special Lesions

30
Traumatic brachial plexus injuries in children

Alain Gilbert and Christian Dumontier

Traumatic injuries of the brachial plexus in children are rare and the literature on this subject is sparse. Merle d'Aubigne and Deburge (1967) reported on 13 cases over a 20-year period. In this series, only one patient was under 10 years old. Rigault (1969) presented seven cases that were treated and followed-up. Some large adult series (Alnot 1977, Sedel 1977, Narakas 1982) include a few children but their treatment and results are not reported separately. However, the brachial plexus lesion is specific, usually more severe than obstetrical lesions and even more serious than the adult lesions.

Diagnosis

The diagnosis is obvious. The brachial plexus lesion often occurs in a multiple trauma situation where association with a head lesion, several fractures and sometimes abdominal trauma is common. The diagnosis is sometimes delayed owing to the severity of the other lesions; patients are sometimes even in coma.

The clinical evolution will be monitored closely with muscle testing and EMG. After two months, if the clinical improvement is absent or limited, and if the EMG does not show clear signs of re-innervation, a myelogram will be performed. The best information will be given by a CT-myelogram. In some cases of older children, MRI has proven effective in determining the presence of meningoceles but in other cases it cannot be interpreted.

The association of clinical testing, myelograms and EMG with evoked potentials will allow a decision regarding surgical exploration to be made.

Surgical exploration and repair

Exposure is often extensive. In over 30 per cent of cases, the lesions are so severe that the incision needs to be extended distally to the mid-arm (Fig. 1). Dissection is very difficult as vascular lesions (Fig. 2) are often associated which had

Figure 1

Extensive lesions need wide exposure and long nerve grafts.

Figure 2

Severe lesions include vascular injuries associated with the brachial plexus injury.

sometimes necessitated previous surgery. The technique and repair of the lesions in children are very similar to adult brachial plexus repair. There are, however, differences:

- The size of the defect is often larger, necessitating long grafts (10–20 cm);
- Neurolysis is used more often as scar is extensive;
- The repair will be more ambitious as in children, particularly younger ones, the repair may obtain recovery of function, even in the hand;
- The severity of the lesions and the number of avulsions necessitate the use of neurotizations which explains the low quality of the end results.

Follow-up and secondary surgery

The recovery time is long and the results of the operation cannot be assessed before three or even four years; although we are dealing with children, the time for re-innervation is not much shorter than in the adult, and certainly not in proportion to age.

Long-term physiotherapy is necessary, in order to keep the joints supple and allow a good mobility when the muscles recover.

In most cases, the recovery is incomplete and when possible, secondary surgery may improve the situation. Two years after the brachial plexus repair, it is possible to have an idea whether the shoulder or elbow flexion will recover. Tendon transfers will be an integral part of the surgical repair. These transfers necessitate a supple shoulder joint and especially a good passive external rotation.

If the shoulder is internally rotated, a subscapularis release or an anterior release will allow excellent external rotation. This internal rotation contracture is rare in traumatic plexus injuries because of the involvement of more nerve roots, which usually gives a flail shoulder.

To improve the shoulder some tendon transfers are possible, such as latissimus dorsi transfer, but this muscle is often paralysed and the most commonly used muscle will be the trapezius.

This also applies to elbow flexion. Again the latissimus dorsi, whose excellent results are well known, is often not usable and it is necessary to find other donors: triceps or pectoralis major.

In C5-C6 lesions the forearm and hand flexions are intact and a Steindler procedure may give an excellent result.

Supination contracture is frequent, especially in complete paralysis. Re-routing of the biceps is possible only with a good muscle and a supple pronosupination. Otherwise rotational osteotomy of the radius will solve the problem. In both these cases, the prerequisite for pronating the wrist and hand is to have an active wrist extension.

Wrist and hand paralysis is a great challenge in these patients as there are often no available muscles to transfer. If wrist extension is active, tenodeses are possible and may give some function.

Recovery of finger flexion is difficult. It is sometimes possible to do complex operations such as extended latissimus dorsi transfer to the finger flexors, albeit when that muscle exists, or biceps transfer, or even free muscle transplantation using the gracilis.

Clinical material

In line with the rare occurrence of brachial plexus injuries in children, we have been able to treat and follow-up just 41 cases from 1977 to 1998, which compares and contrasts with 696 obstetrical cases operated during the same period. The etiology shows a predominance of traffic injuries (32 cases) but two cases were due to stab injuries (Fig. 3).

Of the 41 cases, 33 were boys and only eight were girls. Age range shows that all periods of growth are represented (Fig. 4) but that the largest group is the pre-adolescent age, from 12 to 14 years.

There is a large number of associated lesions, showing that the brachial plexus trauma occurs during a violent insult with multi-tissular lesions. Over 50 per cent of the cases (21/41) were associated with head injury, sometimes coma. Multiple fractures are common (shoulder in 11 cases, lower limb in six cases, upper limb in five cases). The severity of these lesions, the association

Figure 3

A small stab injury with complete C5–C6 lesions at the level of the foramen.

Figure 4

Age at operation for brachial plexus repair in children.

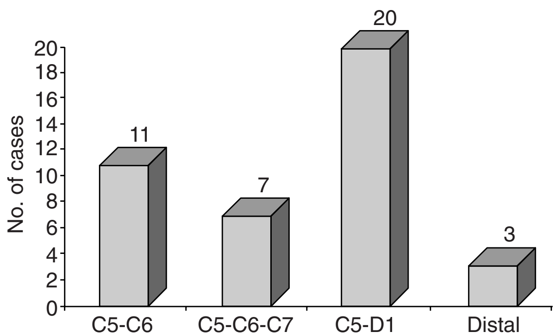


Figure 5

The initial lesions in 41 cases of brachial plexus trauma in children.

with vascular injury (6 cases) which need immediate treatment temporarily put the brachial plexus injury on the backstage. It is sometimes several weeks before the paralysis is studied and a complete evaluation done.

The damage requiring clinical evaluation and treatment shows a majority of complete and distal lesions (Fig. 5). This initial severity of the clinical aspect will be found during operation, with a great number of avulsions of lower and even upper roots. In only 31 cases was it possible to use some kind of intraplexual repair by grafts, sometimes over 15 cm long.

In 35 cases neurolysis was done, which attests to the great difficulty in assessing and repairing the roots. In 17 cases, it was necessary to add some kind of extraplexual neurotization, from the spinal accessory, intercostals, controlateral and ipsilateral or pectoralis major nerves. Recently, in two cases, we were able to use end-to-side sutures of C6 and C7 avulsions to C8 and T1 roots.

Re-innervation is a long process and it is possible to evaluate the results only after a minimum of three years. In cases where the results are poor it is tempting to use secondary transfers. However, only very few were done (ll–25 per cent), demonstrating the lack of good donor muscles (Figs 6–8).

The secondary transfers were: trapezius transfer (three); Steindler operations (three); wrist extension transfers (two); vascularized free muscle transfer (two); biceps to flexors transfer (one). We evaluated the final results according to function of shoulder, elbow and hand, using our scales (Gilbert and Raimondi) (Fig. 9).

a

b

Figure 6

Result after C5, C6, C7 lesion treated by grafts and neurotizations. (a) Good elbow flexion. (b) Poor abduction but good wrist extension.

Conclusion

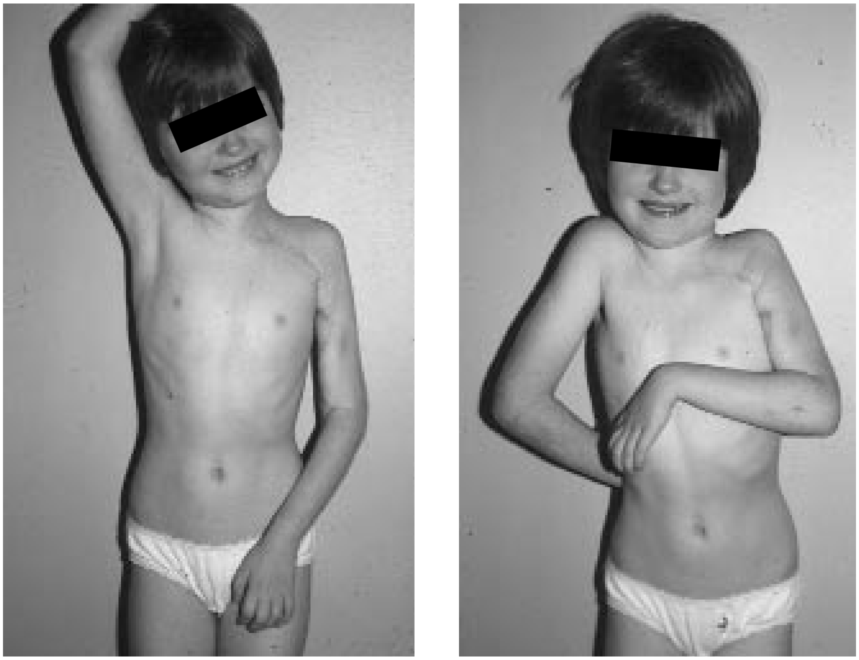
This series, as well as the scattered reports in the literature, confirm the impression that traumatic brachial plexus in children is a very severe lesion because of the multiple traumatic associations and the extensiveness of the avulsion injuries of the nerve roots. Repair is difficult and often limited; neurotizations are necessary but rarely give satisfactory results. Secondary transfers are usually impossible and it may be necessary to use microvascular neurovascular muscle transfers.

a

b

Figure 7

C5–C6 avulsion injury treated by neurotizations. (a) Lack of external rotation. (b) Acceptable abduction.



a b

Figure 8

(a) Complete paralysis with avulsion of five roots. Treatment by cross-chest nerve transfer from pectoralis major and free vascularized gracilis transfer. (b) Elbow flexion is possible with controlateral activation of pectoralis major.

Figure 9

The final results in our series of 41 cases of surgical repair of traumatic brachial plexus injury in children.

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31
War injuries

Jamal Gousheh

Introduction

In modern-day warfare weapons have become increasingly more powerful and the injuries they cause are more extensive, especially if the bullets or fragments hit a bone such as the clavicle. In such a case there will usually be associated injuries such as vascular injuries and extensive necrosis, and saving the patient's life becomes the first priority while the neural repairs are usually delayed. Moreover, although some of the injuries caused by high-speed projectiles are difficult to detect, it is important to understand them fully. Therefore proper treatment of war injuries of the brachial plexus requires full knowledge of two aspects: first, the full extent and nature of tissue damage caused by penetration of high-speed projectiles, and second, the modern treatment techniques including microsurgery. The purpose of this chapter is to convey some of the author's experience gained in the treatment of these injuries (Gousheh 1995).

First, let us discuss briefly the damage caused by a penetrating projectile such as a bullet. This damage is caused by two factors. The first is the physical body of the bullet as it passes through the body. In particular, if the bullet hits a bone all of its kinetic energy is instantaneously released and this causes the most extensive damage. In this case shattered bone fragments become secondary projectiles and travel in almost all directions, causing extra damage to the surrounding tissue. The second and less obvious cause of damage is the compression shock wave accompanying the bullet. The majority of such damage is caused by the phenomenon of cavitation and its aftershocks, which can damage organs far removed from the physical path of the bullet. For further details, the reader is referred to the appendix.

Preoperative considerations

War injuries of the brachial plexus manifest as partial and/or complete disruption of one or more neural elements, and can be segregated into four levels: root, trunk, cord, and terminal branches. Here, by 'terminal branches' we mean lower portions of the brachial plexus down to the lower border of pectoralis major muscle, in the axillary fossa. In this region the injuries usually extend upward toward the cords in such a way that the proximal ends of the disrupted elements are usually located in the cord region. The causes of war injuries, in order of importance, are penetration of high-speed projectiles, explosion injuries, and traction injuries. As mentioned earlier, extensive damage to the brachial plexus, accompanied by significant vascular injuries usually occurs when a high-velocity bullet or shell fragment directly hits the clavicle, the scapula, the first rib or another bone adjacent to the brachial plexus, such as the humeral head. In this case, total paralysis may occur even without anatomical disruption of the brachial plexus elements. Exploration of patients with these 'blunt' injuries usually reveals, upon opening the epineurium, multiple punctate hemorrhagic and edematous areas in the neural elements. When the exploration is carried out a few months or more after the injury, neural elements are often found to be stiff and cord-like with extensive fibrosis. The condition of these patients gradually improves after neurolysis and release of adhesions from the surrounding tissues.

The majority of the patients have complete paralysis in the motor field of the brachial plexus before the treatment. Although EMG usually indicates a complete lesion in the majority of patients with brachial plexus injuries, at the time of operative dissection few patients have complete brachial plexus disruption.

Injuries are usually only to one or a few nerve elements and are often partial. It is not uncommon that nerve elements that were thought to be transected are found intact, but surrounded and compressed by scar tissue.

Operative timing

Clean uninfected wounds caused by sharp cutting objects, such as shattered glass pieces, must be repaired as soon as possible (Dunkerton and Bomme 1988). In our experience, if any emergency operation is necessary (such as for uncontrolled hemorrhage) all of the procedures such as nerve and vessel repairs should be performed in one session. We feel that delay of the nerve repair is contraindicated since the re-operations are usually found to be extremely difficult due to the formation of extensive fibrosis and dense scar tissue as a result of the previous surgery. However, when there is extensive damage infection usually develops in spite of antibiotic therapy and performance of the necessary debridement, and the repair of the brachial plexus is usually postponed until the infection has been eliminated, the soft tissue repair completed, and the general condition of the patient has improved. This waiting period usually lasts 3–8 weeks. It has been observed that for some patients with brachial plexus injuries due to penetration of small and slow projectiles (e.g. shell fragments from a distant source), after a few days there are no signs of associated injuries or infection. These cases are in the same category as clean uninfected cases, and should be repaired as soon as possible.

Preoperative work-up

A complete clinical examination in the field of the brachial plexus should be performed, and all motor and sensory abnormalities meticulously delineated and charted. This detailed investigative method, when carried out serially, helps to differentiate between neuropraxia with potential spontaneous recovery and the clear-cut anatomic injuries that would benefit from surgical repair.

Electromyography (EMG) should be performed in all patients and repeated monthly for those patients who are being followed for suspected brachial plexus injuries. A complete vascular investigation should be performed, and the arterial pulses checked along the entire extremity. If the radial pulse is absent or weak compared with the contralateral side, or if there is suspicion regarding integrity, angiography should be performed.

Operative techniques

General anesthesia is used in all brachial plexus operations. The patient lies supine with a very small cushion placed under the shoulder. The entire upper limb, neck, clavicle, and pectoralis regions are prepared and draped. The limb must stay free and be supported by an assistant as necessary. The head faces contralateral to the injured side. The skin incision depends on the entry point of the projectile. If this point is above the clavicle, the skin incision is made in the shape of an ‘L’ or ‘J’ along the lateral border of the sternocleidomastoid muscle and continued below the clavicle. If the entry point is below the clavicle, the skin incision extends from the infraclavicular region to the deltopectoral crease. In a typical war situation, on average 17 per cent of cases have the entry point above the clavicle causing damage to the brachial plexus at the root level, and in 83 per cent of cases it is below the clavicle, usually causing damage to the terminal branches and the cords and rarely to the trunk. If the brachial plexus exposure is difficult or if associated problems such as vascular injuries are probable, a large incision in the shape of an ‘S’ should be performed extending from the lateral border of the sternocleidomastoid muscle to the upper arm infra-axillary region, and the clavicle osteotomized as necessary. The major and then the minor pectoral muscle tendons are transected and retracted for exposure. This method exposes the entire brachial plexus from top to bottom.

The first step of the procedure is to find and control the proximal and distal parts of the artery in the brachial plexus region. The most important factor in this procedure is precise recognition of neural lesions. For this purpose a careful neural dissection is necessary, and during this procedure care must be taken to ensure that the principal vessels are carefully dissected and put aside. It is best to start the dissection from the median nerve, continuing to reach the lateral and medial cords, and in this region there is the musculocutaneous nerve on the lateral side and the ulnar nerve on the medial side. The posterior cord is found by locating the radial nerve and continuing upwards. The posterior cord is posterior to the axillary artery and lateral and medial cords. The axillary nerve is in this region. If the injury is a few weeks old the search for the musculocutaneous and axillary nerves requires more care and time, but it must be done. In continuing the dissection of the cords upwards, the trunk is reached. Dissection and repair of the nerves in the trunk region is always technically difficult and requires precise anatomical knowledge and extreme care. The nerve trunks divide in a complicated fashion to give rise to lateral, medial and posterior cords. Injuries caused by high-velocity projectiles are often associated with fibrosis and adhesion, which make the recognition and identification of these elements a matter of experience, patience and care. Therefore if the dissection of the neural elements in this region is necessary and scar tissue is present, there should be no hesitation in cutting the clavicle. If the clavicle is cut for better exposure, the neural or vascular repair should be preceded by preparation for the osteosynthesis, since manipulation of the clavicle might damage the neural repairs. After identification of the neural elements in the trunk region, the roots are also dissected and identified if necessary. In this way the entire brachial plexus along with the vascular elements is dissected and exposed from bottom to top, and the injuries can be identified and repaired.

Intact elements should be found and protected. If a nerve element, which is diagnosed as damaged in the preoperative investigation, is found intact during exploration, it must be checked very carefully to exclude 'blunt' injuries (Narakas 1985). Nerve stimulation is useful in this regard. If some fascicles of a plexus element are found to be damaged or severed, they should be identified and prepared for grating. Neural elements that are compressed in fibrous tissue are freed from the surrounding scar tissue and neurolysis is carried out by incision of the epineural cover (epineurium) and removal of all foreign bodies (debris of explosives).

The recognition and diagnosis of partial disruptions and 'lesions in continuity' are difficult. Two methods aid in their detection: serial preoperative EMG, and interneural neurolysis under magnification. Treatment of these 'lesions in continuity' consists of nerve grafting of the severed portions and neurolysis for the unsevered yet disrupted neural segments. The grafts are done using 10-0 nylon suture under a microscope. Generally the fusiform neuromas are also treated by neurolysis. Sometimes a long segment of a nerve element is fibrosed and innumerable tiny pieces of explosive materials are observed penetrating the nerve. Although nerve grafting can be considered, simple neurolysis usually yields unexpectedly good results.

In cases of complete neural disruption of any element, the procedure of choice is direct epiperineural anastomosis whenever possible, suturing the corresponding fascicles to each other without tension and torsion. End-to-end neural anastomosis has been advised by Narakas and others whenever the distance between the two ends of the severed nerve is less than four to five times the external diameter of the disrupted nerve (Narakas 1985). In our experience, the technique of end-to-end anastomosis is not possible for the neural lesions above the clavicle region, but is otherwise indicated whenever the two nerve ends can be re-approximated with an 8-0 nylon suture material without flexion of the joints. Using this method the recovery period is shortened, less muscular atrophy ensues, and there are overall better end results. When this is not possible, nerve grafting is carried out (interfascicular nerve graft is usually constructed).

For the irreparable lower elements (C7, C8 and T1), it is possible to transfer the latissimus dorsi muscle for flexion or extension of the fingers (Gousheh et al 2000).

Autogenous sural nerve is usually used as the graft material of choice. When it is not sufficient, the antebrachialis medialis nerve is chosen (Gilbert et al 1986). Sometimes it is possible to use the nerve elements harvested from the previously amputated limbs of the same patients. When this procedure is performed, the epineurium of the grafted nerves should be excised and the fascicles positioned to lay on healthy well-vascularized tissue to prevent the problem of 'cable graft'.

The ulnar nerve as well as other lower elements of the plexus should be repaired with the same care as that devoted to the upper nerve elements. Although the intrinsic muscles of the hand in the territory of this nerve will not generally recover in adult patients, the presence of sensation in the field of the ulnar nerve is very important for the usefulness of the hand and performs at least a protective function. This is particularly important when accompanied by the recovery of digital flexion, which can be accomplished in the majority of cases. When this is combined with a few tendon transfers, the patient can have a useful hand. Therefore we do not recommend using the ulnar nerve as graft material for the rest of the brachial plexus elements.

The repair of the musculocutaneous nerve usually yields good results. However the repair of the radial nerve for digital extension is usually less successful. Therefore, when one repairs the posterior cord at plexus level, one should consider tendon transfer for digital extension at the same time.

Associated injuries

There are usually some associated injuries, which should be treated in the first operating session, along with the neural repairs, whenever possible. These injuries can be categorized as follows.

1. Vascular injuries related to the subclavian and axillary vessels (McCready et al 1986):
   - Arteriovenous fistulae: these can be treated by autogenous vein graft. In these cases the graft can be obtained from the internal saphenous vein. Rarely, the patient with a lateral laceration of the subclavian artery can undergo repair by simple suture.
   - False aneurysms: these are usually located on the axillary artery and sometimes on the subclavian artery. Due to the severity of the vessel lesions, generally the only feasible treatment is with interpositional autogenous vein graft, rather than direct repair.
   - Complete disruption of the axillary artery in its proximal position: this is usually due to ligation of the bleeding artery in emergency operations in the front-line hospitals to prevent life-threatening hemorrhage.
2. Associated pulmonary injuries: these are usually due to emergency treatments by thoracotomy or chest tubes.
3. Skeletal injuries: these can be either to the clavicle, scapula or head of humerus, separately or in combination. Most of the complicated plexus injuries are associated with comminuted or shattered bone injuries.
4. Causalgia should be mentioned as a sequela. Most cases respond to medical therapy or simple neurolysis. Severe causalgia can be successfully treated with upper thoracic sympathectomy.

For the vessel repair, the whole injured area is usually resected and repaired by vessel graft. To do this, first the proximal and distal parts of the artery or artery and vein are controlled and temporarily closed off. The whole area of the vessel and the vessel graft are rinsed with heparin normal saline solution. When performing the graft, attention must be paid to the direction of the valves in the vessel graft for blood flow. Suturing is with 8-0 nylon. Usually complete vascular disruptions are repaired or at least ligated in the front-line hospitals. If the radial pulse is weak and the blood flow to the hand does not seem sufficient, the damaged vessel area should be re-examined and repaired again if necessary.

Appendix: Injuries caused by high-speed projectiles

Penetration injuries of the brachial plexus due to high-velocity bullets or shell fragments are different from other penetrative injuries such as stab wounds or non-penetrative injuries such as traction injuries. This difference is due to the almost spontaneous high-energy release to the region by the penetrating agent. The amount of energy transfer depends on the following factors:

1. *Speed.* In modern weapons the speed of the bullet is several times greater than the speed of sound in air. The amount of kinetic energy associated with the center of mass motion of a projectile with mass m and speed v is given by $KE = \frac{1}{2}\ m.v^2$. As the projectile travels through the air, its speed decreases due to air friction. The extent of tissue damage caused by the these projectiles obviously depends on their speed at the point of the impact.

Shell fragments slow down faster than bullets due to their irregular shape, which causes more air friction. However, shell fragments could have a much higher initial speed – as much as 2000 m s^{-1}. Generally their effective range as high-velocity projectiles is less than 100 m;

2. *Auxiliary motion.* The projectiles usually have auxiliary motion, in addition to their average velocity towards the target. This additional motion carries extra kinetic energy which, when released in the target, causes extra damage. The additional motions of the bullets consist of the following:
   a. Spiraling: the center of mass of the bullet actually moves on a spiral path, rather than a straight line, between the gun and the target;
   b. Spin: the bullet spins or rotates about its physical axis. This spin is caused by the spiraling grooves of the gun barrel;
   c. Precession: the physical axis of the bullet rotates about the axis defined by the instantaneous velocity vector of its center of mass;
   d. Nutation: the axis of the bullet has small oscillations perpendicular to the direction of its precession and its spin;
3. *Shockwaves.* In many war injury cases we have observed tissue damage far removed from the physical path of the penetrating projectile. This is due to the shockwaves accompanying the projectiles. As is well known in the science of aerodynamics, objects traveling faster than the speed of sound in a given medium produce shockwaves in the form of a cone-like ‘shell’ consisting of compressed and high-pressure material comprising the medium. This ‘shell’ accompanies the projectile and travels just behind it, and inside it there is a partial vacuum. This whole structure, consisting of the bullet, the shockwave and the partial vacuum, is called a ‘Mach’s cone’. This is exactly the phenomenon that we observe when an aircraft breaks the sound barrier.

When the bullet strikes the body, it suddenly slows down. The shockwave accompanying the bullet also strikes the body, like the wagons of a train giving aftershocks once the locomotive strikes an obstruction. The shockwave usually does not stop there, and accompanies the bullet even after it enters the body. There they both cause damage. The damage that the shockwave causes is complicated, and is related to the amount of energy that it transfers to the body. This in turn depends on many factors such as the resistance (or hardness or density) of the tissue and the length of tissue on the trajectory inside the body. For example, a bullet passes through an empty container without appreciable energy loss, and therefore without inflicting appreciable damage to the container, by simply making two holes. However, if the container holds water the bullet loses more energy, and therefore the damage to the container is greater and the exit hole is larger. An extreme case would be when the container holds tar. In this case the bullet loses all of its energy inside the container and is stopped there, imparting great damage to the container.

One important mechanism by which the shockwave inflicts damage inside the body is by making an almost instantaneous cavity. This is due to high pressure contained in the shockwave. The boundary of the cavity becomes necrosed tissue. This phenomenon is called cavitation. It is difficult to detect and debride this necrosed area in the first few days after the injury. The remaining shockwave then travels through the body and might damage organs far from the physical path of the bullet.

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Index

Page numbers in italics denote figure legends. Where there is a textual reference to the topic on the same page as a legend, italics have not been used.

3D-CISS 35, 36

abductor digiti minimi muscle *25*
abductor pollicis longus muscle *25*
accessory nerve 86, *98*
  transfers 220, 222, 223
acromion 110, 141, 182
acromion bone block *119*
acromion transfer 118, 229
Active Movement Scale 161, 162, 163, 168
adduction contractures 178, 179
adductor pollicis brevis muscle *24*
adductor pollicis muscle *24*
adhesions 145, 229, 323
aetiology 47–50, 151–7
against-gravity movement 163
age assessment 189
age effects on nerve repair 102
agnosia 177
Albinus accessory muscle 9
allografting, vascularized 53
amputation 55, 97
anaesthesia 189–90
  general 49, 322
analicular syndromes 11
anatomy *21–9*, 67–8
  surface 192
aneurysm, traumatic 31
angiography 322
ansa pectoralis 125, 126
anterior scalenus muscle *7*, 8, 194
anterior serratus nerve 14
antibiotics 245
aneurysm 96
apnea 189
arm function, distal 108
arterial injury 94
arterial resection 96
arteriovenous fistula 96
arteriovenous fistulae 103
arthrodesis 63, 107–12, 301
  to provide key grip 89
  see also specific joints
arthrograms 242, 252
articular process 5

associated lesions *156*
augmentation transfer of elbow 126
autogenous grafting 323
autologous grafting 95, 110, 196
auxiliary motion of projectiles 325
avascular necrosis *257*
avulsions 58, 198
  of cervical roots 79
  intradural injury 53
  in situ 220, 224
axillary artery 100
  rupture of *97*, 102
  transection *96*
  traumatic occlusion 36
axillary cavity 11, 12
axillary nerve 3, *13*, 14
  muscle innervation *21*, *22*
  neurotization 62, 85
  palsy 116–19
  repair 116
  see also circumflex nerve
axillary region *see* infraclavicular region
axon donors 86–7
axonal supercharging 265–6
axonolateral regeneration 52
axonotmesis 39, 40, 92
axonotomy, permanent 92

behavioural outcomes of OBPP 182
behavioural problems and OBPL 166
Bell's nerve *see* large thoracic nerve
biceps brachii and brachialis muscles *29*
biceps function 174
biceps neurotizations 54, 85
biceps recovery in infants 168, 205–7, 240
biceps re-routing *281*, 282, 286, 288, *294*, 298
  results 300
bilateral lesions *218*, 224
biofeedback 143, 268, 269, 305, 309
bipolar transpositions 125, 128
birth weight 153, *154*, 217
bleeding, control of 193
botulinum toxin type A 264, *304*, 305–9
bowstring deformation 133, 141
brachial plexus 3–15, *91*
  individual variation 52
  reconstruction of 11
  repair in children 316, *317*
  trauma in children *317*
brachial plexus exploration 140

brachial plexus lesions 41–2, 86
  in continuity 323
  outside BP 42
Brachial Plexus Work Group 174–5, 182, 186
brachioradialis muscle *29*
brachiothoracic pinch 70
breast cancer 50
breech deliveries 152, 153, 155, 156, 198, 208
  in forearm supination deformity 277
  results of surgery 217–24
British Medical Council classification 309
Brown–Sequard syndrome 20, 68

C5 plexus root 194
C5 rupture 71–2
C5–C6 avulsion injury 318
C5–C6 injury 198–200, 218
C5–C6 lesions 174–5, 211–13, 251, 276, *317*
C5–C6 palsies 57, 59, 62, *63*
  and elbow stiffness 263
C5–C6 rupture 72
C5–C7 lesions 174–5, 200–1, 276, *318*
  after breech delivery 218
  results of repairs 213
C5–C7 palsies 57, 59, 62
C5–C7 rupture 73
C5–C8–T1 palsies 57
C5–T1 avulsion 69–71
C5–T1 lesions 276
C5–T1 rupture 73
C6 plexus root 194
C6–T1 avulsion 71–2
C7 contralateral nerve root 54–5, 69, 85, 87
  elongation 300
  transfer *296*
C7 experimental grafting 200
C7 plexus root 194
C7–T1 avulsion 72, 289
C8 plexus root 194
C8–T1 avulsion 73, 201
C8–T1 lesion 276
C8–T1 palsies 57, 63
cable graft 323
Caesarean deliveries 156, 157
Carliotz operation 241, 244
carpometacarpal arthrodesis 143, 145
causaglia *104*, 324
cavitation 325
cellular adipose layer 11
central apnoea 189
central mechanism 33, 155, *156*
cephalic deliveries 153, 155
cervical cutaneous nerve 193
cervical nerve roots 47–8, 60
cervical nerves 3, 4–5, 191
  anatomy 9, 11, 12, 13, 14, 15
  avulsion 42, 86
  in classification of BP injuries 165
  damage 152, 154, 155
  and elbow paralysis 262
  foraminal anatomy 6, 7
  injury in OBPP 198
  muscle innervation *21–9*
  and pain 19, 20
  traction lesions 47
cervical plexus 69
cervical surgical approach 59
cervical transverse process fractures 20
cervical–thoracic node *see* star-shaped node
chromatolysis 92
circumflex nerve 100–1
  palsy 100
  rupture *99*
  see also axillary nerve
classification
  of adult traumatic BP lesions 50
  of arthrodeses 108
  of BP injuries 57, 92, 123
  of co-contraction 304, *305*
  of focal mechanical injury *93*
  of function in OBPL palsy 163, *164*
  of hand sequelae 289–90
  medial rotation contracture 251–2
  of OBPP 165, 293
    sequelae 277
  of sensory response in infants 164, *165*
  of shoulder deformities 178
  surgical findings *219*
  of wounds 93–4
Claude–Bernard–Horner syndrome 8
clavicle
  divisions 51
  fracture/dislocation 31
  splitting 191, *192*
  traction injury to 47
  war injuries 321
clawhand deformity 152, *160*, *288*
clinical findings in complete palsy 68
closed injuries 47, 79
  with fracture/dislocation 93, 94
  traction 96–7
  traction rupture 94
coaption 87
cock-up splints 176
co-contractions 71
  deltoid/teres major *304*, 306
  treatment of 303–9
  triceps/biceps 126, 264, 266, 309
    and toxin therapy 306, *307*, *308*
co-contractures 81
collateral branches of brachial plexus 13–14
collum scapulae fracture 32
combined treatments 83
complete palsies 67–74
  shoulder 107
  without recuperation 60–2
  see also total palsies
complete paralysis 321
  old 133–4, *135*
  persistent 173
  of upper extremity 123
  see also total paralysis
complete root avulsion 133, *144*
  from traction injury *48*
complications
  arthrodesis 111
  OBPP surgery 202

compound muscle action potential (CMAP) 39, 40
compression 78
  and traction 49
compression lesions 49
compression shockwave 321
compression theory 151
computer measurements of forces in delivery 156
conduction block *see* neuropraxia
conservative management of OBPP 175–7
contractures 77, 176, 244–6
  capsular 226–7, 230, *233*, *234*
  and dislocation 240, 241–2
  in elbow paralysis 261
  flexion 261, 262
  intentional 143
  internal rotation 316
  medial rotation 249–58
    causation 250–1
    classification 251–2
    diagnosis 252
    treatment 255–8
  pronation 261, 263, 299
  releases 226
  soft tissue 273
  supination 88, 181, 261, 263, 316
    forearm 214, 280, 298–9
  Volkmann's 133, 263
cookie test 169, 170, *308*, 309
coracobrachialis muscle *29*
coracoid process 182, 256
cryoprecipitate thrombin 197
CT (computerized tomography) 242, 252
CT scan arthrography 180, 226
CT-myelography 33–4, 58, 60, 61, 208
  repeated 59
  technical notes 34
cubital nerve 15
cuff lesion 32
Current Muscle Grading System 168
curvature of forearm bones 280, *284*
cutaneous nerves 196

decortication 109, 110, 111
deep muscles of neck, nerves for 13
deep pressure sense test 19–20
degenerative lesions 91–2, 93
dehiscence 229
Dejerine–Klumpke paralysis 151
deltoid muscle *21*
demography of OBPL 152
denervation 42, 156
depressor muscles 115
descending radio-ulnar fibres (DRUF) *278*
descending ulno-radial fibres (DURF) *278*
developmental outcomes of OBPP 182
diagnosis
  of co-contraction 304
  delayed 249
  differential, of OBPP 183
  of injuries to terminal branches 91–3
  lesion 79–80
  medial rotation contractures 252
  of traumatic BP injuries 315
diagnostic cervical laminectomy 37
digital extension 132
digital flexion 133, 324
direct epiperineural anastomosis 323
discriminants of recovery *167*
dissection
  of BP *194*, *195*
  Millesi's technique 84
  of upper trunk neuroma 193
distal fixation 118
distal radio-ulnar joint 281
  dislocation 276
donor muscle tissue 139
donor nerve tissue 86–7, 139, 140
  availability of 73
  outside BP 82, 197
  sural nerve as 196, 323
dorsal artery of scapula 11
dorsal interossei muscles *26*
dorsal scapular nerve 13, 87, *195*, 227
  muscle innervation *23*
double level lesions 68, 102
Duchenne–Erb paralysis 276
Duchenne–Erb–Klumpke paralysis 276
Dutch Health Care Information Centre (SIG) 153
dynamic stability 143
Dysport 306

elbow
  extension 138
    absence, total 261
    functional pathology 264
    and muscle transfer 126, *127*, 146, 272
    secondary reconstruction 143
  extensors 262
  fixation 124
  flexion 85, 111, 134, 137, *308*
    absence, total 261
    after total palsies 61, 62
    assessment after 169
    and BP trauma in children 316
    functional pathology 263–4
    improvement 88, 237
    late restoration *208*
    and muscle transfer 126, *127*
    muscle/tendon transfers for *124*
    neurotizations 62, 198, 200
    reconstruction 123, *125*, *135*, 266
    recovery 70, 174, 214
    scores *167*
    treatment of paralysis 264–72
  flexors 262
  function 111, 117
  palliative surgery 123–9
  paralysis 261–73
  stability 138, 146
  stiffness 261, 262–3, 264, 272–3
elbow arthrodesis 107
elbow deformities 181
electrical stimulation 132, 142, 151
  for nerve identification 270
electrodiagnostic studies 173
electroencephalography (EEG) 39

electromyography (EMG) 39–43, 58, 59, 309
  biofeedback training 143
  in co-contraction *304*
  of traumatic BP injuries 315
  vs clinical examination 42
  of war injuries 321, 322
electrophysiologic studies 79
EMG *see* electromyography
EMG-triggered myofeedback 177
endoscopic harvesting 140
endoscopic investigations 37
energy transfer 103, *104*, 324
epidemiology of co-contraction 303
epineuriectomy 80
epineuriotomy 80, 84
epineurium 48
Erb–Duchenne paralysis 151
Erb's palsy 152, 154, 155, 165, 263
  typical position *159*, 160
evaluation, initial 159–64
evoked potential (EP) measurement 39, 315
examination
  clinical 57, 58, 79, 243, 315
    charts *58*
    neurophysiological 39–44
    repeated 59
    vs electromyography 42
    of war injuries 322
  neurological 183
  OBPP 205–6
  paraclinical 57, *58*
  physical 17–29, 157–64
  shoulder 185
exercises
  for medial rotation contractures 255
  range of motion (ROM) 175–6, 182, 185
extensor carpi radialus muscles *28*
extensor carpi ulnaris muscle *28*, 280, 289
  transfer *282*
extensor carpi ulnaris tendon 289
extensor digiti minimi muscle *27*
extensor digitorum communis tendons 141
extensor digitorum muscles *27*
extensor indicis muscle *27*
extensor pollicis longus muscle *25*
extensor-to-flexor transfer 298
external rotation 85, 88, 112, 225, 244–5
  active 180, 222, 232
  passive 176, 227
  shoulder paralysis *233*, *234*, 236
extraplexal neurotization 68, 197
extra-scalenus anatomy 10–11

false aneurysms 96, *100*, 101, 103
fascia lata grafts 244
fascicular grafts 52
fasciculus lateralis 125
fasciculus medialis 125–6
fibrin glue 196, 197
fibrosis 84, 101, 276, 323
  post-ischaemic 97
finger extension *144*
finger flexion 134
  after complete palsy 72
  correction 297–8
  reconstruction *135*, 141, *144*
  restoration 71
finger function 137, 280
fixed supination deformities 282, *283*, *284*
fixed supination deformity 263, *279*, 286, 287
flail arm 77
  in infants 168, *205*, 207
flail hand *205*, 207
flail shoulder *116*, 225, 227
flail upper limb 137
flexible supination deformity 282, *283*, 287
flexion pronation posture 249
flexor carpi muscles *27*
flexor carpi ulnaris muscle *28*
  in Steindler flexor-plasty 267–8
flexor digiti minimi muscle *26*
flexor digitorum profundus muscles *27*
flexor digitorum superficialis muscles *27*
flexor pollicis brevis muscle *25*
flexor pollicis longus muscle *25*
fluids and anaesthesia 190
fluoroscopy 160
foetal flexion posture 263
foraminate anatomy 5–8
foraminate space 6
forearm
  flexion/pronation 126
  palliative surgery 123–9
forearm deformities *298*
forearm flexors 297, 299–300
forearm supination deformity 275–6, 279–81, 287–8
  classification *280*
  operative procedures 281–9
  see also fixed supination deformity; flexible supination deformity
Former Numerical Score 168
Foundation of Perinatal Epidemiology in the Netherlands (PEN) 153
fracture of intima 96–7
fractures 68
  after breech delivery 217
  and BP trauma in children 316
  indications for intervention 95
free muscle transfers *127*, 128, 133–4, *135*, 271–2, *296*
  complications 145–6
  double *144*, 145
  palliative surgery 137–46
free muscle transplantation 297, 300
functional muscle stimulation 268

Gerdy's ligament 12
Gilbert and Mallet scores *257*
Gilbert and Tassin Muscle Grading Systems *161*
Gilbert shoulder function staging 252–3, *257*
Gilbert/Raimondi assessment 186
Gilbert's classification 11
glenohumeral arthrodesis 70, 138, 145
glenohumeral deformity 246
glenohumeral dissociation 20

glenohumeral joint
  in arthrodesis 107, 108, 117
  deformity 242, 249
  stabilization 128, 146
glenoid deformity 178
glues, biologic 53, 196
gluteal aponeurosis 131, 132, 133
gracilis muscle
  harvesting 140, 141
  transfers 133
graft revascularization 53
grafts/grafting 52–5, 195
  donors 86–7
grasp release 138
gravity-eliminated movements 161, 162, 163
greater auricular nerve 98, 193
gripping function 85, 88
guidelines for action in OBPP 183, *184*, 185
gunshot injuries 50

haematomas 36, 52, 217
haemostasis 110
hand
  deformities *298*
  function 111, 117, 214
    after total palsies 61
    in partial palsies 62, 63
    in S-OBPP 293
  palliative surgery 131–6
  recovery 207, 215
  sequelae 289–90
hand assessment 186
handgrip reconstruction 137
handgun injuries *104*
Hara's technique 62
harvesting from amputations 323
hemidiaphragm paralysis 160
hemilaminectomy 81
hemiparalysis of diaphragm 32–3
high velocity traction injuries 47
high-speed projectiles 321, 324
history, obstetric 159–64
Horner's syndrome 20, 57, 151, 152, 165, 185, 277, 279
  four signs 160
  in infants 159, 168, 170, *206*, 207
Hospital for Sick Children Muscle Grading System *161*
humeral head 321
humerus 32, *257*
humerus fractures 111, 117
hypoglossal nerve 69, 221
hypothermia 190
Hyrtl's intercosto-brachial nerve 15

iatrogenic injuries 49, 49–50
immobilization, postoperative 60, 87–8, 227, 268, 269
  after muscle transfers 229, 231, 232, 237, 245
immunosuppression 53
incisions 51, 59, 83, 191–2
indications
  for arthrodesis 107–10
  for intervention 94, 95
    in OBPP 205
    surgery 206, *207*
industrial traction injuries 49
infant OBPP *see* I-OBPP
inferior gleno-humeral angle 254
inferior trunk 3, 4
infraclavicular branch of BP 13, 14
infraclavicular fossa 84
infraclavicular injuries 50
infraclavicular lesions 67, 94
infraclavicular region 11–13, 14–15
infraspinitus muscle *22*
initial OBPP *see* I-OBPP
innervation of muscles 42
insertion of biceps, advancement of 271
integrated therapy 128
integrated treatment concept 303
intercostal nerves 15, 60, 68–9, 86–7, 139
  transfers 137, 141, 221, 223
  as transformator 301
intercostobrachialis nerve 87
intermediate scalenus muscle 9
internal rotation 112, 177, 226
interneural sclerous nodules 51
interosseous membrane *278*
  released *282*, 286, *294*
  retracted *279*, 286
inter-scalenus artery 9
intra-articular fracture 100
intradural injury 33, 34, 91
intraplexal neurotization 68, 197
intra-plexus distribution 4
intrinsic palsy joint extension 299, 300
intrinsic palsy of hand 299
I-OBPP 293
IP-extension dynamic splint *296*
ischaemic necrosis 145

joint deformities 226
joint mobility 139, 163
joints of scapular belt 108

key grip 137
kinetic energy of bullets 321
Kirschner wire *281*
Kline and Hudson grading system 97
Klumpke's palsy 152, 160, 165, 276, 297

laceration repairs 52
Langer's arch 12
Langer's muscle 12
large thoracic nerve 8, *9*, 12
  see also long thoracic nerve
late exploration 207–8
late OBPP with deformity *see* S-OBPP
lateral cord 4, 12
lateral pectoral nerve *22*, *23*
lateral rotation 243
lateral–cervical surgical approach 5
latissimus dorsi muscle
  bipolar transfer 268–9
  bipolar transposition 125

latissimus dorsi muscle (*cont.*)
innervation *22*, *124–5*
island flap 131
and plication of diaphragm 218–19
transfers 133, 226, *233*, 243
anterior approach 230–1
for BP trauma in children 316
indications 230
posterior approach 231–2
results 232, 236
in war injuries 323
latissimus dorsi transfer 128
latissimus to triceps transfers 272
L'Episcopo transfers 243
lesser occipital nerve 193
levator scapulae muscle
innervation *23*
transfers 227, 236
transposition 230
ligamentoplasty 63, *116*
Limb Motion Scores *166*
long thoracic nerve 13, 14, 194, *195*, 227–8
muscle innervation *24*
neurotization 85
palsy 120–1
see also large thoracic nerve
low velocity traction injuries 49
lower plexus palsy 165
lower subscapular nerve *22*, *23*
lower trunk 11, 12, 194, *195*
lumbricalis muscles *26*

macrosomia 153, 154, 217
magnetic resonance angiography (MRA) 36
magnetic resonance imaging (MRI) 33, 35–6, 80, 226, 242
glenoid visualization 252, 258
magnetic stimulation (Magstim) 39, 42
magnification 191
Mallet and Gilbert scores *257*
Mallet sum scores 222–3
Mallet's movement classification/scale 163, *164*, 205
and disability 223
for infants 206, 221–2
in OBPP management 180, 182, 185
in shoulder dislocation 253, *254*, *257*
manual muscle tests 17
mechanical injury in delivery 157
Meckel's adipose mass 10
medial cervical fascia 10
medial cord 4, *103*
medial epicondyle 267
medial pectoral nerve 14, *22*, *23*
medial rotation 249, *255*
median nerve *13*, 15, 102–3, 126
muscle innervation *24*, *25*, *26*, *27*, *28*
outcome of nerve repair *103*
in Steindler flexor-plasty 268
Medical Research Council Muscle Grading System 17, *161*, 170
Medical Research Council system of outcome measurement 97
meningoceles 35, 61, 208
CT-myelography 33, 34
myelography 219, 223
Meyer's guillotine knife 53
microsurgery 52
microsurgical neurolysis 51
microsurgical repair, early 237
microvascular muscle transplantation 82
middle root lesions 213
middle scalenus muscle 9
middle trunk 194, *195*, 200
anatomy 3, 4, 11, 12
exposed *191*
Millesi's principles 52
Millesi's technique 53, 83–9
Moberg-type reconstruction 137, 138
modelling arthrodesis 109
monopolar transpositions 128
motor functions *19*, 39, 160–3, 173
motor unit potentials 42
MP joint drop/wrist drop 297
MR techniques, variant 35
multiple arthrodeses 107
multiple nerve transfers 137
muscle
function 97
imbalance 241, 242, 279
innervations *115*
muscle grading systems *161*
muscle grafting 83
muscle test charts *17*
muscle transfers 77, 82, 117–19
for elbow flexion *124*
extensor carpi ulnaris muscle *282*
microvascular neurovascular 318
multiple 236
in posterior shoulder dislocation 250
preconditions for success 123–4
secondary 88, 317
shoulder *118*, 242
grade 0 227–30, 232, 236–7
grade II-III 230–6
muscle transposition 243
muscle–tendon transfers 271, 272–3
muscular imbalance 177, 251
musculocutaneous nerve 3, *13*, 15, 59, 101–2, 297
muscle innervation *29*
neurotization 62
results of repairs *101*
transfers 221
myelograms 315
myometric study 100

Nakamura brace 142
Narakas' Grading System for outcome in OBPP *170*, 174
Narakas' Sensory Grading System 164, *165*
narcosis 42
natural history of OBPP 173–4
neck–shoulder angle 47, *48*
necrosed tissue 325
needle EMG 40

nerve
grafts/grafting 60, 77, 82, *318*, 323
bridging 81
elbow reconstruction 126, 128
by gluing 53, 197
for sharp injury 49
growth 134
regeneration 52
repair 58, 95
evaluation 211
grading of results *102*, 211
timing of treatment *102*
retraction 92, 95
rupture 155
severance 39
nerve compression 18
nerve conduction studies 39
nerve root avulsion 47
nerve transfers 81–2
in breech delivery BP lesions 224
for complete palsy 68–9
nerve-crossing 142
neurolysis 51–2, 78, 80–1, 84, 317, 323
in OBPP 195
neurolysis, external 103
neuromas 41, 134, 152, 194, *220*
resection 195, 196, *220*
neurophysiological investigations 39–44, 219
neuropraxia 39–40, 51, 92, 93, 322
physical examination 18, 20
neurorrhaphy 78–9
direct 81, 82
end-to-side 63
for sharp injury 49
neurosurgery
criteria 185
for OBPP 173, 174–5
neurotizations 53–4, 85, 193, *318*
after total palsies 70
of biceps nerve 62
by C7 contralateral nerve root 54–5
in complete palsy 60, 61, 68–9
distal stumps 81
limited 82–3
in OBPP 197, 198, 208
neurotmesis 39, 40, 92
neurovascular pedicle 131
Neutral-0-Method 309
night-splinting 268
non-degenerative lesions 91, 93

OBPL *see* obstetrics brachial plexus lesions
OBPP *see* obstetrical brachial plexus palsy
observation 160
obstetric brachial palsy 42–3, 151
obstetric characteristics of OBPL 152
obstetric lesions 35
obstetric patients 32–3, 34
obstetrical brachial plexus palsy (OBPP) 173–86, 239
obstetrics brachial plexus lesions (OBPL) 153, *155*, 211–15
obstructive apnea 189
Omnipaque 300 34
omohyoid muscle 59, 194
open injuries 47, 49–50, 79, 96, 102
open reduction of dislocations 241
operative techniques
free muscle transfers 134
latissimus dorsi muscle island flap 131–3
war injuries 322
opponens digiti minimi muscle *26*
opponens pollicis muscle *24*
opponensplasty 298
orthosis, functional 142
osteoclasis, closed 282
osteosynthesis 51, 78, 323
osteotomy
clavicle 73, 84, 192
coracoid 230, 246
exorotation 181
glenoid deformity 258
humeral 181, 242, 243, 244, 273
lateral rotation 255
radius 282
rotational *294*
outcomes
behavioural 182
functional 146
of nerve repair 97–8, *103*
of subscapularis recession 258

pain 19, 78
persistent 95
and poor lesion prognosis 57
from radiation injury 50
severe 93, 97
pain syndrome 19, 61, 78, 146
palliative surgery
elbow and forearm 123–9
elbow paralysis 261–73
forearm and hand deformities 293–301
free muscle transfers 137–46
hand 131–6
obsolete in OBPP 237
prosupination 275–90
shoulder paralysis in neonates 225–37
tendon transfers to shoulder 115–21
in OBPP 239–46
palmar interossei muscles *26*
palmar sensibility 61
palmaris longus muscle *27*
paralysis
deep 95
hand 60
patterns 77
serratus anterior muscle 120
paralytic shoulder 115–16
paraneuriotomy 80, 84
paraspinal EMG 41
parental involvement 176, 183
partial lesions 41, 52, 323
partial palsies 62, 63
partial paralysis 123, 128
passive pronation of forearm *283*, *284*
pathogenesis of BP injuries 152

pathophysiology
of co-contraction 303–4
of nerve lesion 39–40
patient re-education 131, 132
patient selection 71, 138–9
patient support groups 208
patients with OBPL 153–7, 217
pectoralis major muscle 126
free muscle transfers 134
innervation *22*, 125
neurotization 85
transfers 120, 128, 269–71
operative steps *269*
transplantation 121
pectoralis minor muscle *22*, *23*, 126
pectoralis nerves *13*, 14, 134, 221
pectoralis nerve transfers 222, 223
pectoris minor muscle 59
penetrating missile injuries 103
penetration injuries 324
peripheral lesions 41
phrenic hemiparalysis 218–19
phrenic nerve 69, 86, 194, *195*
phrenic nerve lesions 224, 272
phrenic palsy *218*
physical therapy 303, 305, 309
physiotherapy 124, 132, 245, 316
pinch test 137
see also deep pressure sense test
platysma colli muscle 10
plexus evaluation system 303
plication of diaphragm 218–19
plication of extensor tendon 297, 300
point of Erb 151
poliomyelitis
arthrodesis after 117
trapezius transfer after 229, 230
polyneural innervation 42
position for arthrodesis *109*
posterior bone block 258
posterior cervical triangle 10
posterior cord 3, 4, 12, 13, 177, 194, 323
posterior cord sequelae 277
posterior gleno-humeral angle 254–5
posterior scalenus muscle 8
postganglionic fibres 92
postganglionic lesions 67
postoperative care 87–8, 202
postoperative management 142
post-traumatic arthritis 100
posture, characteristic, in OBPP 239
predictors of recovery 174
prefixed plexus 4
preganglionic lesions 67, 223
prehension 137, 146
preoperative considerations 321–2
primary BP exploration 166
primary interventions 220
primary operations 223
primary repair, urgent 96
prime mover muscles 115
profundus flexor tendons 132
prognosis 57, 166–7, 173
progressiveness of deformities *279*
pronation deformity *288*
pronator quadratus muscle *28*
pronator teres muscle *28*
prosupination 275–90
proximal axonal stump 40, 58, 195
proximal joint instability 145–6
proximal limb sequelae 277
proximal middle-limb sequelae 277
proximal radial head dislocation 299
pseudoarthrosis *31*, 111
pseudomeningoceles 60, 63
pseudoparalysis 160
pseudotumours 160
pulleys 124, 126
pulmonary injuries 324
pulped bone grafts 110, 111
Putti's sign 279

radial dislocation 176
radial head, dorsal dislocation 299
radial nerve 3, 13, 14, 101
and humerus fractures 32
muscle innervation *25*, *27*, *28*, *29*
results of repairs *101*
radiation 47
radiation injury 50
radical neck surgery 98
radicular artery 6
radicular avulses 7
radicular surgical approach 6–7
radiculo-medullar artery 6
radiological features 250
radiological investigations 31–7, 219
radio-ulnar fusion *284*, *286*, 287, 288
Raimondi's Grading System 171, 182–3, 186
range of motion (ROM)
exercises 175–6
passive 182, 185
range of movement *258*, 309
reconstruction 69–73, 88–9, 166
elbow 293
in OBPP 195, 197–201
shoulder 293
reconstructive goals 69
reconstructive neurosurgery 152
redressing splint 176
re-education 266
regenerated muscles for transfer 82
rehabilitation 142–5, 268, 269
reimplantation, nerve root 69
re-innervation 42, 173, 266, 301, 317
after grafting 61
assessment after 42
delayed/failed 145
electromyographic 142–3
incomplete 225
residual function 123
retraining elbow flexion 269
retroclavicular injuries 50
retroversion of humerus neck 256, 257
rhomboid muscles *23*, 120, 228, 229
rhomboid nerve 9

Richet's clavicular–coracoaxillary fascia 12
road traffic accidents 47, 49
root avulsions 85–6
  comparative incidences 48
  and EMG 41
  and pain 19, 20
rootlet avulsions 58, 152
  and CT-myelography 33, 34
rootlets 35
roots, anterior 42
rotation contractures 177, 178, 179, 180
rotation osteotomy 63, 117, 181
rotational lower arm 186
rotator cuff
  rupture 100
  system 225
Rouvière's clavipectoral–coracoaxillary fascia 12
rupture repair 86, 198

Saha's modification 118
scalenus muscles 8
scalenus region 8–10
scalenus sickle 9
scapula
  fracture 32
  lengthening of 241
  movement 109
  stabilization 85
scapular muscles *115*, *239*, 244
scapular spine fractures 49
scapular winging 120, 246
scapulo-humeral angle 47, 176
scapulo-humeral arthrodesis 107
scapulo-thoracic arthrodesis 121
scapulo-thoracic dissociation 31
scapulo-thoracic joint 115, 227–8
scar tissue/scarring 269, 322, 323
score of ten system 293
Sébileau scalenus–vertebro-pleural space 7
secondary bone deformities 252, *304*
secondary joint deformities 306
secondary operations 223
secondary procedures 303
secondary reconstruction
  elbow flexion 124–7
  free muscle transfers 143, 145
  for grade 0 shoulders 236
secondary shoulder surgery 116–17
secondary surgery 316
  for OBPL 173, 214, 221
Seddon's classification 92
sensibility assessment chart 18
sensibility of hand 146, 324
sensibility tests 18
sensory evaluations 19
sensory function assessment 164
sensory functions *19*, 138
sensory nerve action potentials (SNAP) 39, 40, 140
  in neonates 219
sensory nerve function 39
sensory reconstruction 142
SEP *see* somatosensory evoked potentials
sequelae deformities of S-OBPP 295, 300
  shoulder 177–81
sequelae of OBPP *see* S-OBPP
serial arthrodesis 108
serial casting 176
serial preoperative EMG 323
serratus anterior muscle *24*, 57, 99, 120
  palsy *99*
Sever–L'Episcopo transfers 243
sharp injury 49
shockwaves from projectiles 325
shotgun injuries 50, 103
shoulder
  abduction 237
    and latissimus dorsi transfers *233*, *234*
    scores *167*
    and trapezius transfer *119*
  abnormalities 240
  arthrodesis 61, 62, 107, 117, 246
    results *111*
    X-rays *109*, *110*
  deformity in OBPP 177, 178, 240–2, 263
  dislocation 20, 32, 240, 241–2
    palsy after 57
    posterior 244, 249–58
    simple *257*
  dystocia 152, 156
  elevation 115
  function 174, 211, 240, *257*
    improvement 232
    neurotizations 198, 200
    recording 252–4
    and Test Scores 169
  hyper-abduction 47
  hyperextension 67
  muscles *115*, *239*
  paralysis 225–37
  stabilization 61, 62, 85, 118, 137, 237
  subluxation 240, 241, 244
shoulder assessment 186
shoulder examination 185
shoulder instability, multidirectional *116*, 119
single-fibre EMG 42
skeletal abnormalities 178, 306
skeletal injuries 103, 324
skin as monitoring device 134, 145
skin moisture 19
S-OBPP 293, *294*, *296*
soft tissue damage 103
soft tissue procedures 181
somatosensory evoked potentials (SEP) 42
sonography 37
speed of projectile 324–5
spinal accessory nerve 68, 70, 191, 193, 201
  as donor tissue 139
  injury 98, *99*
  in neurotization 60, 62, 140–1
  palsy 99, 121
  transfers 137
spinal cord 34, *35*, 47
spinal nerve 5, 6, 11
  intraforaminal lesion of spinal nerve 31, 54
spinal-evoked potentials 140

splinting 176, 268
spontaneous recovery 166, 167, 277
  in adults 77–8
  of external rotation 227
  incomplete 225
  in OBPL 221
  in OBPP 174, 205–6, *233*, *234*
sporting activities 177
sports traction injuries 48, 49
stab injury *317*
star-shaped node *7*, 8
steering group muscles 115
Steindler effect 262, 266
Steindler flexor-plasty 266–8
Steindler operation 82, 88
Steindler transfer 126, 181, 306
  modified *127*, 128
stepwise discriminant analysis 166–7
sternocleidomastoid (SCM) muscles 59
  in infants 159–60
sternocleidomastoid to biceps transfer 271
stretch injuries 52, 116
stretching of BP during delivery 151, 152
subclavian artery aneurysm, traumatic 31
subclavian nerve 14
subclavian vein 11
subclavicular and axillary surgical approach 59
subluxation
  acquired 250
  complex *253*, *256*
  radius head 249
  shoulder 240, 241, 244
  typical posture *249*
subluxation of distal radio-ulnar joint 276
subscapular nerves 14
subscapular slide/release 179, 180, 226–7, 230
  and latissimus dorsi transfers *233*, *234*
subscapular tendon lengthening 180, 181
subscapularis muscle *23*
subscapularis operations 179–81
subscapularis recession 255
  obstacles to 256–7
subscapularis tenotomy 180
Sunderland's classification 92
superficial jugular vein 11
superior trunk 3, 4, 12
supinator muscle *28*
supraclavicular branch of BP 13
supraclavicular fossa 84
supraclavicular injuries 50
supraclavicular lesions 57, 67
  vs infraclavicular lesions 91
supraclavicular nerves 86, 193
supraclavicular–extrascalenius region 5
suprascapular artery 11
suprascapular nerve
  repair 116
  rupture 100
  and scapula fractures 32
  transfers 222
suprascapular nerves 3, *13*, 14, 194, *195*
  compression of 49
  innervation *21*
  as landmark 59
  muscle innervation *22*
  neurotization 85
  palsy 116
supraspinatus muscle 226
  innervation *21*
  palsy of 108
sural nerve 134, 196, 323
surface anatomy of BP 192–3
surgery 190–202, 219
  elbow/wrist/hand 181–2
  indications for 59, 167–70, 219
  for medial rotation contractures 255–8
  shoulder 178–9
  timing of 78–9, 219
surgical approach, Alnot's 117
surgical exploration 315–16
surgical interventions 219–21
surgical options 80–2
surgical procedures 59, 295
surgical techniques 51–5, 110–12
  forearm supination deformity 281
  in OBPP 189–202
  shoulder muscle transfers 228–30
  subscapular release 226–7
sutures/suturing 95, 192, 196, 232, 245, 323
  direct 101
  end-to-end 51, 52
  end-to-side 52, 208, 317
  marking 269, 271
  of vessel grafts 324
synostosis *286*, 287
syrinx 41

T1 166
  avulsion 160
technique
  free muscle transfers 139–45
    first 140–1
    secondary shoulder surgery 141–2
temperature during anaesthesia 190
temporary muscle atrophy 305–6
tendon lengthening 181, 230, 244
tendon transfer 82
tendon transfers 230, *231*, 242–3, 301, 306
  for BP trauma in children 316
  for elbow flexion *124*
  multiple *295*
  in OBPP 214
  shoulder 115–21, *240*
tendon transfers to shoulder 115–21, 239–46
tenodesis 82, 143, 301
tenolysis 143, 145
tenorrhaphy 141
tenotomy 244, 306
tension of muscle 134, 140, 142, 232
  adjustment 141, 269
teres major muscle 243
  innervation *22*, 236
teres minor muscle *22*
terminal branches of BP 14, 91–104
Test Scores 168, 169

thoracic nerves 3, 152, 155
  anatomy 4, 7, 8, 12, 13, 14, 15
  muscle innervation *22–9*
  and pain 19, 20
  traction lesions 47
thoracodorsal artery 131
thoracodorsal nerve 14, *22*, *124*
thoraco-scapular muscles 107, 108
thumb function 133, 280
thumb-in-palm deformation 176
timing of treatment 42, *102*, 185
  arthrodesis 111
  contractures 242
  elbow paralysis 265, 266
  forearm supination deformity 281
  OBPP 206, 219
  for paralysis of upper extremity 123
  reconstructive procedures 139
  shoulder paralysis in neonates 226
  shoulder surgery 242
  of war injuries 322
Tinel's sign 53, 79, 80, 93
Tissucol 53
total palsies 152, 155, 276
  with avulsion of all roots 61
  with avulsion of lower roots 60–1
  in infants 160, 168
  see also complete palsies
total paralysis 289
  see also complete paralysis
total plexus injury 201, *202*
  obstetric *235*
  results of repairs 213–15
total plexus palsy 165, 293, 297
traction
  of BP 33
  and compression 49
  foetal 152
  lesions 47–9
  resistance to 7
transfers in hand 182
transverse cervical artery/vein 194
transverse cervical nerve 98
transverse process of cervical vertebrae 5, 31
transverse-radicular ligament 6
transverso-pleuro muscles 9
trapezium, palsy of 108
trapezius muscle 120
  innervation *23*
  transfers 118, 119, *235*, 243, 245
    for grade 0 shoulders 236
    surgical techniques 229
traumatic arachnoid cysts *see* meningoceles
traumatic birth 153, *154*
traumatic BP injuries 315
treatment
  of co-contraction 305–6, *309*, 309
  of complete palsy 68–73
Trendelenburg position 49
triceps 126, 262
triceps brachii muscle *29*
triceps to biceps transfer 128, 271
trumpet sign 264, *304*

ulna dislocation *288*
ulnar deviation of wrist 275–6, 279–81, *284*, 289
ulnar nerve *13*, 102–3
  in biceps neurotizations 54
  muscle innervation *24*, *25*, *26*, *28*
  outcome of nerve repair *205*
  in Steindler flexor-plasty 267, 268
upper humeral fractures 20
upper plexus palsy 165
upper respiratory tract infections 189
upper root lesions *205*, 211–12, 213
upper subscapular nerve *23*
upper trunk 11, *191*, *195*

vascular compromise 145
vascular damage 49
vascular investigation 322
vascular lesions 31, 96–7, 324
  'silent' 36
vascularized grafts 53
vascularized nerve grafts 81
vaso-motor paralysis 92
Velpeau quadrilateral 14
ventral ramus *23*
ventral terminal branches 15
vertebral artery 7
vertex delivery 251
vessel repair 324
volar dislocation *279*, *284*, 299
Volkmann's contracture 133, 263

waiter's tip hand position 152, 218
Waldeyer's vertebral triangle *7*, 8
Wallerian degeneration 40, 79, 91, 92
war injuries 101, 321–5
whole-limb with paralysis sequelae 279
whole-limb with partial recovery sequelae 278
wrist arthrodesis 82, 107
wrist deformity 280
wrist dorsiflexion with ulnar deviation 289
wrist extension 215, 267
wrist flexion after complete palsy 72
wrist fusion 297
wrist ulnar deviation 299

X-rays 31–3, *109*, *110*, 160