Endodontic Prognosis

Clinical Guide for Optimal Treatment Outcome

Nadia Chugal
Louis M. Lin
Editors

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To my family, friends, and mentors for their love, support, and encouragement.

Nadia Chugal

Foreword

It is indeed a privilege to write this foreword for an Endodontics book with prognosis as its main emphasis. While all practitioners aspire to achieve the highest levels of success of treatment, the definition of this success and the factors that affect it receive very little attention among clinicians. Complicating this matter is that, with the exception of resolution of pain or purulent drainage, true and complete endodontic success is not demonstrable clinically until a long period has passed after treatment, typically measured in years. The difficulty in establishing an effective follow-up program for all patients, especially that they are typically asymptomatic, has led many practitioners to rely only on surrogate measures of success like the quality of the obturation and the resolutions of symptoms. While there are some population-based data in the literature to support reliance on these parameters, they clearly provide an incomplete assessment of prognosis.

As one reflects on this book's working definition of endodontics, as the prevention and/or elimination of apical periodontitis, it is reasonable to reconsider whether this is still consistent with recent information as noted in the relevant chapters. For example, the word "prevention" is used in a discipline in which home care is not thought to affect the outcome of treatment. The intent likely arose from the need to diagnose irreversible pathosis more vigilantly, in order to perform the endodontic treatment at this stage, and avoid pathogenesis of apical periodontitis. However, recent advances in vital pulp therapy leads one to question whether the priority is still to remove the vital inflamed pulp at all costs to assure the goal of preventing apical periodontitis. The growing interest in pulp and dentin regeneration, the advent of more biocompatible reparative materials, and the presence of good outcome studies on vital pulp therapy make one reflect more on this classic definition of endodontic therapy.

This book also provides an excellent discussion in several chapters of the radiographic detection of emergent and residual disease, as it has evolved in the last 60 years or so. Today, tools like CBCT allow us to visualize this disease earlier in the diagnostic process, and for a longer period after treatment. Therefore, there is more of an overlap in the pulpitis/apical periodontitis spectrum of diagnosis, and perhaps a longer period when teeth with apical radiolucencies may be considered healing. There are even questions as to whether teeth with long-standing small

radiolucencies, and no other abnormalities, should be retreated or subjected to root end surgery. There is more realization that complete bone regeneration may not be achievable in many of these asymptomatic cases, the way it is not achievable in cases with marginal periodontitis.

Postoperative factors that affect the prognosis are also of particular interest. The profession has in the last decade transitioned from relying on bench-top laboratory studies to clinical outcome studies in making many clinical decisions that are related to coronal leakage. The question remains as to who controls the prognosis to a larger extent: is it the practitioner that did the endodontic therapy or the one who restored the tooth?

Finally, this book eloquently addresses the emerging concept of personalized endodontics, in which the prognosis may be affected by a combination of the unique and complex microbiota that causes the disease, together with the systemic health of the patient, as well as genetic and epigenetic variability among patients. This area promises to provide us in future more detailed predictors for outcomes, which can help the provider with treatment planning and help the patient with decision making.

Ashraf F. Fouad, DDS, MS

Preface

This book distinguishes itself from endodontic textbooks because it is the first textbook completely focused on the prognosis of endodontic treatments. Our goal for this book was to make recent results at the forefront of endodontics accessible for clinical practice.

The book is intended to serve as a clinical guide to help practitioners in their clinical decision-making process and ultimately improve endodontic treatment outcomes.

The goal of endodontic treatment is to prevent and/or eliminate apical periodontitis, a disease entity occurring as a result of microbiologic challenge to the pulp and periradicular tissues. Like many other human diseases, endodontic treatment outcomes are profoundly affected by a multitude of prognostic factors. These determinants of treatment success or failure can exert their effect preoperatively, intraoperatively, and postoperatively. Therefore, it is important for the clinician to be familiar with the favorable predictors of outcome as well as prognostic risk factors. This knowledge is essential to effectively circumvent and manage risks in order to achieve the desired treatment result.

We first outlined the theme of every chapter that we considered important for the book. We then invited experts in their respective areas to write on the specific topics. These topics include both basic and clinical sciences and cover several key aspects of endodontic prognosis. The multidisciplinary authorship by highly respected clinicians and scientists reflects the multifactorial nature of endodontic outcome.

Outcome assessment of endodontic therapy has evolved from Strindberg's stringent criteria that emphasized the absence of clinical symptoms/signs and restoration of normal structure of the periapical tissues to newer patient-centered criteria focusing on the absence of clinical symptoms/signs and survivability and functionality of endodontically treated teeth even with the presence of small and stable periapical lesions. However, as pulpal and periapical pathosis is a disease, a tooth with a persistent inflammatory periapical lesion after treatment, regardless of its size, should be considered as unsuccessful elimination of the disease. Therefore, complete elimination of the disease still remains the ultimate goal of root canal treatment.

We hope that the readers will enjoy this book and benefit from it, as much as we have enjoyed spending our time and energy working on it.

Nadia Chugal
Louis M. Lin

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We thank all contributors for their time, support, and contributions to this book. Without their generosity and dedication, this book would not have been published. We wish to express our deep appreciation for the many cases, radiographic images, photographs, and histologic slides provided by our colleagues. We also thank the editors from Springer for believing in us and for their support, understanding, and patience.

Nadia Chugal
Louis M. Lin

Contents

Introduction: Endodontic Prognosis and Outcome

1

Nadia Chugal, Louis M. Lin, and Bill Kahler

Many authors display a propensity to reduce complex problems such as success and failure to terms so simple that a casual reader with little effort can expand a narrow grasp of the subject into a broad convenient misunderstanding

Dudley Glick, DDS
Excerpt from a lecture
Year unknown

Abstract

Prognosis and outcome are two terms routinely used in medicine and dentistry to predict and assess the treatment of disease. Prognosis is a practitioner's assessment about how a patient will recover from an illness or injury. It is a forecast of the probable course of recovery for any particular disease considering the assessment of the case. Outcome is the end result of the treatment and a consequence of treatment decisions made by the practitioner. In endodontics, there are prognostic factors which are universal to all cases as well as variables unique to a specific case, all of which can affect endodontic treatment outcomes. Prognostic factors can be grouped into preoperative, intraoperative, and postoperative. They influence endodontic treatment outcomes indirectly through control and elimination of infection. Importantly, an understanding of prognostic factors helps practitioners as well as patients decide the appropriate treatment procedures and is especially important for higher-risk conditions such as teeth with a periapical

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lesion, calcified canals, resorption, and others. This applies to immature or mature teeth for consideration for nonsurgical or surgical management. Although many prognostic factors are not under the control of the practitioners, they can nevertheless be managed by a practitioner's thorough evaluation of the presenting condition, risk assessment inherent in each individual case, and application of biologically based therapies alongside with technical competency. Treatment outcome is usually assessed using clinical and radiographic examination and has evolved from Strindberg's stringent criteria to patient-centered criteria. Practitioners have to be familiar with the prognostic factors to inform patients of the appropriate treatment modalities and to achieve the optimal treatment outcome.

1.1 Introduction

The terms prognosis and outcome are routinely applied in medicine and dentistry. They are used to predict and evaluate the result of disease treatment. Prognosis is a forecast about probable course and outcome of a disease and chances of recovery [1]. Applied to endodontics, it is a prediction of the outcome of resolution of apical periodontitis. This forecast of the outcome is summarized by the practitioner for the patients and serves to inform them how they will recover from an illness or injury [1]. It synthesizes the prospect of recovery as anticipated from the usual course of disease, or in the case of endodontics, the risk assessment of variables that may influence the treatment outcome [1]. Outcome, on the other hand, is a measure of the success of the treatment, as a result of an activity or a process, and is a consequence of the decisions made during the course of treatment. Applied to endodontics, outcome is the end result that follows as a consequence of endodontic treatment [1].

There are a number of well-researched studies that elucidated prognostic factors that exert significant effect on endodontic outcome. In turn, this information can be used to prognosticate the course of disease resolution and predict the end result of the proposed treatment.

Practitioners can systematically evaluate prognostic factors to guide their patients in the decision-making process and ultimately propose the best treatment options to achieve an optimal outcome. In accordance with evidence-based dentistry principles, the patients are also members of the treatment planning team and have the right to know the prognosis and expected outcome before commencement of treatment. Given this information, patients can evaluate their treatment options and make an informed decision about the need or preference for their treatment choices [2].

Optimal dental treatment planning requires an accurate assessment of the outcome of the proposed endodontic treatment. This assessment, however, is dependent on a correct understanding of variables affecting the outcome and must be done with both high validity and reliability [3]. When such assessment

is made, it is possible to offer the patient a wide range of appropriate endodontic treatment options.

1.2 Multifactorial Nature of Endodontic Outcome

The multifactorial nature of endodontic outcome has been demonstrated in numerous studies that have addressed a wide range of factors with the potential to impact on endodontic treatment outcome. Outcome studies and recent systematic reviews identified biologic- and treatment-associated variables as well as restorative factors that are the most predictive of treatment outcome for contemporary conventional endodontic therapy [4–9]. These studies applied advanced statistical methods to determine the magnitude of risk the identified variables exert on outcome [3, 10]. Therefore, prognostic factors, which can affect the outcome of endodontic therapies, are multiple and intertwined in complex relationships. An overview of these interconnected variables and their possible relationships is illustrated (Fig. 1.1).

Some prognostic factors, such as the presence and extent of periapical lesion (Fig. 1.2); the complexity of the root canal system, especially in cases with apical periodontitis (Fig. 1.3); obliterated canal(s) due to hyper-mineralization (Figs. 1.4 and 1.5); pathologic or idiopathic root resorption (Fig. 1.6); and infection-induced apical root resorption (Fig. 1.7), are not under the control of treatment providers. However, most conditions can be managed by practitioners through a systematic evaluation and risk assessment followed by application of sound biologic treatment

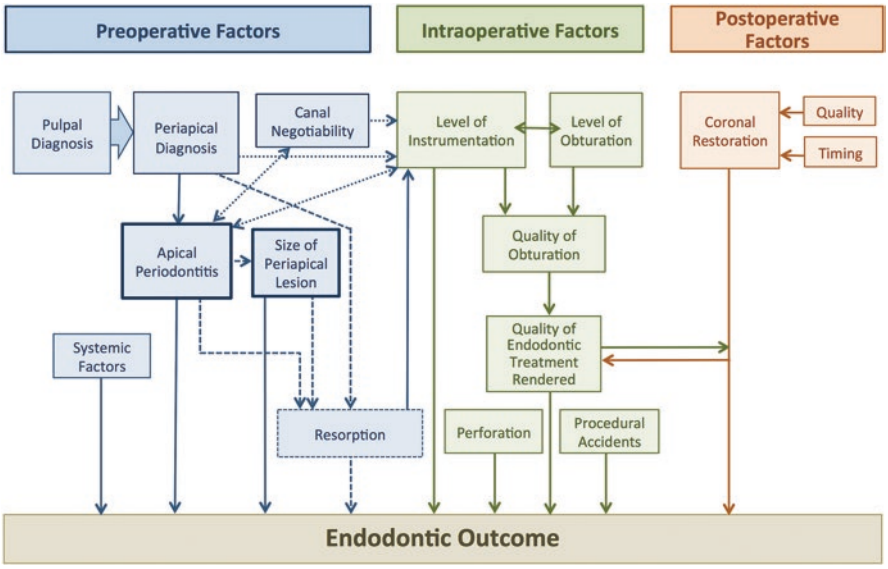

Fig. 1.1 Possible relationships between prognostic factors affecting the outcome of endodontic treatment

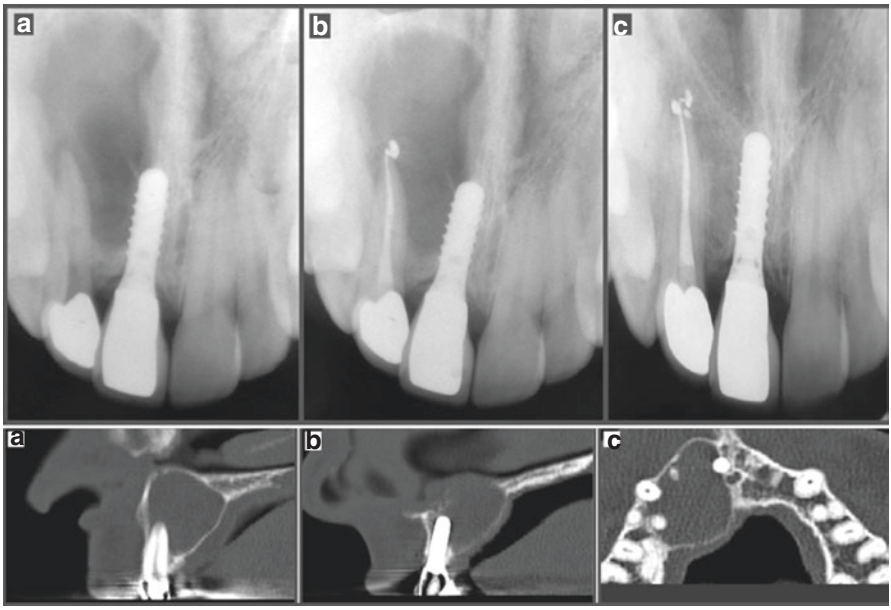

Fig. 1.2 (**a**) Occlusal radiograph showing large periradicular cyst-like lesion that extended to the floor of the nasal sinuses and along the mesial surface of the canine and the distal border of the implant in the central incisor site. (**b**) Occlusal radiograph showing the completed root filling. Some extrusion of sealer is evident. (**c**) Occlusal radiograph showing complete osseous repair consistent with favorable healing outcome.
Lower frame (**a**) Cone-beam imaging showing extent of lesion surrounding the lateral incisor. (**b**) Cone-beam imaging showing extent of lesion surrounding the implant. (**c**) Cone-beam imaging showing lesion involving the distal aspect of the implant and the roots of the lateral incisor, canine, and first premolar tooth (Images reproduced from Kahler B. Healing of a cyst-like lesion involving an implant with nonsurgical management. Journal of Endodontics 2015;41:749–752)

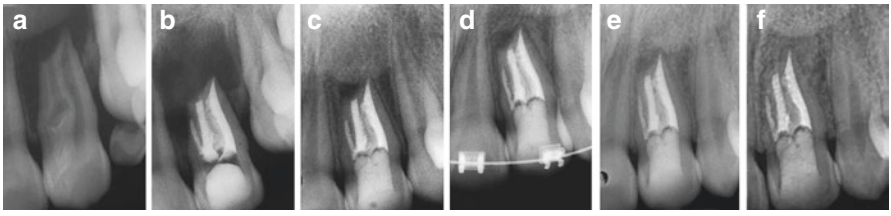

Fig. 1.3 (**a**) Preoperative radiograph of tooth #10 exhibiting complex tooth anatomy. Large periapical radiolucency is approximately 10 mm in diameter. (**b**) Completion of root canal treatment. Final radiograph after obturation shows the extent of periapical bone destruction. (**c**) A 15 month follow up radiograph prior to commencing orthodontic treatment shows significant reduction in size of periapical radiolucency. (**d**) A two year post endodontic treatment and one year in orthodontic treatment. The residual radiolucency that remains may be indicative of healing with scar formation. (**e**) A four year follow up after endodontic treatment and six months after completion of orthodontic treatment, the treatment exhibits successful outcome. (**f**) An eighteen year follow up shows normal periradicular structures (Images courtesy of Dr. Nadia Chugal)

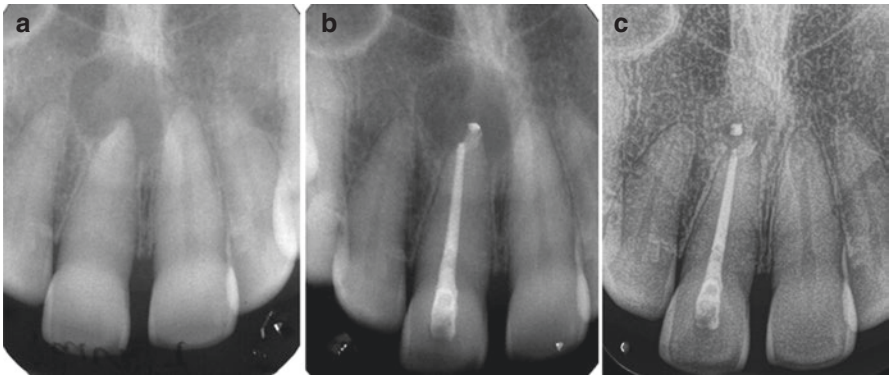

Fig. 1.4 (**a**) Radiograph of tooth #8 showing large periapical lucency and no canal is evident. (**b**) The tooth is root filled though the root filling is not centered in the root which has the potential to affect outcome. (**c**) At 18 month review the PA lucency is reduced in size and the tooth is asymptomatic. This case is an example of a 'functional outcome' as the strict Strindberg criterion has not yet been met. However further healing with time is still possible (Images courtesy of Dr. Bill Kahler)

principles and technical expertise in order to achieve an optimal treatment outcome. Often, a complex-presenting condition of the tooth comprises multiple risk factors (Fig. 1.8).

Importantly, an understanding of these high-impact factors assists practitioner's decision-making process about the appropriate treatment procedures. In addition, it also has practical implications related to treatment execution and preparation of armamentariums necessary to treat these preexisting conditions. For example, protocols may be different for immature vs. mature teeth, teeth with or without a periapical lesion, and for both nonsurgical and surgical management.

For clarity of analysis and comprehension, they can be grouped into three major categories: preoperative, intraoperative, and postoperative.

1.3 Preoperative Factors

An accurate assessment of the pulpal and periapical diagnosis is essential for an understanding of the major biological factors as this diagnosis reflects a change in the disease process and the extent of the infection into the periapical tissues [4, 6, 11, 12]. The literature is unequivocal that preoperative presence *vs.* absence of periradicular osteolysis is one major indicator of postoperative healing or failure [4, 10, 13, 14]. Consequently, teeth with a preoperative periapical lesion have a poorer outcome than teeth without a periapical lesion after nonsurgical root canal treatment [4, 7, 10, 14]. In addition, larger bone lesions show a significantly lower frequency of complete regeneration of the periapical bone than smaller lesions (4, 103). Therefore, when a periapical lesion is present, the smaller the lesion, the more favorable is the treatment prognosis [4, 10]. However, successful resolution of large

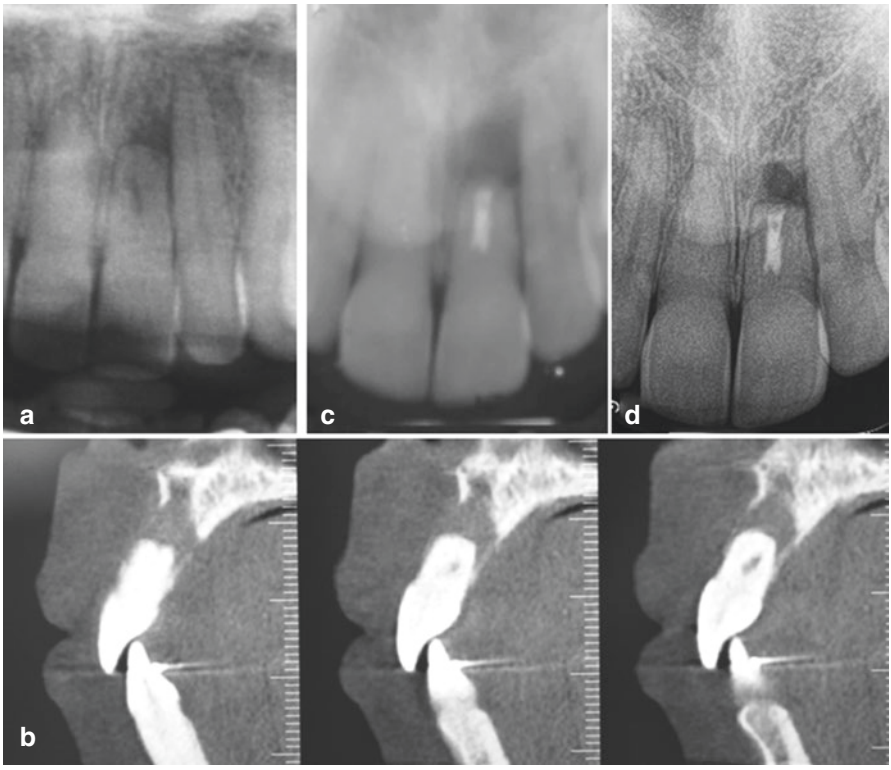

Fig. 1.5 (**a**) Radiograph of tooth #9 with a history of trauma. The root tip is blunted consistent with apical resorption. The canal appears to have undergone complete obliteration in the coronal half of the root. The canal in the apical half of the root is of an irregular shape and not centered in the root. (**b**) CBCT imaging revealed an irregular resorptive lesion in the apical half of the root. Therefore more complex imaging was advantageous as interpretation of conventional periapical radiography was suggestive of canal patency. Furthermore the extensive periapical radiolucency is revealed with erosion of the buccal and palatal cortical bone plates. After consultation with the patient it was decided that optimal treatment option was surgical management due to the prognostic considerations of calcified canal, resorptive defect in the apical third of the root and the extensive periapical radiolucency. (**c**) A radiograph taken after the surgical revision and placement of a MTA retrofill. (**d**) A radiograph at a 2 year review showing an intact lamina dura and periodontal ligament space around the root. The periapical radiolucency is consistent with a periapical scar and is a common observation following surgery when both cortical plates have been eroded (Images courtesy of Dr. Bill Kahler)

periapical radiolucencies is often achieved (Figs. 1.2 and 1.3), although the risk of future surgical treatment remains.

Teeth with a preoperative periapical lesion usually have a long-standing root canal infection compared to teeth without a periapical lesion. Therefore, these teeth have a well-established biofilm in the canal [15]. In addition, bacteria may also establish infection in some periapical lesions, resulting in an extraradicular infection [16].

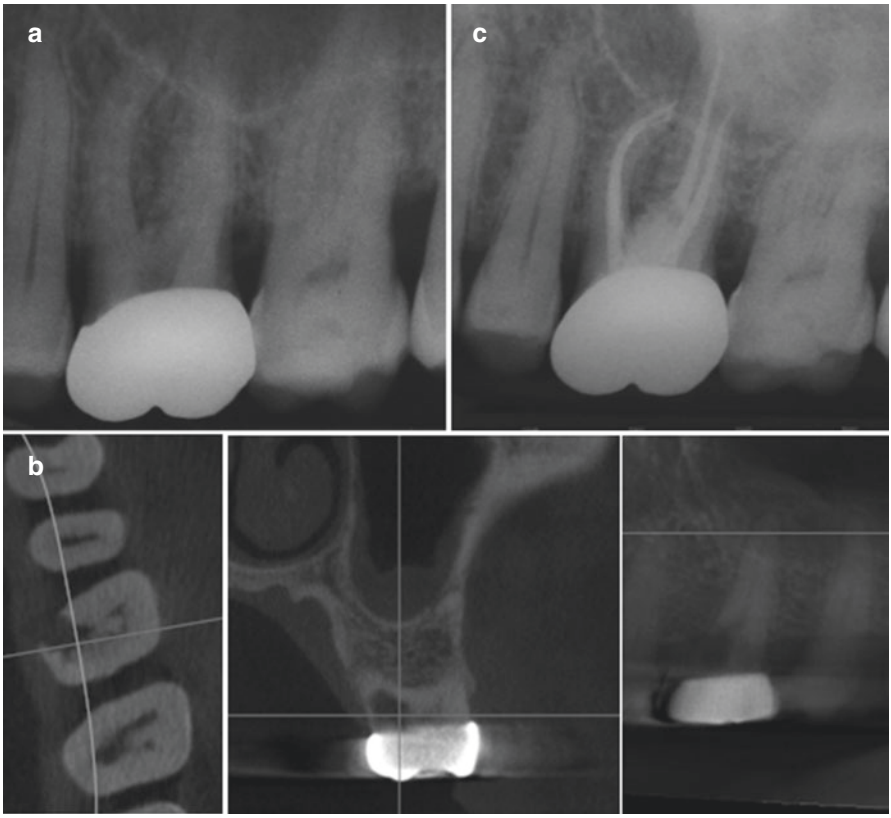

Fig. 1.6 (**a**) Preoperative periapical radiograph of symptomatic first maxillary molar where crown was placed one month earlier. (**b**) CBCT images revealed a Heithersay Grade III invasive cervical lesion highly suggestive of pulpal involvement. (**c**) Radiograph showing completed root filling and resorptive lesion filled with mineral trioxide aggregate (Images courtesy of Dr. Bill Kahler)

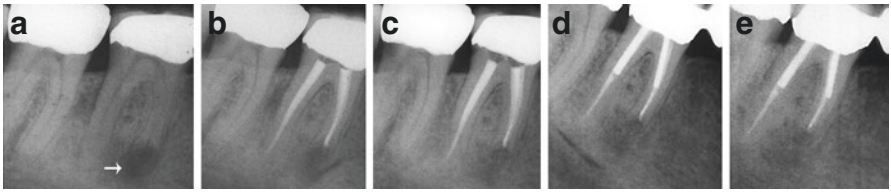

Fig. 1.7 (**a**) Pre-treatment periapical radiograph showing periapical radiolucency around the mesial root of the mandibular first molar (*white arrow*). Note external resorption of the mesial root apex. (**b**–**e**) Sequential periapical radiographs over twenty four months follow up after completion of endodontic treatment show an increase in the radiodensity of the periapical bone, although a minimal area of rarefaction remains. Further resolution of the radiolucency with time is expected and at this stage can be considered as healing and a functional outcome as the tooth is asymptomatic (Images courtesy of Dr. Nadia Chugal)

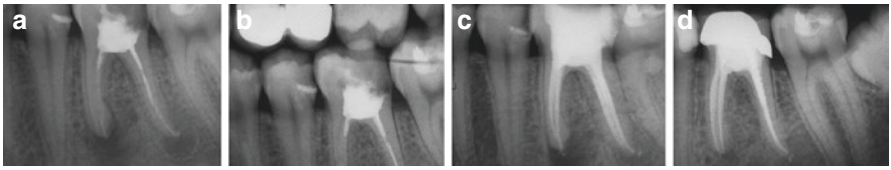

Fig. 1.8 (**a**) Preoperative periapical and (**b**) bitewing radiographs shows large periapical radiolucencies associated with mesial and distal root apices, missed and untreated canals, fractured instrument and near perforation of pulpal floor. (**c**) Completion of root canal treatment. (**d**) Nine months follow up radiograph shows significant reduction in size of periapical lesion. Further healing with time is likely. Patient remained asymptomatic and the tooth was functional (Images courtesy of Dr. Nadia Chugal)

Consequently, it would be more difficult to eliminate bacteria in the root canal system in teeth with than without a periapical lesion, thus affecting treatment outcome.

Medical conditions such as diabetes is one of the constitutive preoperative factors, negatively affecting the success of endodontic treatment of teeth with apical periodontitis [17, 18]. This is in addition to the major effect of the presence and magnitude of the infection of root canal system and structural condition of the tooth in question. The existence of these factors is usually not under the control of the practitioner.

1.4 Intraoperative Factors

Practitioners through systematic and thorough preoperative evaluation and a well-executed clinical protocol can manage most intraoperative factors, such as level of instrumentation, quality of root canal obturation, and procedural mishaps. Over-instrumentation could introduce necrotic tissue and bacteria in the root canal into the periapical tissues [19, 20]. Under-instrumentation could leave bacteria in the apical few millimeters of the root canal [21].

The level of instrumentation of root canals is important for elimination of infection and may not be the same for roots with a normal periapex or with apical periodontitis [22]. For teeth with apical periodontitis, it has been shown that one millimeter loss of working length is associated with 14% and 12% decrease in favorable outcome, respectively [10, 23].

In terms of underfilling, it should be distinguished between complete instrumentation and underfilling and incomplete instrumentation and underfilling. The former has a better outcome than the latter because of elimination of intra-canal bacteria. Inadequate root canal obturation with voids may allow coronal leakage of oral bacteria to reach the periapical tissues [24, 25]. A separated instrument or root perforation may prevent complete chemomechanical debridement of the canal system apical to the separated instrument or perforation, thus preventing effective elimination of bacteria in the root canal system and compromising the treatment outcome [26].

1.5 Postoperative Factors

Postoperative factors, such as timely placement and quality of coronal restoration of endodontically treated teeth, are under the control of the dentist and the patient. The importance of an adequate coronal restoration of endodontically treated teeth in relation to the success of root canal treatment has been demonstrated in many studies [27–30]. For the best outcome, endodontically treated teeth should have both an adequate root canal treatment and adequate coronal restoration [30]. A permanent coronal restoration is critical for prevention of reinfection and further damage to the structural integrity of the tooth [3, 9, 27, 28, 31].

1.6 Effect of Root Canal Infection on Treatment Outcome

Maximizing successful outcomes for endodontic treatment rests on the elimination of microorganisms from the infected root canals [6, 11–14] and without bacterial inoculation of the periapical tissue [19, 20]. It must be emphasized that of all prognostic factors, the reduction and/or elimination of root canal infection is the key to the successful endodontic treatment outcome [32]. The effect of residual infection on treatment results was demonstrated in human and animal studies. A clinical study of the human teeth with apical periodontitis showed that negative bacteriologic cultures before root filling resulted in 94% success rate of root canal therapy. In contrast, if bacteriologic cultures were positive, the success rate was reduced to 68% [13, 14]. An animal model study on monkeys showed that 79% of treated root canals had non-healed periapical lesions when bacteria remained after endodontic treatment, compared to 28% where no bacteria were found [33]. It was also reported that it is the presence of bacteria in the canal and not underfilling or overfilling that is the primary cause of persistent apical periodontitis of endodontically treated teeth [12]. Periapical lesions could heal even without placement of a root canal filling, if the root canal infection was effectively controlled and coronal leakage was prevented [34, 35]. Sometimes, even endodontically well-treated teeth could fail [36]. Therefore, prognostic factors have a profound effect on the control of root canal infection and subsequent treatment outcome.

1.7 Outcomes in Endodontic Therapy

Outcome is the consequence or the result of the treatment of disease, which is profoundly influenced by a multitude of prognostic factors. Outcome of endodontic therapy is usually assessed using radiographic and clinical examination. Radiographic examination is to detect the presence or absence of a periapical lesion and clinical examination for the presence or absence of symptoms/signs. Both conventional periapical radiography and cone beam computed tomography have been employed for radiographic examination in endodontics [37, 38]. Outcome assessment of endodontic therapy has evolved from Strindberg's stringent criteria

emphasizing the absence of clinical symptoms/signs and restoration of normal structure of the periapical tissues [4] to the patient-centered criteria focusing on absence of clinical symptoms/signs and survivability and functionality of endodontically treated teeth even with the presence of small and stable periapical lesions [39, 40]. However, the patient should be fully informed of the difference between disease and survival or function of a tooth. As pulpal and periapical pathosis is considered a disease, then a tooth with persistent inflammatory periapical lesion after treatment, regardless of its size, should be considered as unsuccessful elimination of the disease. Therefore, complete elimination of disease still remains the ultimate goal of root canal treatment.

There is a wide range in reported success rates of endodontic therapy [4–6]. This can be attributed to variations in criteria for outcome measures, proportion of teeth of a given type in a study, length of follow-up period, distribution of preoperative diagnoses, interoperator and inter-evaluator variability, and endodontic treatment-associated factors [4, 5, 41–43]. These variations make it difficult to make a valid comparison between the findings of different studies.

Most prognostic factors in endodontic therapy can be managed by practitioners through careful evaluation of the risk factors and execution of appropriate treatment planning. Practitioners should always perform at the best standard of care to achieve the best treatment outcome [44]. It is paramount that both the patient and practitioner have a full understanding of the prognostic factors and the risks to subsequent outcome before commencement of root canal treatment.

Conclusion

To augment understanding and effective management of prognostic factors associated with optimal outcome of endodontic treatment, individual chapters of this book are dedicated to key facets of endodontic therapy. These include the range of essential topics, from accurate diagnosis of pulpal-periapical status to pathobiology of pulpal-periapical tissues. The appropriate treatment plan for the various stages of pulpal-periapical disease and meticulous treatment procedures to eliminate root canal infection and prevent reinfection are presented. At the end, the outcome assessment of the treatment and post-treatment sequelae is presented.

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Microbiology and Immunology of Endodontic Infections

2

Luis E. Chávez de Paz and Gunnar Dahlén

Abstract

Endodontic infections are complex diseases associated with apical tissue inflammation that is determined by microbial, immunological, and environmental factors. During the past years, the integration of research tools, including molecular techniques for identification, sophisticated in vitro modeling, and human microbiome analysis, has provided additional insight in the understanding of endodontic infections. Recent studies suggest that the basis for infections associated to root canals of teeth is polymicrobial in nature and includes the emergence of microbial colonization in form of biofilms. Biofilms deep seated in areas that are difficult to reach by mechanical treatment will enhance microbial virulence, antibiotic resistance, colonization potential, and resistance. Furthermore, with the advent of the human oral microbiome project, insights on the differences among oral microfloras in different individuals appear to have an important role in progressing endodontic infections. This chapter discusses the current data regarding the role that microbial biofilms play in endodontic infections, as well as its place in the current knowledge of endodontic microbiology. The complex relations between the root canal microflora and the inflammatory response in apical periodontitis are also highlighted in this chapter, as well as their implications in regard to the diagnosis and clinical management of endodontic infections.

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2.1 The Oral and Root Canal Environments

2.1.1 The Oral Ecosystem

The oral ecosystem comprises a group of sites including the tongue, mucosa, gingival sulcus, and tooth surfaces, each of which possesses unique ecological characteristics that foster the growth of different kinds of microorganisms. The general characteristics of the oral ecosystem include a constant temperature; the presence of various soft and hard tissue surfaces to adhere, colonize, and grow; and a variable supply of soluble nutrients. Specific collections of oral bacteria, also known as oral plaque, are associated to different sites in the oral ecosystem [1,2].

2.1.2 Microbial Colonization of Tooth Surfaces

The tooth surface is an ideal site for microbial colonization, as it comprises plenty of moisture, air, and the intervallic input of nutrients during food intake [3,4]. The microbial plaque associated to the tooth surfaces is divided into supragingival and subgingival, in reference to its location from the gingival margin. The microbial composition and differences of these two types of dental plaque are principally connected to ecological changes, pH, and nutritional factors. While the nutritional sources for supragingival plaque include dietary components, saliva, and gingival crevicular fluid, the subgingival plaque depends predominately on host-derived components of crevicular fluid, which has a composition similar to serum [5].

2.1.3 Oral Health and Disease

Health of the different structures in the oral cavity is dependent on the interplay between bacteria and their microenvironments, including the participation of immunological factors such as antigens, both humoral and cellular. This ecological balance affecting oral health is of great complexity as it can also be influenced by external factors such as nutrition, habits, and the social lifestyle of each individual.

Marsh in 2003 proposed the ecological plaque hypothesis to clarify the changes in oral ecology that lead to the development of common oral diseases such as caries or periodontal disease. Caries and periodontitis occur as consequence of imbalances in the resident microflora resulting from enrichment within the microbial community of selected microorganisms that are associated with disease [6,7]. Excessive consumption of dietary fermentable carbohydrates will favor the overgrowth of highly fermentative aciduric organisms, e.g., *Streptococcus mutans* and *Lactobacillus* species. The acidified microenvironment produced by these organisms promotes the demineralization of the hydroxyapatite matrix of enamel, thus increasing the risk of dental caries. In the case of periodontal disease, lack of oral hygiene causes accumulation of dental biofilm in the subgingival sulcus, thus inducing a chronic inflammatory condition. This inflammatory process will concomitantly lead to a change of the subgingival flora favoring the increase of anaerobic proteolytic Gram-negative

bacteria and ultimately result in the destruction of the connective tissues and bone that supports the teeth [8].

2.1.4 The Root Canal Ecosystem

Unlike other sites in the oral ecosystem, the root canals of teeth are naturally sterile compartments that contain healthy dental pulp tissue. Dental pulp is a highly vascularized and innervated connective tissue that extends to the apex of the tooth. Dental pulp also contains an efficient immune system that reacts in response to microbial invasion [9–11].

Once bacteria have invaded the root canal space, they encounter with a highly controlled environment primarily affected by the presence of active inflammatory mediators. After the pulpal inflammatory barrier is defeated, a variety of environmental changes in root canals act as selective factors limiting the growth of one species relative to others [10]. The main selective factors that influence bacterial colonization and growth in root canals are pH, oxygen (redox potential), and nutrient availability. Following root canal treatment, other selective factors become involved, in particular during treatment and the short-/long-term effects of the antibacterial medicaments applied. Hence, microbial survival in root canal environments, especially after root canal treatment, is based on the capacity of organisms to adapt to the existing conditions [12]. Microbial adaptation to environmental challenges is facilitated by survival, in many cases in a dormant stage, and growth in biofilms.

2.2 Root Canal Infections

2.2.1 Pathways of Microbial Entry

The integrity of the hard tissue barriers that protect the pulp may be breached by a number of reasons. The most common microbial challenge of the pulp derives from deep carious lesions. Other routes of entry include trauma, fracture, and cracks as well as following unprotected iatrogenic exposure in mechanic dental procedures. The root canal space may be also exposed in teeth with severe periodontal disease. In the later cases, bacteria may gain access through accessory lateral and furcal canals and lastly through the apical foramen. Root resorption, root caries, and breaches in the cementum may also lead to bacterial invasion into the pulpal space [13,14].

2.2.2 Pulp Inflammatory Reaction

The pulp tissue reacts with inflammation already when the caries lesion and the bacteria reach the dentin. The bacteria and their metabolic products, such as acids, enter the dentin tubuli and have a direct communication with the pulp. At this stage the pulp executes a rapid inflammatory response that neutralizes the invasive agents and repairs the damaged tissue. However, depending on the damage caused by the offensive stimulus, e.g., an extensive caries lesion, the inflammatory response

executed by the pulp may intensify reaching up to destructive levels. The stage when the inflammatory response exceeds the limit from a reversible to an irreversible state is unknown. However, irreversibility is marked by the accumulation of mediators that ultimately lead to necrosis. These alterations in the pulp tissues may result in severe pain that could last for several days [15–17].

2.2.3 Primary Invaders

Typically, the microorganisms that are responsible for the initial inflammatory response of the vital pulp tissue are associated to the carious dentin. The flora is predominantly Gram-positive saccharolytic species, foremost *Lactobacillus* spp. and *Streptococcus* spp (*Streptococcus mutans, Streptococcus sanguinis, Streptococcus oralis, Streptococcus mitis, Streptococcus salivarius*), but also *Actinomyces*, *Propionibacterium*, *Corynebacterium*, and *Bifidobacterium* spp. are commonly present. They are acid producers (acidogenic) and acid tolerant (aciduric). These microorganisms will acquire their nutrients from the saliva through the carious lesion as well as from the exudate of the pulp.

2.2.4 Progression of the Infection

During and after necrosis of the pulp, a critical invasion of the pulp chamber and the canals will occur, with microbial invaders establishing in the necrotic mass or attached to inner dentin walls in the form of biofilms. Bacteria that progress with the invasive mass have an armamentarium of immunoevasive strategies, including the secretion of exoproducts, antibiotic-resistance proteins, and phenotypic changes, which renders them virtually invulnerable from the remaining immune response (Fig. 2.1). The physical and immunological protection provided by the biofilm structures they form is probably key in their long-term survival. After a while, an inflammatory lesion in the periapical tissues known as apical periodontitis will develop.

2.2.5 The Endodontic Pathogen

Endodontic pathogens are defined as any organism capable of inducing the tissue destruction in apical periodontitis [18]. Currently, however, there is no substantial evidence indicating that certain microorganisms of the microbial flora in root canal infections are more virulent than others. Thus, it is very hard to differentiate between simple bystanders (commensals) and those that are actively participating in the infection (true pathogens). The majority of endodontic-microbiology studies refer to the endodontic pathogen as the bacterium isolated from a symptom-associated root canal that grows in the laboratory in a specific media. By this approach, the most frequently recovered species have assumed the role of endodontic pathogen [12].

Production of specific proteases that are produced as modulators or toxins	The bacterial cell surface is modulated to avoid recognition: lipid A of LPS, carbohydrates in capsules, outer membrane proteins and by expressing adhesins & invasins
Inhibition of phagocytosis by multiple-cell clustering	Immune cells/phagocytes are directly subverted or killed by superantigens, avoidance of phagolysosomal fusion, blockage of inflammatory pathways or replication within immune cells
Interference with TLRs ligands to decrease recognition, to dampen inflammation and to inhibit downstream inflammation signaling	Blockage of antimicrobial small molecules by secretion of proteases, alteration of cell surface to avoid peptide insertion, usage of pumps to transport peptides and directly sense small molecules to trigger defence mechanisms
Blockage of acquired immunity by IgA proteases and antigen presentation	Modulation of apoptosis/autophagy by direct inhibition, activation of death signaling pathways and alteration of apoptotic signaling pathways
Production of antigenics: surface structures, pili, outer membrane proteins, LPS (hyper-variable from specie to specie)	Complement system is inhibitied by degrading proteases, capsules and long chain LPS
Inhibition of cytokines interferon/chemokines by blocking inflammatory pathways, activation of alternate pathways and secretion of degrading proteases	

Fig. 2.1 Immunoevasive strategies of bacteria

2.2.6 Polymicrobial Nature of Root Canal Infections

Based on results from traditional culture techniques, root canal infections are provoked by only few pathogens. For example, the predominance of proteolytic black-pigmented anaerobic organisms in cultures from infected root canals associated with acute symptoms and the occurrence of monocultures of *E. faecalis* in persistent root canal infections have suggested that these organisms are primary agents in such cases. However, comprehensive analyses of the root canal microbiome by using high-throughput molecular techniques have revealed that the root canals are a reservoir of previously unrecognized but clinically relevant organisms [19].

The polymicrobial nature of root canal infections was also confirmed by a number of studies using in vivo animal models [20]. In a study with monkeys, different combinations of bacteria were experimentally inoculated in root canals, and periapical lesions were induced. The teeth were treated endodontically and followed up radiographically and histologically for 2–2.5 years. In the root canals with bacteria present when the root filling was removed, 30 of the 31 canals had persisting periapical lesions.

Importantly, more of these non-healed lesions were associated with various combinations of bacterial strains, i.e., mixed infections, than single strains. Additional experiments using an "eight-strain collection" of species, derived from one infected root canal that were reinoculated in equal proportions into other monkey teeth, revealed a more potent capacity for tissue destruction than inoculations with pure cultures [20].

2.3 The Biofilm Lifestyle

The biofilm mode of growth is the preferred lifestyle of bacteria in natural and artificial settings. When bacteria in a liquid phase are in the presence of available surfaces, such as dentinal walls in the root canal of teeth, they have the affinity to adhere and form biofilms. Biofilm communities are structured and heterogeneous, matrix-encased bacterial communities where bacteria adapt their phenotype into highly resistant toward stress, host immunological defenses, and antibiotics [21,22].

2.3.1 How Bacteria Build Biofilms

There are several steps bacteria undertake to build a biofilm. First, a free-floating cell (planktonic) approaches a surface that has been pre-coated with proteins (constituting receptors) and deposits from the environment. The bacterial cell then establishes a transient association with the surface by means of Brownian motion, convective transport, and/or expression of structural elements such as fimbriae and flagella [23,24]. Within short, this cell-surface association becomes stable and starts the formation of a microcolony, either by co-adhesion with other biofilm cells or by active reproductive traits. The colony/biofilm formation is further favored by mechanical forces in areas with narrow compartments and no streaming (flow) system such as the apical labyrinth. Of importance during this phase is the expression of extracellular polymers (EPS) such as polysaccharides, proteins, nucleic acids, and phospholipids [25], which will build up the backbone of the biofilm, the matrix. Lastly, the microcolonies mature into a three-dimensional structure encased in the extracellular matrix. Occasionally, the biofilm-associated bacteria detach from the biofilm matrix. These steps in biofilm formation are shown in Fig. 2.2.

2.3.2 Biofilms Formed in Root Canals

Microorganisms in root canals have been found to colonize by adhering to dentin walls in all the extension of the root canals, such as the inner walls of complex apex anatomies and accessory canals [26,27]. In 2004, Svensater and Bergenholtz proposed a hypothesis for biofilm formation in root canals. Root canal biofilm formation is initiated directly after the first invasion of the pulp chamber by oral organisms following pulp tissue inflammatory breakdown. The inflammatory lesion frontage will then move successively toward the apex providing the fluid vehicle for the invading organisms so these can multiply and continue attaching to the root canal walls. This hypothesis has been confirmed by light microscopy observations, where

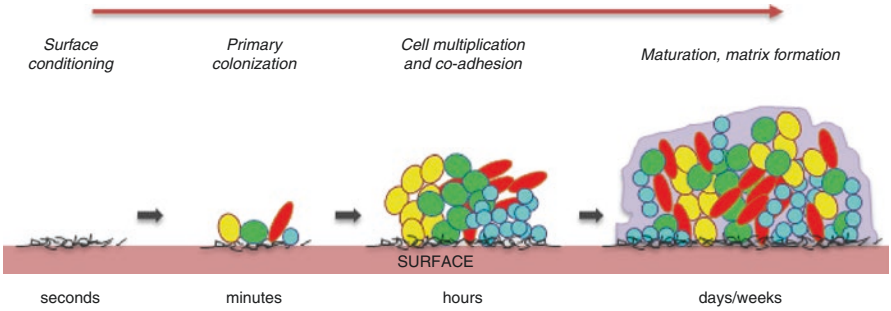

Fig. 2.2 Development of a multispecies biofilm over time. (1) Formation of conditioning film on the surface, (2) initial adherence of bacterial cells, (3) irreversible attachment and multiplication and formation of microcolonies, and (4) maturation of the biofilm, matrix formation

bacteria have been observed to detach from inner root canal surfaces and occasionally mass in the inflammatory lesion per se. This observation could explain how the inflammatory lesion would serve as a fluid source for bacterial biofilm detachment and colonization of apical areas of root canals and beyond.

2.3.3 Why Bacteria Form Biofilms

The physiology of a bacterium in planktonic culture is profoundly different from that of the same organism growing on a surface in a biofilm [28]. Planktonic bacteria are generally more sensitive to antimicrobial agents as they are in direct contact with the agent in bulk fluid. Current knowledge indicates that biofilm formation is regulated in response to environmental conditions that vary among different species. After a planktonic cell has recognized a "surface signal," a number of regulatory mechanisms take place in the cell that turn on the switch from a free-floating to a biofilm lifestyle. These regulatory mechanisms, also known as surface sensing, in many cases involve specialized outer cell membrane receptors and projections such as the bacterial flagellum [29]. This primary mechanosensory role of flagella is critical in the initial stages of the formation of a biofilm and is what triggers a cascade of intracellular events leading to the formation of the biofilm phenotype. Acquiring this biofilm phenotype will cause that bacteria are protected against antimicrobial agents mainly due to the establishment in heterogeneous populations in biofilms, with differences in growth rate and gene expression [30]. The heterogeneous nature of dental biofilms, with cooperation and selective binding of antimicrobials, further makes the biofilm a difficult therapeutic target.

2.3.4 Biofilm Resistance to Antimicrobials

Typically, the efficacy of antimicrobials in endodontics has often been based on their activity against microorganisms grown in liquid cultures in vitro. However, these test systems using planktonic cells do not represent the conditions in vivo because the microorganisms to be targeted rather than being free-floating are organized in biofilm

structures attached to the root canal walls. These microbial biofilm communities are noticeably resistant to and difficult to eradicate with antimicrobials.

The increased tolerance and resistance of biofilm cells compared to planktonics are thought to be regulated by a number of mechanisms including slow penetration of the antimicrobial agent through the biofilm, changes in the chemical microenvironment within the biofilm (leading to zones of slow or no growth), adaptive stress responses, and the presence of a small population of extremely tolerant "persister" cells [31]. These persister cells can tolerate antimicrobial agents (i.e., they are not killed) and can be considered as specialized survivors.

Studying the resistance of biofilm bacteria to antimicrobials calls for relevant in vitro models that will approximate the clinical conditions. Although the testing of antimicrobial agents against bacteria in biofilms has not been standardized, some studies have used models that include the mechanical removal of biofilm cells followed by traditional cell cultures for CFU enumeration [32,33]. Alternative approaches include the use of confocal microscopy combined with fluorescent viability staining for in situ investigation of antimicrobial effects on biofilms [34]. In a recent report, a biofilm analysis method was presented which included the assessment of both cell membrane viability and biofilm structure to assess in situ the effectiveness of antimicrobials against bacteria in biofilms. It was determined that after controlling variables such as substratum conditioning, variations of structure in biofilms and the distribution of viable cells with active metabolism could be monitored after the application of common antimicrobial agents used in the clinic [35]. NaOCl (1 %) affected the membrane integrity of all organisms tested and removed most biofilm cells. Exposure to EDTA (50 mmol/L) affected the membrane integrity in all organisms but failed to remove more than a few cells in biofilms of *E. faecalis*, *L. paracasei*, and *S. anginosus*. Chlorhexidine (2.5 %) had a mild effect on the membrane integrity of *E. faecalis* and removed only 50 % of its biofilm cells. It has to be noted that the antimicrobial effects were substratum dependent and that most organisms displayed increased resistance to the antimicrobials on collagen-coated surfaces. These findings provide further evidence that bacteria in surface-adhered biofilm monocultures have a variable resistance to antimicrobial stress, which demands for reproducible multispecies biofilm models.

2.4 Microbiological Methods Used in Endodontics

2.4.1 Microbial Identification by Culture and Molecular Methods

Conventionally, microorganisms from root canals were identified from samples obtained during endodontic treatment procedures via culture techniques that grew bacteria with improved media. Although culture techniques are laborious and require a great deal of knowledge and lab experience, accurate identification of species by means of anaerobic methods, biochemical tests and analysis for antibiotic sensitivity can be efficiently accomplished. Traditional culture-based studies have

identified an increased number of anaerobes, which in some cases they totally predominate the microbial results from teeth with primary infections.

More recently, however, molecular techniques have been applied on root canal samples [36]. Molecular techniques do not rely on culture but instead use specific probes to search for bacterial DNA and/or RNA. The principle of molecular techniques is based on targeting highly conserved DNA sequences that different species of microorganisms possess. These conserved genes, mainly the 16S rRNA gene, make molecular identification extremely accurate. A plethora of molecular methods now exist some of which can also quantify different bacterial groups, at least in relative values. Molecular studies have shown an unsuspected wide range of bacteria, including previously uncultured bacteria, for which most laboratories do not search with conventional culture. By using even more advanced methods like pyrosequencing, it has been possible also to identify a lot more species previously unknown in root canal infections. On the other hand, molecular biology methods are hampered by the fact that they do not distinguish between dead and viable bacteria. Generally, it is believed that molecular biology methods especially in teeth under treatment disclose dead bacteria or even remaining nucleic acids that are of little relevance for the infection ("false positives"). It is also important to point out that the root canal flora is highly variable depending at the stage of infection.

In conclusion, it is important to point out that both techniques are complementary to each other rather than one can substitute the other. Further clinical trials combining both techniques are granted in order to complement their results (Fig. 2.3).

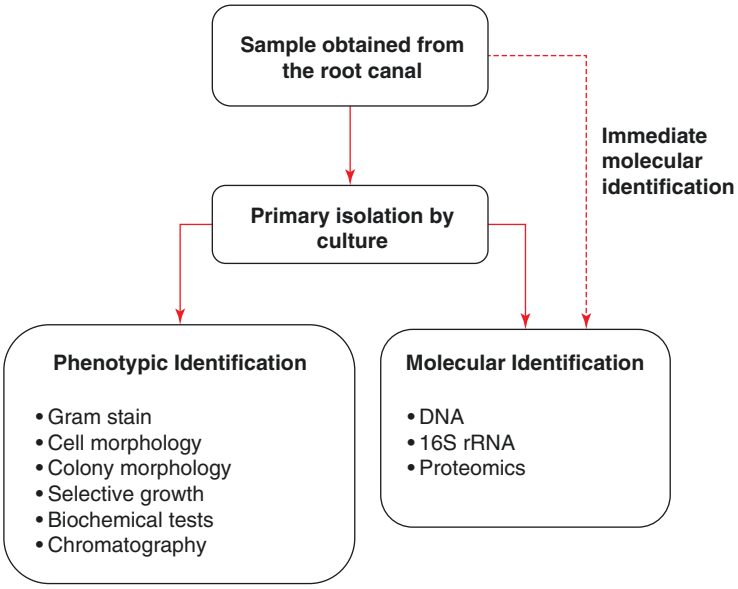

Fig. 2.3 Outline of the methods used for the isolation and identification of root canal bacteria

2.4.2 Differences in Microbial Composition

Conclusively, culture and molecular methods have determined that the root canal flora varies according to the clinical condition. It should be emphasized that even in studies using molecular biology methods, anaerobic Gram-negative bacteria such as *Porphyromonas* (*P. gingivalis, P. endodontalis*), *Prevotella* (*P. intermedia, P. nigrescens*), *Campylobacter* (*C. rectus, C. gracilis*), *Fusobacterium nucleatum*, and *Tannerella forsythia* constitute the dominating part of the microbial recovery. In addition, molecular biology methods have disclosed a number of previously unculturable bacterial species, e.g., *Treponema* (*T. denticola, T. socranskii, T. pectinovorum, T. maltophilium, T. endodontalis*), *Dialister, Megashaera, Olsenella*, and some unnamed clones of *Synergistes*.

2.4.3 In Situ Microscopy

In situ microscopy techniques are valuable tools to study microbial community structures in an undisturbed fashion [37–39]. Techniques such as scanning electron microscopy (SEM) and laser scanning microscopy (LSM) offer impressive views of the structural organization of microbial communities in three dimensions.

SEM offers impressive views of the structural organization of microbial biofilms; however, it needs careful preparation of samples that might affect the natural structure of the communities (Fig. 2.4).

LSM allows the direct analyses of biofilm communities without destructive preparation steps. LSM combines the scanning possibility of the electron microscope with simultaneous observations of organism identity (using specific hybridization probes). One of the main advantages of this technique is that it collects information from discrete points of the sample and removes the information from locations that are not in focus. Sample scanning is performed plane by plane, and it allows passing all images through image analysis. LSM gives thus a detailed and well-resolved 3D illustration of the biofilm sample (Fig. 2.5). Furthermore, information on specific structures in the community can be obtained by applying specific fluorescent markers such as those for microbial viability and metabolism.

2.5 Prognosis of Root Canal Infections

Root canal treatment aims to mechanically prepare (including widening, debridement, and cleaning) the root canal so that no necrotic tissue/bacteria remain and a proper root filling can be made. Removal of bacteria and debris is supported by irrigation of the root canal with antiseptics. The most relevant risk factor affecting prognosis of root canal treatment infections is contamination during root canal treatment in combination with a technically insufficient permanent root filling. This risk factor has been assessed in prospective microbiological studies where it was found that teeth with periapical lesions visualized on radiographs are associated

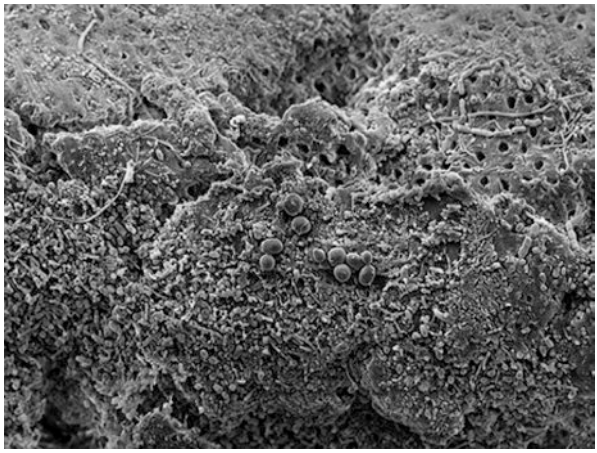

Fig. 2.4 SEM microphotography, the apical region of a tooth with chronic apical infection. An extra-radicular biofilm is observed where bacterial cells are adhered adjacent to dentinal tubuli

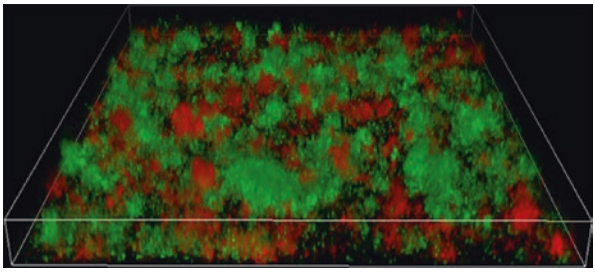

Fig. 2.5 Three-dimensional reconstruction of a biofilm section observed with the CSLM technique. Bacterial viability is analyzed by fluorescence emission where the *green* channel shows intact cytoplasmic membranes and the *red* channel shows damaged cytoplasmic membranes

with remaining bacteria in the root canals [40]. Such studies have clearly shown that the chance of healing is 2–5 times higher if the bacteria are eradicated as indicated by a no growth in a sample prior to root filling. However, if the periapical lesion persists 2 years after root filling, it is up to 4 times more likely that the root canal contained bacteria at the time of root filling. Understanding the ways in which bacteria thrive in root canal habitats after root canal treatment and their cooperative strategies for surviving stress, such as nutrient deprivation, can shed light on chronic apical periodontitis pathogenesis. This may translate into progress in predicting persistent infections and portray biofilm communities as key players in chronic endodontic infections.

2.5.1 Where Are Bacteria Located After Treatment

Bacteria may survive in root canal systems by invading dentinal tubuli along the root canal wall. Although their elimination from these microscopic areas seems very difficult, it is questionable whether these bacteria are necessary to eradicate. The

common view is that if they are not properly removed from the tubuli, they could be entombed with a proper root filling and they may not have any significant implication on the periapical tissues.

Another possible location for remaining bacteria is in complex apical labyrinth. Areas such as apical deltas and lateral canals constitute regions that are extremely difficult to reach by antiseptic measures. Bacteria located in complex anatomies may provoke inflammation even after a permanent root filling has been performed. The extent of inflammation is related to the degree of communication and the complexity of the apical anatomy. In older teeth there is little communication and space, and the remaining bacteria can live there for years without doing much harm but maintain an inflammatory reaction to some degree. Whether these bacteria should be removed is a matter of academic discussion, and a clear consensus has not been reached at present.

It is also possible that persistent bacteria are located on the apical root surface and in root resoptions/lacunae. These bacteria cannot be reached with the antibacterial efforts made through the root canal. They are complicated to sample, and this condition is difficult to diagnose clinically. Apical surgery may be an option to eliminate these bacteria.

2.5.2 How Bacteria Survive Root Canal Treatment

Persistent biofilm bacterial infections with dormant or/and bacteria in low metabolic activity are implicated in the failure of root canal treatments. Biofilm bacteria in dormant or low metabolic states, which remain in the root canal system despite the antimicrobial efforts to remove them, are implicated in most of these persistent infections. Dissemination of bacterial biofilms beyond the apical limits induces chronic immunological responses and in some cases bacteremia through the surrounding tissues.

2.5.3 Most Resistant Species

One of the most persistent bacterial species is *Enterococcus faecalis*. This organism has been isolated, usually as monocultures, from cases with refractory root canal infections [41,42]. *E. faecalis* has been found to be extremely resistant to various antimicrobial measures (chemical and physical) and to have an innate mechanism to thrive in alkaline environments, e.g., the high tolerance against CaOH [43]. Enterococcal species are intermittently present in low numbers in the oral flora in most humans, and with other oral bacteria, they invade together the infected root canal. It is seldom identified among other bacteria in the primary infected necrotic root canal but is selected during treatment. The virulence and ability to cause exacerbations are probably low. Other Gram-positive species have been also found persisting in root-filled teeth. *Streptococcus*, *Lactobacillus* and *Actinomyces* spp., which are mainly commensal organisms from the oral cavity, have been isolated

from persistent root canal infections [12,41,42]. In vitro studies with these Gram-positive organisms found that their resistant capacities to stress conditions, such as alkaline, are very similar to those of *Enterococci* while forming biofilms.

2.5.4 The Chronic Inflammatory Response

The most characteristic histological pattern of a chronic inflammatory response is formation of a granulation tissue with a predominant infiltration of lymphocytes and plasma cells. The granulation tissue forms a barrier against further invasion of bacteria, and the risk of spreading from these lesions is low. Most root canal infections develop directly into this chronic phase when the infection front line reaches the periapical tissues. The communication between the root canal and the periapical tissues is probably the most common factor on how to decide whether the infection will take an acute or a chronic route. The chronic periapical inflammation is also characterized by showing few symptoms. In fact, most of these lesions are not perceptible to the patients themselves, but the dentist may disclose the lesion on radiographs.

2.6 Concluding Remarks

- Bacteria in root canals are established as multicellular biofilm communities, which respond and adapt collectively to survive environmental stress and antimicrobial treatment.
- Infected root canals containing necrotic tissues provide a selective environment with limited oxygen and fluctuating nutrient availability, in which certain oral bacteria may survive and grow.
- Mechanical endodontic treatment including irrigation with antimicrobials and filling with cement and gutta-percha will further select for resistant bacteria. The degrees to which root canal bacteria tolerate these endodontic clinical procedures determine their persistence and are the main cause of chronic inflammatory lesions.
- The establishment of multispecies biofilm communities in root canals expands the overall potential for survival of individual species.
- The pathogenic potential of bacteria in biofilms is determined by intercellular interactions, and the establishment of heterogeneous subpopulations where signal molecules triggered in response to environmental factors plays a key role.
- Finally, the role of bacteria in apical periodontitis relies on the interactions between species and their microenvironment. All species, whether pathogenic or not, will potentiate their resistance capabilities within complex biofilm communities. Deepening our understanding on the mechanisms controlling these interactions is vital to clarify the resistance of root canal bacteria to antimicrobial agents and to open up for new opportunities for the control and treatment of these biofilm infections.

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Diagnosis of Pulpal and Periradicular Disease

3

Katsushi Okazaki, Matthew Malek, Nadia Chugal, and Louis M. Lin

Abstract

Arriving at an accurate diagnosis is essential for the development of an optimal treatment plan and making a proper treatment decision. It is important to distinguish between diagnostic entities, such as reversible and irreversible pulpitis and pulp necrosis. Differentiating between these diagnoses will enable the clinician to plan on a specific course of treatment, be it stepwise caries excavation, pulpotomy, or root canal treatment. This is also important for the assessment of prognosis of the proposed treatment. Large number of studies have demonstrated less optimal prognosis for teeth with pulp necrosis and apical periodontitis, compared to teeth with irreversible pulpitis and without apical periodontitis. Teeth with necrotic pulps and apical periodontitis have well-established infection in the root canal system and require more aggressive root canal infection control protocol. Based on the findings from the prognosis studies, it is essential that a treating dentist be a good diagnostician in order to render appropriate treatment with optimal outcome.

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3.1 Introduction

Correct diagnosis of pulpal-periapical disease determines the appropriate treatment plan, which could lead to predictable prognosis and outcome of the therapy. Diagnosis of pulpal-periapical disease is a complex process and is usually based on several factors, such as chief complaint, medical history, dental history, clinical examination, diagnostic tests, and radiographic examination.

Diagnosis of pulpal-periapical disease made clinically is a provisional or clinical diagnosis. The diagnosis based on histological examination is a final diagnosis and is used to confirm clinical diagnosis. Therefore, clinical diagnosis does not carry a high level of accuracy, when compared to the gold standard – histological examination. Pulpal disease is different from many other diseases in the human body. Biopsy can be performed in many diseased organs to obtain a definitive diagnosis. However, histological examination cannot be carried out to determine the definitive diagnosis of pulpal disease before deciding the treatment plan. In addition, unlike medicine, sophisticated molecular biology technology and other advanced technologies are not available in endodontics to help diagnose the true state of the pulpal-periapical disease. Therefore, under clinical conditions, when making a diagnosis of pulpal-periapical disease, all available information and tests should be employed to reduce the possibility of false-positive or false-negative error and to arrive at the evidence-based best clinical diagnosis.

3.2 Diagnosis of Pulpal Disease

3.2.1 Chief Complaint (CC)

Chief complaint is a subjective statement made by a patient describing the most significant or serious symptoms or signs of illness or dysfunction that caused him or her to seek health care. The patient's chief complaint should be carefully evaluated. Chronological history of chief complaint is important and should be noted.

3.2.2 Medical History

Any medical history related to dental disease or treatment must be recorded, such as cardiovascular disease, renal disease, liver disease, hematologic disease, immune-compromised disease, and neoplastic disease. Peripheral neuropathy of diabetes mellitus may mimic toothache.

3.2.3 Dental History

Dental history gives important information concerning what is happening or happened to the suspected tooth. Did the suspected tooth have history of trauma and what kind of trauma? When and where did the trauma occur? How did the suspected tooth

respond to trauma? The traumatized teeth may temporarily lose sensibility to pulp tests; however, the sensibility may return within the first 2 months [1, 2]. Therefore a long-term follow-up is necessary to determine the sensibility of the teeth after traumatic injury [1, 2]. Did the suspected tooth have operative procedures performed and what kind of procedure? When was the operative procedure performed? How did the suspected tooth respond to operative procedure? The operated tooth may be sensible to thermal stimuli or EPT immediately after operative procedures and then return to normal response gradually. If the sensibility of the operated tooth continues to persist, it may indicate pulp injury [3]. Does the suspected tooth have symptom of pain? When did the symptom first occur? What are the nature, intensity, and duration of the symptom? Can anything provoke or reproduce the symptoms?

3.2.4 Clinical Examination

3.2.4.1 Extraoral Examination

Extraoral examination includes but is not limited to evaluation of facial swelling, sinus tract, and cervical or submandibular lymphadenopathy. All these signs are indications of infection. The source of infection should be determined.

3.2.4.2 Intraoral Examination

Intraoral examination includes evaluation of hard and soft tissues and suspected tooth/teeth. Swelling and sinus tract should be noted. Draining sinus tract should be traced with gutta-percha point to its origin. Caries, discoloration, periodontal condition, and fracture or crack of the suspected tooth must be inspected. Types of restoration or defective restorations of the suspected tooth also have to be examined. Sensibility to palpation and/or percussion is an indicator of apical periodontitis of the suspected tooth. Mobility may be due to periodontal disease, root fracture, or apical periodontitis. Transillumination can be used to detect cracks or fractures of the crown. Caries may or may not cause painful pulpitis [4].

3.2.4.3 Diagnostic Pulp Tests

Cold, heat, and low-voltage electric current are used clinically as diagnostic tests of the pulpal-periapical disease. These tests aim to assess the physiological function of the sensory nerve fibers rather than the vitality of the pulp. The vitality of the pulp is determined by the physiological function of blood supply. Pulp tests are also used to reproduce symptoms, which the patient is or was experiencing.

The dental pulp is innervated by A- and C-type sensory nerve fibers [5, 6]. A-δ and A-β fibers are located around the odontoblast layer and C fibers in the pulp proper. A-δ fibers have a low-threshold for activation. When stimulated, a sharp and stabbing pain is induced and lasts few seconds and is related to dentin sensibility [6]. C fibers have a high-threshold for activation. When stimulated, a dull and lingering pain is induced and may last several minutes [6]. C fiber activation is considered related to pulpal inflammation. The physiological function of A-β fibers is not well defined.

Cold test most frequently used is Endo-Ice (tetra-fluoroethane). It has temperature of about −26.2 °C (Figs. 3.1 and 3.2). Other cold tests include CO_2 snow and

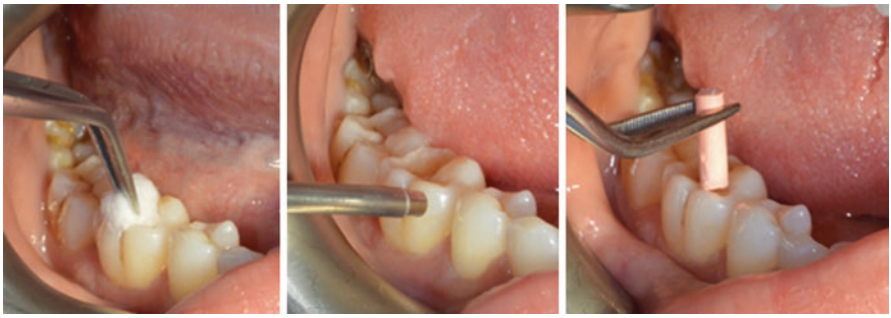

Fig. 3.1 Performing the cold test, EPT, and heat test

Fig. 3.2 Devices or material used for pulp tests

ethyl chloride. Heated gutta-percha is employed as heat test and its temperature varies (Figs. 3.1 and 3.2). The pluggers of System B unit can also be used as heat test (Fig. 3.2). The temperature of System B can be set at desirable temperature. For electric pulp test (EPT), the electric pulp tester is used (Figs. 3.1 and 3.2).

Test Site

It is recommended that the cotton pellet with refrigerate spray for cold test and the probe of electric pulp tester for EPT should be applied to the cusp of the tooth, where the density of nerve fibers is the highest. For the heat test, it is suggested that the heated gutta-percha or plugger of System B should be applied to the cervical area of the tooth. In this area the tooth surface is closest to the pulp cavity and the enamel is thinnest. Pulp tests of the tooth with full-crown coverage can present a diagnostic challenge. The tooth with full-crown coverage can be isolated with the rubber dam. An irrigation syringe is filled with a cold or hot liquid, and the liquid is then expressed from the syringe onto the isolated tooth. For EPT, the tip of

endodontic explorer is placed in contact with the natural tooth structure, and the tip of the electric pulp tester probe is then placed in contact with the side of the endodontic explorer to complete the electric circuit. For all pulp tests, it is recommended to use the teeth without caries and/or restoration on the contralateral side as controls. The pulp tests should be performed several times to confirm the reproducibility.

Thermal Tests Interpretation

It is believed that if the sensibility of the suspected tooth is felt but disappears in few seconds after removal of cold or heat stimulus, the pulp is healthy. However, if the sensibility of the suspected tooth continues to persist for several minutes or intensifies after removal of cold or heat stimulus, the pulp is considered to be inflamed. Abnormal response may also occur as soon as the stimulus is placed on the suspected tooth and the patient immediately feels range of sensation, from moderate to excruciating pain. No response of the suspected tooth to cold or heat test is considered to be the confirmatory test that the pulp is necrotic. If the pulp is inflamed, the suspected tooth will be more sensitive to thermal stimuli, compared to normal (control) teeth, because the inflammatory mediators sensitize the pulp sensory nerve fibers [7].

Electric Pulp Test (EPT) Interpretation

The response of the suspected tooth to EPT only indicates presence of viable sensory nerve fibers in the pulp and does not give any information about the blood supply or health status of the pulp. The numerical readings on the electric pulp tester cannot be used to differentiate the pathological status of the pulp, for example, reversible or irreversible pulpitis. EPT is most useful to determine the necrosis of the pulp when no response is obtained to electric current. Similar to thermal test, if the pulp is inflamed, the suspected tooth can be more sensitive to EPT and respond at lower values, compared to normal (control) teeth, because inflammatory mediators sensitize the sensory nerve fibers [7]

Reliability of Pulp Tests

To determine the reliability of pulp tests, a study was performed to evaluate the sensitivity, specificity, and positive and negative predictive values of pulp tests [8]. The sensitivity value indicates the ability of a test to identify the disease, i.e., that the pulp of the tooth is necrotic. The specificity value implies the ability of a test to identify the absence of the disease, i.e., that the pulp of the tooth is vital [8]. The positive predictive value (PPV) of the pulp tests is the probability that tooth without a sensitive response (a positive test result) indicates a diseased tooth (necrotic pulp). The negative predictive value (NPV) is the probability that a tooth with a sensitive response (negative test result) is free from disease (vital pulp) [8]. Sensitivity, specificity, PPV, and NPV are shown in Fig. 3.3.

The test with the highest sensitivity value of all pulp tests is cold test (Fig. 3.3). The sensitivity of 88% to cold test means that the probability of pulp necrosis is 88% (Fig. 3.3). The remaining 12% of cases may have no reaction to cold test

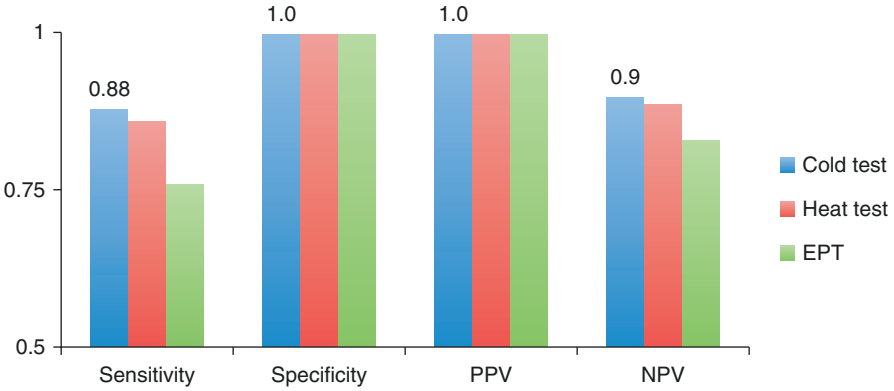

Fig. 3.3 Sensitivity, specificity, PPV, and NPV of pulp tests

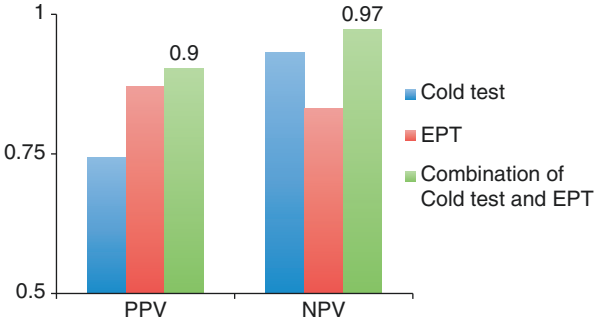

Fig. 3.4 PPV and NPV of the combination of cold and electric pulp tests

because of the other reasons, for example, calcification of the canal space. The specificity of 100% to cold test means that the probability of vital pulp is 100% (Fig. 3.3). The NPV of cold test is 90%; this indicates the probability of 90% that the dental pulp with a sensibility response to cold test is vital (Fig. 3.3). The PPV of cold test is 100%; this indicates the probability of 100% that the dental pulp without a sensibility response to cold test is necrotic (Fig. 3.3). The NPV and PPV of the heat test are 89% and 100%, respectively. For the EPT, NPV and PPV are 83% and 100%, respectively (Fig. 3.3).

A clinical study reported on the reliability of the combination of two commonly used diagnostic pulp tests as well as their PPV and NPV [9]. The NPV and PPV of the combination of cold test and EPT were reported as 97% and 90%, respectively (Fig. 3.4).

The combination of cold test and EPT has a higher reliability to detect vital pulp than if only one test is used. Yet 3% of the teeth may still have risk of pulp necrosis based on 97% NPV (Fig. 3.4). On the other hand, 10% of teeth may potentially have vital pulp and may be subjected to unnecessary treatment based on 90% PPV (Fig. 3.4). Combination diagnostic pulp tests using cold and EPT is more reliable to

predict if the pulp is vital, based on the probability of NPV than it is to predict if the pulp is necrotic, based on the probability of PPV [9].

Correlation of Clinical Signs/Symptoms, Diagnostic Data, and Actual Histological Status of the Pulp

Signs of swelling, sinus tract, as well as symptoms of pain can be related to the pulpal-periapical disease. However, the correlation of clinical signs/symptoms and actual histological status of the pulp appears to be poor [10–12]. Recently, one study indicated that the correlation of clinical and histological diagnosis of irreversible pulpitis could be as high as 84.4% [13]. This discrepancy can be due to the definition of histological criteria of reversible and irreversible pulpitis. The correlation of diagnostic data such as thermal and electric current tests and the actual histological status of the pulp is also poor [10–12].

3.2.5 Radiographic Examination

3.2.5.1 Conventional Intraoral Radiography

Conventional radiography is a two-dimensional view of a three-dimensional structure. Conventional radiography can be used to detect dental caries, restorations, calcification of the pulp chamber and root canal, or external and internal root resorptions of the suspected tooth. However, conventional radiography is not able to detect pulp disease.

3.2.5.2 Cone Beam Computed Tomography (CBCT)

CBCT is able to generate accurate three-dimensional images by means of axial, sagittal, and coronal views of the tooth structure. It is the most advanced clinical contemporary imaging technique available in addition to the conventional radiography. It is an excellent technique for detecting extra canals, root fractures, internal or external root resorptions, and displacement (axial or lateral) of the suspected tooth (Fig. 3.5).

3.2.6 Clinical Diagnostic Terminology of Pulpal Disease

The clinical diagnostic terminology of the pulpal disease is adapted from the American Association of Endodontics (AAE) Consensus Conference Recommended Diagnostic Terminology (2009) [14] (see Table 3.1).

3.3 Diagnosis of Periapical Disease

Diagnosis of periapical disease is based on the results of multiple tests: (1) pulp tests; (2) periapical tests, such as percussion, palpation, and bite tests; (3) periodontal examination that include periodontal probing and mobility; (4) special tests such

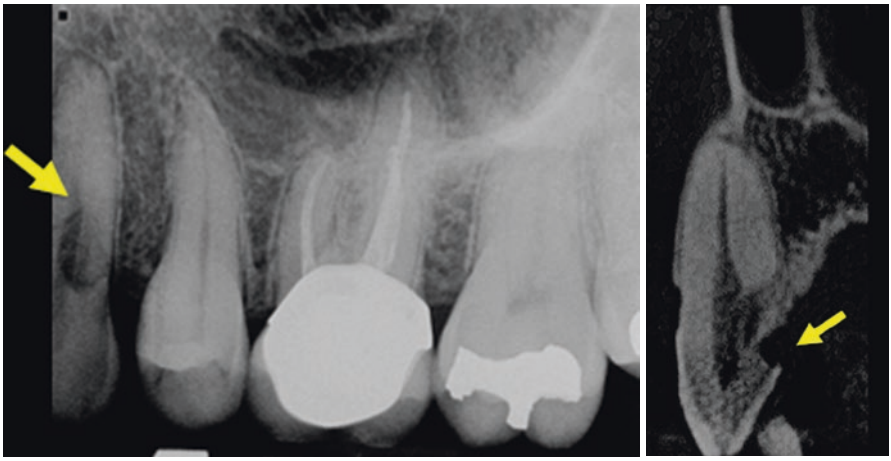

Fig. 3.5 Radiographic presentation of external cervical root resorption by conventional radiography and CBCT (Courtesy of Dr. K. Okazaki)

Table 3.1 Clinical diagnostic terminology of pulp disease

Pulpal	
Normal pulp	A clinical diagnostic category in which the pulp is symptom-free and normally responsive to pulp testing
Reversible pulpitis	A clinical diagnosis based on subjective and objective findings indicating that the inflammation should resolve and the pulp return to normal
Symptomatic irreversible pulpitis	A clinical diagnosis based on subjective and objective findings indicating that the vital inflamed pulp is incapable of healing. Additional descriptors: lingering thermal pain, spontaneous pain, referred pain
Asymptomatic irreversible pulpitis	A clinical diagnosis based on subjective and objective findings indicating that the vital inflamed pulp is incapable of healing. Additional descriptors: no clinical symptoms but inflammation produced by caries, caries excavation, trauma
Pulp necrosis	A clinical diagnostic category indicating death of the dental pulp. The pulp is usually nonresponsive to pulp testing
Previously treated	A clinical diagnostic category indicating that the tooth has been endodontically treated and the canals are obturated with various filling materials other than intracanal medicaments
Previously initiated therapy	A clinical diagnostic category indicating that the tooth has been previously treated by partial endodontic therapy (e.g., pulpotomy, pulpectomy)

Reproduced from AAE Consensus conference recommended diagnostic terminology AAE Consensus conference recommended diagnostic terminology. J Endod 2009; 35: 1634.

as transillumination and tooth sloth; (5) clinical examination of swelling or draining sinus tract; and (6) radiographic examination of the suspected tooth/teeth.

3.3.1 Pulp Tests

Tooth with apical periodontitis usually does not respond to thermal tests or EPT. However, in certain conditions, for example, if an immature tooth still contains inflamed, vital pulp tissue in the apical portion of the canal or if a multi-rooted tooth has vital pulp tissue remaining in one of the canals, the tooth with apical periodontitis may respond positively to thermal test or EPT.

3.3.2 Periapical Tests

3.3.2.1 Percussion

Percussion test is conducted with the flat portion of the dental instrument to tap the tooth edge or the cusp. Percussion test evaluates whether the type and the magnitude of sensibility caused by the percussion of the suspected tooth are the same, compared to the adjacent or contralateral normal teeth (control).

3.3.2.2 Palpation

Palpation test employs digital palpation with a finger to examine the swelling or tenderness of periosteum in the periapical area of the suspected tooth.

Abnormal tenderness to percussion or palpation of suspected tooth is an indication of apical periodontitis, which implies inflammatory involvement of the apical periodontal tissues. However, not all teeth with apical periodontitis are tender to percussion or palpation; for example, teeth with long-standing chronic periapical inflammation may not be tender to percussion or palpation.

3.3.2.3 Swelling or Draining Sinus Track

Swelling in the periapical area of the suspected tooth is the result of acute exacerbation of chronic apical periodontitis or acute apical abscess. Draining sinus track associated with the suspected tooth is usually the result of chronic apical abscess. Sinus track should be traced with a gutta-percha point to the suspected tooth.

3.3.3 Radiographic Examination

3.3.3.1 Conventional Intraoral Radiography

Periapical bone destruction is the hallmark of the tooth with apical periodontitis. This bone destruction may be detectable by conventional radiographs. Therefore, radiographic examination is invaluable in diagnosing apical periodontitis. It has been shown that osteolytic periapical lesion located in the cancellous bone will not be easily detected on a conventional periapical radiograph. However, if the

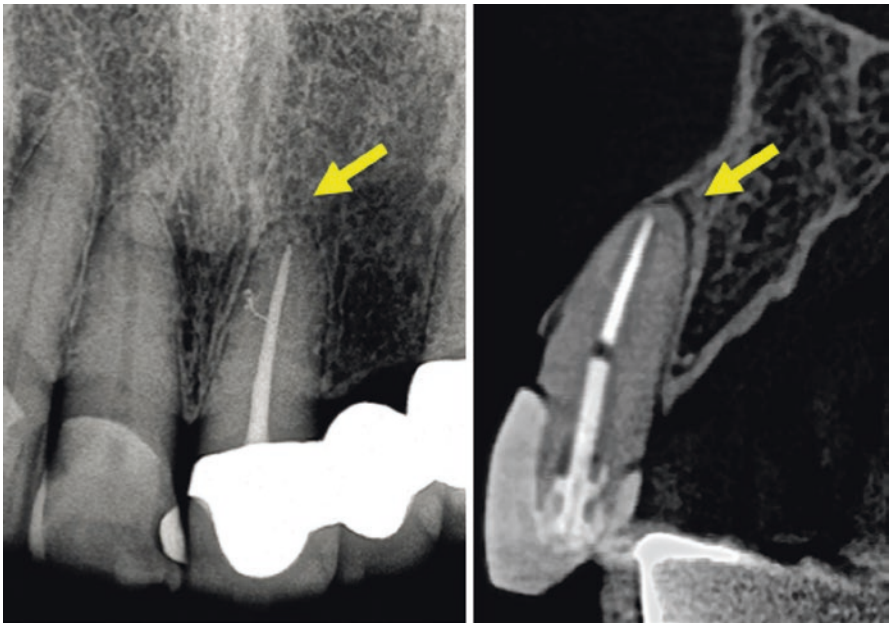

Fig. 3.6 Comparison of periapical radiograph (*PA*) and CBCT images efficacy to detect the osteolytic periapical lesion (Courtesy of Dr. K. Okazaki)

osteolytic lesion extends to the junction of cancellous and cortical bone, the lesion will be observed by conventional radiographs [15, 16]. The radiographic appearance of osteolytic periapical lesion is related to its relationship to the thickness of cortical and cancellous bone [15]. Most anterior and premolar teeth are located close to the junction of cancellous and cortical bone as compared to molars. Therefore, the osteolytic periapical lesions associated with anterior and premolar teeth are easier to detect than those of molars. It is important not to exclude the possibility of apical periodontitis even though there is no radiographic evidence of periapical bone destruction, especially in molar teeth.

3.3.3.2 Cone Beam Computed Tomography

CBCT has been shown to be superior to conventional radiography in detecting the periapical bone destruction in apical periodontitis [17–21]. Some of periapical lesions may not be detected with conventional radiography but can be observed with CBCT (Fig. 3.6), and some may appear much smaller on periapical radiographs than on the CBCT scans (Figs. 3.7 and 3.8).Another advantage of CBCT is that it can provide three-dimensional images of the lesions by means of axial, sagittal, and coronal views. According to recent systemic reviews, the level of diagnostic efficacy of CBCT in endodontics is low. The CBCT is used mainly because of its technical characteristics or the accuracy of its imaging [22, 23].

In addition to being superior in detecting periapical lesions, CBCT scans offer unique advantage to detect canals that cannot be visualized on periapical radiographs.

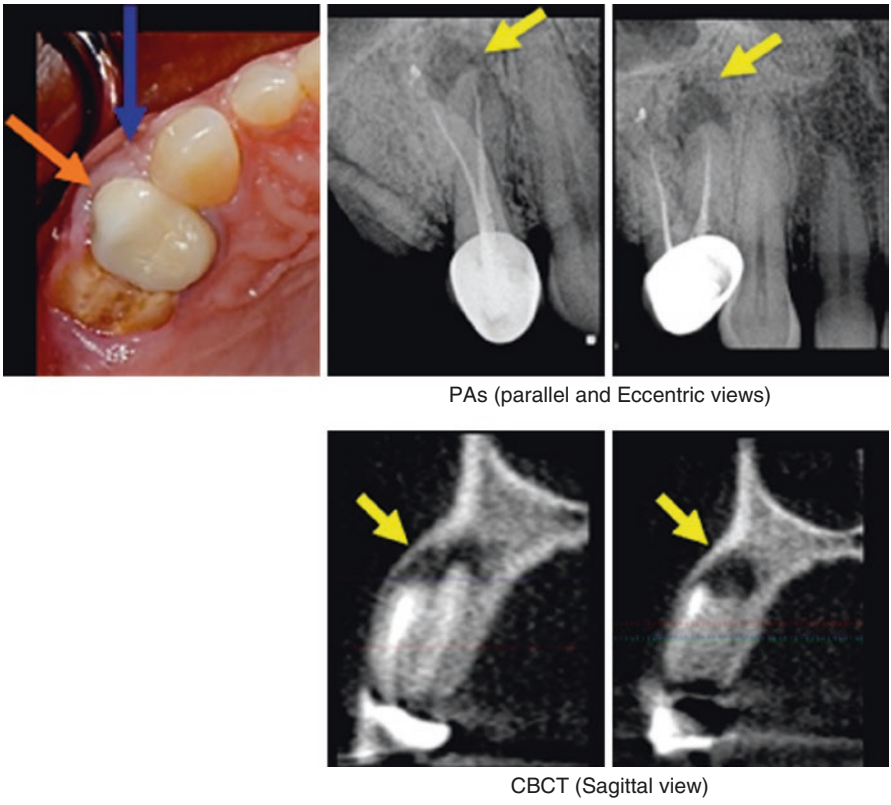

Fig. 3.7 Comparison of conventional radiograph and CBCT to detect the size of osteolytic periapical lesion (Courtesy of Dr. K. Okazaki)

Currently, CBCT is not recommended for routine use for diagnosing the pulpal-periapical disease, because of the concern of radiation to the patients. The ionizing radiation dose of one intraoral radiograph is 1–8 uS, for one panoramic radiograph is 4–30 *u*Sv, and for one CBCT is 34–652 *u*Sv [24]. The joint statement of the American Association of Endodontists and the American Academy of Oral and Maxillofacial Radiology indicates that CBCT should be limited to the assessment and treatment of complex endodontic conditions and should be considered an adjunct to two-dimensional imaging in dentistry [25].

3.3.4 Clinical Diagnostic Terminology of Periapical Disease

The diagnostic terminology of periapical disease is adapted from American Association of Endodontics (AAE) Consensus Conference Recommended Diagnostic Terminology, 2009 [14] (see Table 3.2).

In addition, if the tooth has previous endodontic therapy and the periapical lesion persists or enlarges or new lesion develops, the following terms, such as previously

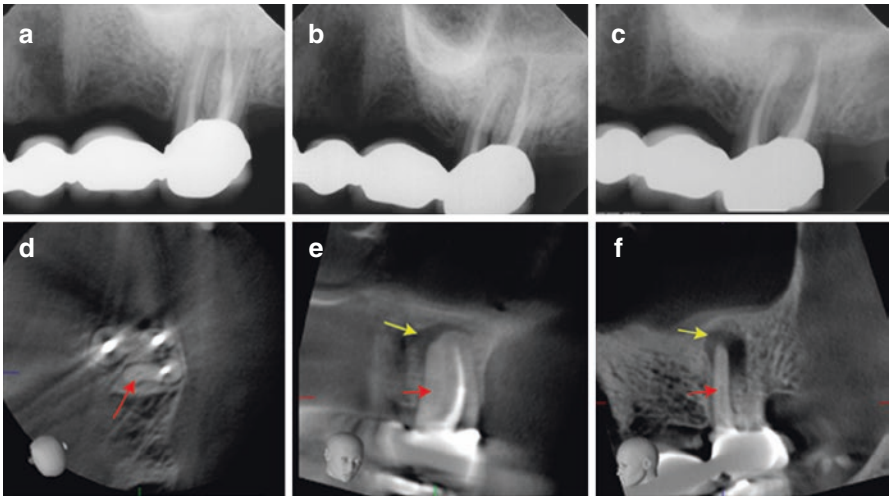

Fig. 3.8 Comparison of conventional radiographs and CBCT to detect the size of osteolytic periapical lesion and missed anatomy. Periapical radiographs (**a**, **b**, **c**) were performed at different angles, but none revealed the presence of an unfilled MB2 canal. CBCT scan revealed the presence of untreated and unfilled MB2 in axial, coronal, and sagittal views (*red arrows* (**d**, **e**, **f**)). The periapical bone destruction appears more extensive on the CBCT scan than on the periapical radiographs (*yellow arrows* (**e**, **f**)) (Courtesy of Dr. N. Chugal and Dr. S. Tetradis)

Table 3.2 Clinical diagnostic terminology of periapical disease

Apical	
Normal apical tissues	Teeth with normal periradicular tissues that are not sensitive to percussion or palpation testing. The lamina dura surrounding the root is intact, and the periodontal ligament space is uniform
Symptomatic apical periodontitis	Inflammation, usually of the apical periodontium, producing clinical symptoms including a painful response to biting and/or percussion or palpation. It might or might not be associated with an apical radiolucent area
Asymptomatic apical periodontitis	Inflammation and destruction of apical periodontium that is of pulpal origin appears as an apical radiolucent area and does not produce clinical symptoms
Acute apical abscess	An inflammatory reaction to pulpal infection and necrosis characterized by rapid onset, spontaneous pain, tenderness of the tooth to pressure, pus formation, and swelling of associated tissues
Chronic apical abscess	An inflammatory reaction to pulpal infection and necrosis characterized by gradual onset, little or no discomfort, and the intermittent discharge of pus through an associated sinus tract
Condensing osteitis	Diffuse radiopaque lesion representing a localized bony reaction to a low-grade inflammatory stimulus, usually seen at the apex of tooth

Reproduced from AAE Consensus conference recommended diagnostic terminology AAE Consensus conference recommended diagnostic terminology. J Endod 2009; 35: 1634

endodontically treated asymptomatic or symptomatic apical periodontitis or acute or chronic posttreatment apical abscess, are used.

3.4 Endodontic Prognosis and Pulpal-Periapical Disease

Teeth diagnosed with preoperative irreversible pulpitis have the best prognosis after root canal therapy [26]. Necrotic teeth without preoperative apical periodontitis have better prognosis than with preoperative apical periodontitis [26]. Therefore, it behooves a clinician to develop excellent diagnostic skills in order to detect and treat pulpal disease in its earlier stages. If irreversible pulpitis is detected, the tooth should be treated endodontically to prevent development of apical periodontitis, which is associated with poorer treatment outcome.

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Endodontic Treatment of Mature Teeth

4

Louis M. Lin, Simona Loghin, and Domenico Ricucci

Abstract

Pulpal-periapical disease can be caused by carious infection or traumatic injury. However, carious infection is the primary etiology of pulpal and periapical disease. When caries involves the irritation dentin, the pulp becomes irreversibly inflamed. If untreated, the pulp will be infected and colonized by oral microbes. The infected pulp is not capable of self-healing because of lack of collateral circulation and restricted blood supply to effectively deliver innate and adaptive immune defense mechanisms. As pulp infection/inflammation spreads apically, periapical inflammation develops. Apical periodontitis is the extension of apical pulpitis. Usually, microbes from the infected canal would not establish infectious process in the periapical tissues, which have plenty of collateral circulation to deliver cellular and humoral defense components. When the pulp becomes infected, nonsurgical root canal therapy should be initiated as soon as possible to prevent the development of apical periodontitis. In teeth with infected pulp and apical periodontitis, the microbes have well-established infection in the canal system, form biofilm on the canal walls and isthmus, and have penetrated into the dentinal tubules and lateral/accessory canals. Therefore, it is difficult to eliminate the majority of microbes in the root canal system by chemomechanical debridement. Accordingly, teeth with irreversible pulpitis without apical periodontitis have a better prognosis than the teeth with apical periodontitis after nonsurgical root canal therapy. Understanding the pathogenesis of pulpal and periapical disease will guide the clinicians to take appropriate treatment procedures to achieve satisfactory wound healing of the disease.

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4.1 Introduction

Inflammatory pathosis of the pulp-periapical tissue complex can be caused by many factors such as caries, trauma, mechanical and chemical injuries, or periodontal disease. Nevertheless, caries, an infectious disease caused by plaque biofilm, is the primary etiology. If caries is not treated, dentin will be gradually destroyed. The bacterial toxins and their metabolic by-products will penetrate through the involved dentinal tubules into the pulp leading to immuno-inflammatory reaction in the pulp. When the pulp is exposed by progressing caries, bacteria start invading the pulp. The infected pulp is not capable of self-healing because of lack of collateral circulation and restricted blood supply to effectively deliver innate and adaptive immune defense mechanisms. If vital pulp therapy or root canal therapy is not performed, bacteria will continue to invade the apical pulp. Eventually, pulpal infection/inflammation will spread into the periapical tissue and result in apical periodontitis.

Bacteria are usually not present in inflammatory periapical lesions, except maybe in acute apical abscess or chronic apical abscess with draining sinus tract or apical cysts because inflamed periapical tissues are equipped with powerful cellular and humoral components of the innate and adaptive immune defense mechanisms [1]. Bacteria may temporarily contaminate the inflamed periapical tissues, only to be killed by the host's immune defense mechanisms after complete root canal therapy. In rare occasions, bacteria may establish an independent infection in the periapical tissues without concomitant intracanal infection. It has been claimed that in some situations perhaps because of specific microbial community and/or compromised host resistance, independent extraradicular infection such as actinomycosis may occur [2–4]. However, in these studies, the bacteriologic status in the associated canals was not examined. One recently published report, however, does not support the possibility of extraradicular actinomycosis independent from the intraradicular infection [5].

Similar to all infectious diseases, endodontic therapy is aimed to eliminate or reduce bacterial count to the level that the host immune defense mechanisms are able to overcome the bacterial insults. Therefore, effective control of root canal infection plays an important role in determining the prognosis of endodontic therapy.

4.2 Pathosis of the Pulpal-Periapical Tissue Complex

Inflammatory disease of the pulp tissue can be caused by caries, trauma, mechanical and chemical injuries, or periodontal disease. However, bacterial infection caused by caries (plaque biofilm) is the primary etiology of inflammatory disease of the pulp tissue [6]. When caries lesion penetrates into the dentin, depending on the caries activity, immuno-inflammatory reaction is usually induced in the pulp beneath the dentinal tubules involved by caries [7, 8] (Fig. 4.1). Bacteria and their products can act as nonantigenic and antigenic irritants to elicit innate and adaptive immune responses in the pulp tissue [9, 10]. If caries is not removed and treated, pulpal

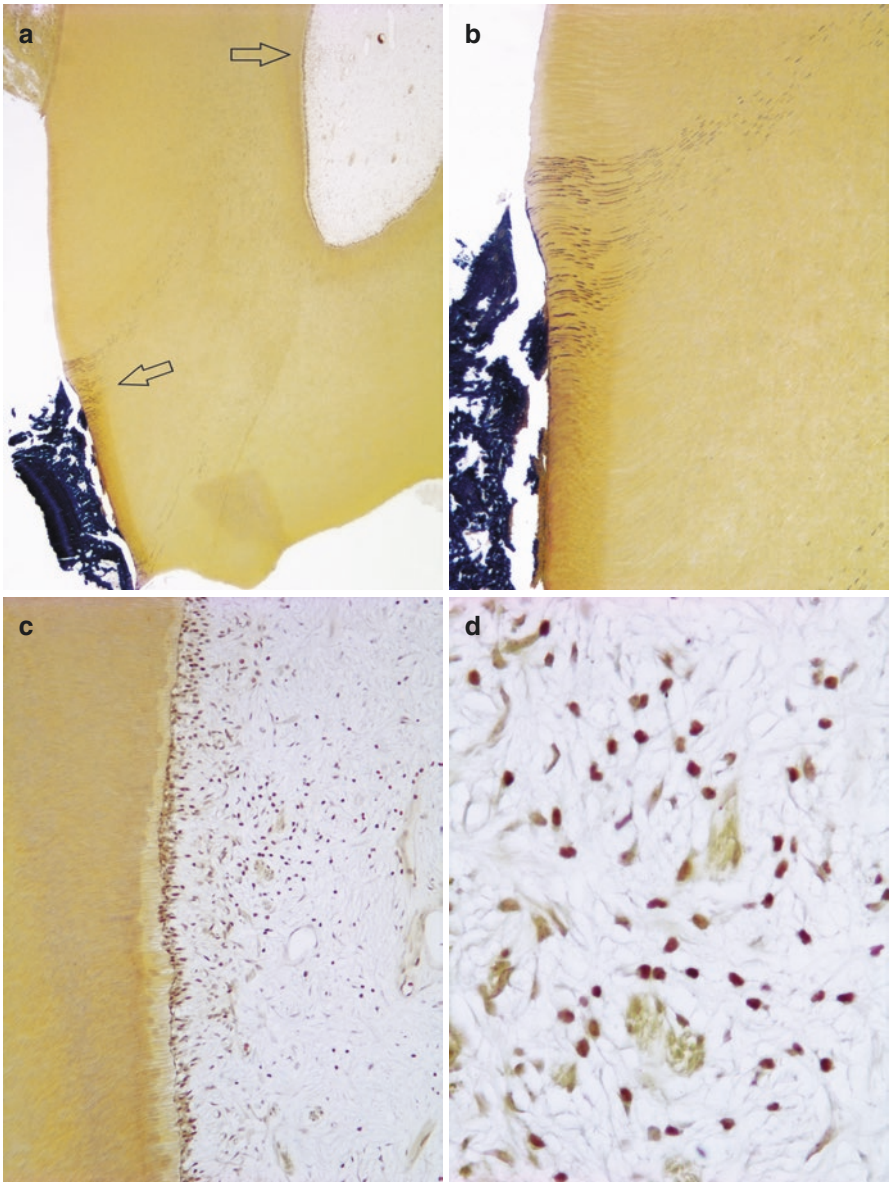


Fig. 4.1 (**a**) Asymptomatic maxillary third molar of a 25-year-old man with a mesial caries. Histologic section cut on a mesiodistal plane. Dentin is not cavitated but is layered by a thick bacterial biofilm (Taylor's modified Brown and Brenn, orig. mag. ×16). (**b**) Detail of the area indicated by the *lower arrow* in (**a**). Dentinal tubules are heavily colonized by bacteria (orig. mag. ×100). (**c**) Detail of the area indicated by the *upper arrow* in (**a**). A mild accumulation of inflammatory cells can be seen subjacent to the odontoblastic layer, where the dentinal tubules involved by caries terminate in the pulp (orig. mag. ×100). (**d**) High-power view shows that these are mononuclear chronic inflammatory cells, mainly lymphocytes (orig. mag. ×400)

immuno-inflammatory reaction will continue to persist because bacteria are in the avascular dentin, which is not accessible to host's defense mechanisms.

The severity of immuno-inflammatory reaction in the pulp is proportional to the depth of bacterial penetration in carious dentin toward the pulp [11]. When the distance between penetrating bacterial front in the involved dentin and the pulp, including the thickness of reactionary dentin, was approximately 1.11 mm or more, the pulpal inflammation was insignificant. However, when the bacteria invaded the reactionary dentin, the pulpal immuno-inflammatory reaction became irreversible [11]. If the pulp is exposed by caries, bacteria are observed in the necrotic tissue at the exposure site because the necrotic tissue is completely deprived of defense mechanisms (Fig. 4.2). The surrounding pulp tissue may be inflamed but is usually free of bacteria [12]. It is assumed that when the pulp is exposed by caries, the pulp is not capable of self-healing because it is enclosed in uncompromised rigid dentin walls and lacks collateral blood circulation to effectively deliver cellular and humoral immune components to the injured site to eliminate bacteria. Therefore, root canal therapy is required. However, recent systematic review of vital pulp therapy in vital permanent teeth with carious exposed pulps showed that vital teeth with carious pulp exposure could be successfully treated with vital pulp therapy [13, 14].

If vital pulp therapy or root canal therapy were not performed after carious pulp exposure, bacteria in the infected canal would continue to multiply and overwhelm the host's defense mechanisms and infect the rest of the pulp tissue. Eventually, the pulpal infection/inflammation will spread into the periapical tissues and results in apical periodontitis. Once bacteria have established infection in the root canal system, they form biofilm firmly attached to the canal walls by extracellular matrix of polymers (Fig. 4.3) [15–18]. They also penetrate into isthmuses [17, 19], root canal dentinal tubules [12, 20], and lateral and accessory canals [21].

Bacteria from the infected root canal may temporarily contaminate the periapical tissue in apical abscess, only to be killed by the host's immune defense mechanism after complete root canal treatment to eliminate the primary source of infection inside the canal. On rare occasions, intraradicular bacteria may invade the compromised necrotic periapical tissues and establish an infectious process as an extraradicular endodontic infection [22, 23].

There are two forms of extraradicular infection, which unlike the acute abscess are usually characterized by the absence of overt symptoms:

1. Formation of biofilm-like structures or bacterial calculus on the external apical root surface [17]
2. Formation of cohesive colonies within the body of the inflammatory lesion such as actinomycosis

Biofilm-like structures have been observed on the external surface of the apical portion of the teeth with a long-standing apical periodontitis [24–26]. Ricucci et al. [27] described two cases in which bacterial calculus was present on the external surface of teeth with a long-standing apical periodontitis and sinus tract that had not responded to the nonsurgical endodontic treatment.

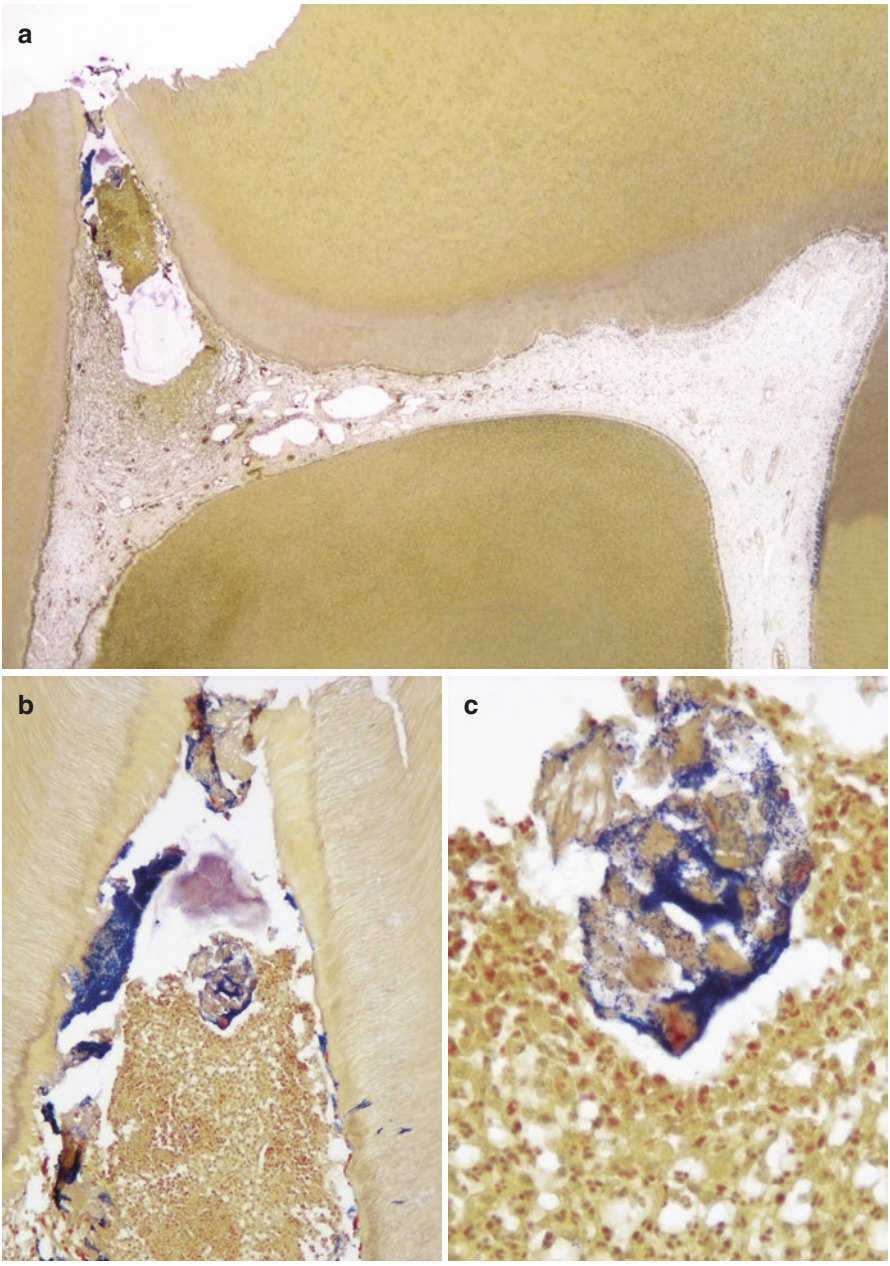


Fig. 4.2 (**a**) Symptomatic mandibular third molar in a 45-year-old man with a deep distal caries. Histologic section encompassing the caries perforation of a distal pulp horn. The pulp tissue under the perforation is necrotic, while the mesial part of the pulp tissue in the pulp chamber shows normal appearance (Taylor's modified Brown and Brenn, orig. mag. ×16). (**b**) Distal pulp horn in (**a**). Tissue debris colonized by bacteria. A biofilm structure is present on the left dentin wall. Bacteria also colonize some dentinal tubules (orig. mag. ×100). (**c**) High-power view of the bacterial colony at the center of the pulp horn. This is surrounded by a concentration of PMNs (orig. mag. ×400)

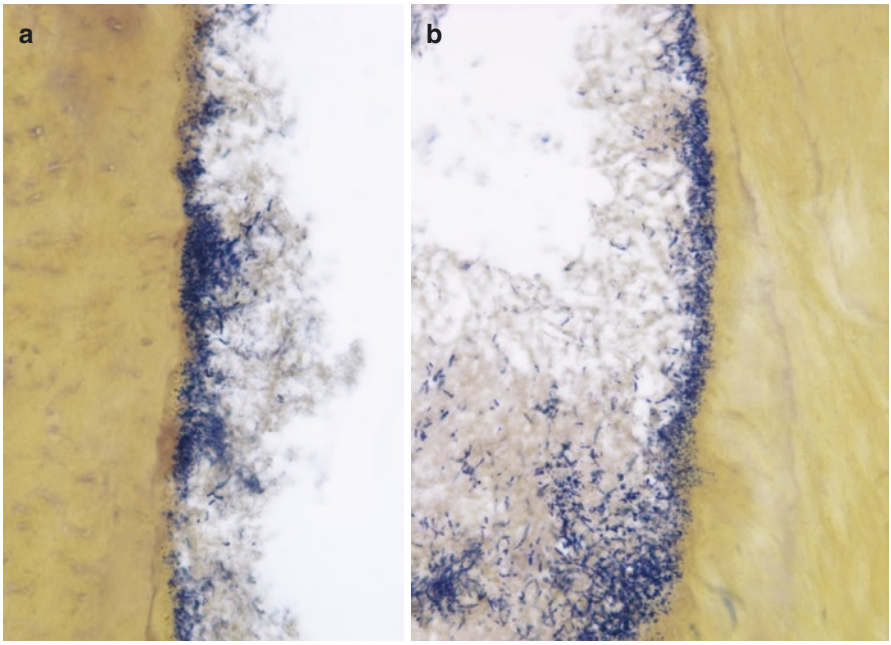


Fig. 4.3 (**a**) left side of the canal wall; (**b**) right side of the canalwall. Biofilm on the root canal walls of a mandibular premolar with a large epithelialized periapical lesion (Taylor's modified Brown and Brenn, orig. mag. ×400)

It has been suggested that in rare instances, extraradicular infection such as actinomycosis may be independent of intraradicular infection [2, 4]. However, the presence of an actinomyces colony in the inflamed periapical tissues as the cause of nonsurgical root canal treatment failure without a continuum of intraradicular infection has been questioned by Ricucci and Siqueira [5]. The mechanism of establishment of extraradicular endodontic infection is not fully understood and may be due to specific microbial community and/or compromised host defense mechanisms.

Pulpal inflammation or necrosis can also be caused by trauma without bacterial colonization and infection [28]. Teeth with this kind of pulpal inflammation or necrosis are self-limited and will not result in periapical inflammation/infection.

The correlation between diagnostic data and actual histological status of the pulps in the diseased teeth is poor [29]. Pulpal disease clinically diagnosed as having irreversible pulpitis does not necessarily imply that the entire pulp tissue is irreversibly inflamed because the apical pulp tissue may be free of inflammation. Likewise, apical periodontitis does not necessarily indicate complete necrosis of the pulp tissue in the canal [30, 31]. Apical periodontitis is the extension of apical pulpitis.

This chapter is focused on biological considerations of treatment of endodontically involved mature teeth with and without apical periodontitis. The chemomechanical preparation and obturation of the root canal system of endodontically treated mature teeth are described in the Chaps. 9 and 10.

4.3 Biological Considerations of Treatment of Endodontically Involved Mature Teeth Without Apical Periodontitis

Similar to all infectious diseases, the goal of root canal therapy of teeth with infected or necrotic pulp is to eliminate bacteria and necrotic pulp tissue in the root canal system. Although antibiotics are effective in helping the host's defense mechanisms eliminate bacteria, they are not useful in root canal therapy since bacteria are in the necrotic pulp tissue, which is devoid of blood circulation. Accordingly, antibiotics cannot make a direct contact with and kill bacteria. Root canal therapy requires mechanical debridement and antiseptic irrigation to disrupt and remove biofilm on the canal walls and antimicrobial intracanal medication to kill bacteria in the root canal system, such as isthmus, lateral/accessory canal, and dentinal tubules. The most frequently used canal irrigant and intracanal medicament are sodium hypochlorite and calcium hydroxide, respectively.

In teeth with irreversible pulpitis, bacteria usually colonize only in the coronal area of necrotic pulp tissue or in the area of pulp abscess (Fig. 4.2). There are no bacteria in the rest of the pulp tissue. Therefore, after elimination of the infected and disintegrated tissue in the pulp chamber by low-speed burs and NaOCl irrigation, the vital pulp tissue in the root canals is removed by routine mechanical debridement and antiseptic irrigation, and a pulp wound – as smallest as possible – is created at the apical constriction. Aseptic treatment procedures should be strictly followed to avoid introducing bacteria into the root canal system. In vital cases, such as irreversible pulpitis, excessive removal of canal dentin walls is not necessary because few coronal dentinal tubules are invaded by bacteria. Teeth diagnosed with irreversible pulpitis, i.e., with infection only confined in the pulp horn (Fig. 4.2), can be treated in one visit, with no need for an intracanal medication, to avoid reinfection between visits.

If bacterial infection involves the entire pulp tissue, biofilm will be formed on the canal walls, and bacteria will penetrate into the isthmus, lateral/accessory canals, and canal dentinal tubules [32–36]. Consequently, mechanical debridement of the root canal with severely infected pulp should be more thorough than that with irreversible pulpitis to disrupt biofilm and remove bacterial toxin-contaminated canal walls as well as bacteria in the dentinal tubules and necrotic tissue debris. In addition, antimicrobial intracanal medication is required to kill residual bacteria remaining in the root canal system between visits because mechanical debridement and antiseptic irrigation are not able to completely eliminate bacteria in the root canal system [37, 38]. Therefore, the remaining anaerobic microbes would begin to multiply in oxygen-deprived environment after the root canal system is closed following chemomechanical debridement. Important note! One or more intracanal medications are also highly recommended in addition to chemomechanical debridement for teeth with severely infected necrotic pulp without apical periodontitis.

If pulpal necrosis of the teeth is caused by trauma without bacterial contamination, endodontic treatment of the involved teeth is not necessary biologically, because this kind of pulp disease is self-limited and does not result in apical

periodontitis. However, the teeth with a necrotic pulp are completely devoid of immune defense mechanisms and can be easily infected and develop apical periodontitis; endodontic treatment is usually recommended before development of apical periodontitis to enhance treatment outcome. Biologically, the traumatized necrotic teeth without bacterial infection can be treated as those teeth with irreversible pulpitis.

4.4 Biological Considerations of Treatment of Endodontically Involved Mature Teeth with Apical Periodontitis

In teeth with apical periodontitis, the infection in the root canal system is well established. Biofilm formation and bacterial colonization in the isthmus (Fig. 4.4), lateral/accessory canals (Fig. 4.5), and dentinal tubules (Fig. 4.6) become more pronounced [16, 17, 39, 40]. Bacterial colonization in the apical 5 mm of the canals is difficult to eliminate. Therefore, chemomechanical debridement of the root canal system in infected teeth with apical periodontitis must be performed even more completely than that in infected teeth without apical periodontitis, and antimicrobial intracanal medication is mandatory to control residual root canal infection. On rare occasions, extraradicular endodontic infection may be associated with therapy-resistant apical periodontitis [23]. In such cases, endodontic surgery is necessary to eliminate infection.

Although bacteria remaining in the dentinal tubules of well-filled roots after chemomechanical debridement and antimicrobial intracanal dressing would unlikely affect the outcome of endodontic therapy [41], bacteria in the dentinal tubules could survive, proliferate, and infect the root canals in poorly filled roots [21].

Because persistent intraradicular infection is the primary cause of endodontic treatment failures [25, 42–46], more effort and attention should be devoted to the treatment of endodontically involved teeth with apical periodontitis.

4.5 Healing of the Apical and Periradicular Tissues Following Endodontic Treatment

Clinical procedures for treating both infected (necrotic or retreatment cases) and noninfected (vital) teeth involve the use of instruments and antimicrobial agents for cleaning, disinfection (infected cases), and shaping of the canals, as well as filling materials. The cumulative effects of these procedures inevitably result in damage to the periradicular tissues. The extent of injury, adding to the damage resulting from the existing pathology, should be kept to a minimum so as not to interfere negatively on the treatment outcome.

The healing process can be separated into regeneration and repair. Regeneration results in the complete restitution of lost or damaged tissue, while repair involves replacement of some of the original structures with fibrosis [47]. Healing in most

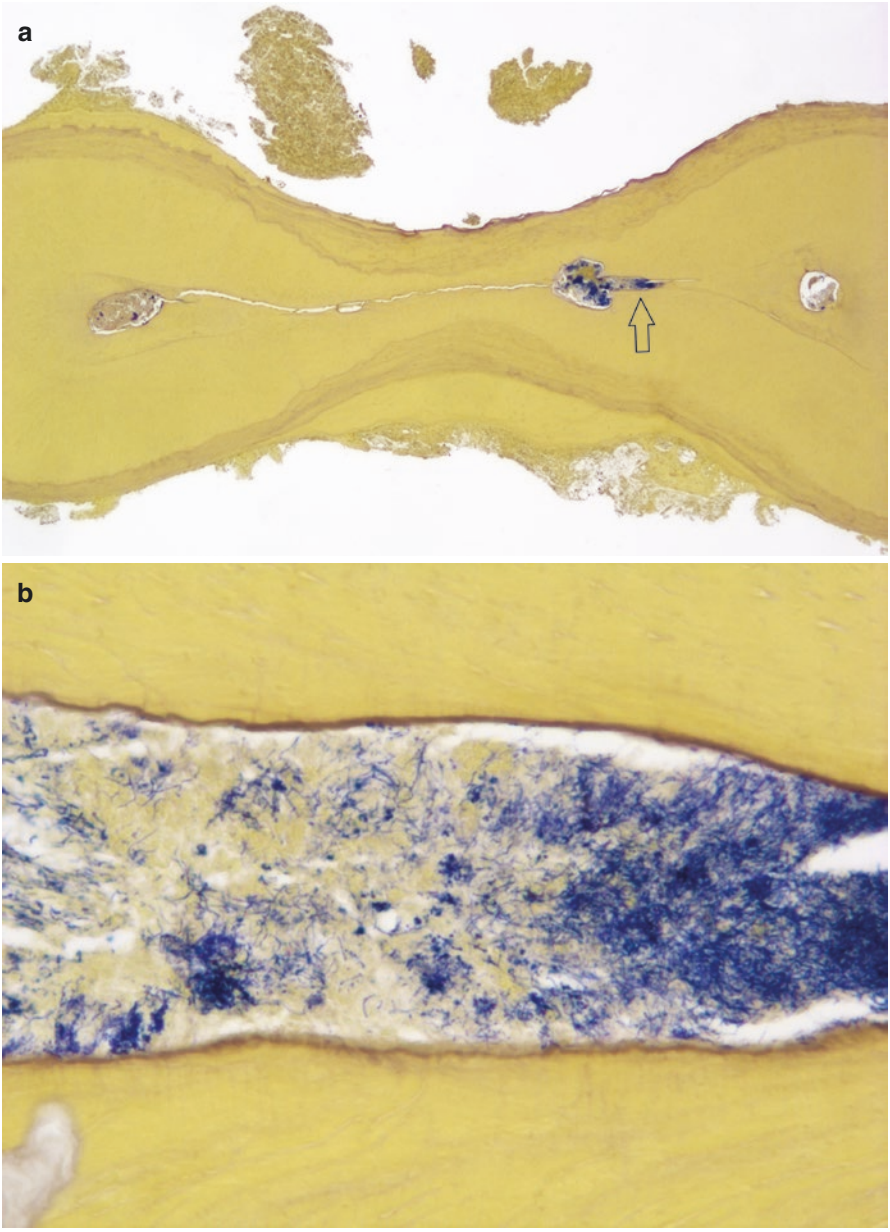


Fig. 4.4 (**a**) Crosscut section of the mesial root of a mandibular first molar with apical periodontitis. The section is taken at the transition between the apical and the middle third. A long narrow isthmus is present, with a dilation in the middle (Taylor's modified Brown and Brenn, orig. mag. ×16). (**b**) High-power view of the area indicated by the *arrow* in (**a**). A thick bacterial biofilm with abundant extracellular matrix fills completely the lumen at this level (orig. mag. ×400)

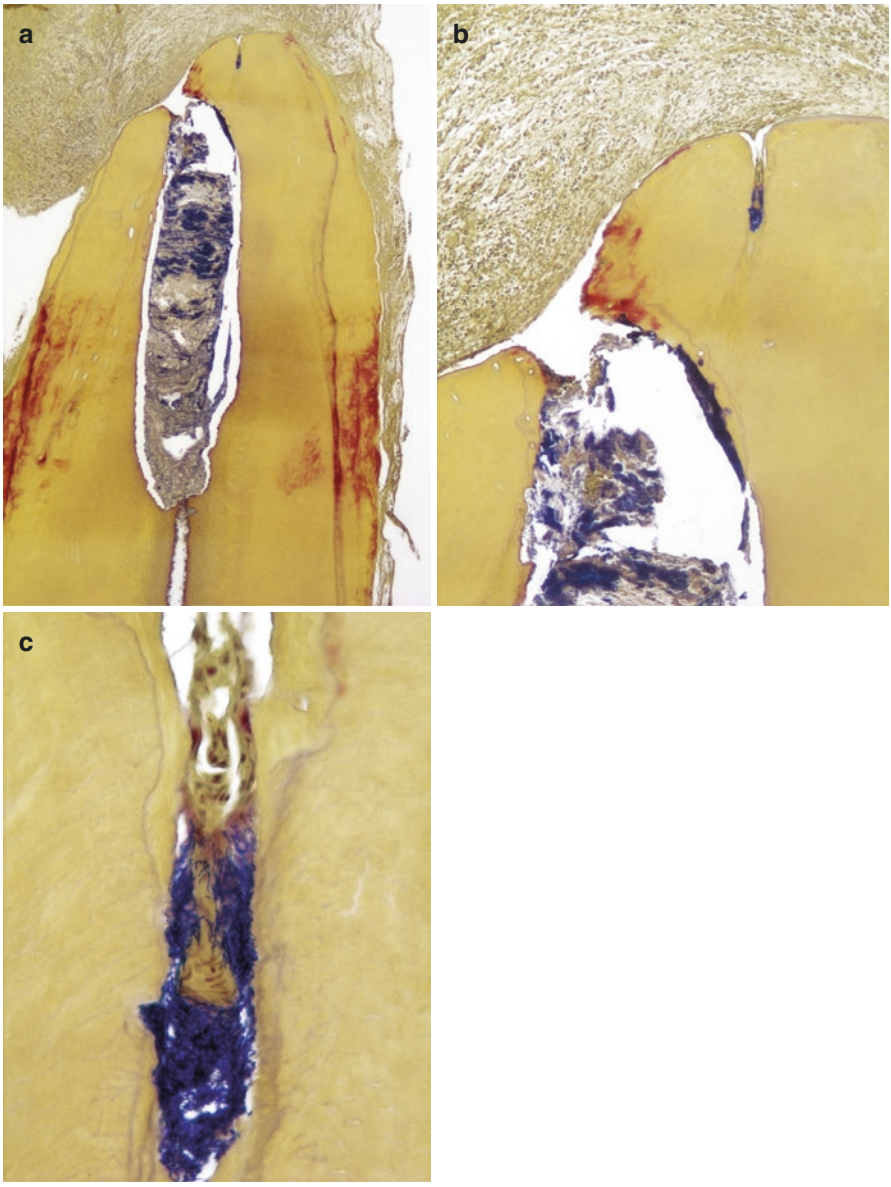


Fig. 4.5 (**a**) Distobuccal root of a maxillary first molar with a large apical periodontitis lesion. Section encompassing the apical canal. The canal is filled with a bacterial biofilm. Note the anticipated foramen and a minor apical ramification more apically (Taylor's modified Brown and Brenn, orig. mag. ×16). (**b**) Detail of the foraminal area (orig. mag. ×50). (**c**) High magnification of the apical ramification. Its lumen is occupied by a bacterial biofilm, faced apically by inflammatory cells (orig. mag. ×400)

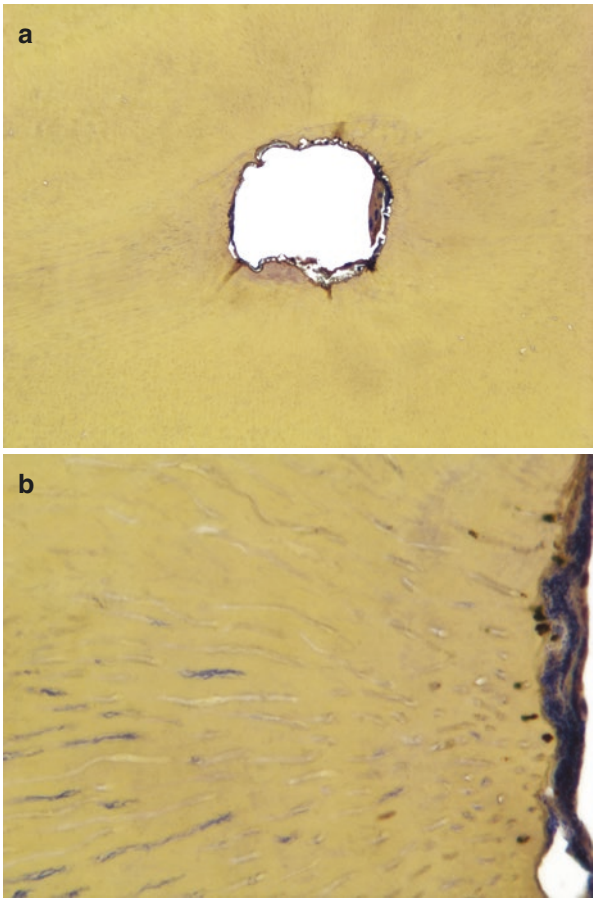


Fig. 4.6 (**a**) Distal root of a mandibular first molar with a large apical periodontitis lesion. Crosscut section from the apical third. Debris and a bacterial biofilm are present on the canal circumference (Taylor's modified Brown and Brenn, orig. mag. ×50). (**b**) Detail of the left wall. Bacteria have colonized deeply some dentinal tubules (orig. mag. ×400)

sites in the body, including teeth and their surrounding structures, involves the following highly integrated and overlapping phases: hemostasis, inflammation, proliferation, and tissue remodeling or resolution [48]. The endodontic treatment of teeth with irreversibly inflamed pulps can be regarded essentially as a prophylactic measure. The pulp tissue is severed at the apical constriction (or at a slightly more coronal seat), and the immediate reactions are characterized by an area of necrosis, which involves varying portions of the pulp stump. In teeth with necrotic pulp, after having removed the disintegrated and infected pulp tissue, the wound surface at the level of the apical canal is established in a tissue that most of the times is vital. This may be pulp tissue that has not yet been affected by the progression of necrosis in an apical direction [1], granulation tissue in the root canal in response to advancing infection, or even periodontal tissue proliferated within the apical canal. Similarly

to all surgical wounds, an accumulation of PMNs can be seen, which in a period of days or weeks is replaced by a chronic infiltrate.

The subsequent stages are generally characterized by the gradual disappearance of the inflammatory phenomena in the periradicular tissues, restoration of a normal bone trabeculature, and reestablishment of a normal periodontal ligament [1, 49]. In the apical portion of the canal, a fibrous connective tissue free from inflammation, with prevalence of fibers over the cellular component, can be observed (Fig. 4.7). This could be a remnant of the original pulp tissue or periodontal connective tissue that proliferated into the apical portion of the root canal. Cementum formation extending from the external root surface into the foramen can be observed, narrowing the lumen of the foramen to varying degrees (Fig. 4.7). With the passage of time, successive layers of cementum may be deposited until the obliteration of the apical portion of the canal is almost complete. The connective tissue in the very apical canal is reduced to a thin strand. The periodontal tissue that covers the apex is free from inflammation (Fig. 4.7).

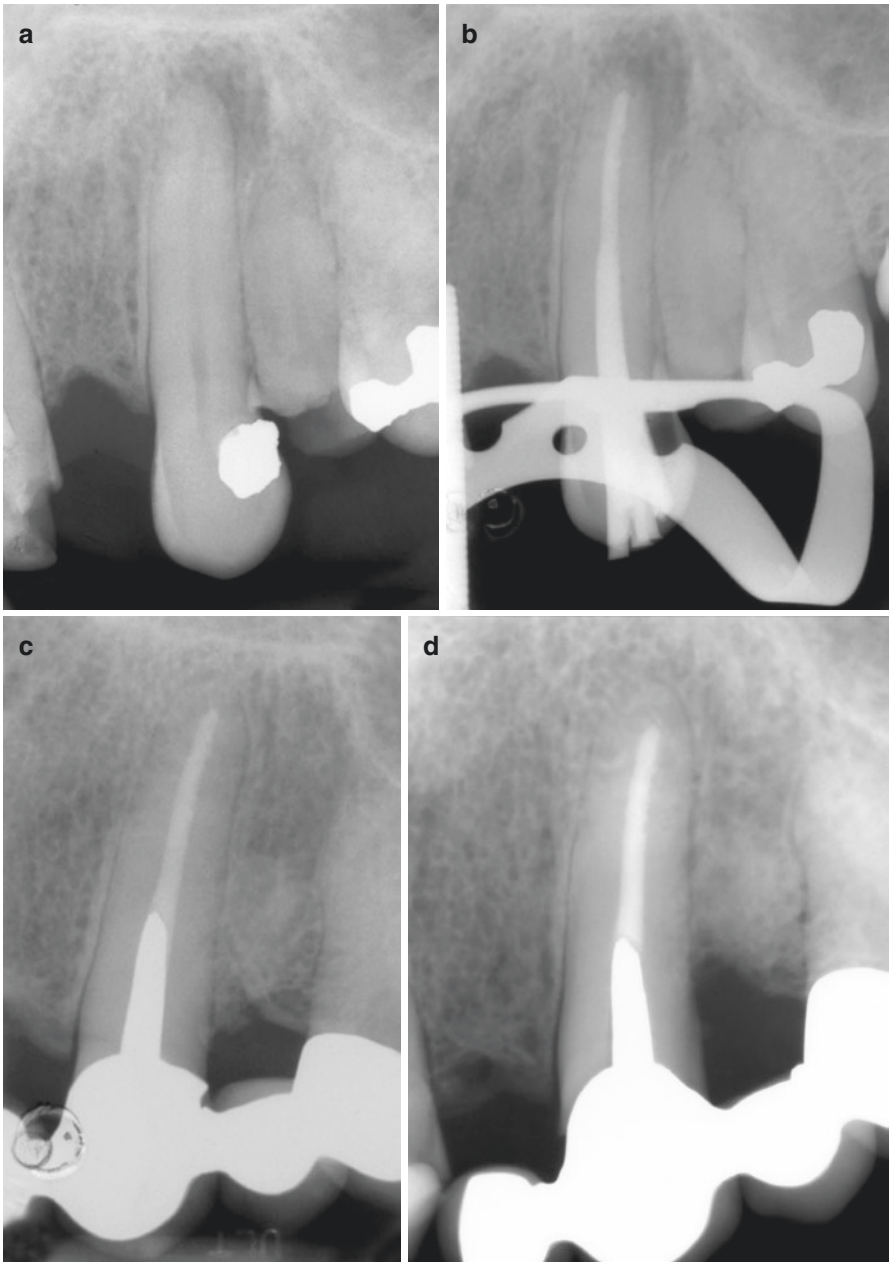
4.6 Management of Emergency of Endodontically Involved Mature Teeth

Endodontically involved teeth can manifest as pain and/or swelling, which could occur before, during, or after treatment as emergency situation.

4.6.1 Symptomatic Irreversible Pulpitis

Pulpotomy with or without anodyne dressing has been shown very effective in relieving pain [50, 51]. If clinician has time, complete chemomechanical debridement with the aid of electronic apex locator and intracanal antimicrobial dressing (calcium hydroxide) is recommended to manage pain (Fig. 4.7) [52]. Partial pulpectomy is not recommended because it has been shown to induce higher incidence of pain [51].

Fig. 4.7 (**a**) Maxillary canine with necrotic pulp and asymptomatic apical periodontitis lesion in a 41-year-old man. (**b**) The canal was instrumented and medicated with calcium hydroxide. Obturation followed after 1 week, with gutta-percha laterally condensed and a sealer. (**c**) Follow-up radiograph taken after 9 years. Normal periradicular conditions could be appreciated. The tooth was asymptomatic. (**d**) The patient presented after 19 years with swelling on the buccal gingiva. Probing revealed a 8 mm deep pocket buccally. A radiograph revealed an angular distal bony defect. Note that the periapical conditions were still normal. The diagnosis of vertical root fracture was made and the tooth extracted. (**e**) Section taken approximately at the center of the canal and encompassing the apical canal and foramen. Calcified tissue is present in the very apical part of the canal (hematoxylin and eosin, orig. mag. ×16). (**f**) Detail of the foramen. The calcified tissue occupying the apical canal resembles cementum and it is crossed by a strand of connective tissue. The periodontal tissue fragment, attached to the root tip at extraction, is free from inflammation (orig. mag. ×100). (**g**) High-power view of the soft tissue at the foramen. Only fibroblasts and collagen fibers can be seen. No inflammatory cells (orig. mag. ×400)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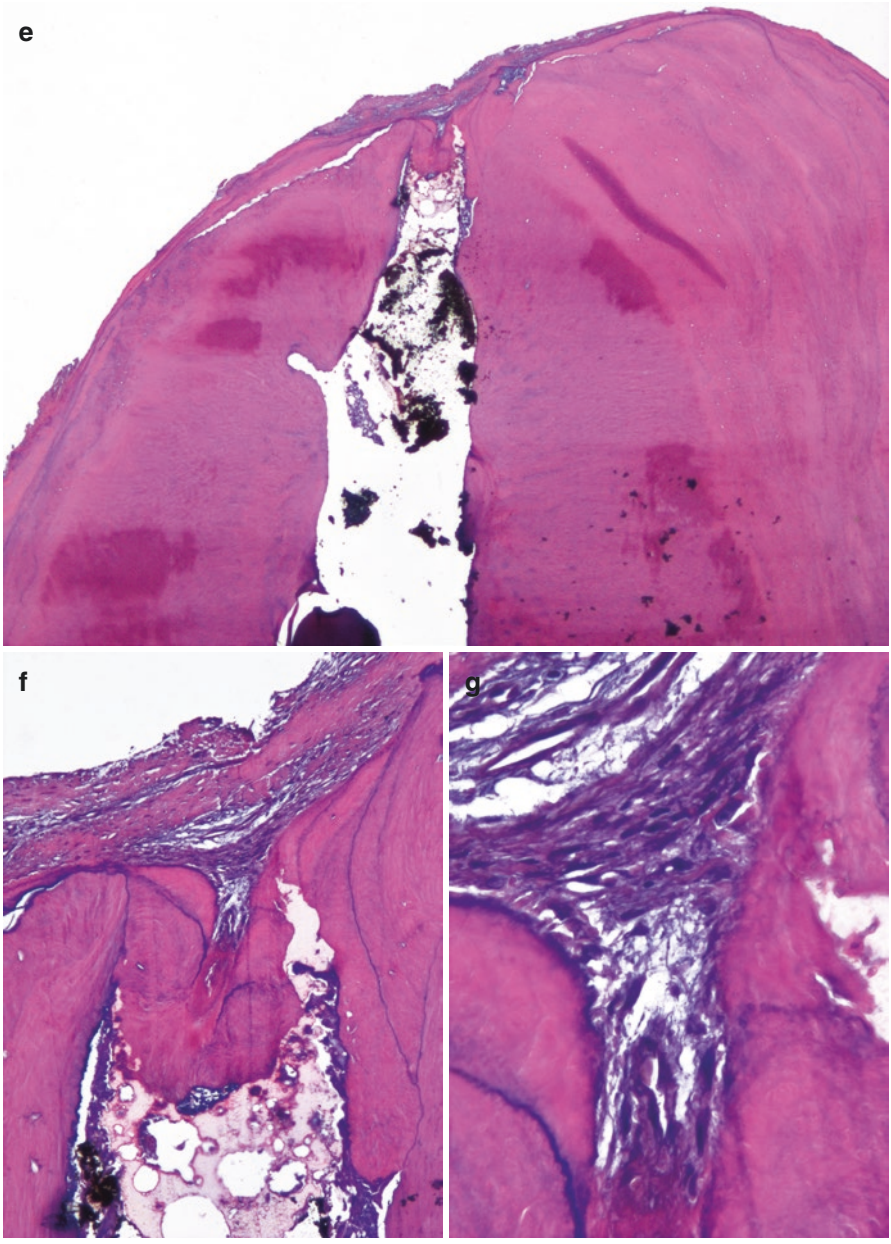

Fig. 4.7 continued

4.6.2 Pretreatment or Inter-treatment of Symptomatic Apical Periodontitis Without Swelling

Complete chemomechanical debridement with the aid of electronic apex locator and intracanal antimicrobial dressing is necessary [52]. If the involved tooth is sensitive to bite, occlusal reduction is highly recommended [52]. Analgesic can be prescribed if necessary. Antibiotic is not indicated.

4.6.3 Pretreatment or Inter-treatment of Apical Periodontitis with Swelling (Localized or Diffuse)

The treatment is similar to that of symptomatic apical periodontitis with the exception of swelling. If the swelling is indurated, incision and drainage (I&D) is not indicated. Usually, drainage can be obtained from the canal after access opening, perhaps due to pressure difference between atmosphere and the periapical tissues (Fig. 4.8). However, if drainage does not occur after access opening and cautiously irrigating the chamber, pushing an endodontic file through the apical constriction with the intention of widening the foramen to evacuate exudate is not indicated, as it can bring more bacteria from the infected canal into the periapical area. Attempt should be made to perform thorough chemomechanical debridement of the infected canal. If swelling is fluctuant, I&D can be performed to help evacuate the exudate from the periapical lesion. Ideally, the involved tooth should also be opened, and the infected canal is chemomechanically debrided because the source of irritant, bacteria, is inside the canal (Fig. 4.9). Antibiotic therapy is not indicated for localized swelling. Antibiotics are not capable of killing bacteria in the infected canal, because there is no blood circulation in the infected necrotic pulp. In case of facial cellulitis (diffuse swelling), antibiotics can be prescribed to prevent spread of infection into fascial spaces of the head and neck. The patient should be closely followed up [53]. Analgesic can be prescribed if necessary.

To leave involved tooth open is not recommended because indigenous oral microorganisms are the primary cause of pulpitis and apical periodontitis. Antibiotics are indicated for systemic manifestations of infection such as fever, malaise, lymphadenopathy, facial cellulitis, progressive diffuse swelling, and medically compromised patients [53] and not for endodontic pain control [54]. Pain should be managed with analgesics [55, 56].

4.6.4 Posttreatment Endodontic Pain or Swelling

The management of posttreatment endodontic pain or swelling is different from that of pretreatment or inter-treatment pain or swelling. Any pain and/or swelling that occurs after completion of root canal therapy should be investigated first for the possible causative factor/factors such as super-occlusion, untreated extra-canal, root fracture, or cracks of the endodontically treated teeth. Posttreatment endodontic pain should be managed with analgesics [56]. If the swelling is fluctuant, I&D is

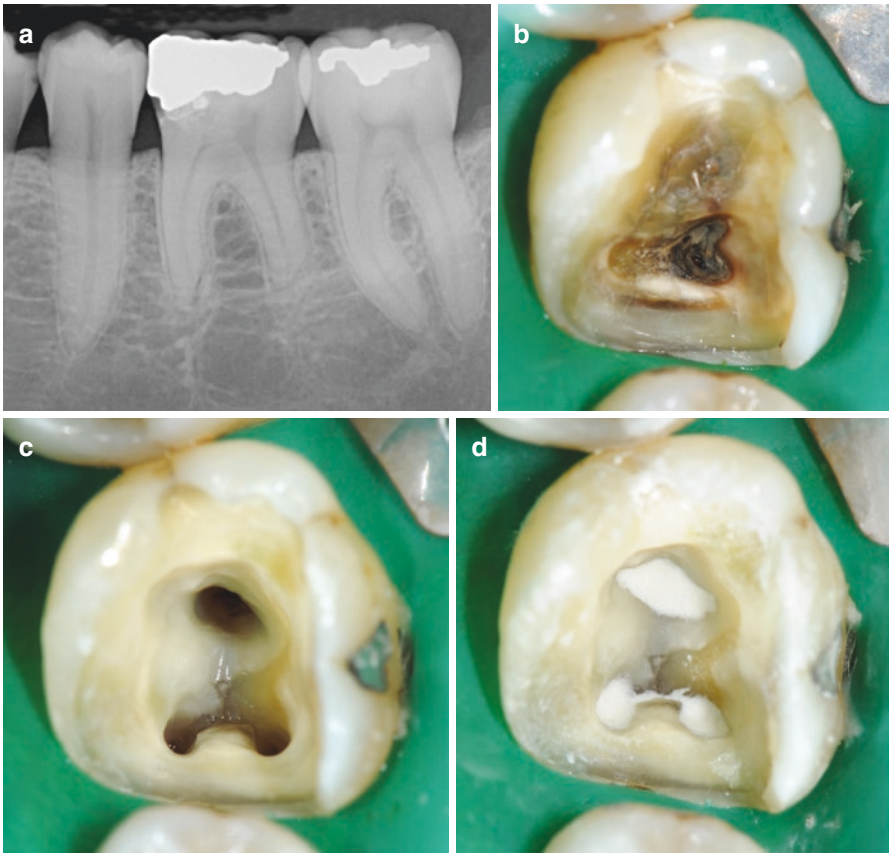

Fig. 4.8 (**a**) Mandibular first molar with the diagnosis of symptomatic pulpitis. The radiographs revealed a leaking restoration, calcification in the pulp chamber, and severe apical resorption. (**b**) Aspect of the crown after removal of the restorative materials and the carious tissue. (**c**) View of the pulp chamber after access and orifice preparation. (**d**) Following root canal instrumentation, the canals were filled with chemically pure calcium hydroxide mixed with sterile saline to a creamy consistency

indicated and the patient should be closely observed. Antibiotic therapy is recommended if the swelling is indurated and persistent. The patient must be closely followed up for the progression of signs and symptoms. If pain and/or swelling continue to persist after analgesic and antibiotic therapy, periapical surgery may be indicated after ruling out root fracture.

4.7 Prognosis of Mature Teeth with and Without Apical Periodontitis After Nonsurgical Endodontic Treatment

According to the systematic review of the outcome of primary root canal treatment, nonvital teeth without periapical lesion have approximately 1.95 time higher odds of success than nonvital teeth with periapical lesion [57]. When comparing the

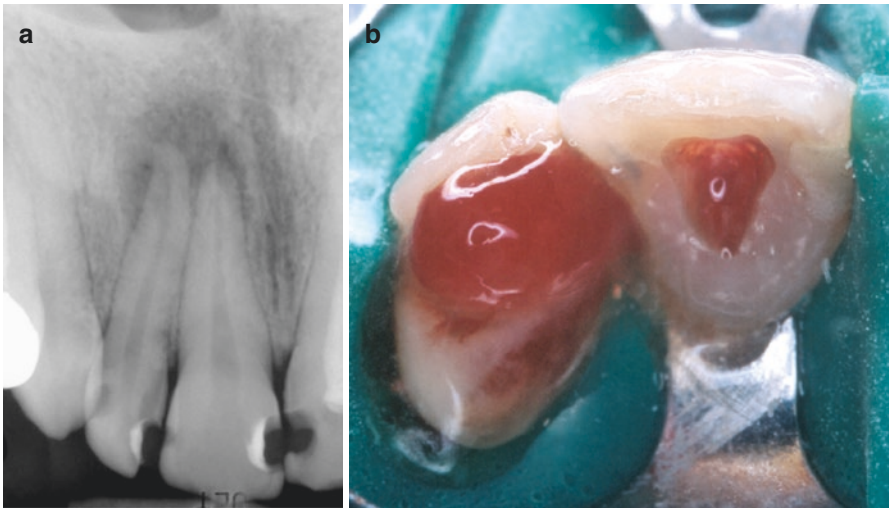

Fig. 4.9 (**a**) 35-year-old woman seeking treatment for severe pain caused by the maxillary right incisors. The diagnosis of symptomatic apical periodontitis was made. There was swelling in the vestibule with no fluctuation, and the teeth were extremely painful to palpation and percussion. (**b**) Incision of the soft tissues was not indicated, and drainage was obtained after opening access cavities in both teeth

lesion size into <5 or >5 mm in diameter, the estimated pooled odds of success for small lesions is higher but not statistically significant when compared with the pooled odds of success for large lesions [57]. Acute flare-ups during endodontic treatment do not appear to have effects on outcome [58]. Another factor affecting the prognosis of endodontically treated teeth is the apical level of the endodontic procedures. The excess of root canal filling material decreases the rate of successful treatment [59].

4.8 Quality of Root Fillings and Coronal Restorations in Endodontic Prognosis

Persistence of root canal infection is the major cause of endodontic treatment failures [45, 60, 61]. Another suggested cause of failure is the leakage of bacteria through the coronal restorations and root canal fillings. The assumption that coronal leakage (secondary infection) plays a major role in treatment failure [62–66] has been recently reviewed on the basis of radiographic [67] and histologic studies [49, 68] demonstrating that well-prepared and filled root canals resist bacterial penetration even upon frank and long-standing oral exposure by caries, fracture, or loss of restoration. However, leakage of bacteria or bacterial elements as a possible cause of root canal treatment failure cannot be ruled out in the presence of less than ideal coronal restorations and root canal fillings. An example is emergent disease, like the one developing in teeth that were vital at the time of treatment but later developed an apical periodontitis lesion in the period following completion of treatment. Clinically and

radiographically, it cannot be determined for sure if the root canal system is bacteria-tight sealed from the oral environment. Accordingly, good coronal restorations prevent coronal bacterial leakage and decrease the prevalence of apical periodontitis. Because studies indicate that the best outcome is achieved in teeth with adequate root canal fillings associated with adequate coronal restorations [69–77], it is advisable to treat the tooth as a continuum, placing a well-adapted permanent coronal restoration as soon as possible after finishing root canal treatment.

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Regenerative Approaches in Endodontic Therapies of Immature Teeth

5

Mo K. Kang and George Bogen

Success is dependent on effort.

_____ Sophocles

Abstract

Regenerative therapies in endodontics have recently gained momentum in clinical dentistry primarily due to the availability of effective root canal disinfection protocols, biocompatible materials with enhanced marginal seal, and discovery of mesenchymal stem cells (MSCs) in the dental pulp. These constitute the "triad" of tissue engineering required for pulp regeneration, assembled to meet the unique needs of the pulp-dentin microenvironment. Endodontic regeneration may be offered to patients at varying levels, including direct and indirect pulp capping, partial and complete pulpotomy, apexogenesis, apexification, and revascularization procedures, all of which require the triad of pulp tissue preservation or engineering. Successful outcomes in revascularization, for example, depend on root canal disinfection employing irrigation and medicaments using biocompatible calcium silicate-based cements (CSCs) paired with adhesion-based restorations that ultimately promote recruitment of MSCs from the apical papillae. These regenerative procedures yield high success rates in treatment outcome, although they are not routinely performed in the day-to-day practice of dentistry. In this chapter, we discuss the rationale for endodontic regeneration procedures in the era of markedly successful conventional therapies, and we outline the procedural aspects of available regenerative endodontic therapies.

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5.1 Introduction

Endodontic regeneration encompasses vital pulp therapy and regenerative procedures. These include direct and indirect pulp capping, partial and complete pulpotomy, apexogenesis, apexification (apical barrier formation), and revascularization strategies. Perhaps the most clinically challenging treatments involve vital and nonvital immature permanent teeth, where therapy options depend on the degree of pulpal involvement and root maturation. These teeth are characterized by incomplete root formation, thin-walled roots, and open apical foramina. Immature permanent teeth also exhibit greater dentinal permeability due to the presence of large dentinal tubules, thus increasing the potential for microbial penetration [1]. After their primary eruption into the oral cavity, these teeth may require one to 5 years to complete maturation and root-end closure [1, 2]. When root development is interrupted or halted due to trauma, caries, or anatomical anomalies, the thin radicular walls and compromised root length predispose these teeth to root fracture and potential tooth loss.

During process of odontogenesis, immature teeth are characterized by a unique soft tissue organ at the developing apical collar known as the apical papilla. The apical papilla is a potent source of stem cells that contribute to pulp and root maturation and can survive after pulpal necrosis [3]. The preservation and proper management of this tissue can promote continued development of radicular structures, thus having a positive impact on long-term tooth function and retention. The same objective applies to vital pulps in immature permanent teeth – preserving and protecting the remaining healthy tissue to achieve tooth maturation and continued maintenance of biological functions. It is therefore critical to adopt biologically driven strategies designed to preserve and harness the healing and growth potential of both the apical papilla and dental pulp in order to encourage continued root formation.

Traditionally, treatment strategies for immature necrotic teeth included extraction, conventional root canal treatment, or apexification procedures. Necrotic teeth with open apices were managed using calcium hydroxide (CH) over multiple appointments in order to generate hard tissue barriers to allow predictable canal obturation using gutta-percha [4, 5]. In immature teeth with reversible pulpits or vital pulp tissue, pulpotomy or pulp capping procedures were performed using a wide variety of dental materials including CH. Some of these obsolete materials like formocresol were designed to embalm tissues rather than to encourage preservation and embrace the innate repair potential of the remaining dentin-pulpal tissue complex. However, with our improved understanding of pulp biology and discovery of the stem cells of the apical papilla (SCAP) combined with the introduction of bioactive silicate cements, a revolution in biologically based treatment alternatives has evolved. These treatment modalities not only encompass vital and reversibly inflamed pulp tissues using vital pulp therapy (VPT) but also address immature teeth with necrotic pulp using regenerative endodontic techniques using calcium silicate-based cement (CSC) obturation methods. Once diseased, immature teeth with open apices may now undergo root maturation after resolution of intracanal infection and periradicular inflammation. Regenerative endodontic therapies have

been introduced in order encourage root maturation of non-vital teeth with future efforts directed to fully regenerate a functional pulp-dentin complex. This chapter will present an overview of current and future treatment modalities in vital and necrotic immature permanent teeth with open apices designed to promote the natural healing dynamics of the pulp-dentin complex and provide the clinicians with treatment regimens that can be incorporated into their daily dental practice.

5.2 Treatment of Teeth with Vital Pulp and Open Apices

5.2.1 Vital Pulp Therapy

Treatment strategies are designed to preserve the existing pulpal tissue/dentin complex, encourage the deposition of reparative hard tissue at the injury site, and promote maturation of incompletely formed roots in immature permanent teeth (apexogenesis). The indications include advanced caries, restorative induced pulp exposures, anatomical anomalies, or traumatic injuries in cases generally diagnosed with reversible pulpitis. The in vivo protocols require the recruitment of dental pulp stem cells (DPSCs) to replace injured or removed odontoblasts and also stimulate SCAP to advance the process of apexogenesis in immature teeth. VPT procedures encompass direct pulp capping (DPC), indirect pulp capping (IPC), and partial (PP) and complete pulpotomy (CP). Clinical outcome studies have been encouraging when advanced treatment protocols have been implemented using MTA and other CSCs compared to other commonly used materials [6–9].

Recent studies have confirmed that CSCs in particular offer physicochemical properties that provide superior characteristics for VPT procedures [10–14]. The setting of the material is not affected by blood, serum, or moisture and forms a zero micron interfacial layer with dentin similar to hydroxyapatite in composition [15–17]. The slow release of calcium ions and the high pH during curing stimulates dentin sialoprotein (DSP) and heme oxygenase-1 (HO-1) and extracts growth factors nested in the adjacent dentin promoting hard tissue barrier formation [18, 19]. A sustained alkaline pH contributes to bacterial neutralization, while the crystallization and occlusion of dentinal tubules during setting allow for entombment of remaining acidogenic microorganisms [20–22]. The surface morphology of the cured MTA also provides a favorable environment for preodontoblast-like cell recruitment and differentiation [23, 24]. Vital pulp therapy can be classified into the following basic categories:

5.2.2 Direct Pulp Capping

The procedure requires the placement of a bioactive material over an exposure site without selective pulp tissue removal. Dental material and clinical protocol improvements have changed the perception that the pulp is a “doomed organ” when an exposure occurs during caries excavation (Fig. 5.1) [25]. Initial success has been

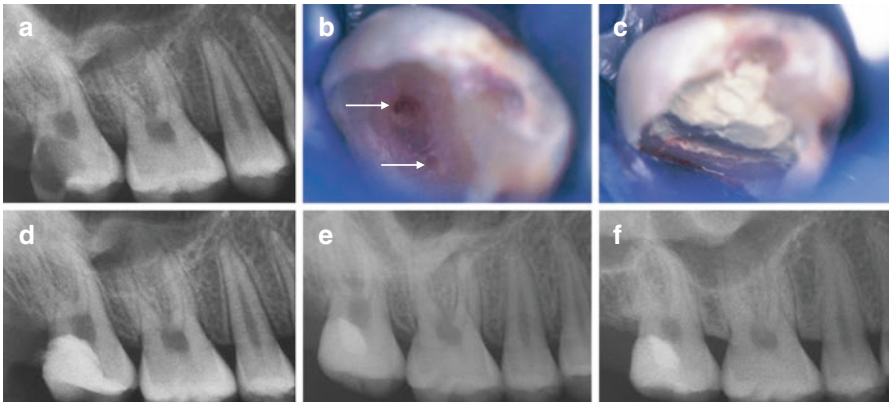

Fig. 5.1 Preoperative radiograph of maxillary right second molar associated with deep caries in a 15-year-old female patient diagnosed with reversible pulpitis (**a**). Clinical photograph of molar after caries removal and NaOCL hemostasis showing two direct pulp exposures in a carious field (*arrows*) (**b**). Photograph showing white MTA placement over axial wall and surrounding dentin (**c**). Postoperative radiograph of molar with wet cotton pellet and provisional restoration (**d**). Radiograph of final bonded composite restoration placed over cured MTA after one week (**e**). Six-year 6-month radiographic review (**f**). The molar was asymptomatic and responded normally to carbon dioxide cold testing ()

seen with DPC in independent studies and clinical trials when the pulp capping materials are CSCs rather than CH, resin-modified glass ionomer (RMGI) cements, or hydrophilic resins [7, 9, 12, 26, 27]. Calcium silicate-based cements appear to reliably promote reparative bridge formation by activating the differentiation of DPSCs or pulpal progenitor cells into newly generated odontoblast-like cells through a complex biological process of recruitment, proliferation, and migration as demonstrated in Fig. 5.2 [28]. Although the origin and specificity of the new hard tissue-forming cells have not been established, a recent histological analysis of directly pulp capped human teeth using CH has shown that reparative calcified barriers generated after injury and loss of the primary odontoblasts may be the end product of pulpal fibroblasts rather than differentiation of the odontoblast-like cell phenotype [29]. Examination of formed hard tissue bridges revealed atubular mineralized tissue exhibiting tunnel defects containing necrotic debris similar to pulp stones produced as a result of dystrophic calcification.

5.2.3 Indirect Pulp Capping

This technique preserves the original odontoblastic cell population in order to stimulate the formation of reactionary (tertiary) dentin by the upregulation of the primary cells in cases of deep caries and avoids pulpal exposure. The treatment involves either stepwise technique (two visit) or one-step techniques leaving carious tissue to remineralize after pulp capping material and restoration placement [30–32]. IPC

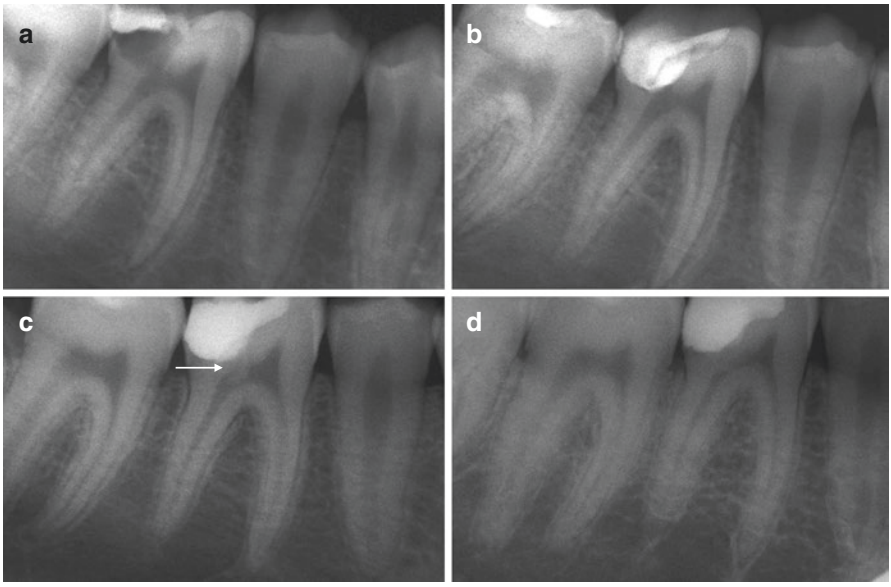

Fig. 5.2 (**a**) Initial radiograph of mandibular right first molar showing temporary restoration and cotton pellet placement in a 12-year-old male patient with advanced caries (**a**). Postoperative radiograph with MTA direct pulp capping, wet cotton pellet, and provisional restoration (**b**). One-year postoperative review radiograph shows reparative bridge formation below MTA placement (*arrow*) (**c**). Nine-year recall radiograph (**d**). The patient was asymptomatic with normal responses to sensitivity testing (©Dr. George Bogen. All Rights Reserved)

studies have shown promising results in younger patients; however, the treatment protocol is technique sensitive and caries reactivation and/or loss of dentin volume during remineralization are potential drawbacks.

5.2.4 Partial and Complete Pulpotomy

Both procedures require pulp tissue removal and are based on clinical appearance of the remaining healthy tissue or the extent and location of tooth fracture in trauma cases. During pulp exposure, irreversibly inflamed or necrotic tissue (representing bacterial colonization) is removed until healthy tissue is reached and capping material placed leaving some portion of remaining healthy coronal tissue during PP. In cases of CP, the pulp tissue is effectively removed to the level of the pulpal floor in posterior teeth to encourage apexogenesis in younger patients. Partial removal of tissue (3–4 mm) in anterior teeth that have sustained traumatic fractures is also known as the "Cvek technique" (Fig. 5.3) [33]. The procedure relies on the SCAP and resident DPSC for reparative bridge formation and continued apexogenesis. The procedures have shown efficacy when CSC materials are used in both children and adults even with a diagnosis of irreversible pulpits [34–37].

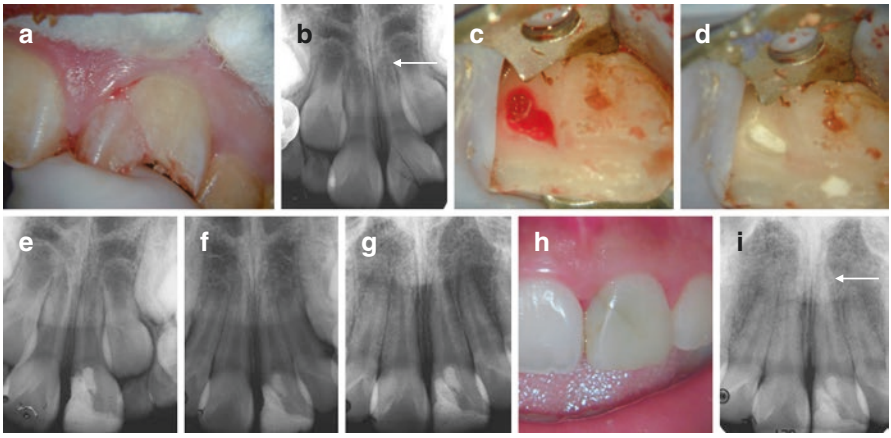

Fig. 5.3 Cvek pulpotomy promotes root-end closure. Clinical photograph of traumatized maxillary left central incisor in an 8-year-old male patient (**a**). Periapical radiograph showing two oblique coronal fractures and open apex (*arrow*) (**b**). Clinical photograph of pulp exposure and Cvek pulpotomy using white MTA after NaOCl hemostasis (**c**, **d**). Radiograph of completed pulpotomy and bonded composite restoration (**e**). Two-year radiographic follow-up (**f**) and 5-year recall radiograph (**g**). Clinical photograph and radiographic review after 7 years showing minor staining of composite restoration and complete maturation of root apex (*arrow*) (**h**, **i**) (Courtesy Dr. Paul Anstey, Beverly Hills, California)

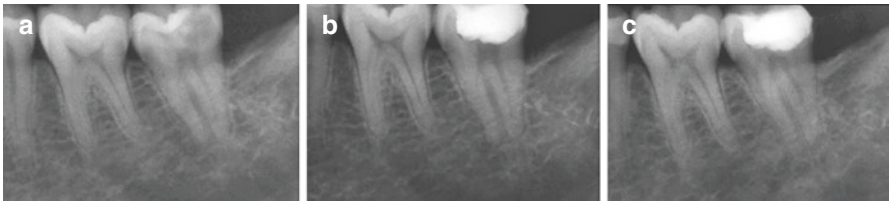

Fig. 5.4 Preoperative radiograph of symptomatic mandibular left second molar exhibiting deep caries in a 32-year-old male patient (**a**). Postoperative radiograph one week after MTA direct pulp capping and restoration with bonded composite (**b**). The patient symptoms resolved 24 h after MTA placement. Two-year 4-month recall radiograph showing normal periapical structures (**c**). The tooth responded normally to sensitivity testing ()

All strategies in VPT rely on the substantial regenerative potential of the dental pulp under a variety of clinical conditions [38]. Treatment options are essentially dictated by the extent of tissue inflammation and the ability to achieve hemostasis when CSCs are used to promote hard tissue deposition and apexogenesis. Partial or complete pulpal preservation can be viewed as a strategic advantage when compared to more aggressive endodontic treatment options [39]. In cases of irreversible pulpitis, CP could provide reliable therapy for adult patients in underserved areas globally. Most importantly, all VPT treatment outcomes are ultimately dependent on the quality and sealing characteristics of the final restoration (Fig. 5.4).

5.3 Tissue Engineering in Endodontic Therapies: Rationale and Progress to Date

Regenerative endodontics is defined as "biologically based procedures designed to replace damaged structures, including dentin and root structures, as well as cells of pulp-dentin complex" [40]. The primary goal of endodontic therapies is to eliminate clinical signs and symptoms of pulpal and periradicular diseases and resolution of apical periodontitis. The goal of regenerative endodontic therapy is to reinstate normal pulp function in necrotic teeth, i.e., restoration of protective functions, including innate pulp immunity, pulp repair through mineralization, and sensation of occlusal pressure and pain. Restoration of these pulpal functions will enhance long-term survival of teeth and help patients retain their natural dentition. Hence, it is critical to develop a novel regenerative approach that will restore not only pulp vitality but regenerate pulp tissue histologically complete with all innate physiological functions.

It is evident that revascularization procedures by way of canal disinfection using CH or triple antibiotic paste (TAP) yield very high success rates, at least short term, when success is defined as resolution of periradicular inflammation and signs and symptoms of endodontic pathoses (Fig. 5.5) [41]. It is also apparent that revascularization without the introduction of exogenous MSCs will result in ectopic tissue formation in the canals devoid of the regenerated pulp-dentin complex [42–45]. Several recent studies indicated that cell-based approaches may be required for pulp-dentin regeneration [46–49]. Hence, the process necessary for pulp-dentin regeneration may be far more complicated than the current strategy of revascularization, which includes root canal disinfection, induced bleeding, clot formation, CSC placement, and the final restoration [50]. It may require isolation of healthy pulp tissues, expansion of stem cells ex vivo utilizing specialized cell culture facilities, and retransplantation of these expanded cells in disinfected root canals. Assuming such complex clinical protocols are developed and materialize, one may pose the question, "why regenerate the dental pulp?"

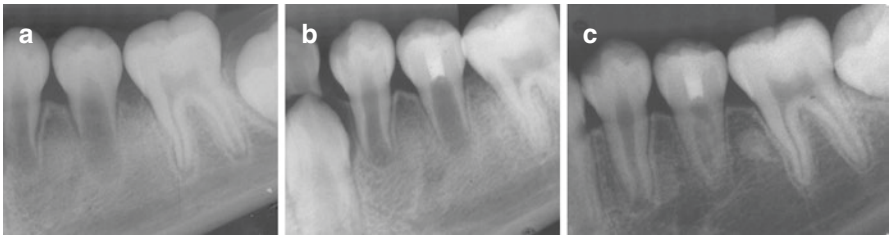

Fig. 5.5 Revascularization promotes root maturation. Radiograph of an 8-year-old male patient showing incomplete root formation associated with a necrotic mandibular left second premolar characterized by *dens evaginatis*. (**a**) Postoperative radiograph after debridement, canal disinfection using NaOCl, dressing with CH intracanal medicament, and final MTA placement paired with bonded restoration (**b**). Two-year radiographic recall shows root maturation – advanced root wall thickening, increased root canal length, and apical closure (Courtesy of Dr. Warunee Sony, Bangkok, Thailand)

This is a valid question in light of the fact that conventional RCT is highly successful; various investigators report success rates of 94–99 % for primary RCTs [51, 52]. However, these high success rates have not been confirmed in the systematic review of primary root canal treatment (Ref by Ng et al. 2007 [53], 2008 [54]). In addition, there is a general perception in the dental community that endodontically treated teeth eventually fail because of root fracture. While this notion may be exaggerated, it is not entirely false. Vire et al. (1991) [55] reported that 59.4 % of all endodontically treated teeth were extracted due to some sort of structural defect, e.g., crown/root fractures, prosthetic failure, and recurrent caries. Interestingly, Toure et al. (2011) [56] reported that periodontal complications were the leading cause of extraction of endodontically treated teeth. However, this article also indicated significant structural defects, e.g., vertical root fracture and crown/root fracture, as the cause of tooth extraction. Hence, it is evident that endodontically treated teeth have been structurally weakened and their ability to withstand occlusal forces is compromised.

The study by Sedgley and Messer (1992) [57] found no difference in biomechanical properties between endodontically treated teeth and vital teeth, supporting the concept that root canal treated teeth do not become more "brittle." Rather, endodontically treated teeth can be weakened due to loss of tooth structure after caries and restoration removal amplified by mechanical canal preparation. Moreover, pulpal and periodontal ligament (PDL) innervations are believed to gauge immediate occlusal force perception [58, 59]; lack of a vital pulp may allow excessive occlusal force generation during normal function, possibly leading to root fracture. Absence of the pain sensory system in devitalized teeth would also lend restored teeth susceptible to progressive recurrent caries, which is one of the main causes of prosthetic failure in root canal treated teeth [55]. Pulp-dentin regeneration, in theory, would restore the functional pulp-dentin complex, resulting in enhanced structural integrity of teeth via synthesis of mineralized dentin and continued reactionary (tertiary) dentin deposition, proprioceptive cognizance, and immune defense mechanisms. Importantly, regenerative endodontic procedures do not involve obturation of root canals with filling materials, e.g., gutta-percha or bioceramics; therefore, the extent of root canal shaping may be minimized so as to leave as much sound radicular dentin during the treatment procedures. Therefore, pulp-dentin regeneration in lieu of nonsurgical RCT may be the next major frontier in endodontics. Successful regeneration of the dental pulp would ultimately expand and improve future treatment options for dental patients with non-vital teeth.

Generally, tissue engineering is described with the "triad" of key components, which include scaffold, growth-differentiation signals, and mesenchymal stem cells (MSCs) [60]. This principle may be applicable for most tissue regeneration, e.g., bone and cartilage in a sterile environment. However, pulp tissue regeneration must be regarded as challenging because the connective tissue performs specialized functions including mechanical proprioception, i.e., occlusal force loading and integration with the existing tooth components and supporting structures. This requires restoration of biological tissues in a disinfected root canal space that may harbor persistent bacterial biofilms. For these reasons, the triad of dental pulp tissue engineering should include biomaterials, infection control, and MSCs (Fig. 5.6).

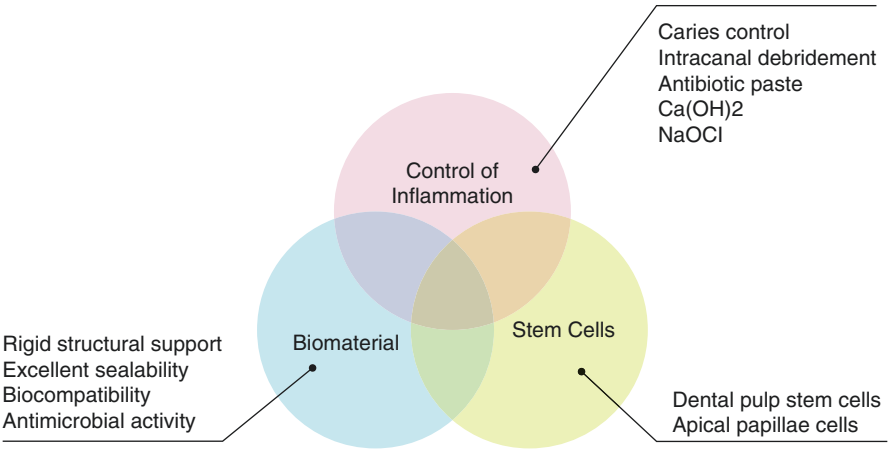

Fig. 5.6 "Triad" of endodontic regeneration. Tissue regeneration in pulp-dentin complex requires control of inflammation, biomaterials, and stem cells. Eradication of pulpal infection is essential in regenerative endodontic procedures and can be accomplished by use of intracanal medicaments and irrigants, including CH and NaOCl. Pulp regeneration is enabled by the advent of biocompatible, rigid, and sealable materials, including calcium silicate-based cement (CSC or Bioceramics), e.g., mineral trioxide aggregate. Finally, undifferentiated mesenchymal stem cells (MSCs) from the dental pulp are required for pulp-dentin complex regeneration. In the absence of pulpal MSCs, de novo pulp-dentin regeneration does not take place

The ideal biomaterials for pulp tissue regeneration would provide a rigid structural foundation supporting the sealed permanent dental restoration that protects regenerated tissues. In addition, antimicrobial properties from the biomaterials would be an added benefit since the biomaterials would be placed within disinfected and previously diseased root canals. MTA or other CSCs would satisfy these requirements due to their enhanced adaptation to dentin and superior biocompatibility [61, 62].

Infection control within the root canal system is an absolute prerequisite for successful pulp tissue engineering. In fact, patients with infected root canals requiring regenerative procedures often present with radiographically large periapical lesions often associated with soft tissue swelling and sinus tracts. One of the primary objectives of pulp regeneration treatment protocols is to eradicate the root canal infection. This allows healing of the radicular periodontium, an important predicator to successful treatment (Figs. 5.7 and 5.8). Hence, infection control is a requirement of pulp tissue regeneration. It can be accomplished by irrigation during canal debridement with 1.5% NaOCl and root canal dressing with antimicrobial agents, e.g., CH or TAP [41, 63, 64].

Finally, dental pulp tissue regeneration requires multipotent MSCs from the dental pulp. Prior studies have demonstrated that MSCs retain the features of their tissue origin; subcutaneous transplantation of DPSCs, PDL stem cells (PDLSCs), and bone marrow-derived MSCs (BMSCs) in immunocompromised mice showed the formation of tissues resembling dental pulp, fibrous cementum, and bone, respectively [65]. Thus, MSCs derived from different tissues are programmed to differentiate to reflect their tissue origin. Many prior large animal studies and some case

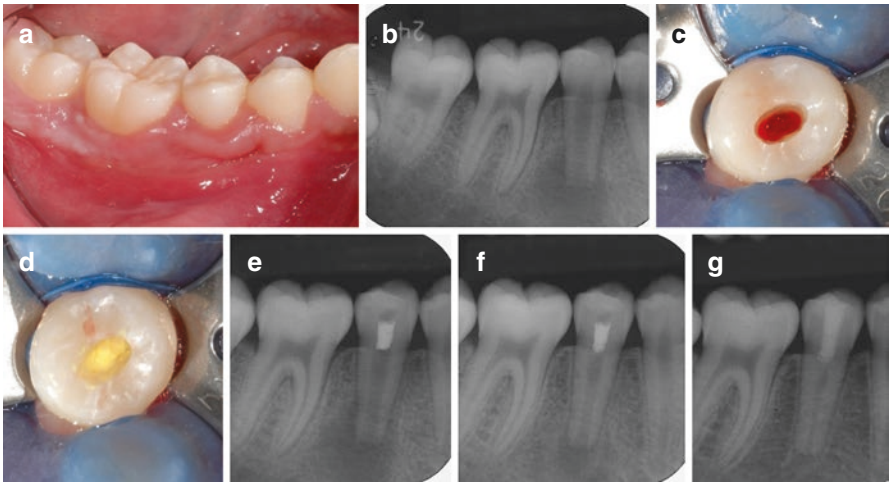

Fig. 5.7 Revascularization eradicates apical periodontitis. A 12-year-old patient presented with pulpal necrosis, swelling, and symptomatic apical periodontitis associated with the mandibular right second premolar due to *dens evaginatus* (**a**–**c**). Root canal debridement and intracanal dressing with CH was performed (**d**, **e**). Immediate postoperative periapical radiograph after completion of treatment (**f**) and recall radiograph at 5 months (**g**). One-year 4-month radiographic review with final bonded restoration shows resolution of apical periodontitis, thickening of root canal walls, increased root length, and subsequent apical closure (Courtesy of Dr. Mitsuhiro Tsukiboshi, Aichi, Japan)

reports in human subjects indicate that revascularization results in formation of ectopic bone, cementum, and fibrotic tissues within the root canal space, without forming pulp-dentin complex [42, 43]. This is somewhat expected because revascularization is based on disinfection of root canals and recruitment of neighboring endogenous MSCs by means of intracanal bleeding. Hence, intracanal bleeding would have recruited MSCs from bone marrow, resulting in ectopic bone formation, and PDL, resulting in cementum and fibrotic tissues. Therefore, in cases where the tooth presents with necrotic pulp tissue and there are no residual viable DPSCs, recruitment of heterologous MSCs from bone marrow and the PDL would fail to induce pulp-dentin regeneration. In these cases, pulp regeneration would require transplantation of autogenous DPSCs or ex vivo cultured cells into the disinfected root canal space. With the current advances in biocompatible material technologies combined with available stem cell resources, the opportunity to pioneer biological approaches to accomplish the future goal of pulp regeneration has arrived.

5.3.1 Revascularization

Initial success for regenerative therapy was demonstrated in necrotic immature teeth after canal disinfection using the TAP and intracanal bleeding (Banchs and Trope 2004) [63]. This “revascularization” procedure has been reported in numerous

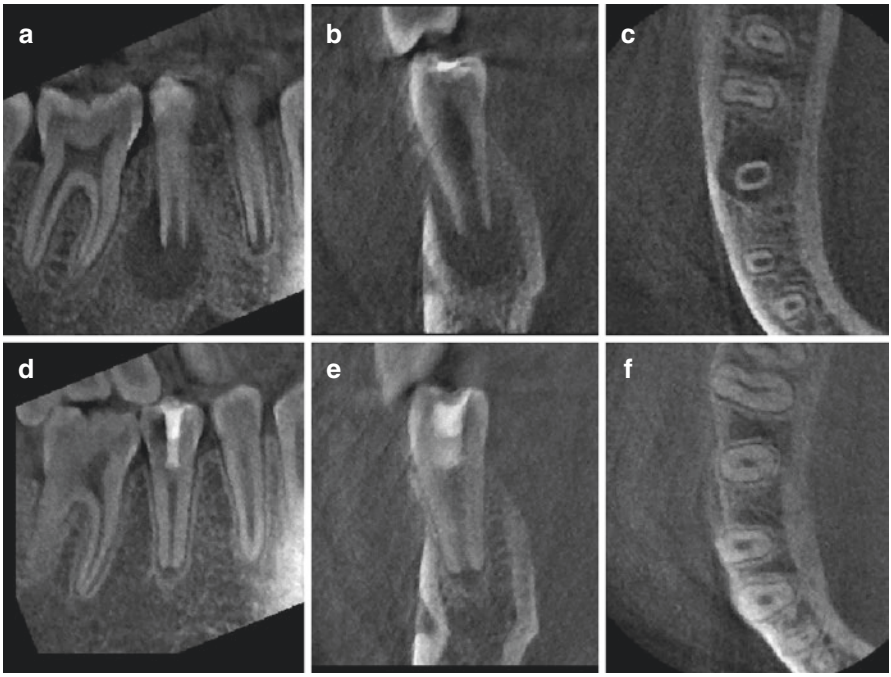

Fig. 5.8 Cone-beam CT corroborates apical healing by revascularization. Preoperative CBCT of mandibular right second premolar shown in Fig. 5.2 with *dens evaginatus*; sagittal, coronal, and axial views are shown in panels **a**–**c**, respectively. CBCT postoperative images at 16 months post-treatment (**d**–**f**) demonstrate resolution of apical periodontitis in all three views with confirmed maturation and root-end closure (Courtesy of Dr. Mitsuhiro Tsukiboshi, Aichi, Japan)

subsequent studies, attesting to elimination of endodontic infection and resolution of apical bony lesions by revascularization [41, 64, 66]. Several variants of this procedure have been published [42, 67, 68], and almost all studies demonstrate inflammation resolution and enhanced root formation after revascularization procedures.

It is important to address the question, "do procedural details matter?" Current investigations in pulp revascularization demonstrate successful resolution of periradicular inflammation and continued root formation (Fig. 5.9) [41, 64, 66, 69–74]. In fact, the vast majority of cases documented in the literature demonstrate nearly 100 % success rate and 100 % rate of apical closure, and such outcomes were achieved in various studies despite altered treatment protocols (Table 5.1). Supporting this evidence, Jung et al. (2008) [69] reported cases with CH or TAP as intracanal dressing and those with or without intracanal bleeding. All eight cases in this study showed resolution of inflammation and apical closure. Shah et al. (2008) [71] showed a series of 14 revascularization cases with NP-CAP that were dressed with formocresol, as opposed to TAP or CH. All these cases showed complete healing of apical lesions and root-end closure. Success of revascularization appears to

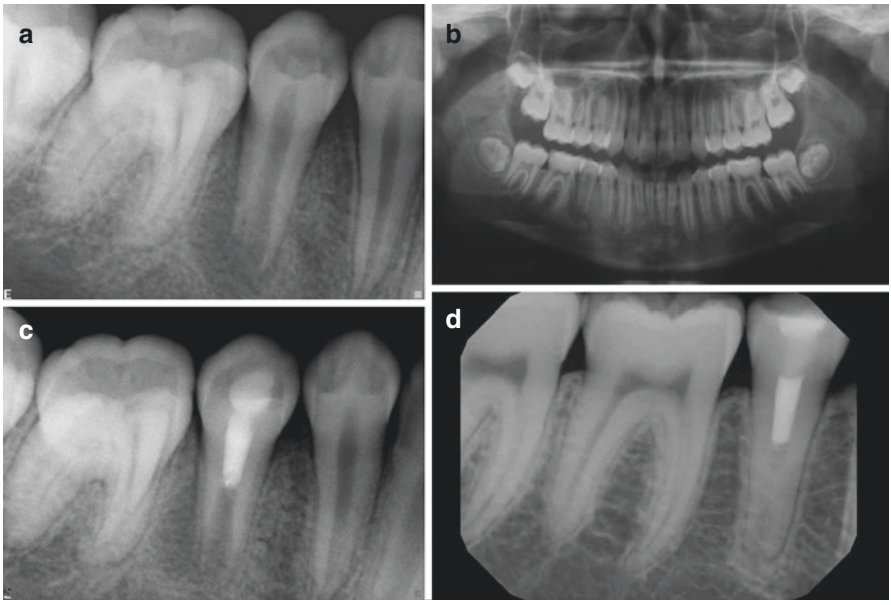

Fig. 5.9 Revascularization promotes root maturation. Radiograph of a 12-year-old male patient exhibiting incomplete root formation and large periapical lesion associated with a necrotic mandibular right second premolar showing *dens evaginatis* anatomy (**a**). Panorex shows gutta-percha point placed through the buccal sinus tract is directed to periapical lesion (**b**). Postoperative radiograph after canal debridement, disinfection with NaOCl and triple antibiotic paste (TAP), and MTA placement coronally and sealed with a bonded restoration (**c**). Six-year radiographic recall shows root wall thickening, root-end closure, and resolution of apical pathosis (**d**) (Courtesy Dr. Mark Olesen, North Vancouver, Canada)

depend largely on disinfection of root canals and recruitment of resident MSCs into the canal space rather than technical details of the revascularization procedure per se. Hence, future endeavors in regenerative endodontic research should focus on restoring the functionality of regenerated dental pulp tissue through pulp-dentin regeneration rather than the technical details of revascularization.

5.3.2 Pulp-Dentin Regeneration

Ongoing research indicates that the success rate of revascularization is very high and approaching ninety percent. However, these preliminary outcomes do not reflect data derived from long-term studies with larger sample sizes (see Table 5.1). The remaining question is whether revascularization achieves regeneration of pulp-dentin complex, which is histologically verifiable, showing the organized structure of a palisading odontoblast layer facing mineralized dentin. According to several animal studies and few case reports of extracted human teeth after revascularization, the answer is “no.” Using a canine model, Wang et al. (2010) [44] showed that

Table 5.1 Characteristics of revascularization protocols and the treatment outcome

Ref no.	No. cases	Disinfection	Canal dressing	Bleeding	No. visits	Duration of Tx	Success	Follow-up[a]
69	Case 1	5 % NaOCl	TAP[b]	None	7	>14 weeks	1/1	60 mo.
69	Case 2	5.25 % NaOCl	TAP	None	2	11 days	1/1	24 mo.
69	Case 3	5 % NaOCl	CH	None	3	10 weeks	1/1	10 mo.
69	Case 4	5.25 % NaOCl	TAP	None	2	2 weeks	1/1	24 mo.
69	Case 5	2.5 % NaOCl	TAP	Bleeding	3	3 weeks	1/1	24 mo.
69	Case 6	2.5 % NaOCl	TAP	Bleeding	2	2 weeks	1/1	24 mo.
69	Case 7	2.5 % NaOCl	CH	Bleeding	3	4 weeks	1/1	12 mo.
69	Case 8	2.5 % NaOCl	TAP	Bleeding	3	7 weeks	1/1	17 mo.
69	14	3 % H_2O_2 2.5 % NaOCl	Form	Bleeding	2–3	ND	14/14	<40 mo.
66	23	2.5 % NaOCl	TAP	None	ND	1–25 mo.	23/23	6 - 108 mo.
73	2	6 % NaOCl 2 % CHX	TAP	Bleeding	3	6 weeks	2/2	18 mo.
72	1	6 % NaOCl 2 % CHX	None	None	1	One Day	1/1	19 mo.
64	6	2.5 % NaOCl	CH	Bleeding	3	7 weeks	6/6	10 mo.
74	3	3 % NaOCl	Misc[c]	Bleeding	3	4 weeks	3/3	<48 mo.
41	20	2.5 % NaOCl	TAP	Bleeding	3	ND	20/20	<29 mo.

Abbreviation: *TAP* triple antibiotic paste, *CH* calcium hydroxide, *ND* not determined, *Tx* treatment, *Form* formocresol

[a]Follow-up period given in months post-op

[b]Varied protocol (TAP/CH/Erythromycin- CH)

[c]misc antibiotics included ciprofloxacine, metronidazole, and cephalosporin

revascularization led to intracanal cementum-like tissues juxtaposed to the dentinal wall. This finding was confirmed in a similar study in which the authors showed absence of organized odontoblastic layer in revascularized canine root canals [75]. Likewise, a case report of extracted human teeth demonstrated the occurrence of ectopic tissue formation in revascularized pulp, mainly composed of bone, cementum, and fibrous tissues, lacking evidence of organized pulp-dentin tissues [43]. Hence, evidence indicates that revascularization with or without growth factors (e.g., PRP) is not capable for regeneration of pulp-dentin complex and induces formation of ectopic tissues in root canals.

Clues in the requirement of tissue regeneration in pulp were suggested by a murine study in which pulp regeneration was performed in the presence or absence of cell transplantation [46, 47]. In both published studies, organized odontoblast-like layer was visible in the groups in which pulp MSCs were transplanted, while those without cell transplantation lacked organized pulp-dentin microstructure. Again, these studies demonstrate the critical requirement of pulp cell transplantation for pulp-dentin regeneration.

An important question is why revascularization with intracanal blood clot formation fails to regenerate dental pulp but allows ectopic osseous and fibro-tissue/cemental tissue formation. The answer to this question can be found in an earlier study, which showed that MSCs from different tissue sources retain their differentiation capacity directly reflecting the tissue of their origin [65]. For instance, upon transplantation into immunocompromised mice, MSCs from bone marrow formed osteogenic nodules; those from dental pulp formed pulp-dentin-like tissues; and those from the PDL formed fibrotic tissues and cementoid tissues. It is presumed that dental MSCs from different sites of the dentoalveolar organ are not the same. Accordingly, intracanal bleeding would recruit endogenous MSCs, primarily from periradicular tissues, that include alveolar bone and PDL, which result in differentiation into osseous and fibro-tissues/cemental tissues, respectively. Therefore, it appears that regeneration of functional dental pulp can only be accomplished by cell-based approaches, which at the present time can only be performed at preclinical levels. While pulp revascularization is highly efficacious in eradication of apical periodontitis, future research should focus on clinical translation of pulp-dentin regeneration techniques. In doing so, endodontists will be able to fully restore the vital pulp with its prescribed functionalities, including the sensibility of the environmental changes, occlusal force cognizance, restitution of the intrapulpal defense mechanisms against microbial insults, and completion of root development and apical closure.

5.4 Treatment Recommendations for Regenerative Endodontic Therapies

5.4.1 Vital Pulp Therapy

The following are treatment guidelines for DPC and pulpotomy procedures [76].

- After a differential diagnosis and local anesthesia, the tooth is isolated with a dental dam and the crown disinfected with 5.25–8.25 % NaOCl or 2 % chlorhexidine. Soft debris is removed with a spoon excavator and a high-speed diamond or carbide bur is used to remove undermined enamel. Illumination and optical magnification are recommended during caries removal.
- Caries removal is augmented with multiple applications of caries-detector dye using spoon excavators and slow speed no. 2–6 carbide round burs until no or only light pink staining is evident.
- Depending on the degree of pulpal exposure and involvement, the operator must assess the health of the remaining tissue and determine the extent of pulp tissue preservation and/or removal. If normal tissue is evident on exposure, then DPC can be initiated after hemostasis. However, necrotic tissue must be removed until healthy tissue is visible with PP or CP using a high-speed round diamond drill with water spray.
- Hemorrhaging is controlled by the placement of a cotton pellet moistened with 5.25–8.25 % NaOCl with a contact time of 1–10 min. If tissue hemostasis is not

attained in 10 min or the entire pulpal roof or axial wall removed during excavation, then a CP or pulpectomy is indicated.

- Excess NaOCl should be removed using water spray and the dentin gently dried before applying the CSC. The material is mixed according to the manufacturer's instructions. It is placed directly over the exposed pulp tissue and majority of surrounding dentin with DPC procedures. It should cover all exposed tissue and proximal dentin in PP or CP procedures. The CSC placement should have a minimum thickness of at 1.5–2.0 mm with DPC and thicker when initiating PP or CP. The CSC can be padded down using a moist cotton pellet during placement.
- With slower setting CSCs, a moist cotton pellet or gauze can be placed over the material and a provisional material provided in the two-step technique. The patient is then re-evaluated on a second visit using a cold test to determine pulp vitality with DPC or PP and a permanent restoration placed after confirming cement curing.
- When using faster setting CSCs, a flowable resin-modified glass ionomer cement can be used to cover the hardened cement before a final restoration is provided on the same visit. This can also be used for slow setting CSCs; however, it becomes challenging when a larger aliquot of the unset cement is used. Bonded composite restorations must be placed according to manufacturer's recommendations using a dental dam and are preferable to amalgam restorations.
- Radiographic follow-up, cold testing, and subjective symptomatology should be evaluated at 6 and 12 months for DPC and PP and yearly thereafter if possible. In immature permanent teeth, the cases should be followed up to evaluate root maturation. For CP, teeth should be monitored radiographically for absence of periapical disease and symptomatology at 6 and 12 months and continued on a yearly or biyearly basis to assess apexogenesis.

5.4.2 Root Canal Obturation (Apical Barrier Formation) with CSCs

Treatment for pulpless teeth with open apices for apexification procedures demands profound local anesthesia and proper isolation protocols with minimum canal preparation. This is a valid option for challenging behavioral management cases in pediatric patients. The working length is established using radiographic confirmation. Passive irrigation with 1.5 % NaOCl for 15–20 min is recommended and the canal or canals are minimally filed along the walls circumferentially with larger K-files since canal enlargement is not required.

- After the canal is dried with large paper points, the bioceramic cement or CSC can be placed with a MTA or amalgam carrier and the cement compacted down into the canal by using the back end of an extra coarse paper point, gutta-percha point, endodontic plugger, or Glick instrument. A large K-file is used to compact the CSC toward the apical limit using gentle pressure to avoid cement extrusion, although CSC overfill does not compromise the outcome.

- Clinicians should exercise caution when using ultrasonic devices with endodontic pluggers in order to compact MTA or other CSCs, as excessive extrusion of the cement is a common drawback in teeth with open apices. It has been shown that manual compaction of MTA provides dense compaction and may be preferable to using ultrasonic condensation techniques [77].
- When uncontrolled hemorrhage is present during the obturation procedure, larger amounts of the CSC must be placed and condensed quickly. The cement can be introduced into the canal in bulk using a Glick instrument or transported with an amalgam carrier.
- Dry cotton pellets with or without calcium hydroxide powder or the back end of extra course paper points can be placed over the CSC using moderate pressure until hemostasis and cement stability are achieved. In cases where hemostasis is not attainable, the canal should be filled with CH paste and the patient rescheduled for CSC obturation at a later time.
- A radiograph should be taken after CSC barrier placement to assess density and position in relationship to the apical collar or rim. When completed, the obturation should ideally produce a 4–5 mm CSC plug to ensure an adequate seal [78].
- If the obturation appears satisfactory, the excess CSC can be flushed with sterile water using a side-venting needle (Vista ™ Dental Products) and the remaining canal space dried with large paper points. The cement is then flattened with a plugger and the canal backfilled with warm vertically compacted gutta-percha and sealer. Superior outcomes are achieved when the access orifice is restored and sealed with a bonded composite material [79].
- Radiographic follow-up to assess apical maturation and resolution of periapical pathosis is recommended at 6 and 12 months postoperatively and continued on a yearly or biyearly basis as indicated (Fig. 5.10).

5.4.3 Pulp Revascularization

Treatment of necrotic teeth with open apices can be accomplished using revascularization approaches, which depends largely on resolution of intracanal infection and periradicular inflammation.

- During the first appointment, root canal debridement and disinfection are to be performed. The disinfection protocol follows those published in the literature [41, 66]. Briefly, patients are anesthetized with 3 % mepivacaine without vasoconstrictor. Tooth should be isolated with dental dam placement and accessed with no. 4–6 round bur while removing all caries. Canals are instrumented with gentle circumferential filing using ISO no. 60 file for enlarged canals or using rotary systems, e.g., profile no. 25–40 with 0.04 taper (Dentsply). Necrotic debris must be irrigated using 20 ml 1.5 % NaOCl and rinsed with 10 ml saline to remove residual NaOCl. Canals are then dressed with CH, and the tooth is temporized with IRM.

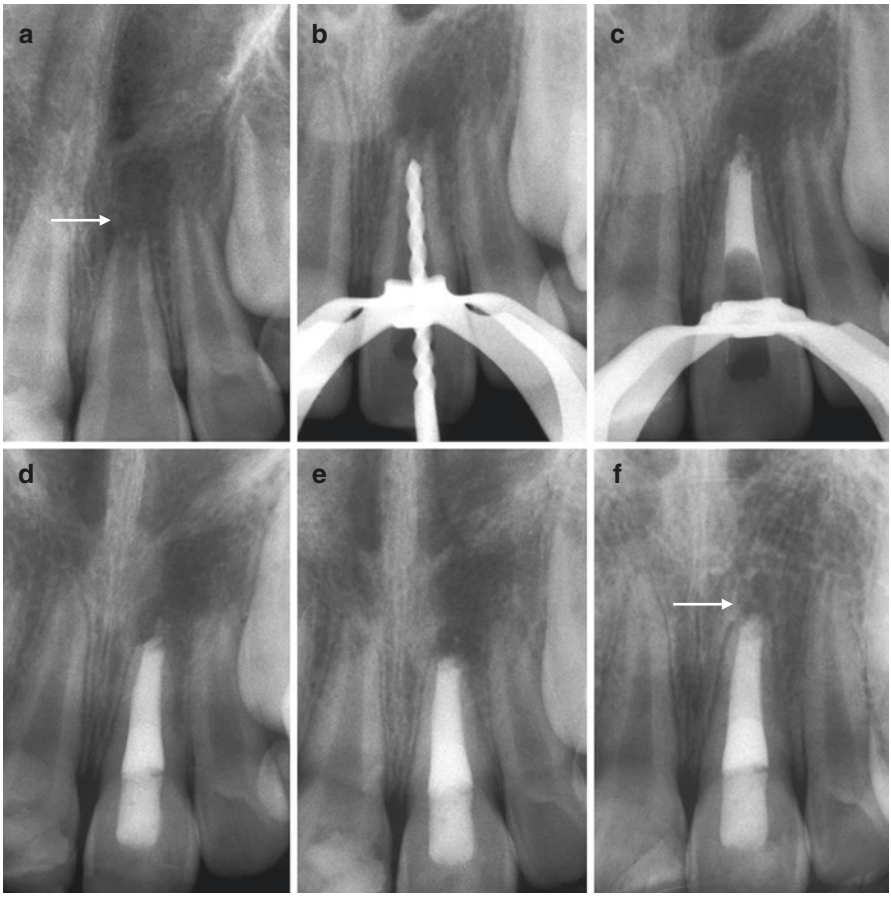

Fig. 5.10 Periapical radiograph of traumatized maxillary left central incisor in an 8-year-old male patient shows a wide-open apex and large periapical radiolucency (*arrow*) (**a**). Radiograph of file placement establishing approximate working length (**b**). Radiographic confirmation of MTA apical barrier placement (**c**). Final radiograph after obturation with thermoplastic gutta-percha, sealer, and bonded core (**d**). Three-month radiographic recall shows advancing remineralization of the periapical defect (**e**). Four-year 6-month radiographic review demonstrates apical closure and satisfactory periapical healing (**f**). The patient remained asymptomatic and presented without staining of the clinical crown (©Dr. George Bogen. All Rights Reserved)

- On the second visit, revascularization will be performed by accessing the canals under local anesthesia, 3 % mepivacaine without the vasoconstrictor under dental dam isolation. Canals are irrigated with 20 ml 1.5 % NaOCl to remove CH and 17 % EDTA to remove the smear layer and then rinsed with 10 ml saline [80]. If the patient is symptom-free and canals lack evidence of residual infection, canals are revascularized using induced bleeding with no. 25–35 K-files. If there is evidence of residual canal debris, infection, or continued symptoms, the canal should be debrided again with 1.5 % NaOCl, medicated with CH and

temporized. For these patients, revascularization is performed in subsequent visits, pending resolution of intracanal infection, and patients' symptoms. After the induction of bleeding to the cementoenamel junction (CEJ), blood coagulation, and subsequent clot formation, the canal is coronally sealed with CollaPlug (Zimmer Dental) or similar material and MTA (Dentsply) or other CSC, and the tooth is provisionalized.

- At the final treatment visit one week postoperatively, the tooth is evaluated to ensure setting of MTA or CSC and, if satisfactory, restored with a permanent restoration.
- Patients should be recalled after 6 months and 1 year for postoperative clinical and radiographic evaluation to assess root maturation and root canal wall thickening.

Conclusions

Conventional RCT has been the treatment choice for teeth with pulpal and periradicular pathosis for nearly a century. During this period, a profusion of new techniques, materials, and technologies has emerged to enhance the efficiency and predictability of treatment. However, the procedure itself has essentially centered on the identical concept, e.g., pulp debridement, shaping of root canals, and obturation with foreign materials. This practice has clearly led to remarkable success in retaining the natural dentition and restoration of masticatory function. Nevertheless, the outcome of root canal therapy has not been improved for the past two decades [53]. In conventional root canal therapy, the physiological functions of the dental pulp are permanently lost and therefore compromise long-term tooth survival.

In recent years, with persistent interest in maintaining pulp vitality, several important events have contributed to the advancement of regenerative approaches in endodontics. Primarily, the introduction of biocompatible and dimensionally stable biomaterials such as MTA and other CSCs that enable repair, preservation, and partial or complete regeneration of dental pulp tissues [81, 82]. Another key component has been the discovery of undifferentiated MSCs in dental pulp that permit regeneration of the pulp-dentin complex [83, 84]. These events constitute the two elements of the "triad" of endodontic regeneration, while the final component is the control of inflammation, which can be accomplished by conventional materials, including CH and NaOCl.

The endodontic specialty is currently positioned to advance beyond conventional root canal therapies and embrace future strategies in vital pulp therapy and bioengineering technology. These new pathways focus on research and clinical efforts with the main goal of vital pulp preservation and de novo functional pulp tissue regeneration in devitalized teeth. These developments have coincided with major advancements in adhesion technology and the introduction of permanent restorations and biomaterials that reliably seal and promote continued pulpal protection. With combined treatment approaches based on stem cell engineering and the bioactive material evolution, a new horizon in restoring, maintaining, and regenerating functional dental pulp tissue has emerged. Finally, pulp biology and endodontic therapy are coming together.

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Endodontic Pharmacotherapeutics

6

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Abstract

Managing dental pain of endodontic origin is complicated by the multiple biological mechanisms that contribute to several distinct painful clinical entities including dentinal hypersensitivity, pulpitis pain, periapical pain, postoperative pain, and persistent posttreatment pain. In general pain of endodontic origin is best managed by initiating endodontic treatment, during which time the source of inflammation is mostly removed. In order to successfully perform endodontic treatment, the affected pulpal tissues and adjacent periodontal tissues must be completely anesthetized using local anesthetics. This is complicated by the fact that inflammation reduces the efficacy of local anesthetics. Strategies for obtaining successful pulpal anesthesia so that endodontic treatment can be administered with minimal or no discomfort to the patient are discussed. Postoperative endodontic pain is common and can be severe, and clinicians need to utilize anti-inflammatory analgesics to manage their patient's symptoms. Occasionally antibiotics are required to manage a spreading infection. In summary, successful endodontic treatment requires the wise use of pharmacotherapeutics before, during, and after clinical treatment. This chapter provides a review of the evidence and practical guidance for the use of pharmacotherapeutics with the overall goal to improve the prognosis of eliminating endodontic pain for our patients.

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6.1 Pain Is a Complex Sensory Experience

Orofacial pain is a widespread problem that accounts for around 40% of an estimated $80 billion in pain-related healthcare costs annually in the United States [1]. Odontalgia, or toothache, is a common source of orofacial pain and can be a distressing and intensely painful experience, often leading to disruption of daily activities [2–5]. Pain is an important motivator for symptomatic patients to seek dental care, while a fear of pain during or after dental procedures causes some patients to avoid seeking routine dental treatments [6–9]. Pain is a complex sensory experience with emotional, conceptual, and motivational components. As such the experience of pain is unique to each individual [9]. Given the multifaceted nature of pain, it is not surprising that there are numerous and diverse means to prevent or inhibit the pain in a clinical setting, which run the gamut from relaxation strategies to reduce patient anxiety, to blocking sensory nerves with local anesthetics. This chapter will focus on pharmacological approaches to managing pain and infection before, during, and after endodontic treatment.

6.1.1 Mechanisms of Pain of Endodontic Origin

One might think the term odontalgia or toothache should describe a fairly homogenous clinical phenomenon. However, we now know that there are multiple etiologies for pain originating from teeth that include inflammation of the dental pulp, inflammation of periapical tissues, transdentinal stimulation of pulpal neurons, and even persistent pain after surgical intervention.

6.1.1.1 Nociceptive Pain

Nociceptive pain describes the inherent ability of pain fibers, or nociceptors, to detect stimuli that are potentially tissue damaging, and can be of a thermal, mechanical, or chemical nature. Nociceptive pain is mediated by smaller-diameter sensory afferents that include the myelinated Aδ- and unmyelinated C-fiber classes. The dental pulp appears to have a unique sensory capacity, as almost any stimulus that activates pulpal nerve endings produces the sensation of pain. The neural component of the pulp tissue consists of sensory trigeminal afferents and sympathetic and parasympathetic efferent fibers [10, 11]. These fibers project into the pulpal tissues of the root canals through the apical foramen and are closely associated with blood vessels, forming a collagen-bound neurovascular bundle. Anatomical studies have demonstrated that the terminal portion of pulpal afferents can extend up to 150 μm into the predentin or the dentinal tubules and form a close association with the processes of odontoblasts [12, 13]. These sensitive fibers act like nociceptors, in that they produce pain when stimulated. However, according to their diameter, conduction velocity, and expression of specific markers that identify classes of neurons, most of these fibers are large-diameter myelinated Aβ-fibers, which typically transduce non-painful stimuli such as light touch [14–16]. This is an apparent paradox, as pain is thought to be exclusively mediated by the activation of Aδ- and C-fiber

nociceptive afferents. In an attempt to explain this paradox, Fried and colleagues have proposed the novel term "algoneuron" to explain the observation that the pulp is innervated primarily by larger-diameter fibers that appear to, paradoxically, transduce painful stimuli [17].

Also found in the pulp are Aδ-fibers, which have a smaller diameter and slower conduction speed relative to the Aβ-fibers. At this time it is not known whether these fibers have a distinct function from that of the Aβ-fibers. Collectively the Aβ- and Aδ-fibers respond to stimuli that would produce fluid movement in dentinal tubules such as drilling, sweet foods, cold air, and hypertonic solutions and produce a sharp, bright, pain when activated [18, 19]. The low threshold for activation and the peripheral localization of these fibers suggest that they can become activated and produce pain without the presence of irreversible damage to the pulp. These fibers contribute to the increased sensitivity observed after restorative work involving enamel and dentin removal or toothbrush abrasion (see Dentinal Pain Sect. 6.1.2.3) [20].

Finally, the C-fiber subtype of sensory neurons, although less abundant, is are also found in the pulp. These are unmyelinated fibers with a low conduction velocity, a smaller diameter, and a higher excitation threshold. They are located deeper within the pulp than the myelinated fibers. C-fibers are activated by heat, mechanical, and chemical stimulation and produce a dull, diffuse, and longer-lasting pain [13]. It is thought that when C-fiber involvement produces pulpal pain, the patient reports a diffuse, dull, and achy pain that can be difficult to localize. This type of pain may suggest that concomitant damage to the pulp proper has occurred, which is more likely to be irreversible. While an injury results in an interruption in the pulp microcirculation, the C-fibers continue to function for a longer time compared to A-fibers as their oxygen consumption is higher than A-fibers [20]. This characteristic also underlines the familiar clinical occurrence in which a tooth that responds negatively to testing with a cold CO_2 stick is painful to mechanical instrumentation during endodontic therapy [21].

The ability of a sensory neuron to detect specific types of stimuli is dictated by the receptors that are expressed in the peripheral terminal. Of particular relevance to the detection of painful thermal, mechanical, and chemical stimuli is the presence of transient receptor potential channels (TRPs) [22, 23]. The most-studied TRP channels are TRPV1, TRPV2, TRPA1, and TRPM8, all of which are expressed in pulpal afferents and thus have the potential to mediate thermal and mechanical sensation in the dental pulp (Fig. 6.1). For example, applying heat directly in the tooth produces pain, which is most likely mediated by activation of the TRPV1 channel [24, 25]. In addition to heat, Aδ- and C-fiber neurons also are responsive to noxious and non-noxious cold temperatures. Calcium imaging studies revealed that neurons responding to cold temperatures <18°C are more common in the trigeminal ganglion (14%) than in the dorsal root ganglion (7%) [26]. Both the TRPM8 and TRPA1 channels are stimulated by cold temperatures with thresholds of 25°C and 17°C, respectively, and both receptors have been localized in nerve fibers innervating the dental pulp [27, 28]. Further work is needed to determine whether TRPM8 and TRPA1 contribute to the transmission of painful cold in the dental pulp.

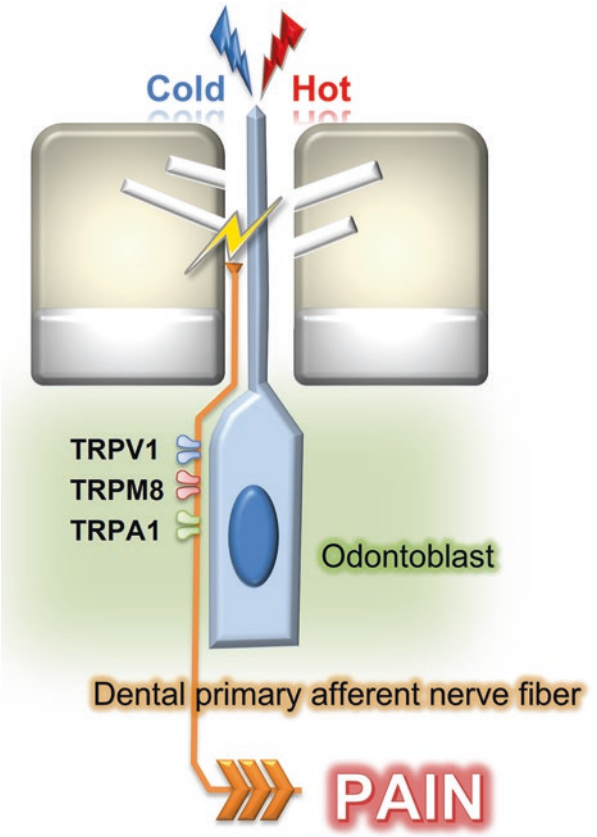

Fig. 6.1 Molecular mechanisms of neural theory. Thermo-TRP channels are functionally expressed by dental primary afferents (Figure adapted from Chung et al. (2013) [22])

The role of odontoblasts in transducing nociceptive pain in the dental pulp is an active topic of debate [29]. Importantly, odontoblasts also appear to express several of the TRP receptors, which support their role in detection of sensory stimuli [30, 31]. The mechanism transduction of sensory stimuli from odontoblast to peripheral nerve is not clear, and studies attempting to better understand these mechanisms are ongoing.

6.1.1.2 Inflammatory Dental Pain

Inflammation is a normal protective immune response of the host to tissue infection. Circulating immunocompetent blood cells migrate through the endothelial barrier to gain access to the damaged tissues and eliminate injurious pathogens. However, uncontrolled inflammation may result in a full range of acute, chronic, and systemic inflammatory disorders [32]. Dental pulp tissues are rich in blood vessels and nerve fibers and have a relatively low interstitial compliance because of its enclosure in a rigid dentin chamber. Inflammation of the dental pulp, or pulpitis, can be intensely painful [33].

When infected dental caries approximates the dental pulp, lipopolysaccharide (LPS) from bacterial cell walls, and other virulent factors, stimulate an

inflammatory response from a variety of cells residing in the dental pulp tissues [34, 35]. The affected cells release inflammatory mediators such as prostaglandins and bradykinin, which then activate or sensitize pulpal sensory neurons, leading to thermal and mechanical hyperalgesia and allodynia [24, 36]. In advanced stages of pulpal inflammation, large parts of the pulp become inflamed and the pulpal tissue may ultimately degrade. During the degradation process, pulpal nerve fibers might remain partially intact and continue evoke spontaneous pain sensations. The diagnostic terms reversible and irreversible pulpits are based on the clinical prognosis of the pulp, but evidence-based clinical measurements to determine whether a pulp is truly reversibly or irreversibly inflamed are lacking [37–39]. Nonsteroidal anti-inflammatory drugs (NSAIDs), opioid analgesics, acetaminophen, and steroids are all effective analgesics for treating inflammatory pulpal pain.

6.1.1.3 Dentinal Pain

The loss or compromise of enamel or cementum can cause exposure of the dentin to the oral cavity and produce the clinical condition of dentinal hypersensitivity. Dentinal pain is usually a brief, sharp pain that occurs in response to thermal, evaporative, tactile, osmotic, or chemical stimuli. The hydrodynamic theory explains that stimuli producing fluid movement within the dentinal tubules can activate the very sensitive nerve fibers that innervate the dentinal tubules [40]. Dentin sensitivity has a direct correlation with the dentinal tubule size and patency [41]. The loss of the enamel or cementum is commonly a consequence of attrition, erosion, abrasion, or abfraction. It is estimated that 30% of adults have dentin hypersensitivity at some point in their lives [11, 42]. Ultimately the symptoms may resolve when the tubules become occluded by salts, smeared dentin, peritubular dentin, and secondary or reparative dentin. Most existing therapeutics for dentinal hypersensitivity occlude the tubules, thus preventing dentinal fluid movement and, eventually, pain. Therapies include toothpastes containing strontium or oxalate salts, which deposit salts within the dentinal tubule. Professionally applied glass ionomers, resins, and resin adhesives are also effective [43]. Conservative treatments such as these are recommended as an initial strategy for providing pain relief, as there is usually little pulpal inflammation or pathology observed in teeth with dentinal hypersensitivity. Rather, this condition is just the expression of the profound sensitivity of normal pulpal sensory neurons to stimulation when the protective enamel or cementum is compromised.

6.1.1.4 Neuropathic Pain

Neuropathic pain is a type of chronic pain condition, which is caused by a primary lesion or dysfunction in the peripheral or central nervous system. Neuropathic pain has a complicated pathophysiology and can affect the orofacial region as well as other parts of the body. Of relevance to dentistry and endodontics is that it is now understood that neuropathic pain might be initiated by dental procedures including third-molar or implant surgery, surgical and nonsurgical endodontic treatment, and even dental injections [44, 45]. Neuropathic pain can also occur as a consequence of other disorders including diabetes (diabetic neuropathy), HIV (HIV neuropathy), and herpes zoster (postherpetic neuralgia). These peripheral neuropathies can occur

in orofacial regions including inside the mouth, in which case diagnosis can be very challenging. Unfortunately, many patients undergo unneeded dental procedures in an attempt to alleviate their pain. As neuropathic pain can be severely debilitating and intractable, measures to prevent or minimize nerve damage should always be implemented during treatment planning [46]. Lower molars and premolar teeth with apical roots approximating the mental nerve foramen of inferior alveolar canal should be approached with care to minimize damage to major nerve branches [47]. Typical analgesics and NSAIDs have minimal efficacy for treating neuropathic pain, although opioids are somewhat effective. In general, drugs that depress the nervous system have been found to have efficacy in treating neuropathic pain, including anticonvulsants such as gabapentin and antidepressant drugs such as nortriptyline [48, 49].

6.2 Endodontic Pain Management

When an odontogenic source of pain has been identified, and the clinical intervention decided on by the practitioner and patient is root canal treatment, the most predictable route to alleviating pain is to remove the source of the infection, usually by caries removal, pulp extirpation (in vital cases), and some form of chemomechanical canal debridement. Pain management is essential, both during and after endodontic treatment, and knowledge of the judicious usage of pharmacotherapeutics is critical to a practitioner's success.

6.2.1 Intraoperative Pain Management: Local Anesthetics

The foundation of intraoperative pain management in the practice of endodontics is the effective administration of local anesthetics to block the transmission of sensory input from the nerve endings found in the dental pulp and periodontal tissues surrounding the treated tooth. Although this class of drugs is generally safe, practitioners should be familiar with dose limitations, side effects, and potential allergic reactions [50, 51]. Local anesthetics bind to sodium channels located on the cell membrane of sensory neurons, preventing the influx of sodium ions into the nerve fiber (Fig. 6.2). This prevents depolarization and action potential propagation along the neuron, effectively blocking the transmission of pain and other sensory signaling. As pain is the dominant sensation produced when stimulating sensory fibers of the dental pulp, complete pulpal anesthesia is required to be able to perform endodontic treatments, as well as many restorative treatments on teeth containing vital pulpal tissue.

6.2.1.1 Inflammation Reduces the Efficacy of Local Anesthetics

The ability to reliably obtain effective anesthesia is challenged in the setting of inflammation. A vital but inflamed dental pulp can be especially difficult to anesthetize, especially when attempting to utilize an inferior alveolar nerve (IAN) block to

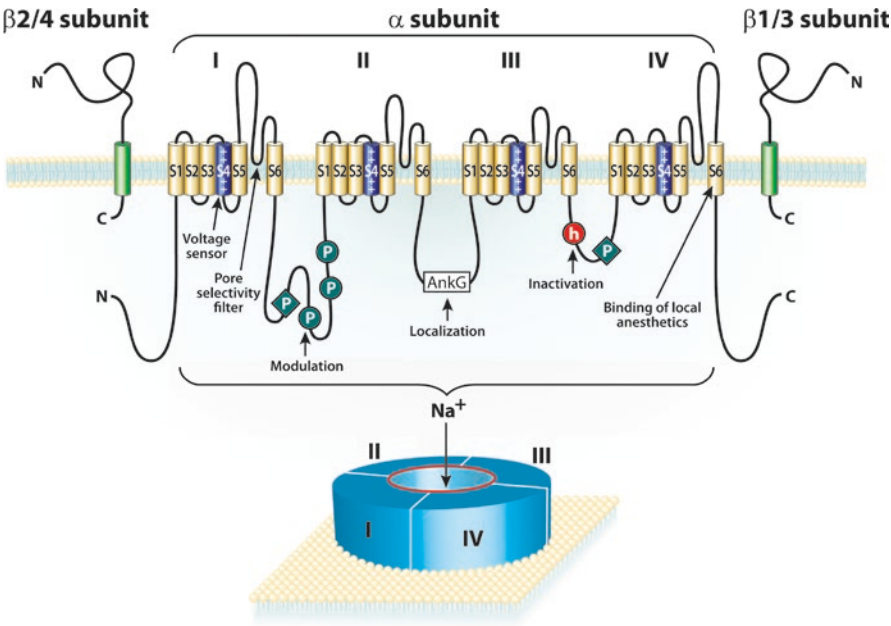

Fig. 6.2 Primary structures of the α- and β-subunits of the voltage-gated sodium channel. The α-subunit is composed of four homologous domains (DI–DIV), each with six α-helical transmembrane segments (S1–S6). The S4 segment of each domain contains positive charged amino acid residues and forms part of the voltage sensor. The linker that connects S5 and S6 forms the external mouth of the channel pore and the selectivity filter. The cytoplasmic linker between DIII and DIV contains a critical hydrophobic motif that acts as a "hinged lid" (h) and is responsible for fast inactivation. Slow inactivation depends in part on residues located in the external pore lining of the channel. The α-subunit contains several receptor sites for neurotoxins (not shown). Amino acid residues in the S6 segment of DI, DIII, and DIV in the inner cavity of the channel pore form the binding site for local anesthetics and related antiepileptic and antiarrhythmic drugs such as lidocaine, mexiletine, carbamazepine, and phenytoin. Sodium channel blockade by these drugs is relatively weak at resting potential but strong if the membrane is depolarized ("use-dependent" blockade). A conserved amino acid sequence at the intercellular loop linking the DII–DIII binds ankyrin G (Ank) and is critical for targeting the channels to specific domains of the cell. The large intracellular loop between DI and DIII contains several modulatory phosphorylation sites (P) by protein kinases A and C. The carboxy-terminus domain associates with the β-subunit and other adaptor and cytoskeletal proteins. The auxiliary β-subunits are proteins with a single transmembrane domain, a long, heavily glycosylated extracellular amino-terminal domain that has an immunoglobulin-like structure with homology to cell adhesion molecules, and a short intracellular C-terminal tail. These subunits regulate targeting and kinetics of the channel (With permission from [208])

treat a painful mandibular molar. In this scenario, the attempt to successfully anesthetize the inflamed pulp with IAN block alone is more likely to fail than to succeed, with success rates reported in the range of 25–40 % [52–55]. Multiple hypotheses exist to explain the reduced efficacy of local anesthetics in inflamed dental pulp (summarized here [56, 57]). Currently, the most accepted theory hinges on the concept of neuronal plasticity.

Neuroplasticity describes the inherent property of individual neurons and complex nervous tissues (e.g., the brain or spinal cord), to adapt to injury or disease, as well as changes in behavior or environment. More specifically, sensory neurons are fundamentally altered when the nerve terminals themselves are damaged or the surrounding tissues are inflamed. The amount and type of receptors and neurotransmitters that are expressed in a given class of sensory neurons are dynamic and change in response to growth factors and inflammatory mediators. Ultimately these changes can cause the neuron to exist in a sensitized state, where it is more easily activated by both painful and non-painful stimuli. These molecular changes underlie the clinical observations of hypersensitivity and allodynia after injury. Clinical examples of the manifestation of allodynia in the inflamed periodontal ligament include pain on biting or to mild percussion of the tooth. A typical example of hypersensitivity in the inflamed dental pulp is an exaggerated painful response to a cold stimulus. Of interest to the discussion of local anesthetics, inflammatory mediators directly influence the expression and activity of several important sodium channels, thus influencing the excitability of sensory neurons, and the efficacy of local anesthetics (Fig. 6.2).

6.2.1.2 Sodium Channel Subtypes

Sodium channels are divided into two distinct classes based on the presence or absence of sensitivity to tetrodotoxin (TTX). The Nav1.8 and Nav1.9 channels mediate the TTX-resistant (TTX-R) current [58, 59]. The $Na_v1.8$ channel is expressed at higher levels under inflammatory conditions, and an increased expression has been demonstrated in human dental pulp in persons experiencing painful pulpitis [60–63]. Importantly, increasing the expression of the $Na_v1.8$ channel reduces the efficacy of lidocaine in blocking neural transduction. Thus, the upregulation of $Na_v1.8$, within nerves innervating the inflamed dental pulp, could contribute to the clinical challenge of achieving adequate local anesthesia during dental procedures. Other sodium channels are likely also involved in mediating inflammatory pain. The channel $Na_v1.7$ is upregulated in many animal models of inflammatory pain and also in humans with painful pulpitis [64, 65]. In summary, multiple sodium channels are involved in the sensitization of sensory neurons. A change in expression of sodium channels, especially $Na_v1.8$, is likely responsible for the clinical observation of reduced local anesthetic efficacy in the setting of inflammation.

6.2.1.3 Pulpal Anesthesia Versus Soft Tissue Anesthesia

When attempting to anesthetize asymptomatic, i.e., noninflamed pulpal tissues, it is important to remember that soft tissue anesthesia of adjacent tissues does not guarantee that pulpal anesthesia was achieved. This is especially true in the mandible, where successful pulpal anesthesia after an inferior alveolar nerve block is 35–60 %, depending on the tooth [66–68]. So before initiating endodontic treatment, especially in the setting of inflammation, it is important to determine whether pulpal anesthesia was obtained. This can be accomplished by repeating pulpal sensibility tests with either a cold or electrical stimulus. However, in the setting of irreversible

pulpitis, even cases where pulpal anesthesia was confirmed using sensibility tests, some patients will still experience pain during treatment [69]. For this reason, supplementary injections and/or other adjunctive therapies are always recommended to minimize the chance of patient discomfort.

6.2.1.4 Supplementary Injections/Adjunctive Therapies

As mentioned previously, given the high rate of local anesthetic failure when performing endodontic treatment on painful teeth, especially in the mandible after IAN block, it is essential to administer additional anesthesia via supplementary routes before attempting to initiate treatment [70, 71]. Although a comprehensive review of the methods and evidence for the various supplementary anesthetic approaches are beyond the scope of this chapter, we wanted to mention that there is a strong support for the use of buccal infiltration (especially with 4% articaine), periodontal ligament injections, as well as intraosseous injections to supplement the IAN block and improve the likelihood of obtaining pulpal anesthesia [69, 72–78].

6.2.1.5 On Choosing a Local Anesthetic

Although there are several types of local anesthetic agents to choose from in the United States, the vast majority of dental practitioners utilize 2% lidocaine, and it remains the standard against which other anesthetics are compared. Articaine (4%) is another commonly used local anesthetic, and numerous studies have compared the ability of lidocaine to articaine in achieving soft tissue and pulpal anesthesia in teeth with normal pulps as well as those with symptomatic irreversible pulpitis. In general the two agents demonstrate comparable efficacy in achieving pulpal anesthesia [79, 80]. The exception is that articaine is more effective at accomplishing anesthesia when administered via infiltration [81]. This appears to be especially true for pulpal anesthesia in both symptomatic and asymptomatic cases when administering supplementary anesthetic via buccal infiltration in the mandible [53, 72, 73, 82]. Therefore, there is strong support for the choice of articaine over lidocaine as a supplementary anesthetic for buccal infiltration, in order to accomplish pain-free endodontic procedures in posterior mandibular teeth [81].

Lidocaine is the anesthetic of choice for nerve blocks including IAN, lingual, and mental nerve blocks. All local anesthetics are neurotoxic and have the potential to cause a neuropathy when administered in sufficient concentration adjacent to a nerve bundle or branch [83, 84]. Clinically this can produce prolonged numbness (anesthesia), prickling or "pins and needles" sensations (paresthesia), or more severe neuropathic pain symptoms in the region innervated by the damaged nerve. Higher concentration formulations such as articaine (4%) and prilocaine (4%) are associated with a higher risk of nerve damage, usually when administered for an IAN block [85–87]. Given the comparable efficacy of articaine and lidocaine in accomplishing pulpal and soft tissue anesthesia, combined with the increased risk of nerve damage with articaine, lidocaine is the anesthetic of choice for IAN block.

Bupivacaine (0.5%) is notable as a local anesthetic agent because it produces long-lasting anesthesia of up to 8 h [88]. Administration of bupivacaine at the end of a clinical procedure is a useful strategy to help reduce postoperative pain

[89–91]. This is ideal when significant levels of postoperative pain are anticipated, including surgical endodontic cases, and for patients who present with a high level of preoperative pain.

6.2.1.6 Preemptive Analgesics for Improving the Efficacy of Local Anesthetics

Given the inherent challenge in obtaining adequate pulpal anesthesia in the setting of inflammation, multiple strategies are needed to optimize the chances for clinicians to perform pain-free endodontic procedures. Studies evaluating the effects of inflammatory mediators on sodium channels have demonstrated that prostaglandin E2 increases the activity of TTX-R sodium channels [92]. Given that TTX-R channels are more resistant to local anesthetics, the important, clinically relevant question is whether pretreatment with an anti-inflammatory agent, for example, the nonsteroidal anti-inflammatory drug (NSAID) ibuprofen, improves the chances of obtaining pulpal anesthesia in patients with symptomatic pulpitis.

This hypothesis has been well tested in clinical studies, many of which were high-quality randomized controlled clinical trials. Several studies demonstrate efficacy for NSAIDs versus placebo in achieving more frequent pulpal anesthesia and/or pain-free endodontic treatment [93–96]. However several trials failed to observe significant differences between drug and placebo, although it should be noted that in the majority of these studies, the trend was for the subjects receiving the NSAID to have more successful rates of anesthesia [97–100]. The variance in results between the studies could be due to differences in study design including varying definitions of irreversible pulpitis (i.e., different subject populations), differences in the definition of successful vs. failed anesthesia, and differences in how the study was powered (i.e., sample sizes). Importantly, the overall evidence supports the use of a single preoperative dose of NSAIDs for improving the chances for successful mandibular pulpal anesthesia via IAN block in patients with painful pulpitis, as demonstrated in a recent systematic review (ibuprofen 600–800 mg, lornoxicam 8 mg, and diclofenac potassium 50 mg were demonstrated to be better than placebo with ketorolac, ibuprofen/acetaminophen combination, and acetaminophen alone being no better than placebo) [101]. Although less studied, there is evidence that pretreatment with other anti-inflammatory agents, such as steroids, can increase the efficacy of pulpal anesthesia or the duration of anesthesia [102, 103]. In summary, pretreatment with an NSAID, such as 600 mg ibuprofen, 1 h prior to initiating endodontic therapy will increase the chances of obtaining pulpal anesthesia, helping to minimize the amount of pain experienced during endodontic treatment.

6.2.2 Postoperative Pain Management

6.2.2.1 Prognostic Factors Related to Endodontic Postoperative Pain

Studies regarding postoperative pain after endodontic treatment, both post-obturation or post-instrumentation for multi-visit treatments, suggest that the frequency and severity of pain are quite varied [104]. This is likely due to differences in when and

how pain was measured, in the patient population studied, and, importantly, in the preoperative pulpal and periradicular status of the subject populations. A recent systematic review reports that the prevalence of postoperative pain reported in individual studies ranges from 20–90 % and severity is usually in the mild-moderate range (10–60 mm on a 100 mm VAS). One week after endodontic treatment, pain prevalence is typically less than 10 %, and reported pain is, on average, reported to be at a low level of intensity [105]. Administering endodontic therapies is clearly an effective way to reduce pain of endodontic etiology, with postoperative pain levels dropping to 50 % of preoperative levels after 24 h [105, 106]. This supports the idea that endodontic interventions, including root canal treatment, and emergency procedures such as pulpectomies and pulpotomies, in the appropriate clinical situations (e.g., the tooth is restorable, the tooth is in function), are the best way to quickly and predictably reduce the frequency and intensity of odontogenic pain.

Several patient factors have been identified that appear to predict the occurrence of postoperative pain. Numerous studies have identified the presence and/or intensity of preoperative pain to be one of the strongest predictors of postoperative pain (Fig. 6.3) [107–109]. This strong association was found in studies on subjects receiving endodontic therapies as well as studies involving subjects receiving other non-dental surgical interventions [110]. The clinical implication of this finding is that patients presenting with pain are more likely to experience significant postoperative pain, and care should be taken to ensure that appropriate postoperative analgesics are prescribed. Biologically, this observation is likely associated with plasticity in the central nervous system associated with the increased input from nociceptors in the peripheral nervous system, with central sensitization likely being an important contributory mechanism.

Other factors associated with postoperative pain include gender (with females experiencing more pain), tooth type (with posterior multi-rooted teeth more painful), and experiencing inter-appointment pain [107–109, 111, 112]. Most importantly, postoperative pain after completion of root canal treatment, or after a first of two or more visits, is a common enough occurrence that analgesics should be

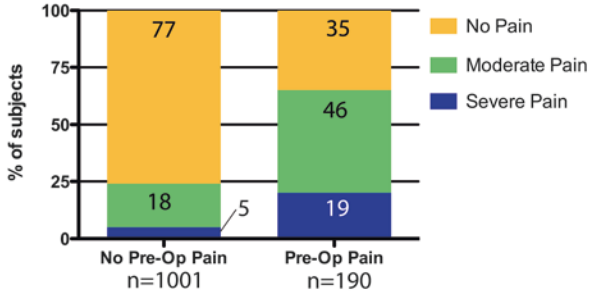

Fig. 6.3 Preoperative pain level is an important predictor of postoperative pain level. This figure shows an example of a study demonstrating how the severity and incidence of postoperative pain after the first day of root canal treatment are predicted by the presence or absence of preoperative pain (Modified from Genet et al. 1986 [209])

regularly prescribed, regardless of the presence or absence of predictive factors. However, the presence of some of these predictive factors might make a clinician more likely to consider a multimodal analgesic approach and/or higher doses, as discussed further below.

6.2.2.2 Nonsteroidal Anti-inflammatory Drugs

The first choice of analgesic class for odontogenic pain, including postoperative endodontic pain, is the nonsteroidal anti-inflammatory drugs (NSAIDs) and includes common analgesics available over the counter such as ibuprofen, aspirin, and naproxen. As inflammation is an important contributory mechanism to odontogenic pain, it follows that anti-inflammatory drugs are quite effective analgesics. Ibuprofen is more effective than aspirin, acetaminophen, or combination drugs such as Vicodin that contain acetaminophen and an opiate type drug such as hydrocodone, in relieving postoperative pain in an oral surgery model [113–115]. There is also good evidence that ibuprofen is an effective analgesic for relieving postoperative endodontic pain [116, 117]. It is important to note that many of these studies are testing a single dose of drug given perioperatively and measuring effects out to 24 h or longer. Continued dosing of the analgesic, at the recommended time intervals, will have a greater impact on reducing postoperative pain. In conclusion, a single dose of ibuprofen (400–600 mg) administered perioperatively will predictably reduce postoperative pain, but dosing should be continued for 24–48 h every 6–8 h, in patients in which this class of drugs can be safely administered (for more detail regarding the safety, see [118] and Fig. 6.4).

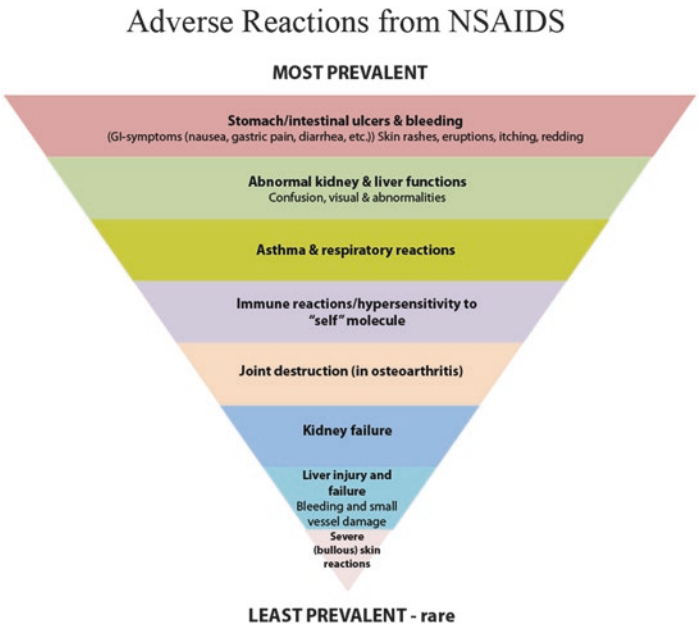

Fig. 6.4 Adverse reactions from the NSAID class of drugs. The occurrence and severity of these reactions differ with each drug (Reproduced with permission from Birkhäuser Verlag [118])

6.2.2.3 Combination Ibuprofen and Acetaminophen

Strong evidence exists that the combination of ibuprofen and acetaminophen produces greater analgesia than either analgesic alone in the relief of acute pain, as described in several controlled clinical trials and summarized in a recent Cochrane review [119, 120]. There is also evidence for the efficacy of this combination specifically in postoperative endodontic pain ([121] but also see [122]). The concept of using combination analgesics makes sense from a biological standpoint, as different analgesics target different pain pathways, and so combining analgesics will more broadly inhibit pain signaling pathways, producing greater analgesia. The combination of ibuprofen and acetaminophen should be prescribed when moderate to severe pain is anticipated.

6.2.2.4 Opioids and Combination Opioid Drugs

Combination opioid drugs such as those that combine acetaminophen and hydrocodone or codeine (e.g., Vicodin or Tylenol III) are commonly prescribed for the management of odontogenic pain and postsurgical pain. However, on their own they are less effective pain relievers than analgesics available over the counter with anti-inflammatory properties, such as ibuprofen [114, 123]. As the availability of prescription opioid pain killers has increased in recent years, so has the nonmedical use and abuse of these agents, as well as the most undesirable outcome of death by overdose [124]. In looking further into this alarming trend of prescription opioid misuse and abuse, dentists have been identified as a major source of opioid prescriptions (second only to family physicians). This has brought attention to the fact that greater care should be taken when prescribing these types of medications, as there is a chance that the drugs could end up being used for nonmedical purposes by someone other than the patient [125, 126]. With caution, combination opioids can be used in cases when severe pain is anticipated and NSAIDs are contraindicated, or pain is not relieved by NSAIDs or the combination of ibuprofen/acetaminophen. To prevent mishandling of any leftover medications, the dosing period can be limited to 24–48 h, during which time pain is anticipated to be most severe.

6.2.2.5 Steroids

Numerous studies have evaluated systemic and locally administered corticosteroids for the reduction of postoperative pain. Generally, there is ample support in the existing literature that steroids are effective at reducing postoperative pain after an endodontic intervention [127]. Systemic steroids, most commonly dexamethasone, administered intramuscularly or by oral tablets, decrease the incidence and intensity of postoperative endodontic pain [128–131]. These agents are also effective against postoperative pain when administered locally including intracanal, by intraligamentary injection and intraosseous administration [132–135]. Local administration has the benefit of limiting the systemic exposure to corticosteroids, thereby limiting potential side effects (although the short-term administration of steroids is quite safe for the vast majority of patients [136]). Further clarification is needed regarding which subclasses of endodontic pain are most responsive to corticosteroids (e.g., irreversible pulpitis pain versus periapical pain from a tooth with a necrotic pulp versus flare-up pain) [127].

6.2.2.6 Persistent Posttreatment Pain

Persistent pain after surgical procedures has gained attention recently as a public health problem and a potential opportunity for implementation of preventative methods to prevent the transition from acute to chronic pain [137]. Although occurring much less frequently than after major medical surgical procedures, the possibility for persistent pain after surgical dental interventions including surgical and nonsurgical root canal treatment, implant placement, and oral surgery procedures has been recognized for quite some time [138–143]. Although persistent symptoms after endodontic treatment could be due to ongoing odontogenic causes such as an undetected root fracture or recurrent infection, there are clearly cases when pain persists despite the absence of detectable pathology. Historically, such persistent pain was referred to as atypical odontalgia, or phantom tooth pain. The more current nomenclature is persistent dentoalveolar pain or peripheral painful traumatic trigeminal neuropathy [144, 145]. Although debates regarding the criteria for classification of this clinical entity are ongoing, and will surely continue, it likely represents a very specific type of persistent postsurgical pain. The etiology of non-odontogenic persistent post endodontic therapy pain is unknown, but there is some evidence that neuropathic mechanisms are involved [146–148]. More research is needed to better understand the biological mechanisms contributing to the development of persistent posttreatment endodontic pain.

6.3 Infection Management

6.3.1 The Role of Bacteria in Endodontic Pathology

Invasion of the root canal system by microorganisms precipitates the subsequent pathology of pulpal and periradicular tissues. The ultimate goal of endodontic treatment is biomechanical preparation of the root canal system, which includes cleaning, shaping, and disinfection, as well as hermetically sealing the canals, thereby creating the conditions for the healing of diseased periradicular tissues [149–151]. Primary endodontic infections are polymicrobial and caused predominantly by gram-negative anaerobic bacteria such as *Prevotella* ssp., *Porphyromonas* ssp., *Treponema* ssp., and *Fusobacterium* ssp. [152, 153]. Endodontic infections can spread beyond the root canal system producing localized inflammation and swelling in the soft tissue adjacent to the involved teeth or, more rarely, a nonlocalized spreading cellulitis.

As such, root canal disinfection is the fundamental component of successful root canal treatment. Contemporary techniques to eliminate or significantly reduce microorganisms in the root canal system include mechanical debridement, intracanal irrigation with antimicrobial/tissue dissolving agents, and placement of intracanal dressings. Importantly, the process of obturating the root canal and subsequently sealing the coronal aspect of the tooth prevents the introduction of new microorganisms. However, even during ideal treatment, some microorganisms can survive within the root canal system, causing persistent periapical inflammation, persistent

symptoms, and sometimes flare-ups [154]. Some patients can experience flare-ups of endodontic infection within a few hours or a few days following the root canal treatment [149, 154–156]. The flare-up rate after endodontic treatment varies from as low as 1.5 % [157] to as high as 20 % [158–162].

The composition of the microbiota in secondary or recurrent infections in previously treated teeth differs from that found in untreated teeth. Gram-positive bacteria are more frequently present and gram-negative bacteria, which are the most common component of primary infections, are usually eliminated. Frequently found organisms include streptococci, *Parvimonas micra*, *Actinomyces* species, *Propionibacterium* species, *Pseudoramibacter alactolyticus*, *Lactobacillus*, and *Enterococcus faecalis* [163]. *Enterococcus faecalis* is the species most often found in the case of treatment failure (Fig. 6.5) [164–166]. Existing evidence suggests

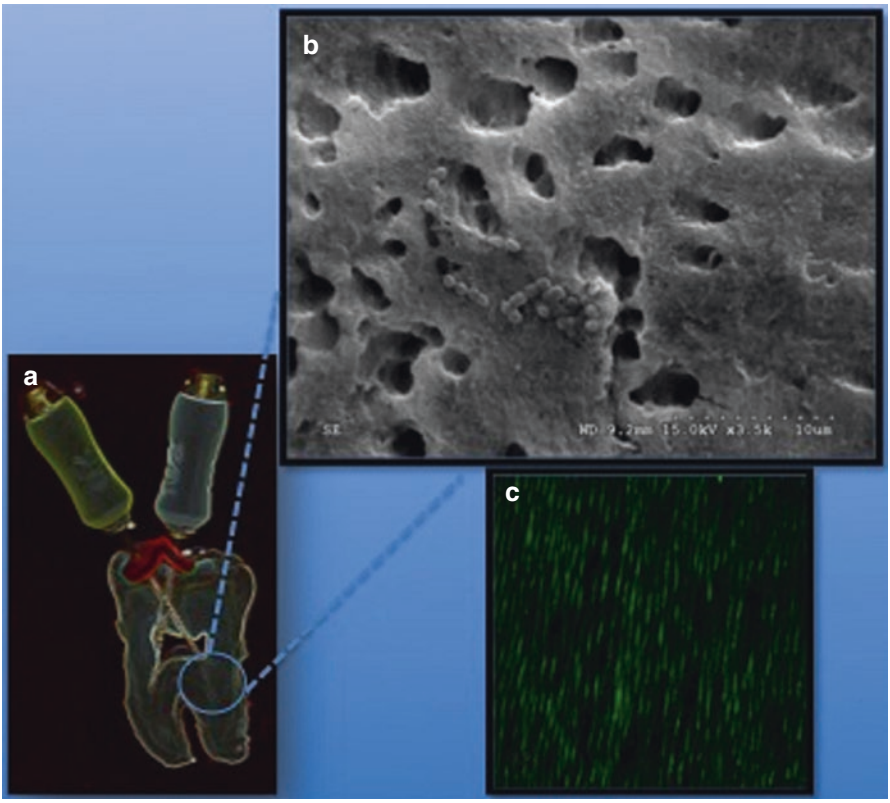

Fig. 6.5 (**a**) Longitudinal aspect of an extracted tooth with a necrotic pulp, showing hand files placed in a working length. (**b**) A colony consisting of cocci of *Enterococcus faecalis* in an ecological niche on the root canal wall. The aggregated bacteria also show some penetration into the dentinal tubules. Scanning electron microscopy, magnification ×3,500. (**c**) Images using a confocal laser scanning microscopy of dentin tubules with *Enterococcus faecalis*. These fragments were stained with Live/Dead dye, showing alive bacteria stained with *green* (Acknowledgment to Dr. Simone Duarte and Department of Basic Science of Craniofacial Biology. New York University)

that, after *Enterococcus faecalis* and *Actinomyces* species, *Candida albicans* are the most prevalent microorganisms associated with failed endodontic treatment [167, 168]. This species can colonize and invade the dentin and seems to be resistant to calcium hydroxide dressing (Fig. 6.6) [153, 169].

The presence of microorganisms in the root canal system evokes the pathogenesis of apical periodontitis. The microorganisms and their virulent factors can penetrate periradicular tissue, resulting in an inflammatory process, the intensity of which depends on the virulence and amount of the microorganisms present (Fig. 6.7) [170]. In the case of symptomatic apical periodontitis, the predominant strains of microorganisms found are *Parvimonas micra*, *Eubacterium*, *Porphyromonas endodontalis*, *Porphyromonas gingivalis*, *Prevotella*, and notably the "black-pigmented bacteria" which have gained much attention [171]. In the complex anatomy of the root canal system with its ramifications, isthmi, apical deltas, and accessory canals, the complete removal of microorganisms from the root canal system remains a challenge (Fig. 6.7) [165, 170, 172]. Positive correlations were found between the persistence of high levels of bacteria and endotoxins and pain on palpation, exudation, and levels of TNF-α and IL-1β [173].

6.3.2 Antibiotics in the Management of Endodontic Infections

The first-line treatment for teeth with either symptomatic apical periodontitis or an acute apical abscess is the removal of the source of inflammation or infection by local, operative measures including endodontic treatment or extraction of the tooth

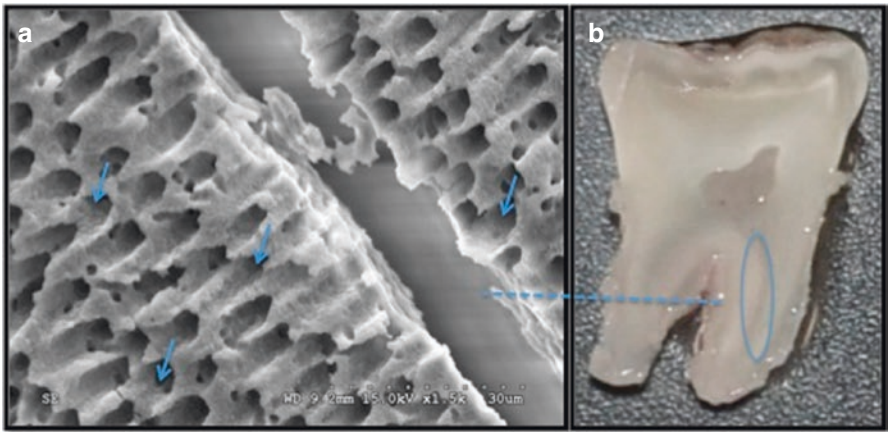

Fig. 6.6 (**a**) Scanning electron microscopy showing a hand file after passing the apical foramen while carrying smear layer from the root canal wall. Magnification ×120. (**b**) Image using a fluorescence microscopy of the smear layer with *Candida albicans*. These fragments were stained with Live/Dead dye, showing alive bacteria stained in *green* and dead in *red* (**c**) (Acknowledgment to Dr. Simone Duarte and Department of Basic Science of Craniofacial Biology. New York University College of Dentistry)

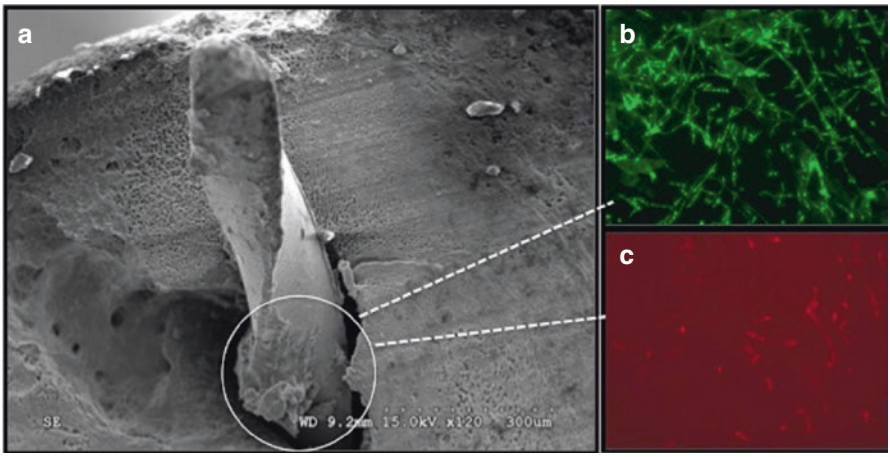

Fig. 6.7 (**a**) Dentinal tubules of root canal wall filled with a colony consisting of cocci along its path to the pulp, after the mechanical debridement with hand files. (**b**) Extracted human mandibular molar: longitudinal aspect of the endodontic space. Scanning electron microscopy, magnification ×1,500 (Acknowledgment to Dr. Simone Duarte and Department of Basic Science of Craniofacial Biology. New York University)

and incision and drainage for localized swellings [174, 175]. Systemic antibiotics are recommended in situations where there is evidence of a spreading infection (cellulitis, lymph node involvement, diffuse swelling) or systemic symptoms (fever and malaise) as well as in treating refractory infections [176]. The overuse of antibiotics increases the chances for bacteria to develop antibiotic resistance and of an alteration of the commensal flora, thus increasing the potential for adverse events such as allergies, anaphylactic reactions, nausea, vomiting, etc. [177–179]. Since dentists prescribe approximately 8–10 % of the antibiotics dispensed in developed countries, it is important not to underestimate the contribution of the dental profession to the increasingly serious problem of antibiotic-resistant bacteria [180, 181].

Systemically administered antibiotics should be considered an adjunct to endodontic therapy, and they should not be used to treat localized inflammatory conditions such as pulpitis and apical periodontitis. Several studies appear to indicate that antibiotics do not reduce the pain or swelling arising from teeth with symptomatic apical pathology in the absence of systemic involvement [45, 76]. Nevertheless, in a survey of members of the American Association of Endodontics, 54% of respondents reported that they would prescribe antibiotics as a first treatment for people with dental pain [182]. Except in patients with compromised immune system, antibiotics are not curative but instead function to assist in the reestablishment of the proper balance between the host's defenses and the invasive agent [183].

In order to maximize the effects of antibiotics and minimize the chances of resistant strains developing, patients must be instructed to initiate the course of antibiotics as soon as possible. Some controversy exists regarding the prescribing of long-term antibiotics. The typical regimen for treating an endodontic infection is 6–10 days on an around-the-clock schedule.

6.3.3 Endodontic Dressings

The anatomical complexity of the root canal systems, especially in the critical apical region, makes it impossible to completely remove all pulp tissue remnants and residual microorganisms, even when applying the highest technical standards of chemomechanical debridement (Fig. 6.7) [164, 165]. Because root canal infections are polymicrobial, consisting of both aerobic and anaerobic bacterial species, several intracanal dressings have been suggested to accomplish root canal disinfection [184, 185]. Local applications of antibiotics within the root canal have been proposed to overcome the potential risk of adverse systemic effects of antibiotics and as an active mode for drug delivery in teeth lacking blood supply due to necrotic pulps or pulpless status [185–187].

Several reports have been recently published describing revascularization or revitalization of immature permanent teeth with a necrotic dental pulp. In addition to traditional nonspecific endodontic disinfecting irrigants, these reports have documented the use of triple antibiotic paste (ciprofloxacin, metronidazole, and minocycline) [185–191], calcium hydroxide [192–195], or formocresol [196] as inter-appointment intracanal dressings. The triple antibiotic mix and calcium hydroxide appear to sometimes allow for continued increased root thickening and lengthening, but formocresol did not achieve the same effect [197]. The antimicrobial effectiveness of intracanal antibiotics versus calcium hydroxide requires further study, but the combination appears to be effective against endodontic pathogens [185, 198].

Calcium hydroxide has been widely accepted as an intracanal medicament because of its antimicrobial properties, especially on gram-negative bacteria [199, 200]. Studies *in vitro* and *in vivo* have shown an intracanal reduction of the microbial population or at least inhibition of bacterial proliferation [201–203]. Some authors have discussed whether calcium hydroxide is effective at eliminating *Enterococcus faecalis*. Other studies have evaluated the effect of intracanal calcium hydroxide on the incidence of posttreatment pain and found that calcium hydroxide is not very effective in reducing posttreatment pain when it is used alone [204, 205], but its effectiveness increased when used in combination with other medicaments like 2% chlorhexidine gluconate and camphorated monochlorophenol [206]. Additionally, several other studies have concluded that medicaments with the corticosteroid component in them are significantly better than calcium hydroxide in reducing the posttreatment pain, attributing to the anti-inflammatory action of corticosteroids (see Sect. 6.2.2.5) [206, 207].

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Anatomy, Access, and Length Determination

7

Frederick Barnett

Abstract

A sound knowledge of root canal anatomy is the first step in providing optimal treatment for the endodontic patient. In fact, each successive step in the clinical procedure is built upon the technical quality of the preceding step. However, modifications of the access preparation and especially the working length should be checked, rechecked, and modified as the clinical situation dictates. This chapter provides current and evidence-based information on three significantly important steps of the endodontic procedure.

7.1 Introduction

This chapter is comprised of three parts that are significantly important for successful clinical endodontics. Knowledge of root canal anatomy is required as it enables the clinician to prepare an appropriately shaped access preparation which then will allow for identification of the orifices of the root canals. Establishing and maintaining an optimal working length has been directly tied to clinical outcomes so its importance is obvious.

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7.2 Root Canal Anatomy

A proper working knowledge of root canal morphology and the ability to find all of the canals within the tooth being treated is considered to be significantly important in improving endodontic outcomes. The failure to find and therefore treat all of the root canals could be the major cause of posttreatment endodontic disease [1–3]. As early as 1921 [4], it was clearly illustrated that root canal "systems" had wide variations and complexities and that the belief that a root contained a tapering canal and a single foramen was the exception rather than the rule.

Over the last decades, there have been several methods of studying tooth and root canal anatomy; histology, radiography, tooth clearing, micro-computed tomography to name a few. Tooth clearing allows for three-dimensional observation of the root canal anatomy [5, 6] and, in fact, provides more accurate information than do periapical radiographs (Figs. 7.1, 7.2, 7.3, 7.4 and 7.5). Micro-computed tomography (micro-CT) is a nondestructive imaging method used for the ex vivo study of dental anatomy because it can provide a detailed quantitative and qualitative description of the external and internal anatomy of the teeth [7, 8] (Figs. 7.6a–e and 7.7a–b). For example, the mesiobuccal root (MB) of the maxillary first molar has been extensively studied over the years, because it has caused many difficulties for clinicians. A recent study that utilized micro-CT for study of human tooth anatomy [9], and specifically the MB roots of maxillary first molars, found the following:

1. Second MB canal (MB2) was present in 90 % of the roots.
2. Isthmuses (intercanal communications) were observed in 55 % of the roots.
3. A single apical foramen was observed in 15 % of roots, two foramina in 20 %, and three or more foramina were present in 65 %.
4. At the furcation level, 50 % of the roots had two orifices, 40 % had one orifice, and 10 % had three orifices.
5. Accessory canals were present in 85 % of the roots.

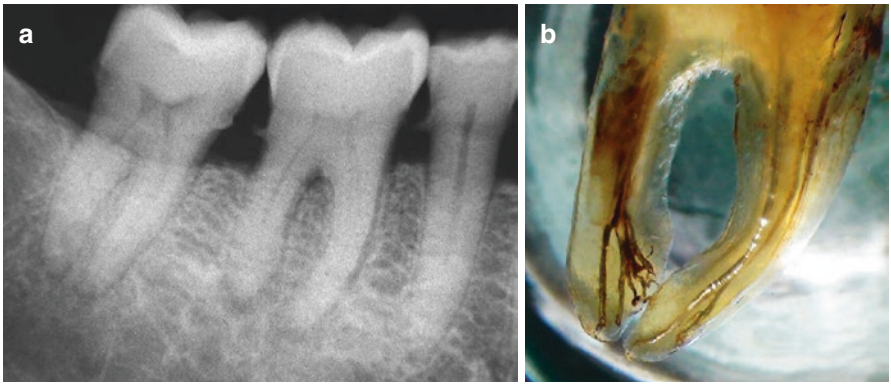

Fig. 7.1 (**a**) Periapical radiograph of mandibular first molar prior to extraction. (**b**) Photograph of that same tooth after being cleared. The complex anatomy is clearly evident (Courtesy of Dr. Craig Barrington)

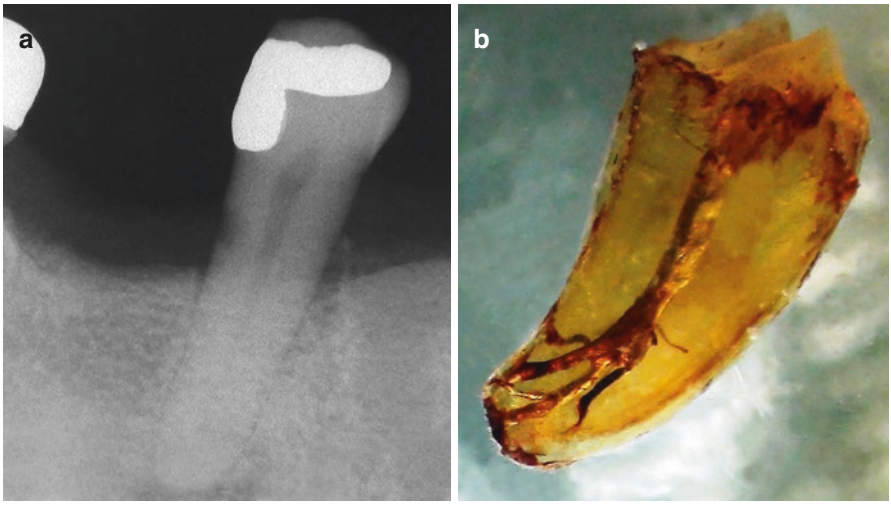

Fig. 7.2 (**a**) Periapical radiograph of mandibular second premolar prior to extraction. (**b**) Photograph of that same tooth after being cleared. The complex apical anatomy is clearly evident (Courtesy of Dr. Craig Barrington)

Fig. 7.3 Photograph of maxillary second premolar after being cleared. The unexpected and complex apical anatomy is clearly evident (Courtesy of Dr. Craig Barrington)

Fig. 7.4 Photograph of MB root of maxillary first molar after being cleared (Courtesy of Dr. Craig Barrington)

Fig. 7.5 Photograph of DB root of maxillary first molar after being cleared. This extremely complex canal anatomy may be described as a 1-2-1-2 system (Courtesy of Dr. Craig Barrington)

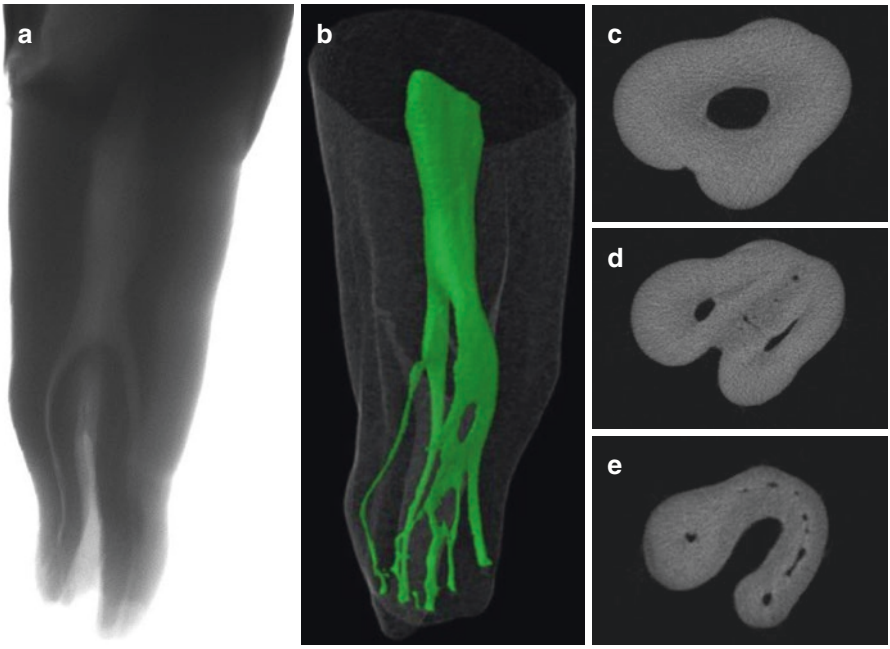

Fig. 7.6 (**a**) Radiograph of extracted mandibular premolar with 2 roots. (**b**) Micro-CT reconstruction demonstrating complex root canal system in *green*. (**c**) Micro-CT axial slice of same tooth, coronal third. Only a single canal is evident. (**d**) Micro-CT axial slice of same tooth, middle third. Multiple canals are observed. (**e**) Micro-CT axial slice of same tooth, apical third. C-shaped anatomy is observed along with multiple separate canals (Courtesy of Dr. Ronald Ordinola-Zapata)

It is clear that the maxillary first molar has an extremely complex root canal anatomy, and the clinician must be prepared to manage these complexities.

Clinically, two or more angled periapical radiographs as well as a bite-wing radiograph should be taken following a thorough clinical examination. These angled images may provide the required information on tooth anatomy as well as the presence of caries at the osseous level that may go unnoticed by a single periapical radiograph. By changing the horizontal angulation of periapical radiographs by 20–40°, it was found that the number of roots in maxillary and mandibular molars were accurately detected [10]. However, 2-dimensional imaging often fails to provide accurate information on tooth and root canal anatomy as compared to cone beam computed tomography (CBCT) [11–13].

CBCT is a three-dimensional radiographic modality that offers the possibility to view an individual tooth or teeth in any view and has proven to be a powerful tool in endodontic diagnosis and treatment planning [13]. It has been reported that digital radiographs, regardless of the system used, failed to identify at least one root canal in 40 % of teeth when compared with CBCT [14]. The presence of MB2 canals in maxillary molars is significantly better demonstrated with CBCT than with conventional periapical radiographs [15]. A recent study reported, using

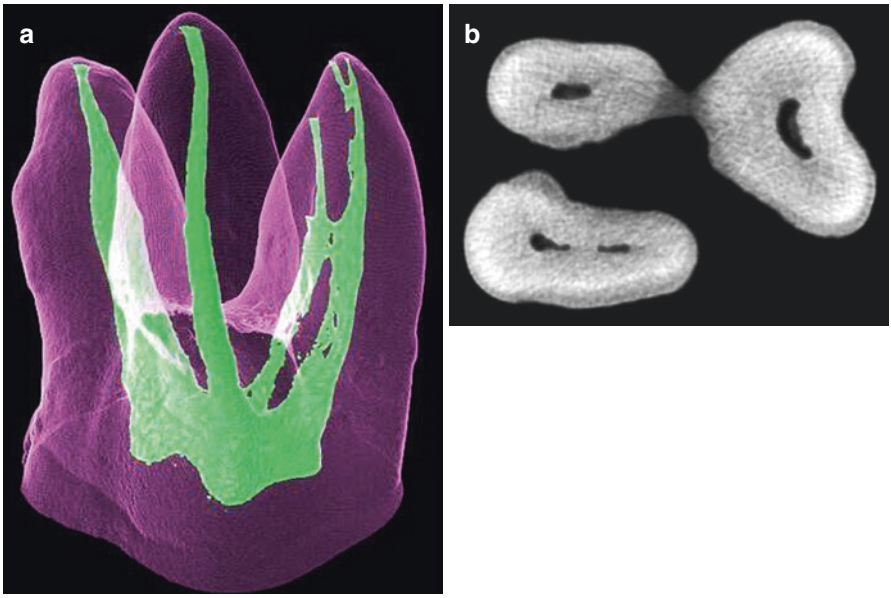

Fig. 7.7 (**a**) Micro-CT reconstruction of maxillary first molar tooth. The MB root canal system appears to have a 2-1-2-2 complex system. (**b**) Micro-CT axial slice of maxillary first molar tooth at mid-root. The MB root canal system appears to have 2 canals at this level (Courtesy of Dr. Ronald Ordinola-Zapata)

micro-CT as the "gold standard," that CBCT imaging was very effective for detecting a missed MB2 canal in endodontically treated teeth [16]. In addition, the study results showed CBCT sensitivity for detecting MB2 was 96 %, specificity was 100 %, and total accuracy was 98 %.

7.3 Access Preparation

7.3.1 Principles of Access Preparation

Clinical endodontic treatment commences with access preparation. The purpose of access preparation is to locate all the canal orifices in the tooth being treated for the purpose of proper debridement, irrigation, disinfection, and root filling. Prior to gaining access into the pulp chamber, all caries and defective restorations should be removed to ensure an aseptic technique and to prevent coronal leakage in between visits. It has been shown that it may be essential to remove all existing restorations from teeth requiring endodontic treatment in order to ensure complete caries removal, to visualize the presence of cracks, and to properly assess the restorability of the tooth [17].

7.3.2 Conservative vs. Traditional Access Preparation

Traditionally, the terms *outline form* and *convenience form* were used to describe the recommended shapes of access preparations. These access design shapes are from a projection of the internal chamber anatomy to the external tooth surface which also allows for straight-line access. The result would be that the clinician would be able to visualize all root canal orifices at the same time, without having to tilt their mirror. It appears that there may be an opportunity to preserve a significant amount of dentin while retaining the ability to locate all the root canal orifices with more conservative access preparations [18–23].

Recently, the traditional and previously accepted access cavity preparation designs have been questioned because of the potential weakening of the tooth caused by excessive dentin removal, making it more susceptible to eventual fracture under functional loads over time [18–23]. Post-endodontic tooth fractures have generally been attributed to weakened tooth structure caused by dental caries and subsequent restorative procedures, large endodontic access preparations, excessive canal enlargement especially in the cervical 1/3, and post preparations [18]. By changing/switching to a more conservative access preparation design, a significant amount of internal dentin may remain, thereby increasing the fracture resistance in mandibular molars and premolars [23] (Figs. 7.8, 7.9 and 7.10). Thus, the concept of "minimally invasive endodontics" has entered into our lexicon, and its purpose is to preserve the maximal amount of healthy dental structures during all endodontic procedures to enhance long-term tooth survival [18–25]. In this regard, access openings must be made, with a goal to preserve sound tooth structure; especially important is the prevention of gouging cervically, laterally, or into the floor of the pulp chamber when using a high-speed handpiece with a large round bur [24]. There must be a balance between a properly constructed conservative access and too small of an access that may prevent locating all of the canals and lead to an endodontic failure. Excessive dentin removal within the canal orifice by large Peeso reamers, Gates-Glidden drills, and large tapered orifice openers should be questioned and perhaps replaced with smaller tapered rotary instruments (i.e., .04 or .06).

7.3.3 Pulp Chamber Anatomy and Canal Location

It has been shown that the pulp chamber floor and wall anatomy provide a guide to determining what morphology is actually present. In a study evaluating 500 extracted teeth, it was determined that the cementoenamel junction was the most important anatomic landmark for determining the location of pulp chambers and root canal orifices [26]. The study demonstrated that specific and consistent pulp chamber floor and wall anatomy exist, and the authors proposed laws for assisting clinicians to properly identify canal morphology. The relationships expressed in these "laws" were found to occur in 95 % of the teeth examined and are particularly helpful in locating calcified canal orifices

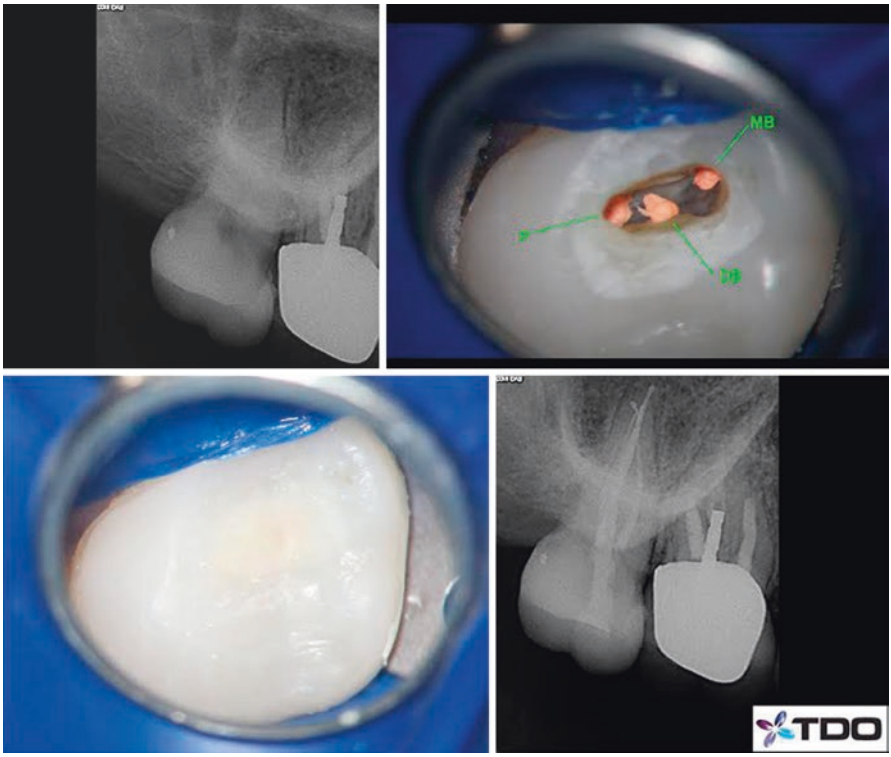

Fig. 7.8 Conservative access on tooth #2 (Courtesy of Dr. J. Joe)

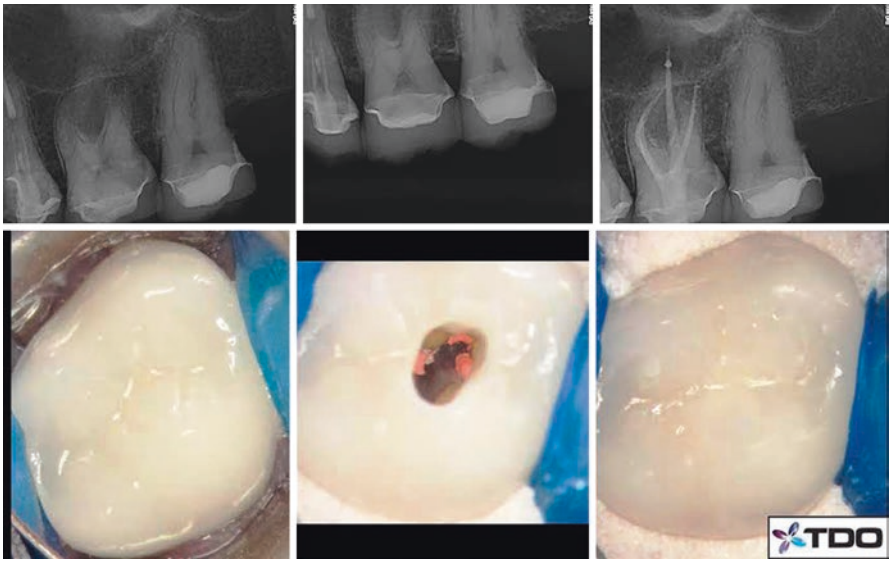

Fig. 7.9 Conservative access on tooth #2 (Courtesy of Dr. J. Richards)

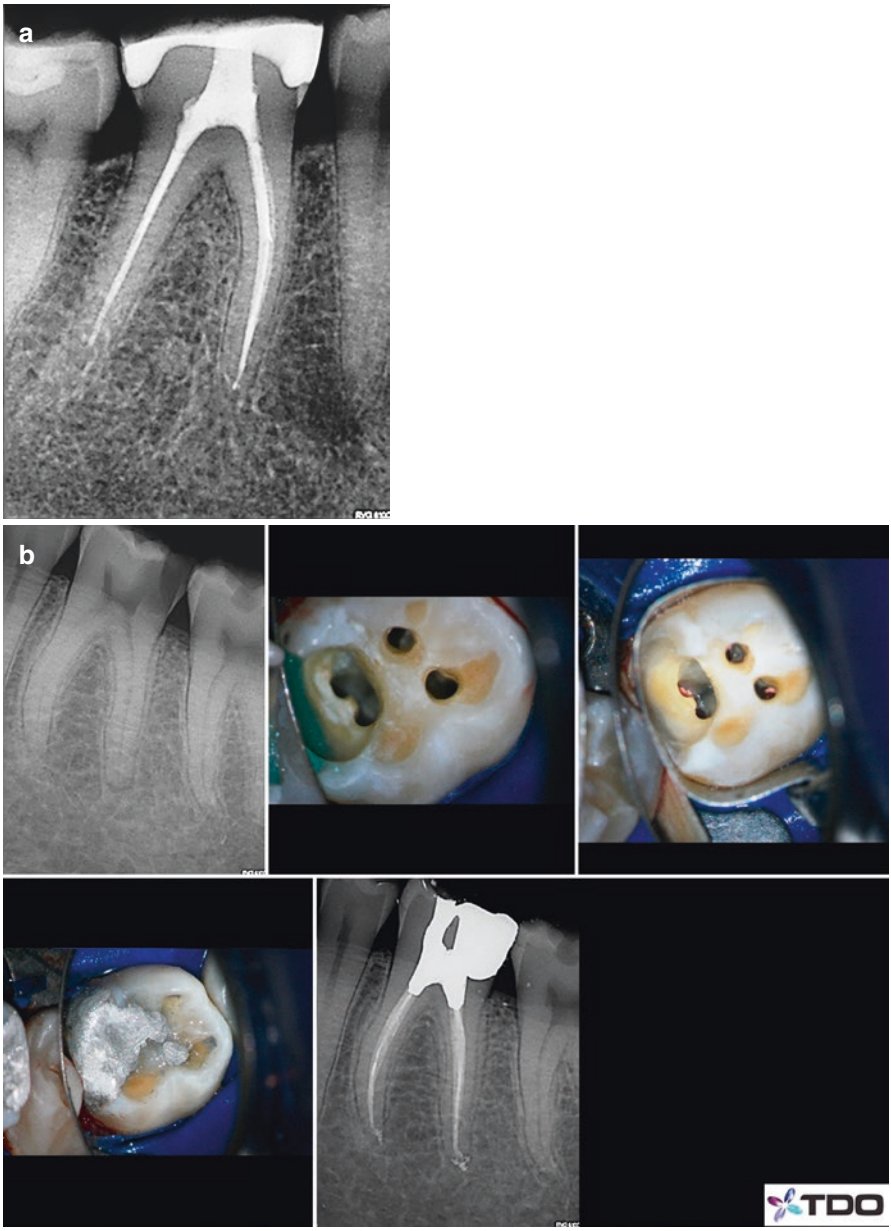

Fig. 7.10 (**a**) Post-op radiograph illustrating conservative access on tooth #30 (Courtesy of Dr. M. Trudeau) (**b**) Tooth #19 illustrating "truss access" (Courtesy of Dr. M. Trudeau)

Laws for locating canals:

- Law of Centrality: the CEJ is the most consistent and repeatable landmark for locating the position of the pulp chamber as the floor of the pulp chamber is always located in the center of the tooth at the level of the CEJ. Knowledge of this should help prevent crown perforations in a lateral direction regardless of how much coronal tooth structure has been lost or how extensive a crown restoration may be.
- Law of Color Change: the color of the pulp chamber floor is always darker than the walls (Figs. 7.10 and 7.11). This is often referred to as the "color map." Additionally, reparative dentin and calcifications are lighter than the pulp chamber floor and may often obscure the canal orifices. This law provides guidance to the clinician as to when the access preparation has been completed. Once accomplished, the following laws can be used to locate the exact position and number of canal orifices.
- Laws of Symmetry 1 and 2: except for maxillary molars, the orifices of the canals are equidistant and canals lie on a line perpendicular to a line drawn in a mesiodistal direction through the pulp chamber floor.
- Laws of Orifice Location 1 and 2: the orifices of the root canals are always located at the junction of the walls and the floor and the angles in the floor–wall junction (Fig. 7.11). The laws of orifice location in conjunction with the law of color change are often the only reliable indicator of the presence and location of an MB2 canal in maxillary molars.

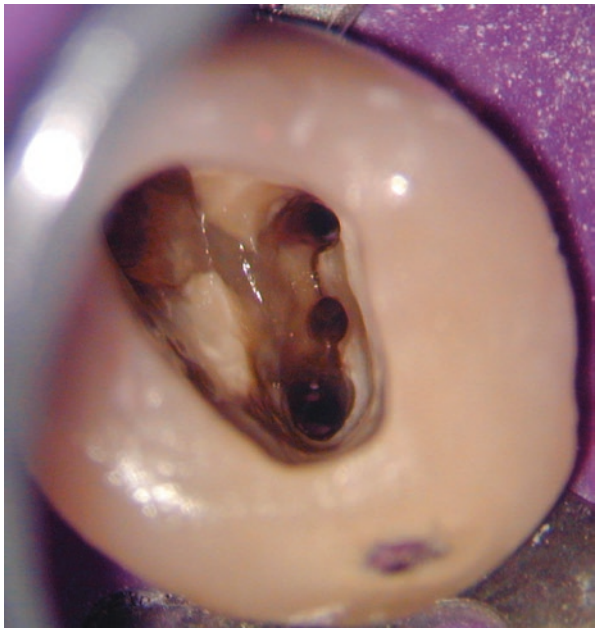

Fig. 7.11 Photograph of molar chamber floor illustrating the color map. There are 2 distobuccal orifices evident (Courtesy of Dr. F. Barnett)

7.4 Working Length Determination

Working length (WL) is defined as the distance from a coronal reference point to the point at which canal preparation and filling terminates [27]. Ideally, instrumentation and root filling should terminate at a "biologically suitable" location within the root canal system in order to achieve the best outcomes [28–39]. Interestingly, this exact location of this termination of canal preparation and obturation has remained controversial over the decades. However, if the termination of the root-filling material is too short or too long from the radiographic apex, the outcome has been shown to be negatively influenced [28, 30–39]. Many studies are in agreement that in teeth with vital pulps, the apical level of instrumentation and obturation should be short of the apical foramen [28, 30–39]. For teeth with necrotic pulps with apical periodontitis, the apical limit was recommended to be closer to the radiographic apex [28, 30–39]. In fact, it was shown that for every millimeter loss in working length (away from the radiographic apex), the odds of failure increased by approximately 14 % [36] and 12 % [38].

Traditionally, the apical constriction (minor foramen) appeared to be an appropriate location to terminate the root preparation and filling. It was defined as the narrowest part of the canal and was located just short of the major apical foramen [40]. However, this apical constriction was identified in less than 50 % of the teeth studied, and frequently, the apical canal was parallel [41]. Recent study using micro-CT analysis of the apical constriction (cement–dentinal junction) (AC) in extracted molar teeth found the following [42]:

1. An AC was found in all examined canals.
2. The most prevalent shape of the AC found was parallel.
3. The AC was in close proximity to the apical foramen (AF) (0.2 mm).
4. The size of the AC in molars corresponded to instrument size 30. Young patients had a significantly larger AC.
5. The location of AF was short of the radiographic apex in 88 % of the canals; in 5 % of the canals, the AF was more than 2 mm short of the anatomic apex.
6. The mean distance of the AC-radiographic apex was 0.9mm.
7. In 68 % of the canals, the distance AC-radiographic apex was 0.5 mm shorter or longer than the mean (as shown in number 6), showing that determining the constriction by radiographs may be accurate in only 32 % of the canals.

Additionally, the apical foramen, major foramen, defined as the most apical opening on the root, was shown not to be located at the anatomic apex in about 60–80 % of the teeth examined and could be found from 0.0 to 3.0 mm away from anatomic apex [41, 43, 44].

Endodontic outcomes studies assess root-filling length only in relation to the radiographic apex, which does not necessarily correspond to the major apical foramen. However, it appears that all outcomes studies agreed, without exception, that

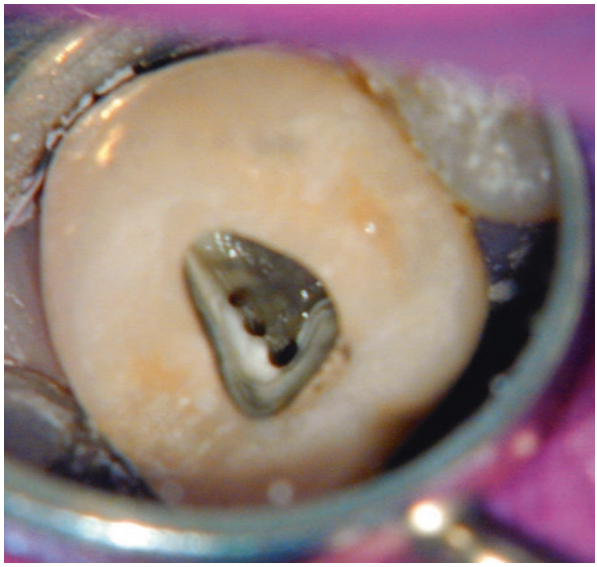

Fig. 7.12 Photograph of molar chamber floor illustrating the color map. There are 3 separate MB orifices evident. The orifices of the canals are observed to be at the junction of the dark chamber floor and the lighter walls (Courtesy of Dr. F. Barnett)

the overextension of the filling material indeed adversely influenced the treatment outcome [28, 30–39].

It becomes apparent that proper working length determination and its maintenance is important to achieve the best outcomes possible. As working length radiographs are not very accurate in determining the location of the apical constriction or foramen (Fig. 7.12), other methods, such as electronic apex locators (EAL) and paper point measurements (PPT), have become increasingly important in clinical practice. A recent in vivo study compared the accuracy of working length determination with EALs and radiographs, on 482 canals in 160 maxillary and mandibular teeth [45]. After extraction, the true location of apical constriction was determined by direct observation. The results showed that the measurements made by apex locators were within ±0.5 mm of the minor foramen (apical constriction) 100 % of the time, whereas for the radiographs, the measurements were within this range only 15 % of the time. The implications of this are that proper use of an EAL will allow for more precise working length determination than do periapical radiographs.

7.5 Concluding Remarks

It has been well established that knowledge of root canal anatomy, locating and negotiating all canals and by achieving and maintaining proper working length throughout the entire endodontic procedure, the clinician can expect the best possible outcomes for their patients.

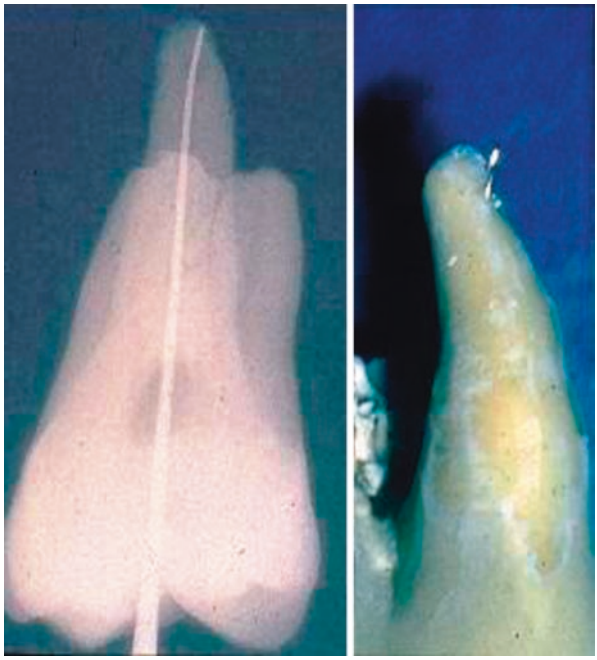

Fig. 7.13 Picture shows that the file in the palatal canal is at the radiographic apex, but in fact, it is extending past the root end by about 2 mm (Courtesy of Dr. F. Barnett)

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Instrumentation and Disinfection of Root Canals

8

Frederic Barnett and José F. Siqueira Jr.

Abstract

Preparation of the root canal system is recognized as being one of the most important steps in achieving successful endodontic treatment outcomes. However, thorough root canal preparation is quite demanding for the clinician because of the highly variable root canal anatomy and the inability to visualize this anatomy from routine periapical radiographs. In addition to mechanical shaping, it is well accepted that the use of antimicrobial irrigating agents is beneficial in dissolving inflamed as well as necrotic infected pulp tissue and disrupting the intracanal biofilm. Additionally, the use of interappointment antimicrobial dressings has also been recommended for teeth with periapical disease as a result of root canal infection.

8.1 Introduction

Preparation of the root canal system is recognized as being one of the most important steps in achieving successful endodontic treatment outcomes. In addition to removing inflamed vital and infected necrotic pulpal tissues, it also allows for the introduction of disinfecting irrigants and interappointment antimicrobial medications. Mechanical

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preparation along with chemical disinfection is commonly referred to as chemomechanical preparation. However, root canal preparation is quite demanding for the clinician because of the highly variable root canal anatomy and the inability to visualize this anatomy from routine periapical radiographs [1, 2].

8.1.1 Biologic and Technical Goals of Root Canal Preparation to Achieve Optimal Clinical Outcomes [2–6]

1. Sufficient removal of inflamed, necrotic, and infected pulpal tissues to reduce or arrest the host's inflammatory response.
2. Creation of sufficient space for adequate irrigation, medication, and root filling to best allow for the reduction/elimination of the root canal irritants and ensure an optimal obturation.
3. Preservation of the apical foramen to prevent complications (i.e., zipping, transporting, blocking, overfilling during obturation).
4. Prevention of iatrogenic complications (i.e., separating files, perforations, ledging, blocking, transporting).
5. Preservation of enough intact tooth structure for long-term tooth survival (to reduce the possibility of subsequent vertical root fractures).

8.1.2 Challenges in Root Canal Preparation [1, 2, 5]

1. Locating all canals: Missed canals have been attributed to decreased clinical outcomes. Therefore, knowledge of tooth and root canal anatomy is necessary as is the use of magnification and illumination devices (i.e., surgical loupes with light source or a dental operating microscope). These devices have significantly enhanced the ability to find and treat more canals.
2. Working length: Establishing and maintaining proper working length throughout the entire procedure will ensure more optimal debridement and will prevent canal blockage and over-instrumentation. Contemporary electronic apex locators have become a predictable and important adjunct for canal length determination.
3. Anatomic factors: Lateral and accessory canals, fins, isthmuses, curvatures, oval-shaped canals, etc., present a considerable challenge for optimal canal debridement. This highlights the significance of irrigating solutions and interappointment medications in routine endodontic treatment.
4. Degree of canal shaping: Optimal canal debridement is necessary for sufficient disinfection, irrigation, and subsequent root filling to achieve clinical success. However, it is not known how much cleaning and shaping is necessary for any given canal to achieve optimal success. Inadequate cleaning and shaping may leave excessive amounts of diseased and infected tissue in the root canal system which may cause persisting symptoms and periapical inflammation. Overzealous canal shaping with the removal of excessive root dentin may make the tooth susceptible to eventual fracture.

5. Canal disinfection: Sufficient reduction/elimination of the microbial burden (biofilm) within the root canal system is regarded as essential for successful outcomes. However, despite meticulous cleaning, shaping, disinfection, and root filling, some cases with preoperative apical periodontitis may still fail. The causes of these failures have been attributed to the persistence of infection in the apical canal that was unaffected by our treatment procedures [2].

8.1.3 Working Length (WL) and Working Width (WW)

Most clinical studies have shown that the best outcomes were achieved when the instrumentation and subsequent root filling were confined within the root canal system [6–11]. Root fillings ending 0–2mm short of the radiographic apex appeared to yield 94% success, underfilling greater than 2 mm short gave a 68% success rate, and overfilling yielded 76% success [9]. More recently, it was shown that instrumenting and root filling to 0.5mm short of the radiographic apex provided the highest success [10]. A meta-analysis has confirmed that overfilling the root canal is associated with a decreased success [11].

Working width is the degree of apical enlargement or final apical preparation size chosen by the clinician. However, there is little agreement about the final apical size and clinical success. In fact, a prospective outcome study [7] found that there was no significant difference in outcomes between cases enlarged to sizes <#30 and those enlarged to >#30. However, achieving patency was associated with higher success. A recent randomized prospective clinical study [12] evaluated the effect of apical preparation size in relation to the first apical binding file (FABF) on the clinical outcome of endodontic treatment in mandibular first molars. They found that the proportion of successfully healed cases increased with an increase in apical preparation size. They concluded that enlargement of the canal to 3 sizes larger than the FABF is adequate, and further enlargement did not provide any additional benefit during endodontic treatment.

8.1.4 Root Canal Disinfection

8.1.4.1 Irrigants

The main steps of endodontic treatment involved with infection control are represented by chemomechanical preparation (instrumentation and irrigation) and intracanal medication. The former plays a pivotal role in root canal disinfection, because instruments and irrigants act primarily on the main canal, which is the largest area of the root canal system and consequently harbors the highest numbers of bacterial populations. A large proportion of bacterial populations are eliminated from the root canal by the mechanical effects exerted by instruments and the flow of the irrigant solutions during preparation [13], but the use of an antimicrobial irrigant is required for enhanced disinfection [14–16]. In addition to promoting mechanical and chemical elimination of microorganisms from the root canal, irrigation serves other

important goals during preparation as it also promotes cleaning by washing out necrotic and inflamed pulp tissue and debris and dissolving soft tissue, acts as a lubricant for instruments during negotiation and cutting, prevents packing of dentinal and pulp debris in the apical canal, and removes the smear layer.

8.1.4.2 Main Irrigants

Sodium Hypochlorite (NaOCl)

NaOCl is the most commonly used irrigant in endodontic practice, and no study has hitherto definitively shown that another substance is more effective than it in terms of disinfection [17]. Solutions ranging from 0.5 % to 8% have been proposed for irrigation.

NaOCl has a strong broad-spectrum antimicrobial activity, rapidly killing vegetative and spore-forming bacteria, fungi, protozoa, and viruses. Most oral bacteria are killed after a short-time contact with NaOCl. NaOCl exerts its antibacterial effect mostly by inducing the irreversible oxidation of sulfhydryl groups of essential bacterial enzymes.

Chlorhexidine (CHX)

CHX is a cationic bis-biguanide that has been widely used as a topical antiseptic. CHX is highly effective against several oral microbial species [18, 19]. It also presents substantivity in dentin [20] and displays acceptable tissue compatibility [21, 22]. Because of these properties, CHX has emerged as a potential irrigant and interappointment medication. At the high concentrations used in antiseptic/disinfectant preparations, CHX enters the cytoplasm via the damaged cytoplasmic membrane and promotes precipitation of cytoplasmic contents, particularly phosphated entities, with resulting cell death.

Intracanal Antibacterial Effectiveness of Irrigants

The use of NaOCl as the main irrigant significantly enhances intracanal disinfection when compared to irrigation with saline [14, 23, 24]. Chemomechanical procedures using 2.5 % NaOCl as the irrigant reduce 10^2 to 10^5-fold the numbers of bacteria, with an overall reduction exceeding 95 % [25]. After irrigation with NaOCl (in concentrations ranging from 0.5 % to 5%), about 40–60 %, the canals show no detectable cultivable bacteria [26–29].

In the root canal environment, increasing the NaOCl concentration has been shown to have no significant effects on bacterial reduction [26]. Most importantly, the regular exchange and the use of large amounts of irrigant help maintain the antibacterial effectiveness of the NaOCl solution, compensating for the effects of concentration [15].

8.2 Irrigants for Smear Layer Removal

Smear layer comprises a layer of organic and inorganic material, which is formed on mineralized dental tissues whenever they are cut with hand or rotary instruments [30] (Fig. 8.1). The smear layer covering the instrumented canal walls is

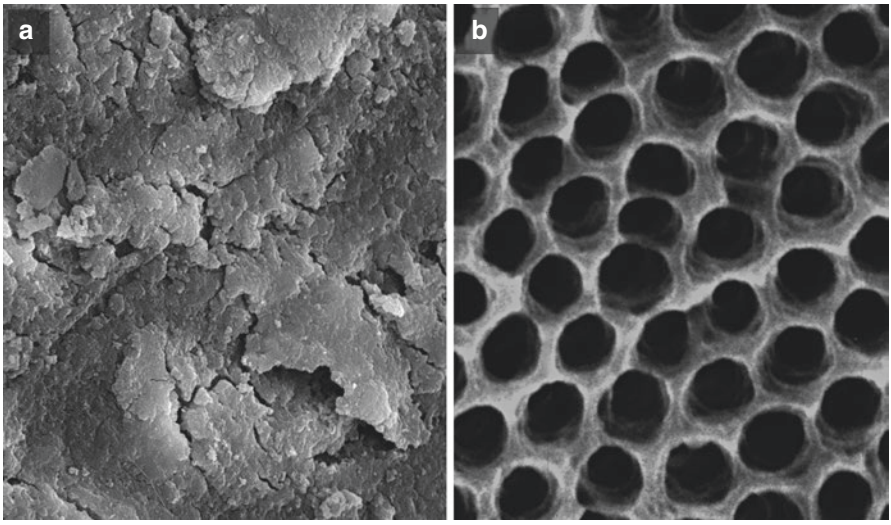

Fig. 8.1 Scanning electron micrographs showing the smear layer formed on the root canal wall (**a**) and after its removal (**b**)

approximately 1–2 μm thick and can also be observed in some regions as plugs packed into the dentinal tubules, sometimes called smear plug.

Removing the smear layer may be required for enhanced disinfection, as this layer may contain residual bacteria and substrate that might serve as a potential source for persistent root canal infection [31, 32]. In addition, the smear layer delays diffusion of antibacterial intracanal medications from the canal to the dentinal tubules, reducing their effectiveness [33].

The inorganic component of the smear layer can be removed by demineralizing substances or products, including ethylenediaminetetraacetic acid (EDTA) [34], citric acid [35], and doxycycline-containing products [36, 37] (BioPure MTAD, Dentsply, Tulsa, OK, and Tetraclean, Ogna Laboratori Farmaceutici, Milano, Italy)

EDTA does not act immediately when placed in contact with the mineralized tissue, taking a few minutes to achieve the chelating effect. Although EDTA has some antibacterial activity [38], it is not expected to improve disinfection beyond that achieved by the previous irrigation with either NaOCl or CHX. Therefore, its main use in endodontic therapy is for smear layer removal.

8.3 Intracanal Medication

Bacteria that escape from the effects of chemomechanical procedures are usually located in areas not reached by instruments and irrigants [5, 39–41]. Unaffected areas include dentinal tubules, isthmuses, lateral canals, apical ramifications, and even some areas of the main root canal walls that may remain untouched by instruments [39, 40, 42–44] (Figs. 8.2 and 8.3).

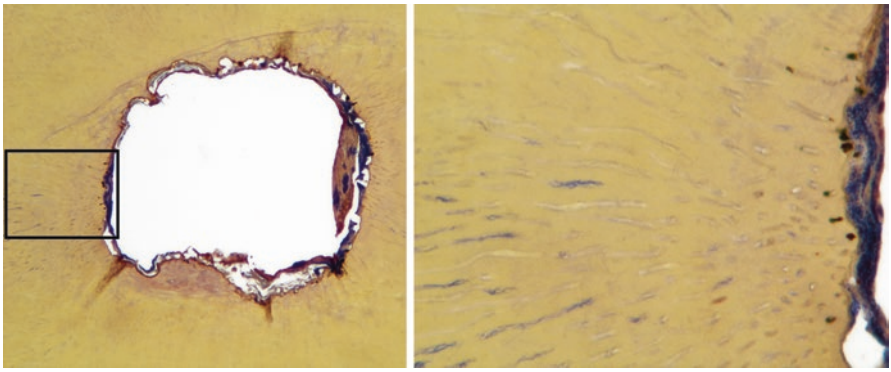

Fig. 8.2 The root canal infection may spread to areas that are difficult to reach. (**a**) A bacterial biofilm is covering the irregular root canal walls and the subjacent dentinal tubules are invaded by bacteria from the biofilm. (**b**) Higher magnification of the rectangle in A (Courtesy of Dr. Domenico Ricucci)

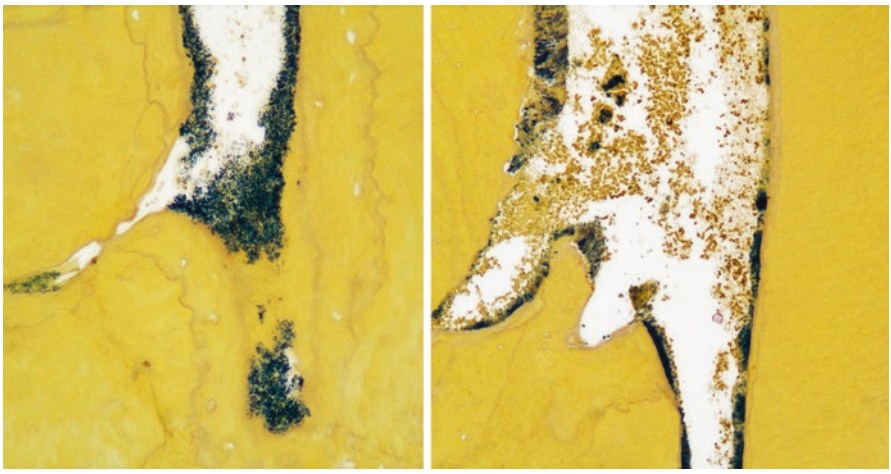

Fig. 8.3 Difficult-to-reach areas. (**a** and **b**) The root canal infection spread to lateral and apical ramifications. Note the formation of biofilms not only in the main canal but also in the ramifications. In these areas, bacteria may survive the effects of instrumentation and irrigation (Courtesy of Dr. Domenico Ricucci)

Although irrigants such as NaOCl and chlorhexidine have strong antimicrobial activity, their effects are mostly limited to the main canal. Even there, these substances need to be frequently replenished and remain for sufficient time to exert antibacterial and antibiofilm effects on areas not touched by instruments. In the clinical setting, the irrigant should diffuse to reach the areas mentioned above, but the short time they remain in the canal during preparation represents a major limitation. For the sake of comparison, whereas the irrigant remains in the canal for 10–30 min, an interappointment medication can remain for days. Therefore, the

intracanal medication has more chances to diffuse, reach, and eliminate bacteria in areas not affected by instruments and irrigants. Of the numerous substances that have been proposed as interappointment medication over the years, calcium hydroxide is the most commonly used.

8.3.1 Calcium Hydroxide

Calcium hydroxide is an inorganic compound, with the formula $Ca(OH)_2$, and has a strongly alkaline pH (approximately 12.4). In the presence of water, it dissociates into hydroxyl and calcium ions, and most of the biological effects attributed to this substance are related to the former [45]. Pure calcium hydroxide is available as a powder, but it should be mixed with a liquid, gel, or creamy carrier (or vehicle) for easier intracanal application and enhanced antimicrobial performance. Because calcium hydroxide effects are pH dependent, the ideal vehicle should enable the ionic dissociation of this substance. Dissociation varies according to the type of vehicle used. It is questionable if viscous or oily vehicles are of any value, since they do not permit a high dissociation and consequent release of hydroxyl ions.

Most bacterial species commonly found in infected root canals are eliminated in vitro after a short period of exposure to the high pH of calcium hydroxide [26]. Lethal effects of hydroxyl ions on bacterial cells are resultant of the effects on lipids, proteins, and DNA, leading to subsequent damage to the cellular apparatus and drastically altered cellular functions [45]. Calcium hydroxide has also been shown to inactivate bacterial virulence factors, such as lipopolisaccharides (endotoxins) and the lipoteichoic acid, components of the cell wall of gram-negative and gram-positive bacteria, respectively [46, 47]. The antimicrobial effects of calcium hydroxide depend on the availability of hydroxyl ions in solution, which is much higher where the paste is applied (the main root canal). If this substance needs to diffuse to tissues and the hydroxyl concentration is decreased as a result of the action of tissue buffering systems (bicarbonate and phosphate), acids, proteins, and carbon dioxide, its antibacterial effectiveness may be reduced or even impeded [45]. Moreover, some microbial species like *Enterococcus faecalis* and some *Candida* species have shown some resistance to calcium hydroxide [48].

8.3.2 Outcome Studies: Intracanal Medication

Although there are several studies showing improved disinfection of the root canal system after using an interappointment medication [16, 28, 40, 49, 51], there are not many well-controlled clinical studies comparing the success rate of the endodontic treatment of infected root canals performed in one or more visits. Some studies revealed that two or more visits with calcium hydroxide as the intracanal medication increase the success rate in 10–20 % when compared with one-visit treatment [9, 51–54] On the other hand, there are studies showing virtually no significant difference [55, 56] or even 10 % more success for one-visit treatment [57, 58]. The

conflicting results are probably related to the fact that available data was insufficient for definitive conclusions, making statistical analyses underpowered. A study using a large sample size of treatments performed by a single operator [8] demonstrated a significantly higher success rate for infected teeth treated in two or more visits using calcium hydroxide interappointment dressing when compared with cases treated in one visit.

8.4 Concluding Remarks

To achieve the best possible treatment outcomes, the clinician must have a strong knowledge of root canal anatomy and be familiar with effective cleaning and shaping principles and making use of appropriate intracanal antimicrobial agents.

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Obturation of Root Canals

9

Dag Ørstavik

Abstract

The root filling is the final leg of the endodontic triad of instrumentation, disinfection, and obturation. The *purpose* of treatment (prevention or cure of apical periodontitis) is served by the *functions* of the obturation (sealing, killing microbes, and filling the space), which depend on some *properties* of the materials. Over time, materials have been developed that take part in the excellent prognosis of teeth root filled after vital extirpation and in the very good results achievable after treatment of apical periodontitis. Current types and brands of endodontic sealers all seem to perform adequately for conventional, orthograde root filling: ZnO-eugenol-, synthetic resin-, silicone-, $Ca(OH)_2$-salicylate- and ceramic-based materials appear to work well clinically. They may however rely on different properties to serve the functions of the obturation. For retrograde fillings and perforation repair, the need to ensure tissue regeneration is an added requirement. Mineral trioxide aggregate (MTA) has become the standard of reference for this application, while newer, calcium-phosphate-based products show promise but lack extensive clinical documentation.

9.1 Introduction

Obturation is the final step of the classic triad of endodontics: instrumentation, disinfection, and obturation. It includes all the procedures and materials used to replace the empty spaces left after instrumentation and cleaning. Traditionally, the

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endodontic part ended in the pulp chamber, but the concept of coronal leakage [1] has caused an extension of the endodontic procedures to include also the coronal part of the final restoration.

Any attempt to relate clinical practices to the prognosis of treatment must use the ultimate *function* of a procedure as the yardstick for evaluation. Sundqvist and Figdor [2] offered a simple and clinically useful description of the ultimate functions of the root filling: it should (1) prevent coronal leakage, (2) bury remaining microbes in the prepared canal, and (3) keep fluid from accumulating and serving as nutrients for bacteria entering or remaining in the root canal. Thus, all three functions seek to limit or eliminate microbial growth in and around the root canal; they are therefore an extension of the *purpose* of endodontic treatment in general: the prevention or cure of root canal infection and apical periodontitis. In cases where larger areas of soft connective or bone tissue are exposed, a fourth function may be added: promotion of tissue regeneration.

In order for the filling to achieve these functions, it is assumed that certain important *properties* are essential. Table 9.1 is a compilation of the purpose, function, properties, and some tests devised for them.

Table 9.1 The purpose of obturation, the clinical functions of the root fillings, the properties of materials, and test methods for them

Level		Test methodology
Purpose	Prevent or treat apical periodontitis	Clinical follow-up and comparison
	Stimulate regeneration	Clinical studies and animal experiments
Clinical functions	Seal coronally	Clinical studies and animal experiments
	Bury and kill microbes	
	Fill to prevent stagnant fluids	
	Promote cell differentiation	
Properties	Leakage resistance/sealing ability[a]	Functional test: fluid filtration
	Adhesion to dentin	Standard testing machine
	Antibacterial activity[a]	Various in vitro methodologies
	Sterility[a]	
	Nontoxicity, nonallergenicity, noncarcinogenicity	Standards: ANSI/ADA, ISO; CEN
	Dimensional[a] and chemical stability	
	Handling properties[a]: working and setting times, flow, film thickness	
	Radiopacity[a]	
	Nonstaining[a]	Clinical case reports and experience
	Removability[a]	Ex vivo testing in extracted teeth

[a]Items marked with an asterisk are properties in the classic listing of "requirements" by Grossman [3]

While product research and development typically target one or a few of the material's properties, many of them are potentially in conflict with each other. Therefore, one cannot rely only on one property to ensure clinical success.

Many of the properties are affected by the means of material delivery as much as by material chemistry, and endodontic materials come in various stages of viscosity, from stiff solid cores via heat-softened core materials to easy-flowing cements or sealers.

9.2 Indications for Endodontic Obturating Materials

Conventional Root Fillings These aim simply at sealing off the root from the external environment. The exposed area of connective tissue is very small; thus, there is less need to heed the tissue reaction outside the root apex. The clinical purpose is similarly simple: keeping microbes down and out to prevent recurrence of infection.

Pulp Amputation (Pulpotomy) This is mainly a pedodontic-endodontic procedure. The exposed pulp tissue area is larger (up to a few square millimeters) than for root fillings; therefore, the tissue reactions are of importance.

Pulp Capping An exposed noninfected pulp should be covered by a filling material that ideally induces regeneration of the damaged parts of the pulp. There is an incentive to develop materials that may stimulate such processes, which in addition have adequate properties related to control/elimination of bacteria. This is an area of intense research activity, with emphasis on synthetic and biological chemicals that may promote true pulp tissue regeneration and dentin formation [4–6]. However, these techniques and materials have not reached common clinical practice, and this particular aspect of endodontic obturation will not be discussed further.

Coronal Restoration The restorative aspects of the coronal filling will be dealt with in a separate chapter. Here, it may suffice to state that it has become firmly established that the coronal restoration is an integral part of the efforts to keep microbes out of the root canal system and thus to ensure optimal prognosis [7–9].

Apexification/Apexogenesis/Regeneration Microbial control by the filling remains essential also for these procedures. In apexification/apexogenesis procedures, one aims at maintaining and stimulating cells to produce hard tissue or dentin against a barrier of an otherwise inert root filling. In regenerative procedures, the aim is to stimulate cells to repopulate the pulp space with both vascular and connective tissues, but this is not done by the obturating material, which here serves as a barrier to microbial ingress [10].

Root Perforations These often destroy tissues in the periodontal ligament. The final filling is thought to function best if it may support/induce regeneration of these tissues [11, 12].

Root-End Filling The large size of the bony lesion makes it natural to focus on biocompatibility of procedures and materials for root-end filling and on regenerative aspects of the treatment. However, the area of material/tissue contact is usually quite small, and control of infection remains the primary purpose also of this type of endodontic filling. Modern techniques and materials have significantly improved treatment outcome of apicectomies [13–15].

In this chapter, focus will be on conventional obturation of root canals and on root-end fillings. It may be assumed that most of the properties and qualities of materials used for root-end filling are relevant also for many of the other applications aside from regular root fillings.

9.3 Evidence-Based Practice and Endodontic Prognosis

The triad of clinician (knowledge and skills), patient (needs and desires), and evidence (verified by research) constitutes evidence-based dentistry [16]. Materials and methods for endodontic obturation as such deal with the evidence part only; patients' preferences and operators' competence are outside the scope of this chapter.

The compilation of evidence in clinical practice has its own hierarchy of testing levels. Whether an endodontic obturation serves its purpose can only be verified in the patient receiving it. Research evidence produced in patients therefore outranks laboratory data, which can only assess certain properties assumed to be important in serving the clinical purpose. Experiments and surveys beat case series; randomized studies are better than cohort studies, and meta-analyses and systematic reviews of clinical research data are at the peak of the "evidence ladder" [17, 18] (Table 9.2).

While few obturation materials or methods have been developed using the evidence ladder from top to bottom prior to marketing, over time data have been produced that give some insight in the actual clinical performance of many material types. New materials should always be tested against this accumulated research data base.

The evidence sought for in regard to the influence on *prognosis,* by obturation techniques and materials, is directly linked to the development or healing of apical disease. Prognostication after treatment of vital pulps deals with the possible development of apical periodontitis, whereas after treatment of infected pulps, it concerns with the healing of apical periodontitis.

Monitoring of apical periodontitis after endodontic treatment is traditionally expressed as success or failure, assessed clinically and radiographically. A 1-year

Table 9.2 Levels of evidence and their associated sources for information

Level	Source of information
Comprehensive	Systematic review of comparative clinical data[a]
	Meta-analysis of comparative clinical data[a]
Clinical comparison	Randomized clinical study
	Cohort comparison
Clinical feasibility	Case series
	Case report
Nonclinical information	Experts' opinion
	Animal experiments
	Laboratory testing

[a]*Note*: Systematic reviews and meta-analyses of data from lower-level test results do not bring the findings up the ladder

control will discover almost all developments of apical periodontitis in initially healthy periapices [19–21]. Teeth with a lesion at start will in most cases show signs of healing, even though completion may take 4–5 years [22], which is another favored time period for defining outcome [23–25]. Numerous cohort and comparative clinical experiments have established success rates after 1 year well above 90 % for teeth without and 60–80 % for teeth with apical periodontitis at start (for review, see [26]). The latter may rise significantly from 1 to 4–5 years, but then recall rates often fall to levels that reduce validity [27]. For purposes of comparing treatment variables including obturation materials and techniques, the results after 1 year should be suitable even if further healing may take place.

9.4 Types of Material and Their Rationale for Use

Table 9.3 gives an overview of material types and their areas of indication.

Core Materials Metals have been used, but currently gutta-percha and synthetic resins dominate. The standard of reference is gutta-percha.

Conventional gutta-percha points consist of up to 80 per cent zinc oxide and some 20 per cent beta-phase gutta-percha [28–30]. Coloring and softening agents are a minute addition to the basic material. Alpha-gutta-percha has a lower softening temperature and is a component of specialized points used in warm gutta-percha techniques [31, 32]. The purpose of gutta-percha points is primarily to passively fill the instrumented space and to serve as a piston for pressing sealer peripherally. Concern over the toxicity [33, 34] and nonpermanence of sealer materials has led to a precept that as much as at all possible should be filled with gutta-percha. The stability of most sealers used today [35, 36] and the necessity of solubility for long-term biological activity [37] cast doubt on the validity of this presumption.

Table 9.3 Overview of material types and their areas of indication

Material	Subgroup	Common brands or types	Retro and repair	Root filling
ZnO-eugenol	Reinforced	IRM, Super-EBA	x	
	Sealer	Proco-Sol, Tubli-Seal		x
Resins	Epoxy	AH26, AH plus		x
	Methacrylate	EndoREZ, Real Seal		x
	Composites	RetroPlast, generic flowable	x	
$Ca(OH)_2$		Apexit, Sealapex		x
Silicone		RoekoSeal, GuttaFlow		x
Ceramic	Ca-Si	MTA, Biodentine	x	(x)
	Ca-Si-P	Bioaggregate, EndoSequence	x	x
Gutta-percha	Beta	generic		x
	Alpha	GuttaFusion, GuttaCore, Herofill		x
Resin cores	Complete	Resilon		x
	Resin coating	EndoREZ, EndoSequence		x

Resin cores are used in the so-called monoblock technique with a composite sealer [38]. The advantage over gutta-percha lies in the possibility of a chemical union with the resin sealer. Alternative approaches have used manufactured coatings of resins or minerals onto the gutta-percha points, for bonding either to a resin [39] or to a bioceramic sealer [40].

Sealers for Root Filling Most of the plastic, setting materials used in dentistry have also found application for this purpose. Currently, synthetic resin-, zinc-oxide-eugenol-, silicon-, and ceramic-based materials dominate, with epoxy resin or zinc-oxide-eugenol frequently used as reference materials for comparisons. The sealers are primarily responsible for achieving the purpose of the filling. To combat (re) infection, leakage prevention has long been considered a critical property. Biocompatibility was – and is – also seen as important. But as the microbial etiology of endodontic disease has become established [41, 42], and since tissue reactions usually overcome initial toxicity [43], a degree of tissue irritation does not seem to impair the clinical performance of sealers. So, the focus today is on prevention of leakage and bacterial penetration, and promotion of adhesion is seen as a corollary to this property.

Leakage prevention was the rationale for the monoblock concept with chemical integration of sealer with dentin as well as with the core material. The synthetic resin core provides an all-synthetic root filling; in other techniques, a gutta-percha core is coated during manufacture with a compound selected for its ability to bond to the sealer. First marketed with composite resin materials for sealing (EndoREZ®), this principle is now applied to gutta-percha points used with sealers based on ceramic-type materials (EndoSequence®).

Cements for Root-End Filling, Repair, and Regeneration Mineral trioxide aggregate (MTA) has become the standard of reference [44–46], but ZnO-eugenol-based materials (IRM®, Super-EBA®) are extensively used [47], and adhesive resin has its proponents [48]. See Table 9.1. The toxic properties of ZnO-eugenol-based materials [49] may be viewed as a drawback, particularly in repair of perforations. Current testing of this type of materials is concentrated on their ability to permit or promote repair and regeneration, primarily of hard tissues [50], although it is recognized that microbial control also in these situations is paramount [44, 45].

New Developments MTA appears to stimulate healing in a manner previously not experienced with other endodontic materials, but it has some practical drawbacks. It may stain tooth substance, it may be difficult to manipulate and apply, it contains some aluminum compounds in small quantities, and it may not be optimal for induction of hard tissue formation. The search for alternative or supplemental formulations has been extensive [51]. In some formulations, aluminum has been removed and the handling properties modified (Biodentine®) [52]; in others, calcium-phosphate compounds have been added to more selectively stimulate hard tissue production (e.g., EndoSequence®) [53–56].

9.5 Research Basis for Material Selection in Endodontic Obturation

9.5.1 Core Materials

Clinical Studies The chemical properties of gutta-percha and synthetic resins as core materials may have minimal influence on the clinical-radiographic outcome of endodontic treatment and do not seem to have been the object of any clinical study. As the sealer would most likely provide the properties that are important for the purpose of the filling, it would be the mechanical properties of the core in serving as piston for the fluid sealer that serves its function. For core materials applied cold, one would therefore not expect great differences among different types. Softening of the core material by heat is promoted as improving the physical filling of the prepared canal space [57]. There are insufficient data to critically assess any clinical effect of softened gutta-percha techniques [58, 59]. (See under Sect. 9.8)

Laboratory Studies Moving down the evidence ladder, studies ex vivo (extracted teeth) or in vitro (material testing without the use of clinical material) show differences among materials and techniques that have been given great importance in the past. Gutta-percha consists mainly of zinc oxide, which is a quite potent antibacterial substance [60, 61]. This may provide an additional insurance against (re)infection of the obturated canal space. Gutta-percha points may also have chlorhexidine added as an antibacterial ingredient, but this is marketed for temporary use [62, 63].

Synthetic resin core materials may also have additions of antimicrobial agents, such as bioglass [64] or other substances of very low solubility. There is little information about the relative potency of the antibacterial activity of different core materials, and the true impact on prognosis by the composition of the core is unknown.

9.5.2 Sealers

Whereas gutta-percha has maintained its dominance as core material and successfully withstood challenges from synthetic resin core materials, selection and use of sealer for seating and setting of the root filling have seen significant changes over many decades. See Table 9.3 for endodontic sealer types and commercial examples.

Clinical Studies Results from clinical studies provide little support for claims of superior performance for any of the many chemical variants used in the formulation of sealers. In several randomized clinical experiments where sealers have been compared, hardly any significant difference in clinical outcome has been found, irrespective of the clinical diagnosis (vital or infected teeth) [65–70]. Thus, ZnO-eugenol-based materials (with or without $Ca(OH)_2$), epoxy resin, $Ca(OH)_2$-salicylate- and silicon-based materials, and composite sealers all show the same clinical outcome when compared. A possible small reduction in success rate for chloroform-based sealers [24] may have been one factor that led to the virtual extinction of this otherwise time-honored method of obturation. Ceramic- or bioceramic-based materials do not currently have data from clinical studies sufficient for comparison.

Laboratory Studies The sealers come in a wide variety in chemical composition. It is not unexpected, therefore, that they perform differently in various laboratory tests ex vivo and in vitro. It is rather more of a surprise that the differences are not greater than what has been found. Resistance to leakage is considered a primary purpose of the filling and an important property of the sealer. Composite sealers have been developed based on the adhesive technology used for plastic fillings, but conventional epoxy resins also adhere to dentin to a similar degree. Moreover, adhesion to dentin ex vivo as a measure of leakage prevention may not be realistic for the clinical situation, as the bond may be intermittent over the surface as well as vulnerable to chemical and biochemical degradation. Furthermore, though silicone may not interact chemically with dentin, there is measurable physical adhesion to dentin also for this type of sealer material [71].

Testing leakage directly ex vivo has been promoted as relevant for the clinical situation, and so-called functional tests for leakage have been designed. Bacterial penetration tests [72] and fluid filtration tests [73] explore the concept of coronal leakage as a source of (re)infection of the root canal space. These tests are very hard

to standardize, and bacterial penetration tests have been shown to be very technique sensitive and to produce results that are highly variable [74, 75].

Another property of sealers presented as influencing leakage is infiltration of dentinal tubules [76–78]. Microscopic demonstration of sealer occupying large distances (up to 1 mm) into opened dentinal tubules would seem to reflect a clinically relevant property, but most commonly used sealers show some penetration, and the depth may not be a decisive factor [79].

The presence/absence of bacteria in the prepared root canal at the time of obturation is related to clinical success [80, 81], and bacteriologic sampling has been suggested as a crude means of prognostication. Laboratory studies have followed this concept by assessing survival of bacteria on the dentin surface and inside tubules after exposure to sealer [82, 83]. Epoxy resins and ZnO-eugenol materials appear able to eliminate bacteria or limit their activity in these situations, whereas composite materials may be less effective [84]. Silicone sealers have additions of silver nanoparticles, and bioglass is added to some composite and ceramic materials to give a degree of antibacterial activity. As the three primary purposes of a root filling are all related to microbial activity, it seems reasonable to assume that such antibacterial properties may be important particularly in the treatment of apical periodontitis. While sustained antibacterial properties are usually accompanied by some degree of tissue toxicity [85], toxicity may not be of clinical significance in conventional root fillings where the material/soft tissue interface is very small (see below under root end and repair materials for other situations).

Two factors have recently reactivated an interest in the microbial status of the root canal as important for all endodontic procedures: the final acceptance (long overdue) of bacteria as the only source of clinically relevant, chronic, or acute apical periodontitis [86, 87] and the rapidly increasing knowledge in the general field of biofilm formation and activity [88]. Most aspects of endodontic treatment are being reevaluated with a view at how they deal with biofilms in the root canal. This may become a major focus also for filling materials [89]; but biofilm disruption and inactivation may depend on more soluble factors than are available in current materials for permanent obturation.

9.5.3 Materials for Root-End Filling and Perforation Repair

Clinical Studies The procedure of apicectomy with root-end filling provides a relatively standardized clinical situation that lends itself easily to clinical experiments for testing of prognostic variables, including materials. When the procedures for application of the material are similar for two or more materials, one may assume that accumulated clinical data may reflect true differences in outcome. However, treatment outcome for apical surgery may be quite operator sensitive, so for materials and techniques that differ in this respect, the effect of operator influence must be considered.

Many of the classical and recent materials used have been tested and compared in fairly large cohort studies and in some randomized clinical experiments. The introduction of MTA for root-end filling initiated several clinical studies of this kind. MTA has been compared with IRM, Super-EBA (both based on ZnO-eugenol), and RetroPlast, a composite material relying on an adhesive bonding to dentin for retention of the filling and containment of residual infection [90–93]. In all these studies, MTA performs as good as, or better than, materials used for comparison. The size and significance of the difference may vary among studies, but this stable trend has placed MTA as the product of reference for this indication; however, IRM shows similarly good clinical outcomes [90, 94]. Root perforations may create a similar biological environment as that of apical surgery: a fairly large area of periodontal tissues may be damaged and control of regeneration as well as infection becomes important. Clinical case series have documented good clinical results also for these applications of MTA [11, 45, 95, 96].

Clinical data for the calcium-phosphate-based cements and other recent products for retrograde filling are still largely lacking.

Laboratory Studies The perceived good clinical performance of MTA is mainly related to three factors: initially, a very high pH which emulates the good clinical properties of calcium hydroxide, the inhospitality of the surface for colonizing microorganisms, and the ability of connective tissue to grow and differentiate very close to the surface. This combination of tissue compatibility [35, 36, 97] and antibacterial activity [44, 98], is probably caused by a very steep pH gradient and by the fact that the substances which cause the antibacterial effects are bland and easily accepted as part of the tissues when reaching live cells even close to the materials' surface. Cell compatibility data for the calcium-phosphate-based cements appear as good as or better than MTA products [33, 35, 36, 99].

As with sealers, materials for retrograde filling have been extensively tested for leakage [46, 100–106], adhesion [107], and a number of practical properties such as working and setting time, radiopacity, etc. While they may perform differently in such tests, no property has been singled out as crucial for their clinical efficacy.

9.6 Modes of Placement

Warm Techniques Current techniques for softening the core material all relate to Schilder's concept of "filling root canal in three dimensions" [57]. The rationale is that more gutta-percha (or resin core material) will flow into recesses and irregular areas of instrumented or otherwise cleared areas in the root canal system. The traditional method employs heat-carrying instruments into the canal to softened pieces of gutta-percha already seated inside. Originally controlled by heating steel instruments over a flame, the technique has been developed and supplemented with several types of automated devices (Obtura®, System B ®, BeeFill®). A simpler variant

of warm placement of the bulk filling is obturators with a solid or stiff core and a softer and thermoplastic outer coating (Thermafil®, Soft-Core®). The "core of the core" was first metal, then more pliable synthetic resin. Recently, obturators for warm placement have been made of gutta-percha throughout, with the center made of beta-phase gutta-percha cross-linked for stability, and the outer parts of alpha-phase gutta-percha, which softens at lower temperatures than the center (GuttaFusion®, GuttaCore®) [29, 32].

Lateral Condensation and Single-Cone Techniques Hand instrumentation cannot predictably yield a standardized prepared canal. To support the piston effect of the master points and to maintain a high gutta-percha-to-sealer ratio, lateral condensation of accessory cones have become the filling method of reference. But rotary and reciprocal machine instrumentation and greater instrument taper produce more standardized canal shapes than conventional hand instrumentation, and single-cone techniques with gutta-percha cores closely matching the final instrument are gaining acceptance. However, oval and complex canal systems will need special consideration and some form of lateral condensation.

Clinical Studies As mentioned, warm gutta-percha techniques have been compared to lateral condensation. A systematic review from 2007 did not find a difference in outcome for warm vertical and cold lateral filling techniques [58]. Case reports and case series of special situations (e.g., internal root resorption [108], dens invaginatus) show warm methods for application to fill effectively the irregular spaces, and to the extent that this may influence prognosis, warm gutta-percha techniques for obturation may offer an advantage in these cases.

Laboratory Studies Adhesion is for the most part determined by the sealer and less by the method of core placement. Variations in leakage may also be more influenced by the sealer, although several studies have assessed the effect of warm methods for filling in regard to microbial or liquid passage along root fillings [31, 109–112]. Warm techniques for application of gutta-percha and resin cores usually perform better with regard to completeness of fill, while only small and varying effects of the method of placement have been found in regard to penetration of bacteria or chemical compounds along root fillings ex vivo. Furthermore, the ratio of sealer to core material (gutta-percha) may be diminished when warm techniques are employed, which is seen as positive.

9.7 The Radiograph of the Final Root Filling: Factors of Prognostic Significance

Retrospective analyses of success and failures after endodontic treatment have found a few predictors for success in the radiographic appearance of the final root filling [68, 113, 114]. Some of these may be related to the materials or techniques

used in the procedure; others may be more reflecting of other aspects of treatment (e.g., instrumentation).

Length of Obturation The relative position of the end point of the root filling and the radiographic apex is relatively easy to measure and has been associated with success. Overfilling and fillings short of the apex have long been shown to give a reduced prognosis in large follow-up studies [25, 115]. A more detailed analysis of the data have found this to be true primarily for cases with preoperative apical periodontitis [116], whereas vital cases heal well even when the filling is longer or shorter than the perceived ideal of 1–2 mm distance from the radiographic apex. This probably means that in the absence of infection, apical periodontitis does not develop irrespective of the position of the root filling. Similarly, a surplus may not influence the outcome of treatment of apical periodontitis if the canal has been effectively disinfected. In this situation, a "sealer puff" will not negatively influence prognosis. But if the surplus filling material carries with it microbes or if it is placed in an infected area, it may serve as a surface for microbial colonization and disease persistence.

The differential effect of a short filling is similarly related to the microbial status of the tooth: in a noninfected case, disease does not develop and healing may take place irrespective of the end point location of the root filling; in an infected case, a short filling may leave infected pulp tissue toward the apex which will maintain the periodontal inflammation.

Homogeneity of the Root Filling In radiographs, the quality of the root filling is often judged by subjective characterization of voids or slits. There may be problems with standardization of such assessments [117], but there is general consensus in the literature that dense and homogenous fillings carry a better prognosis than fillings with voids or slits along its course [8, 115]. It must however be remembered that homogeneity is also a function of the material's radiopacity. High radiopacity may cover up real voids or slits; low radiopacity in a material may give the impression that the material is absent when in fact it is not.

Width of Instrumentation/Filling at the Apex The argument has been made that effective disinfection requires extensive instrumentation and removal of all pulpal tissue at or near the apex [23, 118]. This would translate into bold and wide root fillings apically in radiographs. However, whereas extensive instrumentation removes more bacteria [82, 118], there are no known studies relating the actual width of the root filling at its terminus to disease development or persistence. Typically, studies record the size of the last file used in instrumentation [113], but it is unclear how this theoretical value translates into actual removal of dentin and into the volume occupied by the root filling. Moreover, the size of the final instrumentation does not seem to have prognostic value.

9.8 Concluding Comments

True prognostication can only be based on clinical data. In endodontics, data are compiled fairly easily. While it may not be a necessary requirement that all new materials are tested in randomized experiments in comparison with a standard before they are placed on the market, such or similar studies must be carried out to support any claim of superiority. For laboratory data to take preference, they should document properties related to the pathogenesis/etiology that would likely make a difference in the prevention of a disease or its cure. However, it remains an unfortunate fact that no laboratory property has been linked unequivocally to clinical performance in the prevention or treatment of apical periodontitis.

Vital pulp extirpation followed by conventional root filling (prevention of apical periodontitis) is associated with a high level of success by traditional, clinical, and radiographic criteria [23–25, 115]. This translates to a high resistance against microbial leakage, in that teeth with root fillings judged adequate in radiographs have withstood the pressure from oral microbes to penetrate the filling, colonize the root, and produce disease. This is a universal finding testifying to the predictability of the endodontic treatment procedure. Given that success rates are so high for root fillings of noninfected teeth, changes in chemical formulations and modes of delivery cannot be expected to yield significant improvements of prognosis and would probably require prohibitively large randomized clinical studies for documentation of superior performance. This high success rate with chemically different materials also indicates that microbial leakage along root fillings *due to chemical particularities of the materials* is not a major problem. If it were of great practical importance, a much higher percentage of noninfected teeth would become infected and present with apical periodontitis at recall.

By contrast, there is greater uncertainty about the prognosis after root filling of teeth with apical periodontitis. Healing may take a long time and progress for decades after treatment. Most studies list preoperative apical periodontitis as the factor with the greatest negative influence on prognosis after root filling [24, 26, 113]. But it remains questionable whether improved leakage resistance in new products will lead to an improved prognosis compared to current materials and techniques.

Focus on the second and third purpose of the obturation may hold greater promise for improving treatment results: killing as well as burying bacteria (second purpose) by the material may be enhanced in new sealer materials, and it may be desirable and feasible to make the environment so hostile to bacteria as to prevent any (re)colonization (third purpose).

The current emphasis on biocompatibility and induction of repair is important and stimulating. Fortunately, treatment of apical periodontitis by conventional or surgical approaches already carries quite high success rates. It is as important as ever to maintain focus on asepsis and antisepsis and disinfection during all phases of endodontic treatment, including obturation.

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Restoration of Endodontically Treated Teeth

10

Nadim Z. Baba, Shane N. White, and George Bogen

You cannot open a book without learning something.
— Confucius

Abstract

The restoration of endodontically treated teeth must be planned before initiating root canal treatment. Provisional (temporary) restorations during root canal treatment protect the root canal system form bacterial ingress and include zinc oxide eugenol or calcium sulfate preparations used for short periods and glass-ionomer or resin-modified glass-ionomers for longer interim periods. Ideally, a definitive core restoraton should be placed at the time of obturation, before removal of dental dam. The prognosis of mature teeth improves by conservation of tooth structure, avoiding posts whenever possible, avoiding gaps between gutta-percha and core restoration interface as well as full coverage restorations on anterior teeth and by the provision of cuspal coverage restorations on posterior teeth. Recent evidence suggests that conservative approaches, using direct-bonded resin-composite restorations, have promise for restoring largely intact posterior teeth. Fiber posts are associated with a higher incidence of restoration failure than metallic posts, but with a lower incidence of tooth fracture. When posts are indicated, preparations should be conservative, removing minimal radicular structures. The survival of immature teeth with open apices is enhanced by the use of bonded translucent resin composite core restorations rather than preformed stainless-steel crowns. Restoration quality is critical for both temporary

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and definitive restorations; bacterial contaminaitons must be permanently excluded. The main reason for extraction of endodontically treated teeth is not failure of endodontic treatment, but caries, inadequate restoration, periodontal disease and root fractures.

10.1 Introduction

Restoration of endodontically treated teeth (ETT) is often considered as being distinct from root canal treatment (RCT). However, both are inseparable in planning, execution, and prognosis. The restoration of ETT may be as important as the actual root canal obturation and has a profound effect in the ultimate goal of excluding microorganisms, the primary cause of endodontic disease [1–3]. Therefore all dental providers restoring ETT share the responsibility to ensure that every phase of treatment is appropriate, well executed, and timely.

The restoration of mature ETT has been extensively investigated, and existing literature is abundant with a broad range of benchtop and clinical outcome studies. However, there is paucity of high-quality clinical outcome data. Furthermore, much of the available information is outdated, applies to only specific situations, or is confounded by significant variables, making interpretation of the results difficult. It is not surprising that dentists are inconsistent in the restorative decision-making process regarding treatment protocols [4, 5]. This chapter reviews evidence-based clinical outcome data that will provide practical guidance to the restorative dentist and focuses on restorative prognostic factors that favorably influence the long-term performance of ETT.

10.2 Interim Restorations

Interim or provisional restorations (PRs) (former term “temporary restoration”) must be durable and leak resistant to prevent microleakage and microbial ingress. Coronal microleakage is considered to be the most common cause of endodontic failure. Multiple investigations [6–12] have confirmed that inadequate root canal treatment and poor coronal restorations both contribute to increased microleakage and vulnerability to bacteria and their by-products (Fig. 10.1). Salivary recontamination of the root canal system and exposure to bacterial endotoxins can lead to periapical inflammation and endodontic failure [3–12]. The use of reliable interim prostheses will reduce the possibility of microbial leakage before, during, and after RCT.

Provisional restorations generally produce a poor coronal seal [13–17]. They are primarily used to provide a short-term restoration that is esthetic and functional while protecting the soft and hard tissues before the definitive restoration is delivered. Well-fitting PRs prevent mechanical failures such as fractures and help avoid root canal reinfections [16, 18]. A retrospective study that evaluated 775 ETT in 508

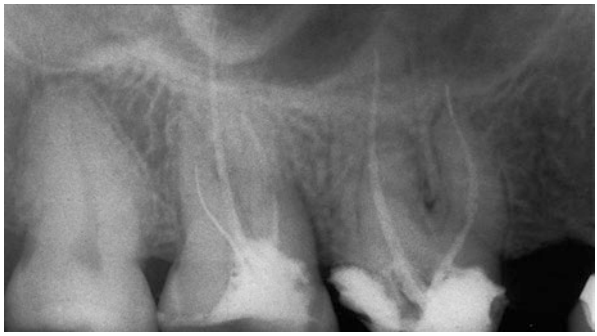

Fig. 10.1 Periapical radiograph of maxillary right molars exhibits poor-quality endodontic obturation with a carrier-based gutta-percha system. Visible are untreated canals and substandard foundation restorations with multiple material voids ()

patients found a higher survival rate for teeth restored within 2 weeks after root canal therapy [19].

The duration of interim provisionalization must be considered before the appropriate material can be selected. For short restorative periods, it is recommended that cements such as zinc oxide eugenol (ZOE) be used only for periods of up to 1 or 2 weeks [20]. For longer periods, particularly when definitive restorations may be delayed, stronger cements should be used to assure a better seal against tooth structure. Glass ionomers, Zinc Phosphate, Polycarboxylate, or resin-modified glass ionomers (RMGIs) exhibit acceptable seals against dentin and have advantageous physical characteristics, making them suitable for short- to long-term temporization. However, these cements do not display adequate properties to be used as definitive buildups; therefore, their removal is required before placement of final restorations. Soft self-cured calcium sulfate-based temporary filling materials tend to be easily abraded, unstable over time, and absorb moisture. They can only be used for short periods of time in small cavities and must be removed completely along with the cotton or sponge pellet before placement of definitive restorations [21]. A contemporary investigation compared the leakage of different provisional materials (Intermediate Restorative Material (IRM®), Cavit™, and TempBond™) and showed that none of the provisional materials examined using microbial markers prevented coronal leakage when tested for 30 days [13]. They also demonstrated that the delayed placement of the definitive restorations had an impact on the prognosis of ETT. When comparing definitive coronal restorations with PR, it has been shown that ETT restored with permanent coronal restorations have a higher survival rate than teeth restored with provisional restorations, even if the definitive restoration is delayed [17].

Before restorative treatment of ETT begins, all existing restorations should generally be removed, unless recently placed by the treating dentist [22]. Leakage under failing restorations is a major cause of new and recurrent endodontic disease. Carious dentin should also be completely removed before accessing the root canal system. Radiographs and oral examination should be performed to assess the quality of the root canal obturation, the presence of cracks, and the need for periodontal therapy (e.g., crown lengthening). When insufficient tooth structure is available, PR may be required before root canal treatment is initiated to ensure that the tooth can be isolated from the oral environment and salivary contamination (Fig. 10.2). For example,

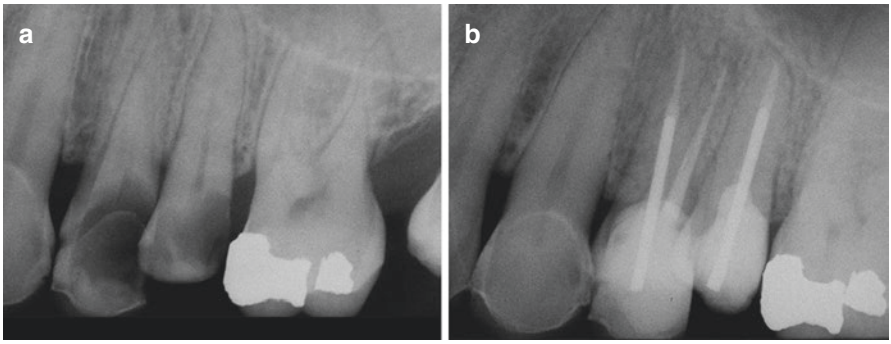

Fig. 10.2 Radiograph of (**a**) two severely decayed maxillary left premolars before clinical isolation with glass ionomer cements during conventional endodontic treatment. (**b**) Final radiograph of premolars restored with stainless steel posts and bonded core buildups (© Dr. George Bogen. All Rights Reserved)

teeth with large defects, deep proximal boxes, can be quickly temporized using glass ionomer or RMGI restorations. This will facilitate effective dental dam isolation and contribute to improved cavity access preparation form. Opaque white or blue-colored materials can be employed because they are easily distinguished from tooth structure and facilitate removal when replaced by permanent restorations.

During endodontic treatment, microbial exclusion from the root canal system is a strict requirement. Therefore, placement of a durable thick temporary filling is essential between treatment sessions [23]. The thickness of the temporary restorative material should be maximized, while the height of the underlying cotton pellet should be minimized. A pellet of synthetic foam sponge is preferred to cotton, because bacterial growth will not be supported.

Extensively damaged teeth may require provisional crowns or onlays prior to endodontic care. Several materials can be used in the fabrication of provisional restorations, including acrylic and composite resins. Formulations of the most commonly used acrylic resin materials are based on polymethyl methacrylate (PMMA). Acrylic resin can be used for the fabrication of either direct or indirect provisional restorations. Investigations [24, 25] have demonstrated that indirect fabrication demonstrates improved marginal integrity compared with prostheses made by direct fabrication.

Indirect fabrication provides high-strength provisionals indicated for patients requiring long-span fixed partial dentures and prolonged treatment regimens and for patients with above-average masticatory strength. Alternatively, preformed provisionals made from polycarbonate, composite resins or other materials can be used. Intracoronal and extracoronal restorations can also be provided using composite resin-based materials.

Coronally compromised anterior and select premolar teeth may require, in addition to the provisional restorations, temporary posts to secure resistance and retention form. Minimal cement should be placed on prefabricated temporary posts, so that they can be easily removed at the time of final restoration placement. Different materials have been introduced for use as temporary posts; however, prefabricated permanent posts can also provide adequate retention when cemented temporarily.

Temporary cements utilized for luting provisional crowns (former term "temporary crowns") and posts are generally zinc oxide-based cements. Some of these formulations contain eugenol, but non-eugenol cements are also widely used. If composite resin or resin-based cement is going to be utilized as a buildup material, it is strongly recommended to use a non-eugenol zinc oxide-based temporary cement. Eugenol plays a possible role in the inhibition of resin polymerization, so any eugenol-based sealer needs to be carefully removed before using resinous adhesives or restorative materials [26]. Contradictory conclusions have been reported regarding the inhibition of resin polymerization by eugenol. Some studies [27, 28] describe the decrease in bond strength to dentin, while others show no effect [29–33]. However, provisional restorations often leak and can produce discomfort for patients with vital teeth. More importantly, they can permit microbial contamination in teeth undergoing root canal treatment, especially if a temporary post is used [13, 17]. Similar to permanent buildup restorations, the prefabricated temporary post should be placed before the dental dam is removed.

After root canal treatment has been completed, a durable PR should again be placed to ensure protection and temporary sealing. Preferably, the definitive foundation restoration made from composite resin or amalgam should be placed before the dental dam is removed. It is critically important that any underlying cotton pellet is removed before final restoration placement: damp cotton is an excellent culture material for unwanted microorganisms and an inferior foundation for the final load-bearing restoration. Residual provisional restorations such as Cavit™ and IRM® also compromise the integrity of the permanent restoration and must be completely removed from the access cavity.

10.3 Restoration of Mature Teeth

The foundation restoration should ideally be placed immediately after the final obturation and before the dental dam is removed. There is no benefit postponing restorative care while waiting for resolution of symptoms or signs of healing. Adequately condensed gutta-percha (GP) or other obturation materials can then be safely removed and the post space prepared immediately, when indicated, after endodontic treatment or generated during the root canal procedure [34, 35]. Several studies have indicated that there is no difference in leakage of the root canal filling material when the post space is prepared immediately after completing endodontic therapy [36–39]. The primary goals of bacterial exclusion and conservation of tooth structure must be observed during all phases of treatment [40].

Immediate restoration of structurally compromised anterior teeth after completion of RCT can be achieved with a prefabricated post and a composite resin core buildup when indicated. However, challenges related to the use of prefabricated posts in some anterior teeth require consideration. When the post space is too wide in the coronal aspect of the ETT, the cemented post may only contact the tooth in the most apical portion of the post space. Under these conditions, post retention depends primarily upon the cement. In the presence of minimal or no ferrule, when the tooth is subjected to occlusal forces, the cement seal will eventually break, leading to

leakage, caries, loss of post retention, and crown failure. Additionally, when certain anterior teeth (e.g., canines) with ovoid canals are prepared for prefabricated round posts, the post preparation using a matching drill for the post may result in excessive removal of tooth structure, or the post will only contact the root canal space laterally. These types of teeth may benefit by using custom cast posts fabricated to better adapt the existing root canal morphology. On the other hand, the vast majority of posterior teeth not indicated for post placement can receive a definitive core buildup after canal obturation, thus sealing and protecting the RCT (Fig. 10.3).

Excess obturation materials should be removed to a millimeter below the level of the pulpal floor, or slightly below, in posterior teeth. For intact anterior teeth except for the access opening, GP or other filling materials should be removed to the level of the cemento-enamel junction or shortly below. It is important that excess sealer be removed after root canal obturation from the pulpal floor and remaining internal walls. Zinc oxide-based sealers inhibit the polymerization of dentin agents and composite resin as well as prevents adhesion of glass ionomer to dentin [41]. Some ZOE sealers set quickly and can be removed mechanically. Others set slowly and may need to be removed using chloroform and/or alcohol-soaked cotton pellets.

Most anterior teeth with intact coronal structure can be restored using direct composite resin restorations. Anterior ETT with lingual access cavities do not require complete coverage crowns except when they are structurally weakened by large or multiple coronal restorations. This includes teeth used as abutments for fixed partial dentures and removable partial dentures or when significant changes in morphology or shade are required. Preservation of tooth structure is paramount. Root canal preparations generally enlarge the root canal and pulp chamber rendering the walls of the tooth thinner and weaker; crown preparations concomitantly contribute to further reduce tooth strength [42].

In anterior ETT that are intact except for the access opening, direct restorations without further removal of tooth structure are preferred. Gutta-percha or other obturation materials should be placed to a few millimeters below the CEJ. A glass ionomer base can be placed to seal over the GP and against dentin, which protects the root filling material and reduces the bulk of resin composite required. If the tooth is discolored, internal bleaching, using sodium perborate, without heat or superoxyl, can be used to improve the value or brightness of the tooth. A deep core using

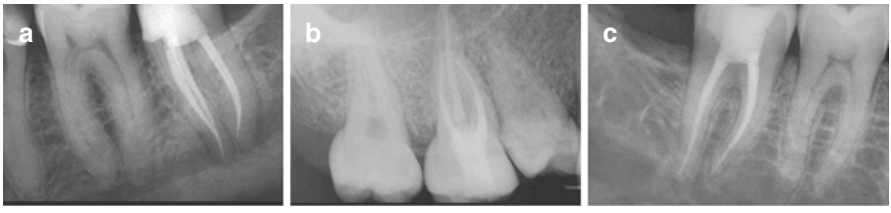

Fig. 10.3 Intraoral radiographs of (**a**) mandibular left second molar, (**b**) maxillary right first molar, and (**c**) mandibular right second molar restored with bonded composite core restorations without post placement ()

opaque white composite resin can be used to improve value, but the restoration should be finished using natural shades. If the esthetic appearance is still unsatisfactory, a conservative porcelain veneer can be used.

Posts are only needed in anterior teeth when there is minimal coronal tooth structure remaining. Posts can provide resistance form against tipping or lateral forces and contribute to retention form. Posts do not strengthen teeth; they tend to weaken teeth through additional dentin removal and unfavorable stress concentration [43–49]. For ETT molars adequate resistance and retention can routinely be obtained from the remaining walls of the pulp chamber through a bonded corono-radicular buildup [48, 49]. It is always preferable to restore molars without post placement when adequate remaining tooth structure is available.

In posterior teeth, two and or three intact walls are necessary for the corono-radicular buildup. If the material is bonded to dentin and enamel, there is no need to extend the materials into the root canal orifices. If however unbonded material such as amalgam is used, it may require countersinking into the orifices. However, none of the restorative materials provide a permanent leakproof seal. If the tooth cannot be restored immediately, it is recommended to seal the orifice of the canals with an orifice barrier such as flowable composite resin, hydrophilic resin, or glass ionomer [50–53]. Composite resin core buildup can be prepared for crowns immediately after curing and formulated to encompass light, chemical (self-cure), or dual polymerization. Self-curing composite resins assure that the entire thickness of the buildup will be completely cured. A recent in vitro study tested the bond strength of selected dual-polymerizing composite resin foundations using light, chemical, or dual-polymerized adhesive systems which suggested that dual-polymerized systems may not provide acceptable adhesive strength to dentin [54]. It can be concluded that light-polymerized adhesives without chemical activators produce improved bond strength to dentin.

Endodontically treated premolars present an intermediate situation between anterior teeth and molars. Mandibular first premolars with conservative access openings may not require cuspal coverage restorations. These teeth have no substantive occlusal intercuspation and are characterized by small, poorly developed lingual cusps. Premolars retaining both buccal and palatal walls can normally be restored without post placement using only a core buildup as the foundation restoration.

In the small minority of ETT where posting is indicated, the post design should be conservative, parallel, passive, vented, serrated, or roughened [40, 55] (Fig. 10.4). It is recommended that parallel-sided metal posts with tapered apical 2–3 mm are

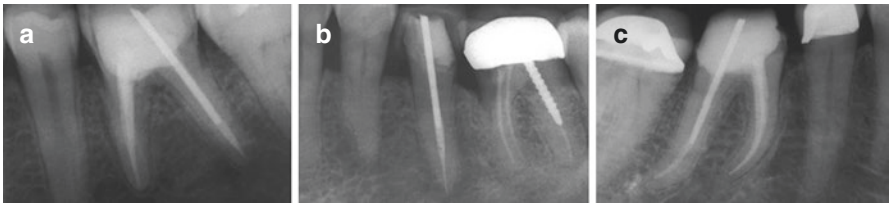

Fig. 10.4 Final radiographs of mandibular (**a**) left first molar, (**b**) left second premolar, and (**c**) right first molar restored with conservative parallel-sided stainless steel posts and composite core buildups ()

used to favorably reduce spreading forces and thereby preserve maximum radicular dentin thickness before post cementation. The post design can be critical in securing a favorable prognosis. Stainless steel has long been the material of choice being stronger than titanium and glass fiber-reinforced (GFR) epoxy resin posts. Glass fiber-reinforced epoxy resin posts are more flexible than stainless steel posts; this appears to increase the risk of restoration failure and decrease the risk of catastrophic root fracture when compared to metal posts [56–62].

Custom cast posts, when indicated, should also be conservative, passive, and airborne particle abraded; they have advantages that include better adaption, superior strength, and improved stress transfer from their shoulder to the root structure. It is important to leave at least 4–6 mm of GP or alternative obturation material to ensure adequate apical seal (Fig. 10.5). In addition to providing an apical seal, the 4–6 mm of remaining obturation material in the apical third of the root will protect the area containing additional complex anatomy, accessory canals, fins, bifurcations, apical deltas, etc. The apical part of the root is also extremely thin, weaker, and easily perforated when generating a post space.

Several guidelines have been proposed for determining the ideal length of post placement [63–67]. Ideally, the minimum length post should equal the height of the clinical crown but compromise, and a shorter post may be necessary under certain clinical conditions. While short posts cannot be recommended, they may be unavoidable in short or thin roots. Short posts do not distribute spreading forces equally along the long axis of the root and can often produce fractures in the coronal and mid-radicular areas (Fig. 10.6).

Longer posts offer the greatest rigidity and produce less root deflection; however, rigidity is a double-edged sword, protecting the restoration, but stressing the root itself, and sufficient root filling material must remain [68]. Care must be also be taken with longer posts to ensure that adequate root thickness is preserved apically, particularly with narrow or concave roots. When two or more coronal walls are remaining that are 1 mm in thickness after preparation, and 4 mm in height, a core, bonded or not, can be placed without using the post.

The post should be only one quarter, or less, of the width of the root. However, the delivery of the optimal post length can be challenging in many cases. When a tooth has an average or below average root length and the post occupies two-thirds or more of the root length, it may not be possible to retain 4 mm or more of filling material at the apex [69]. Therefore, optimal post length is determined by retaining 5 mm of apical GP or other filling materials and extending the post to that depth. However, in teeth which anatomically display shorter roots, the amount of remaining root filling material must be carefully determined on a case-by-case basis with the ultimate goal of avoiding the short post.

Multiple posts placed to support foundation buildups for premolars and molars are not recommended. A single post should be placed in the distal root of mandibular molars, the palatal root of maxillary molars, and the longest and straightest root of maxillary premolars (Fig. 10.7). The post diameter should not exceed one-third

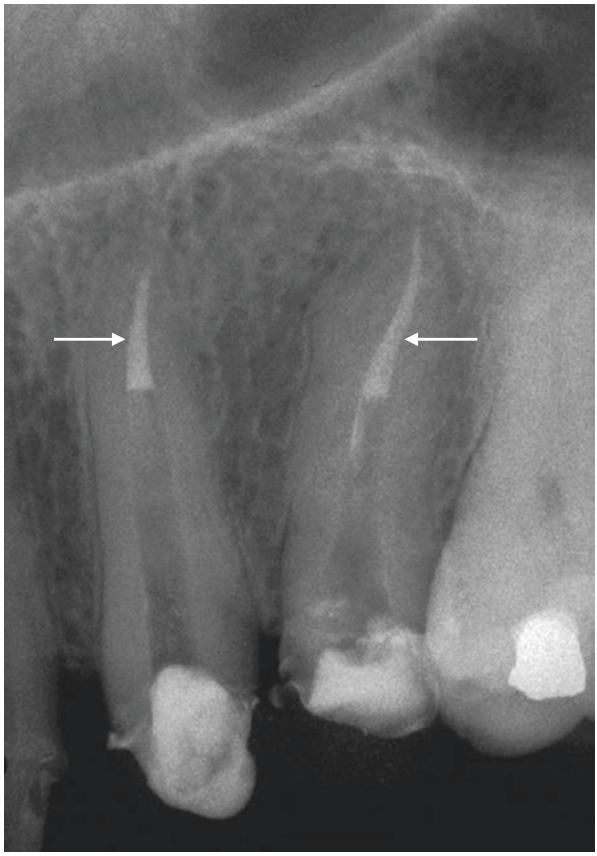

Fig. 10.5 Periapical radiograph of maxillary left central and lateral incisors after orthograde retreatment and post space placement. The central incisor shows 4 mm of remaining gutta-percha (*arrow*) and the lateral incisor 6 mm of remaining root filling material (*arrow*). A greater length of root filing material was left in lateral incisor due to the presence of apical curvature (© Dr. George Bogen. All Rights Reserved)

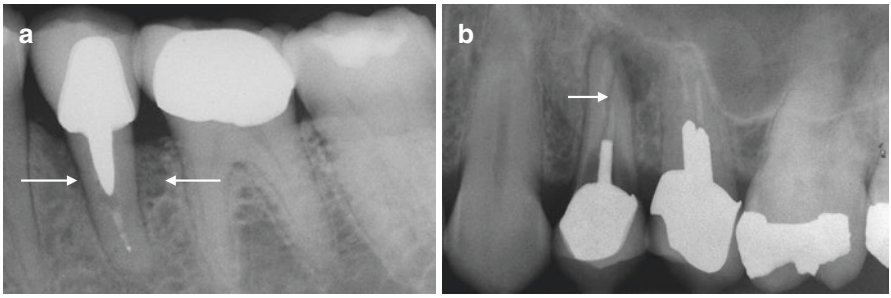

Fig. 10.6 Recall radiograph of a (**a**) mandibular left second premolar with a short cast post shows loss of supporting bone (*arrows*) and periodontal ligament thickening consistent with a vertical root fracture. (**b**) Radiographic review of maxillary left first premolar with short preformed stainless steel post, vertical root fracture (*arrow*), recurrent caries, and apical pathosis (© Dr. George Bogen. All Rights Reserved)

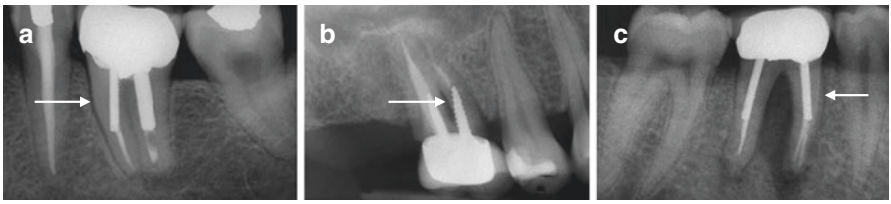

Fig. 10.7 Periapical radiographs of (**a**) mandibular left first molar, (**b**) maxillary right first molar, and (**c**) mandibular right first molar with multiple post placements and concomitant resultant vertical root fractures (*arrows*) ()

the root diameter. The diameter of the post should be 0.5–1.5 mm depending on the tooth, and only post preparation instruments that match the desired post diameter should be used [70].

When preparing the post space, be cautious of root concavities not easily detected on two-dimensional radiographs. Carefully observe multiple periodontal ligament outlines that are indicative of root concavities and potential root curvature in or out of the plane of the radiograph. Use a periodontal probe to explore the root anatomy and inclination. The endodontist may be best equipped to prepare the post space, as they are more familiar with the canal anatomy after treatment and can prepare the post space under dental dam isolation.

A variety of materials can be used for permanently cementing posts [71–74]. Polycarboxylate cements have poor physical properties and should be avoided. Zinc phosphate can be used, but newer adhesive cements offer many advantages; the one advantage of zinc phosphate is its brittleness which allows for post removal if endodontic retreatment is required. Glass ionomer cements have good physical properties, seal against dentin, and release fluoride. As for any cement, attention to moisture control and protection during initial set are important when using glass ionomers [75–78].

Composite resin cements are advocated for the cementation of glass fiber-reinforced (GFR) epoxy resin posts. However, there are notable differences in the retention values of the various types of composite resin cements that include etch-and-rinse, self-adhesive, and self-etch systems [79–85]. Several investigators found that self-adhesive resin cements are adequate for cementation of posts [81–85]; but further trials are needed before confirming the superiority of self-adhesive cements to the other available systems. Additionally, it has been shown that thermocycling, cement type, and other factors influence the bond strength of self-adhesive cements [84, 85].

Regardless of the type of post used and the location of the restoration in the mouth, when restoring an ETT, a cervical ferrule should engage 2 mm of tooth structure to optimally prevent root fracture. Different lengths and forms of the ferrule have been studied [86–89] and are essential factors for the success of the resultant "ferrule effect." When possible, encompassing 2.0 mm of intact tooth structure below the entire circumference of a core creates an optimally effective crown ferrule. Ferrule effectiveness is enhanced by grasping larger amounts of tooth

structure. The amount of tooth structure engaged by the overlying crown appears to be more important than the length of the post at increasing a tooth's resistance to fracture.

10.4 Restoration of Immature Teeth with Open Apices

Tooth structure preservation is the ultimate objective in restoring endodontically treated immature permanent teeth in children. Young patients that receive vital pulp therapy or conventional RCT have teeth that can typically exhibit extensive loss of coronal structure as a result of deep caries, trauma, or developmental anomalies (Fig. 10.8). A majority of these permanent teeth present with incomplete root formation and open apices that require apexification or apexogenesis procedures [90–92]. These unique characteristics require a restorative treatment strategy that recognizes the fragility of immature permanent teeth and ensures tooth retention. Treatment is required that maintains normal masticatory function, preserves arch integrity, guards against microleakage, and protects teeth from cuspal fractures. Progress in adhesive dentistry has been instrumental in providing restorative options that conserve the remaining valuable tooth structure and allows continued tooth maturation while contributing to improved long-term survival.

Carious lesions in immature permanent molars can be aggressive, rendering teeth structurally weak after extensive carious dentin removal, endodontic treatment, and traditional restorative care. Consequently, these teeth are at a greater risk of fracture due to unsupported enamel, large pulps, and thin radicular walls (Fig. 10.9) [93]. Complicating factors such as hypocalcification, malformation of the enamel, and trauma can further compromise the tooth integrity and resistance to fracture [94, 95]. Due to these clinical features, some authors have advocated placing a preformed metal crown or stainless steel crown (PMC/SSC) after pulpal therapy to maintain the tooth as a space maintainer until implant placement [93]. However, innovative obturation and regenerative techniques using mineral trioxide aggregate (MTA) and other calcium silicate-based cements (CSCs) or bioceramics

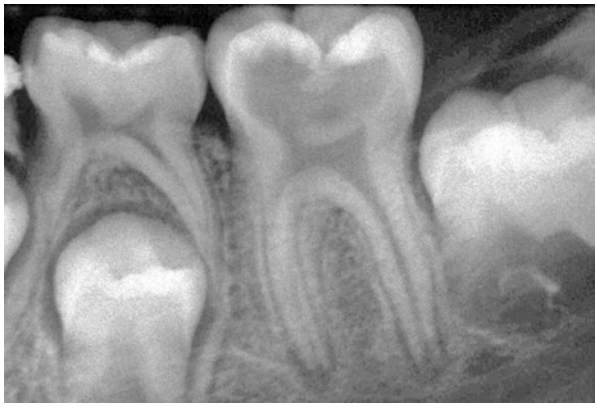

Fig. 10.8 Periapical radiograph of mandibular left first molar in a 7-year-old patient with deep coronal caries and open apices. Pulp testing revealed normal pulpal responses (© Dr. George Bogen. All Rights Reserved)

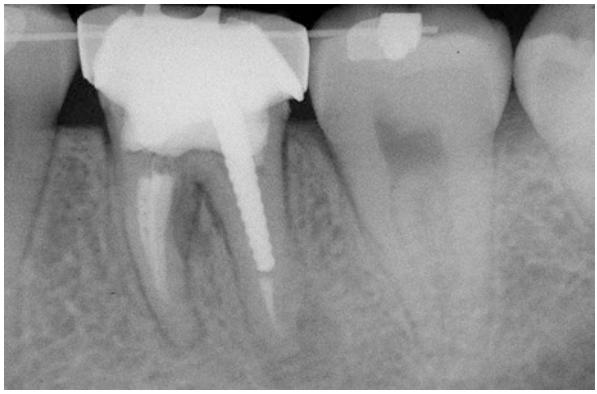

Fig. 10.9 Six-year recall radiograph of mandibular left first molar in an 18-year-old patient treated for symptomatic apical periodontitis. The tooth has a poorly fitted PMC/SSC and was diagnosed with a distal root vertical fracture (© Dr. George Bogen. All Rights Reserved)

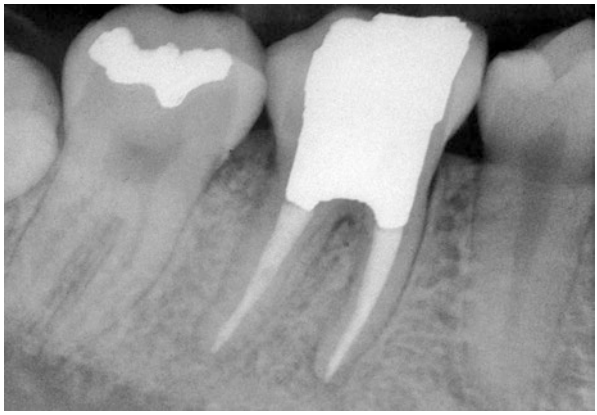

Fig. 10.10 Three-year recall radiograph of a permanent molar after RCT. Tooth was restored with an amalgam core without stainless steel crown coverage and was diagnosed clinically to have a vertical root fracture (© Dr. George Bogen. All Rights Reserved)

that encourage continued root-end formation in necrotic and vital immature teeth are changing currently accepted restorative strategies. These new biologically based treatment options can increase the structural integrity of immature teeth by promoting increased root length and wall thickening [90–92, 95–98].

Endodontically treated immature teeth that exhibit extensive loss of coronal structure have traditionally been restored with amalgam as the core material [99, 100]. However, the difference in the modulus of elasticity between amalgam (28–60 GPa) and dentin (12–18 GPa) can contribute to a greater risk of coronal and radicular fractures in these compromised teeth (Fig. 10.10) [101–103]. The material has much higher modulus of elasticity than dentin, can sensitize teeth care workers, and may not provide an impenetrable seal against microleakage and bacterial contamination [104–106]. Therefore, PMC/SSCs have been advocated with the goal of preventing irreparable coronal fracture, protecting against cuspal breakage, and acting as a secondary barrier against microleakage in the typically weakened crowns [95].

The PMC/SSC was initially developed to restore primary teeth and has shown to be a reliable restorative option in the deciduous dentition. They have also been

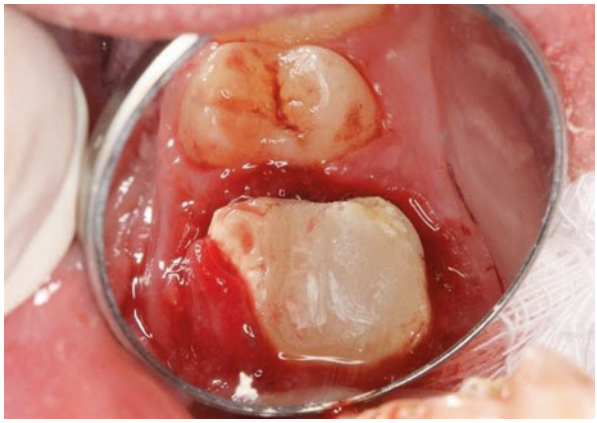

Fig. 10.11 Clinical photograph shows edematous and hyperplastic gingival tissue associated with a poorly fitted stainless steel crown placed over a composite core buildup (© Dr. George Bogen. All Rights Reserved)

recommended for structurally compromised permanent molars in children as an interim restoration during the transitional dentition until such time a permanent restoration can be placed [106–109]. Clinical investigations have shown that well-adapted and cemented PMC/SSC shows little or inconsequential damage to periodontal health [110, 111]. However, poorly contoured PMC/SSCs predispose the gingiva to inflammation, and poor oral hygiene increases the probability of a compromised periodontium (Fig. 10.11) [112]. Since the crowns are pre-sized, they cannot always be ideally crimped to provide accurate marginal adaptation [94, 110–115]. Poor marginal adaptation of the PMC/SSC and potential cement leakage can lead to recurrent caries, gingival inflammation, tooth impaction, potential periodontal defects, and premature tooth loss [99, 112, 115–129] (Fig. 10.12). Although the PMC/SCC offers some advantages, the placement also requires additional tooth preparation and reduction of the remaining valuable tooth structure [94].

General dentists and pediatric dentists routinely place PMC/SSC restorations on permanent immature teeth that have been treated with direct and indirect pulp capping, partial or complete pulpotomies, hypomineralization or generalized developmental problems, and orthograde RCT [99, 119, 120]. However, the PMC/SSC has become the standard restoration in immature permanent teeth without any clear clinical evidence to support its continued application [94, 121, 125]. Although data demonstrates that these restorations have a much higher success rate when compared to amalgam alone for compromised primary teeth, there is no distinct understanding of how beneficial PMC/SSCs are for permanent molars in children after receiving endodontic treatment [106, 119].

It is generally recognized that the chairside time required to properly fit a permanent molar with a preformed metal crown is greater than that for a primary molar crown [106]. Multiple factors contribute to the difficulty in ensuring that all parameters for successful PMC/SSC placement are implemented. It has been estimated that approximately 80 % of pediatric dental treatment is completed by general dentists who may be challenged because the permanent PMC/SSC is not shaped accurately at the cervical level to accommodate the variations in crown

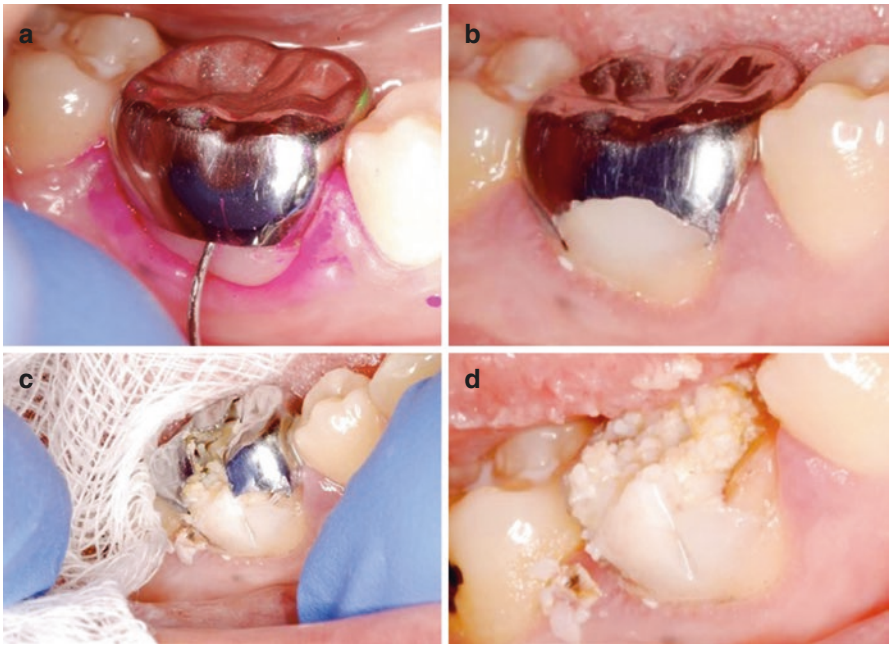

Fig. 10.12 (**a**) Clinical photograph of stainless steel crown with open margin after plaque disclosure. (**b**–**d**) Removal of a stainless steel crown over an amalgam core buildup reveals recurrent caries, debris accumulation, and moderate gingivitis (© Dr. George Bogen. All Rights Reserved)

length and height encountered during the transitional dentition (Fig. 10.13) [112, 114, 126–128]. These preformed restorations can also pose a problem in sedation cases where aspiration of the crown is a risk that can be detrimental to the health of the child [129].

Improperly fitted PMC/SSCs can also cause impaction of erupting teeth and loss of leeway space resulting in orthodontic problems in the mixed dentition [118, 130]. Moreover, PMC/SSCs can release nickel, chromium, and iron that are absorbed by the root cementum at much higher rates when compared to intact molars [131]. Another major concern for teeth restored with amalgam cores and PMC/SSCs is that they predispose the patient to multiple future restorative procedures that may include posting and re-coring, crown lengthening, and extensive full-coverage restorations as the patient ages [132–138]. These procedures further reduce valuable tooth structure and may hasten tooth loss via root fractures, microleakage, and other restorative failures [132]. It has been shown that endodontically treated teeth that retain a greater amount of coronal tooth structure after restorative procedures are more resistant to fractures that can be irreparable [139–141]. Bonded core materials offer an alternative conservative approach that can preserve the often structurally weakened endodontically treated tooth in young patients (Fig. 10.14).

Three varieties of composite resin cores are available alternatives for restoring immature permanent teeth and include light-cured, self-cured, and dual-cured

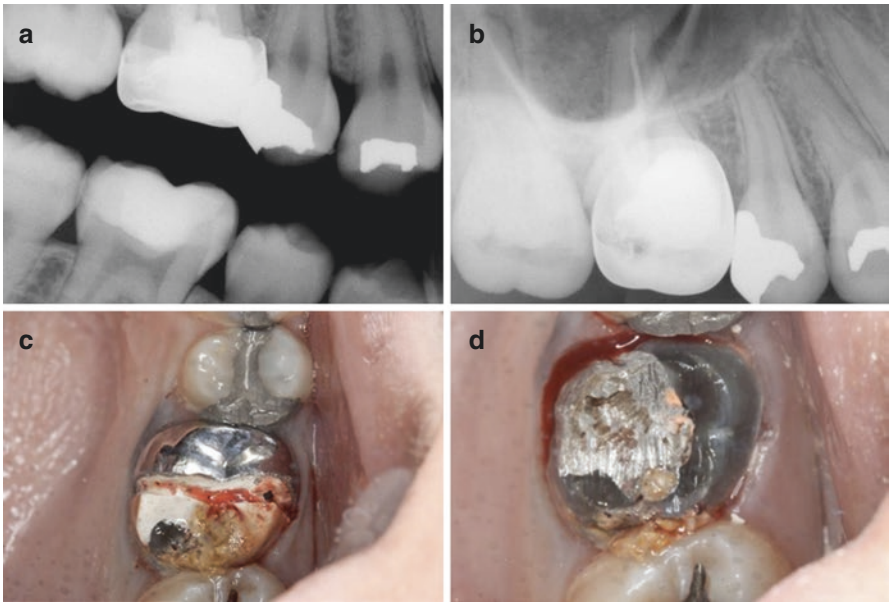

Fig. 10.13 (**a** and **b**) Bitewing and periapical radiographs of maxillary right first molar after endodontic treatment. (**c**) Clinical view of molar after initial stainless steel crown removal shows accumulation of debris. (**d**) Amalgam core after stainless steel crown and cement removal reveals inflamed gingiva, caries, and staining of the clinical crown (© Dr. George Bogen. All Rights Reserved)

composite resins. When physical characteristics are considered, light-cured composite cores that have translucent properties offer distinct advantages over amalgam cores paired with PMC/SSC coverage when placed in endodontically treated immature teeth [142–145]. Translucent (clear) composite resin cores are directly bondable to dentin and enamel, which reduces the indication for additional retention and cavity preparation before placement. These specifically designed materials along with other composite core materials exhibit high compressive strengths and improved fracture resistance and tensile strengths [130–151]. Clear core materials can be light-cured in larger bulks in the majority of cases without incremental placement because of their translucent properties. Due to the high bonding strengths when paired with fourth- and fifth-generation self-etching hydrophilic resins, the "C" factor shrinkage is minimized during the early stages of polymerization when translucent core materials are incorporated [146–151].

Currently available translucent core materials include Build-It™ (Pentron, Inc. Orange, CA, USA), Light-Core™ (Bisco, Inc., Schaumburg, IL, USA), and Clearfil™ Photo Core (Kuraray Co. Ltd., Osaka, Japan). Photo Core exhibits unique properties that include a curing depth of 8 mm in 20 seconds, a flexural modulus similar to dentine (12 ± 1.2GPa), a high flexural strength (125 ± 12MPa), and a compressive strength approaching that of amalgam (334 MPa) [60, 69, 152–154]. This material can be easily applied and bonded with Clearfil™ SE Bond, SE Bond 2, or SE Protect

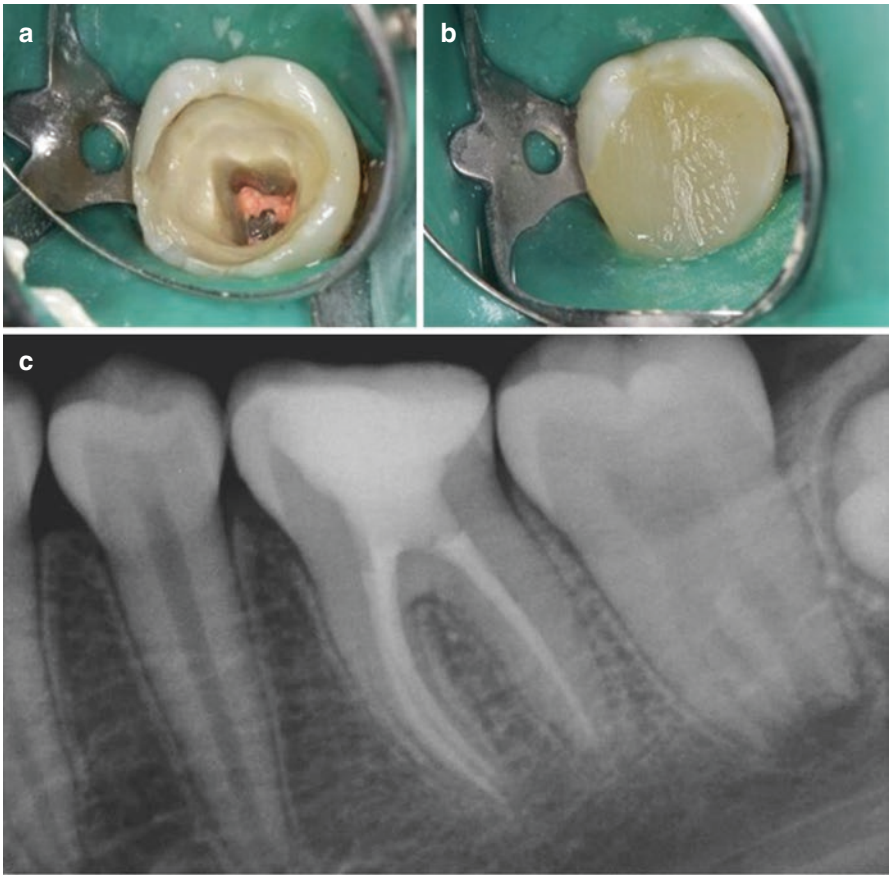

Fig. 10.14 (**a**) Clinical image of a structurally compromised mandibular right first molar in a 12-year-old patient after caries removal and completion of root canal therapy. (**b**) Tooth after bonded Clearfil™ Photo Core placement and (**c**) radiographic recall 1 year postoperatively shows normal alveolar bone height (© Dr. George Bogen. All Rights Reserved)

Bond into severely broken down immature permanent teeth after RCT or complete pulpotomy procedures. It will generally perform to acceptable levels long-term before permanent cuspal coverage restorations are provided (Fig. 10.15). Moreover, immature teeth that undergo indirect and direct pulp capping or pulpotomy procedures can also be reliably restored with other currently available opaque direct composite restorations when proper delivery protocols are observed [155, 156]. Although bonded composite restorations are currently more widely used to restore vital carious teeth in children than amalgam, the replacement rates have been higher [106, 150]. Restorative trends show glass ionomer and composite restorations are replacing amalgam in the restoration of primary teeth with vital pulps. Although some studies show that retention rates for amalgam restorations are superior when used in

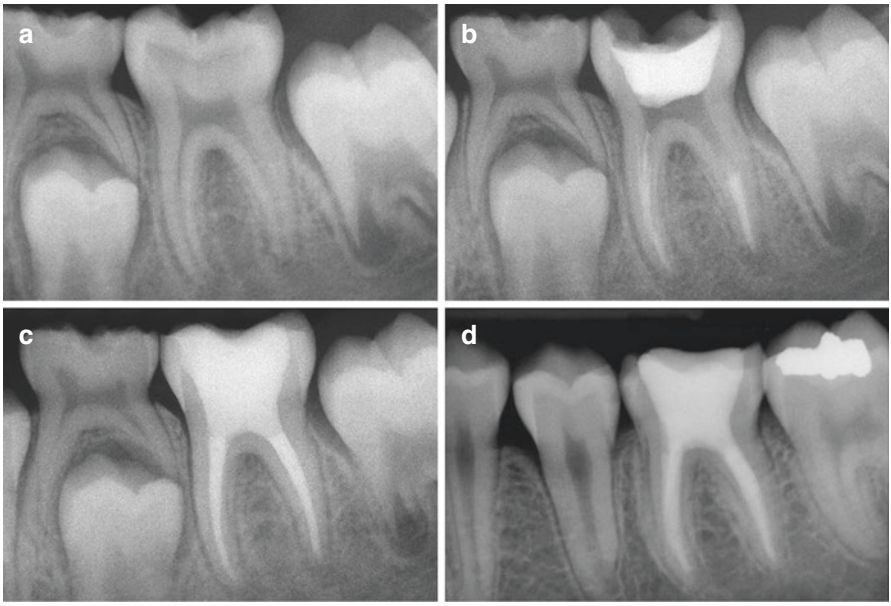

Fig. 10.15 (**a**) Preoperative radiograph of mandibular right first molar with open apices in a 9-year-old patient with irreversible pulpitis. (**b**) Molar after placement of mineral trioxide aggregate apical plugs. (**c**) Finished obturation with thermoplastic gutta-percha, sealer, and translucent core buildup. (**d**) Periapical radiograph of molar at the 4-year 10-month recall shows normal crestal bone and intact crown ()

teeth with vital pulps, survival times for composites are improving as material developments advance and tooth isolation requirements are recognized [157–159].

The main advantage in using bonded translucent composite core restorations in root canal treated immature permanent molars is the conservation of tooth structure when compared to amalgam core and PMC/SSC placement [159–161]. The bonded composite core may also provide superior microleakage resistance at the gutta-percha/MTA/CSC interface that protects the obturation material from further contamination and allows for continued root maturation (Fig. 10.16). Moreover, avoiding PMC/SSC placement may better preserve the periodontium and crestal bone height during the various stages of the transitional dentition. Bonded composite core delivery also requires less chairside treatment time for operators and may be more economical when compared to the alternative treatment requiring a second appointment to place the PMC/SSC. Root-filled and pulpotomized young structurally compromised permanent teeth can be successfully maintained until the patient reaches a stable point in craniofacial development and cuspal coverage is indicated. If immature endodontically treated permanent teeth can be restored without using the PMC/SSC, the advantages for both the patient and the treating dentist can be beneficial in optimizing tooth longevity and retention.

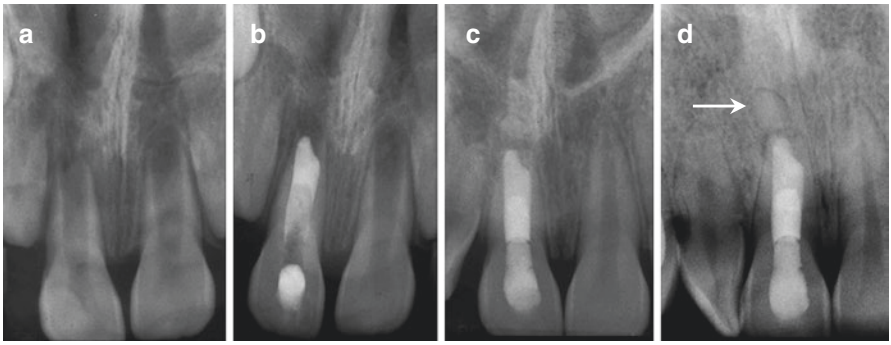

Fig. 10.16 (**a**) Periapical film of maxillary right central incisor after avulsion and reinsertion into socket in a 7-year-old. The extra oral time was 15 minutes. (**b**) Radiograph shows the tooth immediately after MTA obturation and placement of conservative core in the access cavity. (**c**) Three-year recall shows advancing root maturation. (**d**) 14.5-year recall demonstrates completed apexogenesis (*arrow*). Tooth had normal mobility and was in complete function (© Dr. George Bogen. All Rights Reserved)

10.5 Prognostic Factors and Treatment Outcome

The main reason for extraction of ETT is not failure of the endodontic treatment, but caries, periodontal disease, restorative factors, and root fracture [162–167]. Endodontic failures may occur earlier than failures from other causes, such as caries, periodontal disease, or prosthetic failure; however, endodontic factors are much less frequent than other related causes [166]. Clearly, the quality of the root canal treatment is critical, but the quality of the restorative treatment is equally as important to the long-term prognosis for the tooth [3, 164–166, 168–176].

Timely placement of a definitive restoration improves tooth survival [19]. Investigations have demonstrated that the lack of a permanent restoration dramatically decreases survival rates [16, 172, 177]. Crown and cuspal coverage placement protect against extraction in posterior teeth [16, 136, 165, 166, 170, 177, 178]. However, the high demand for esthetic and conservative restorations along with the requirement of an occlusal material stiffer than dentin has directed clinicians to use all-ceramic onlays, crowns, endocrowns, and partial-coverage restorations. These include gold partial veneers, onlays, and three-quarter crowns that capably cover the cusps and acceptably stabilize ETT [179–185]. The use of a composite resin buildup beneath a crown may provide a supportive effect [179], but is less significant than the presence of the coronal coverage [186–188]. Generally, teeth restored with single crowns or used as bridge abutments have a lower incidence of fracture than teeth with direct restorations [179].

Direct restorations are the preferred method of restoring anterior ETT. Conservation of tooth structure is critical when balanced with access cavities prepared observing minimal enlargement protocols to facilitate cleaning, shaping, and obturation. Crown preparations can remove considerable tooth structure,

principally in the cervical area, which demands preservation to resist destructive sheer forces. If this standard is not observed, it can lead to an unfavorable outcome [178]. Alternatives to crown preparation such as direct composite resin restorations, internal bleaching, and conservative porcelain veneers are preferred.

Restoring posterior ETT with composite resin restorations has been proposed as an alternative treatment option to full coverage. Some investigators [179, 189–192] recommend the use of composite resin buildup when one or both proximal marginal ridges or more than one or two coronal walls are intact. One study using a small sample size examined the cusp fracture of endodontically treated premolars restored with MOD amalgam or MOD composite resin restorations and concluded that composite resins may be preferred to amalgam [193]. Conversely, after a second analysis, the same group [194] also acknowledged that MOD cavities are unacceptable for restoring ETT posterior teeth if cuspal coverage is not treatment planned.

Another retrospective cohort study [177] evaluated the survival rate of ETT without crowns and determined that ETT teeth could be successfully restored with composite resin restorations when intact except for a conservative access opening. It confirms that survival rates improve with increased preservation of tooth structure. It was also concluded that the overall survival rate of ETT restored with composite resin diminishes after 5 years and supports the requirement of placing a cuspal coverage restoration on ETT molars. In a similar study, ETT premolars restored with a post and composite resin with and without complete coverage crowns showed similar success rates after 3 years [195]. Collectively, when compared with amalgam, direct restoration of posterior access cavities using composite resins appears to be associated with a lower incidence of cuspal fracture and higher survival rates [167, 177, 179, 193, 196].

Two systematic reviews [197, 198] examined the outcome of ETT restored by direct restorations versus crowns. One [197] concluded that ETT without crown coverage had a lower long-term survival rate than teeth covered with crowns. It was also revealed that the survival rate of ETT restored using only a core buildup without the benefit of cuspal coverage was 84 % in the first 3 years. However, a significant decrease in the survival rate was recorded after this period. The other concluded that there is currently a lack of well-founded evidence to determine whether restoring a premolar with ample coronal tooth structure with a composite resin restoration is more effective than a crown [198].

When restoring ETT with a composite resin core buildup, it is critically important that light-cured resin composites be fully cured through the sequential addition and careful curing of 2 mm increments, with the exception of translucent core materials. Teeth restored using auto-curing resin composites have higher survival rates than those restored using light-cured composites [196], possibly due to increased polymerization. A current in vitro study tested adhesion strengths of selected dual-polymerizing composite resin foundations to dentin using light, chemical, or dual-polymerized adhesive systems [54] and determined that dual-polymerized dentin adhesive systems may not provide acceptable bonding strength to dentin. It appears that light-polymerized adhesives without chemical activators produce superior bond

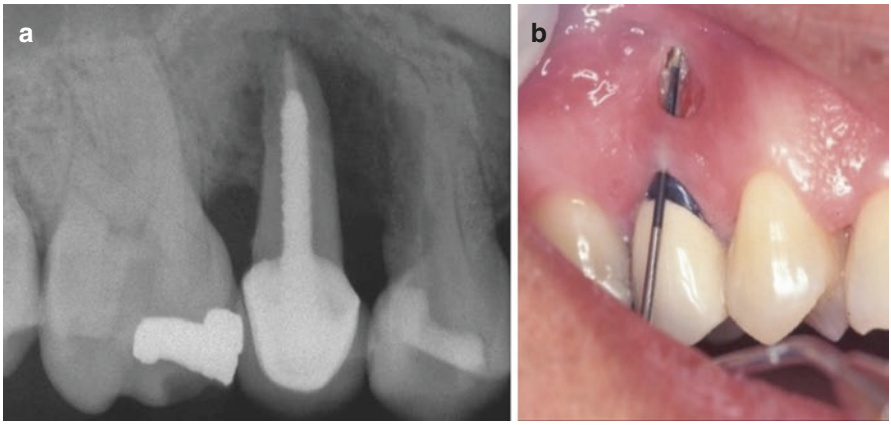

Fig. 10.17 (**a**) Periapical radiograph of maxillary right second premolar restored with threaded post shows vertical fracture with advanced loss of supporting alveolar bone and buccal cortical plate. (**b**) Clinical photograph demonstrates absence of cortical bone (© Dr. George Bogen. All Rights Reserved)

strengths to dentin and that stronger, more highly filled, hybrid composite resins increase tooth survival rates over microfilled composite resins [194]. Glass ionomers are markedly inferior to all other restorative options when restoring ETT [179], and they should only be used as liners or bases, not as core buildup or coronal restorations.

Overwhelming evidence exists to show that teeth restored with posts are generally lost more often than teeth without posts [19, 179, 180, 188]. Active threaded posts cannot be recommended. Laboratory studies have shown that all variations of threaded posts promote the greatest potential for root fracture [66, 163, 199–202] by generating undesirable levels of intracanal stress [66] (Fig. 10.17). Threaded tapered posts can increase the incidence of root fracture by 20 times compared to threaded parallel posts [200, 201]. When evaluating the combined data from multiple clinical studies, threaded posts generally produced the highest incidence of root fracture (7 %) compared to tapered posts (2 %) and parallel designed posts (1 %) [45, 61, 179, 203–215].

Perforations, whether caused by post preparation or due to endodontic instrumentation, are not uncommon. They compromise the outcome for ETT and are a strong argument for avoiding post placement [162, 165, 216]. Teeth restored with posts appear to have an elevated risk of failure when used as abutments for fixed dental prostheses or removable partial dentures [137, 179].

Although implants and implant-supported prosthesis are optimal treatment options for restoring edentulous areas, alternative treatment options must be considered. The low-risk option of doming endodontically treated teeth for use as overdenture abutments to provide important vertical support for complete dentures is currently underutilized and even more so for support of removable partial dentures.

This treatment modality for restoration and retention of endodontically treated teeth is a viable treatment option and, sometimes, the only option for medically compromised patients when tooth extraction is contraindicated or for economically disadvantaged populations worldwide who cannot afford an implant and implant-supported prosthesis. Importantly, application of this treatment modality may offer the advantages for preservation of alveolar bone height in all age groups, including pediatric patients with irreversible damage to the tooth/root as a result of traumatic injury and who are not of the age to receive an implant.

In recent years, prefabricated posts have become very popular. An exhaustive selection of systems and materials are available. Glass fiber-reinforced epoxy resin posts are generally the most frequently used. When compared to metallic posts, GFR posts exhibit favorable mechanical and physical properties [206]. However, they are more flexible than metallic posts and have a low modulus of elasticity [149]. When GFR posts are used in ETT with minimal or no ferrule, their ability to flex can produce more stress cervically, generating a high risk of post fracture, debonding of the post and/or core, and the loss of post retention followed by leakage and caries. Investigations using thermocycling and cyclic loading have indicated that GFR posts themselves exhibit a 40 % reduction in strength and a 10 % decrease in flexural modulus [207, 208]. Thus, direct exposure to oral fluids reduces their flexural strength, which is typically associated with a higher incidence of post debonding, post fracture, crown debonding, and root fracture [207]. Glass fiber-reinforced epoxy resin posts show a higher prevalence of restoration failure than metallic posts, but also a lower incidence of tooth fracture [61, 209–214]. Similarly to prefabricated metallic posts, the placement of a GFR post does not improve the survival of ETT using direct composite resin restorations, suggesting that the amount of remaining tooth structure is paramount and that their primary function is core retention [187, 212, 215].

Overall, fixed dental prostheses, bridges, replacing extracted teeth, generally have significantly lower long-term survival rates than teeth retained through RCT and restoration or those replaced using single implant crowns [34, 35, 217]. The individual ETT has a very high survival rate and a lower complication rate than treatment alternatives, particularly, when proximal teeth are still present [47, 134, 136].

Gaps within the buildup or between the post and obturation material can provide niches for bacterial growth and recontamination of the root canal system (Fig. 10.18). Voids between a restoration and the obturation interface are equally detrimental and similar to obturation voids that can lead to increased incidence of apical disease [173, 218, 219]. It is recommended that clinicians confirm the post length/distance insertion placement before permanent cementation. Furthermore, care must be taken to ensure that sufficient gutta-percha or obturation material remains after post preparation to avoid the potential future emergence of endodontic disease [173].

The amount of remaining tooth structure is more important than any restorative strategy, and [177, 179, 187, 189–191, 195, 209, 210, 212, 220, 221] the risks due to caries and periodontal disease must always be recognized [222, 223].

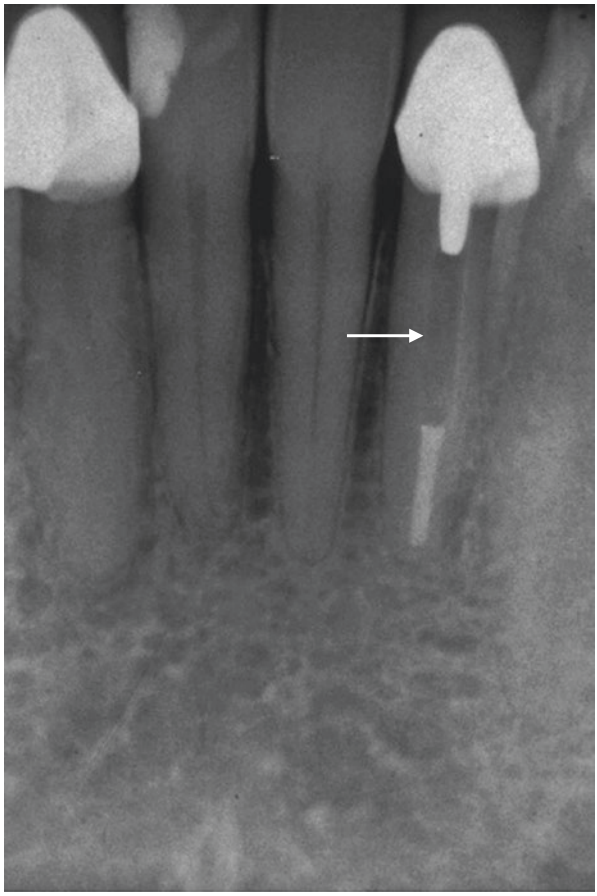

Fig. 10.18 Radiographic recall of mandibular left lateral incisor exhibits short cast post and the presence of a large unfilled space between the post and obturation material (*arrow*) (© Dr. George Bogen. All Rights Reserved)

Conclusions

Restoration is an integral component of root canal treatment. The quality of the restoration is paramount for both temporary and definitive restorations with the primary objective to exclude microorganisms from the root canal system. Definitive restorations should be placed as early as possible, preferably at the time of canal obturation and before the dental dam is removed. Tooth structure must ultimately be conserved. Immature permanent teeth can be conservatively restored using direct translucent resin composite restorations until the transitional dentition has concluded, when indirectly fabricated cuspal coverage restorations are indicated. Anterior teeth should not receive full-coverage restorations if structurally intact after RCT and conservative access cavity preparations. Posterior teeth that are largely intact can be restored using composite resin restorations short term; however, coronal coverage will benefit those that have lost substantial structure to protect them against potential root or cuspal fracture.

Posts do not strengthen teeth; they should only be placed when no other means can be used to secure resistance and retention forms. Most ETT extracted are removed due to caries, periodontal disease, restorative failures, and root fractures; these outlying factors must be considered. Restorative microleakage compromises the outcome and success of all endodontic treatment. No matter what kind of post and core system is employed, the incorporation of an adequate ferrule in the crown design correlates highly with success. Most importantly, the preservation of coronal tooth structure increases the long-term prognosis and retention of the ETT.

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Local, Systemic, and Genetic Considerations of Endodontic Treatment Prognosis

11

Matthew Malek and Louis M. Lin

Abstract

The outcome of nonsurgical endodontic treatment/re-treatment and the survival of the endodontically treated tooth depend on many known and possibly unknown factors. Among the ones that have been identified in the literature, 21 factors will be discussed in this chapter. These factors are classified under local (including anatomical, preoperative, intraoperative, and postoperative) and systemic (including demographic, genetic, systemic disease and medications, and geriatric) factors. Each factor is reviewed, and its effect on the outcome of the endodontic treatment and/or survival of the treated tooth is discussed based on the highest available evidence. Among the factors discussed in this chapter, the ones that are believed to be strongly associated with the outcome of the root canal treatment/re-treatment are periapical status, apical extent of root canal filling, quality of the root canal filling, and quality of the restoration.

Many studies have been performed on the outcome of endodontic treatment. However, the results of these studies are not always consistent with one another. These inconsistencies may be due to different factors, such as adopting different definitions of success and failure [1–3], varied follow-up periods [2, 3], different sample sizes [1, 2], different geographical locations of study [3], different study methodologies [3], etc.

In order to reconcile these inconsistencies and identify the most commonly accepted predictors, the base of this chapter will be focused on systematic reviews that have been done in those areas. Regarding the factors that have not been fully

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developed in systematic reviews, or if the reviews failed to satisfactorily identify the factors, an overview of the most important studies regarding those factors would be presented.

For the sake of this chapter, the factors involved in the prognosis of root canal treatment are categorized under local and systemic factors listed below:

Local Factors:
- Anatomic factors
- Preoperative factors
- Intra- (inter)operative factors
- Postoperative factors

Systemic Factors:
- Demographic factors
- Genetic factors
- Systemic diseases and medications
- Geriatric patients

11.1 Local Factors

11.1.1 Anatomical Factors

11.1.1.1 Tooth Type

Many studies have assessed the outcome of initial root canal treatment in relation to the tooth type, but the findings differ from one another. Kerekes and Tronstad [4] found that specific teeth (maxillary canines, second premolars, and mandibular canines) might have a better prognosis than others. Few other studies [5–7] found that mandibular molars had significantly lower success rates than other tooth types. In contrast, one study [8] observed that mandibular teeth might have a better success rate than maxillary teeth.

Studies on re-treatments have also shown that mandibular teeth in general have lower success rates compared to maxillary teeth [9–11].

A systematic review on survival rates of endodontically treated teeth has shown that non-molar teeth have higher chance of survival than molar teeth [12].

11.1.1.2 Number of Roots

Few studies have evaluated the outcome of endodontic treatment based on number of roots. Strindberg [13] and Engstrom [14] found that single-rooted teeth had more frequent failure rates than two-rooted and three-rooted teeth. Grahnen and Hansson [15] also found that treatment result was better for three-rooted than for two-rooted teeth and poorest for single-rooted teeth. In contrast, Friedman [16] found that teeth with single canals showed a higher success rate than teeth with multiple canals. The results of the Toronto study also reported that single-rooted teeth might have a better outcome than multi-rooted teeth [17].

11.1.1.3 Proximal Contacts

The effect of proximal contacts has been studied mostly in relation to tooth survival. Teeth with two proximal contacts have shown to have a better survival rate than teeth with one or no proximal contacts [18]. In some studies it was found that root canal-treated teeth with fewer than two proximal contacts were lost at a rate three times that of teeth with two proximal contacts [19, 20].

11.1.2 Preoperative Factors

11.1.2.1 Pulp Status

There is a great amount of contrast between the results of studies that examined the effect of pulp status on the outcome of the endodontic treatment. It must be noted that since necrotic pulp is mostly associated with periapical periodontitis, an endodontic treatment on a tooth with necrotic pulp may have a low success rate due to the existence of a periapical periodontitis, not necessarily the pulp status. In a systematic review, after controlling this possible confounding factor, no significant difference was found between the outcomes of endodontic treatment between vital and non-vital teeth [3].

11.1.2.2 Clinical Symptoms

There is no good correlation between clinical symptoms and actual histology of pulp and periapical pathology [21]. Therefore, any studies based on this correlation should be evaluated with caution.

Few studies considered preoperative pain to have a significant influence on the long-term success of root canal fillings [16, 22]. However, according to the majority of outcome studies that considered this factor, preoperative symptoms did not have a significant effect on initial treatment [8, 23–26] or re-treatment cases [17].

In one study [27], preoperative sinus tract was found to have a significant effect on the outcome of root canal treatment. In contrast, an earlier study did not find this factor to be of any significance [28].

11.1.2.3 Periapical Status

Existence of a periapical lesion is one of the most agreed preoperative factors that can negatively affect the outcome of the root canal treatment. Regarding initial root canal treatment, in a systematic review based on 14 studies, it was concluded that non-vital teeth without periapical lesion had approximately 1.95 times higher odds of success than non-vital teeth with periapical lesions [3]. With respect to re-treatment cases, another systematic review based on eight studies concluded that non-vital teeth without periapical lesion had approximately 6.32 times higher odds of success than non-vital teeth with periapical lesions [2]. It therefore appears that the existence of periapical pathology has more significant effect on the outcome of re-treatment cases than treatment cases (Table 11.1).

Table 11.1 The effect of periapical lesion and its size on the success of treatment

	Existence of periapical lesion	Size ≥ 5 mm
Effect on primary treatment	1.95 times less successful	No significant effect
Effect on re-treatment	6.32 times less successful	Significantly less successful than <5 mm

11.1.2.4 Size of the Periapical Lesion

A systematic review on the outcome of primary root canal treatment did not find the size of the periapical lesion (5< or ≥5) to have a significant effect on the outcome of the treatment [3]. However, a systematic review on the outcome of secondary root canal treatments found that teeth associated with lesions equal or larger than 5 mm had a significant less chance of success than teeth with lesions smaller than 5 mm [2] (Table 11.1).

11.1.2.5 Factors Related to Previous Treatment

Time Interval Between the First and Second Treatment Based on the current evidence, time interval between the first and second treatment does not seem to affect the success of re-treatment [9, 29]. However, this finding should be considered with caution, since the precise time of primary root canal treatment is usually difficult to establish.

Quality of Previous Root Canal Treatment According to one study [30], the quality of the root filling material did not have an effect on the success of re-treatment. However, another study [29] found that in cases with preoperative periapical lesions, the success of re-treatment of teeth with high-quality root filling (0–2 mm to the radiographic apex and no voids) was significantly higher than teeth with low-quality root filling. Another study [27] evaluated the same factor, but the results were not statistically significant after adjusting the results for the presence of periapical lesion.

Foreign Materials in the Canal Regarding foreign materials in the canal, the results of the studies vary [2]. It seems that intracanal foreign materials can affect the outcome of re-treatment if they prevent chemomechanical debridement of the canal apical to the foreign materials [27]. Regarding re-treatments, it has been suggested that as long as patency is achieved at the canal terminus, success of treatment would not be affected by the type of foreign material, whether it was removed or bypassed [27].

Preexisting Perforation In a systematic review, it was shown that preexisting perforations in the root canal might lower the success rate of re-treatment cases up to 32 % compared to the teeth without perforations [2].

11.1.2.6 Periodontal Status

Studies have shown that the main reason for extracting endodontically treated teeth is usually not endodontic failure, but restorative failure or periodontal disease [31–33]. In one study, marginal bone support was found to have a significant effect on the success of endodontic treatment [8]. Setzer [34] also found significant positive correlations between the attachment loss of the tooth and untoward events (any form of re-treatment or extraction) in molars. Another study found that cracked teeth with >3 mm periodontal pocketing might affect the long-term survival of the tooth [35]. These findings emphasize the need for periodontal evaluation prior to endodontic treatment.

11.1.3 Inter-/Intraoperative Factors

11.1.3.1 The Use of Rubber Dam

The use of rubber dam is mandatory in root canal treatments [36]. Not only it protects the patient during treatment procedures but also enhances the treatment efficiency [37]. Few studies have evaluated the use of rubber dam in root canal treatment. In a retrospective study, using rubber dam during post preparation was associated with a significantly higher success rate in root canal-treated teeth [38]. Regarding the use of rubber dam during root canal treatment, one study found that re-treatment outcome with the use of rubber dam was significantly higher than with cotton roll isolation [39]. Another study also found that the lack of use of rubber dam was one of the main reasons for postoperative pain [40].

11.1.3.2 Factors Related to Cleaning and Shaping

Culture Test Results

In a systematic review, the meta-analysis showed that the odds of success of primary treatment on teeth with pre-obturation negative culture were not significantly different from those of teeth with a positive culture regardless of periapical status. When the results were stratified for teeth without periapical lesion, the difference was still not significantly different. But when the results were stratified for teeth with periapical lesion, the odds of success of those teeth with negative culture were two times higher than those teeth with positive culture results [3] (Table 11.2).

Table 11.2 The effect of culture test results on the success of treatment with or without periapical lesion

	Negative compared to positive test results
Teeth without periapical lesion	No significant effect
Teeth with periapical lesion	Two times more successful

Apical Size of Preparation and Taper of the Preparation The available data regarding these factors are either insufficient or variable [2, 3]. However, most of the findings do not concur with the views that more effective bacterial debridement may be achieved with larger apical preparation [27] and wider taper [2].

Apical Extent of Instrumentation Orstavik [8] reported that over-instrumentation could influence treatment outcome. Regarding re-treatment cases, a study found that over-instrumentation (beyond apex) was associated with significantly lower success rates compared to when instrumentation was limited to the root canal space, regardless of the preoperative periapical status of the teeth [41].

Sjogren et al. [25] found that in teeth with preoperative apical periodontitis, 90 % of cases healed when instrumented to the apical constriction, but only 69 % of the cases healed when it was not possible to instrument the canal to its total length. Such a difference was not found in re-treatment cases.

Another study used radiographic apex as their reference point and found that the instrumentation level for successfully treated teeth/roots with normal preoperative pulp and periapex was farther away from the radiographic apex (1.23 ± 0.13 mm) than for teeth/roots with an unsuccessful outcome (0.20 ± 0.09 mm). However, successfully treated teeth/roots with pulp necrosis and apical periodontitis had working length levels closer to the radiographic apex (0.55 ± 0.12 mm) than did teeth/roots with unsuccessful outcomes (1.73 ± 0.30 mm). In teeth/roots with apical periodontitis, a millimeter loss in working length increased the chance of treatment failure by 14 % [42].

11.1.3.3 Procedural Errors

Separated Instruments The results of different studies are not in agreement. Few studies found that instrument separation during treatment significantly reduced the success [13, 27]. Others found that in the absence of a periapical lesion, the presence of a fractured instrument might not affect the outcome of the root canal treatment [43, 44]. Some studies found that in cases with periapical lesion, separated instruments might lead to delayed healing [41] or persistent infection [45]. Another study reported that separated instruments decreased the success rate only in necrotic teeth [4]. A systematic review (with only two included studies) did not find separated instruments to have a significant effect on the outcome of endodontic treatments [46].

Perforations Perforation location and its size seem to significantly influence the occurrence of perforation-associated periodontal damage. Crestal perforations (at the level of crestal bone) induce significantly more pathological changes in the adjacent periodontal tissue than perforations coronal or apical to the crestal bone [47]. Few studies have reported that perforations reduced the success rate [25, 27, 45]. Other studies found that in cases with periapical lesion, perforations might lead to delayed healing [41] or persistent infection [17, 45]. Another study reported that perforations would lower the success rate only in necrotic teeth [4].

Table 11.3 Clinical situations divided to root canal morphology respected (RCMR) and root canal morphology altered (RCMA)

RCMR	RCMA
Calcification	Apical transportation
Apical stop (blockage)	Perforation
Broken instrument	Stripping
Underfilled canal	Internal resorption

Careful examination of aforementioned studies shows that procedural errors may not be the direct cause of endodontic disease. It has been suggested that endodontic procedural errors are not the direct cause of treatment failure; rather, the presence of pathogens in the root canal system is the cause of periapical pathoses [48]. In light of this explanation, Gorni and Gagliani divided clinical situations in re-treatment cases to two categories (Table 11.3): root canal morphology respected (RCMR) – including calcification, apical stop, broken instrument, and underfilled canal – and root canal morphology altered (RCMA), including apical transportation, perforation, stripping, and internal resorption. In their findings, the overall success in RCMA cases was significantly less than RCMR cases (48.7 % vs. 83.3 %). This difference was more significant in the presence of periapical lesion, whereas in cases without periapical lesions, the difference was insignificant [49].

11.1.3.4 Intracanal Irrigants and Medications

There are few studies that have focused on the effect of intracanal irrigants and medications on the outcome of root canal treatment. However, due to different methodologies, significant amount of heterogeneities, and varied protocols, their results vary. As a result, systematic reviews have failed to prove any irrigant or medication to be superior or significantly more efficient compared to others. For instance, two systematic reviews did not find calcium hydroxide an efficient intracanal medication to eliminate bacteria from human root canals [50] or to increase the healing rate of root canal treatments [51]. Regarding intracanal irrigants, systematic reviews on root canal treatments and re-treatments did not find sufficient data to perform further analysis or even a meta-analysis [2, 3].

11.1.3.5 Number of Visits

Two systematic reviews have explored the difference between the outcomes of single- and multiple-visit treatments. One study reported that the healing rate of single- and multiple-visit root canal treatments is similar [52]. The other study reported that no detectable difference was found in the effectiveness of root canal treatment in terms of radiologic success between single and multiple visits [53].

11.1.3.6 Flare-Up

The average prevalence of flare-up is reported to be around 8.4 % [54], and most studies have shown that it does not have an effect on the treatment outcome [4, 25, 55]. However, a more recent study showed that the occurrence of flare-up significantly reduced the outcome of endodontic treatment [27].

11.1.3.7 Obturation

Filling Materials, Techniques, and Type of Sealers Two systematic reviews did not find sufficient data to analyze the effect of root canal materials, techniques, and type of sealers on the outcome of the treatment [2, 3].

Apical Extent of Root Filling A systematic review on primary root canal treatment showed that there was no significant difference in the odds of success between root canal treatments with flush (within 0–2 mm short of the radiographic apex) and short (>2 mm short of radiographic apex) root fillings in teeth without preoperative periapical lesion. However, in teeth with preoperative periapical lesion, flush root fillings had higher odds of success. Flush root fillings had always more odds of success than long (beyond the radiographic apex) root filling regardless of the periapical status. Short root fillings had higher odds of success than long fillings in cases without preoperative periapical lesion, but in cases with preoperative periapical lesion, there was no significant difference between long and short fillings [3].

In re-treatment cases, short and flush root fillings had significantly higher success rates than those with long root fillings. In the presence of periapical lesion, the same trend was observed but with less significant difference [2] (Table 11.4).

Another systematic review on the optimal obturation length showed that after at least 2 years of follow-up, obturation 0–1 mm short of the radiographic apex had a better outcome than obturation 1–3 mm short of the apex; both were superior to obturation beyond the apex [56].

Quality of Root Canal Filling The success rate of treatment with satisfactory root canal fillings (adequate seal and absence of voids) is significantly higher than the success rate of treatment with unsatisfactory root canal fillings [3]. This difference was found to be higher in re-treatment cases than primary treatments [2].

The above findings emphasize the fact that endodontic disease is mainly a result of bacterial infection. Therefore, any kind of obturation deficiency would amplify the effect of bacterial contamination. In cases that the bacterial contamination is

Table 11.4 The effect of apical extent of root filling on the success of treatment (measurements are from radiographic apex)

	Long (>2 mm long)	Flush (0–2 mm short)	Short (>2 mm short)
Primary treatment without periapical lesion	Less success than flush and short	No significant difference	
Primary treatment with periapical lesion	Less success than flush but similar to short	Flush has higher success than short	
Re-treatment without periapical lesion	Less success than flush and short	Flush and short higher success than long	
Re-treatment with periapical lesion	Less success than flush and short	Flush and short higher success than long	

under control, such deficiencies have less effect on the outcome of the treatment. This observation is consistent with previous studies. In an animal study, well-instrumented, but non-obturated, teeth healed similarly to the obturated teeth with the presence of apical periodontitis [57]. Lin [58] also found that the apical extent of root canal fillings, i.e., underfilled, flush filled, or overfilled, seems to have no correlation to treatment failures. In another study, it is clearly shown that when no bacteria are present, healing occurs regardless of the quality of the obturation. But when bacteria are present at the time of obturation, there is a correlation between the quality of obturation and nonhealing [59].

11.1.4 Postoperative Factors

11.1.4.1 Type and Quality of Restoration

Type of Restoration In general there is adequate evidence to show that restored teeth (temporarily or permanently) are associated with significantly higher success rates than unrestored teeth [9, 16, 29]. Regarding the type of restorations, a systematic review reported 10-year survival of 81 % for crowned endodontically treated teeth and a 10-year survival of 63 % for endodontically treated teeth with direct restorations (resin composites, amalgam, cements) [60]. Another systematic review showed that teeth not functioning as fixed or removable prosthesis abutments were associated with a significant higher survival probability than those that functioned as fixed prosthesis abutments [12].

The Effect of Post Regarding the effect of post on the outcome, study results are varied. In general, it seems that teeth with post-retained restorations may have a slightly lower survival rate than teeth without post-retained restorations [12].

Quality of Restoration The odds of success of primary treatment and re-treatments are significantly higher for teeth with satisfactory restorations (no evidence of discrepancy, discoloration, or recurrent caries at the restoration margin with absence of a history of decementation) compared to unsatisfactory restorations [2, 3].

Quality of Filling vs. Quality of Restoration There are few studies comparing the importance of the quality of root canal fillings with the quality of coronal restoration. One study reported that high-quality post-endodontic restorations resulted in significantly more successful cases when compared with good endodontics (80 % vs. 75.7 %) and poor restorations resulted in significantly more periradicular inflammation cases when compared with poor endodontics [61]. Another study found no difference between the quality of coronal restoration and root fillings [62]. Yet another one reported that the technical quality of the endodontic treatment as judged radiographically was significantly more important than the technical quality of the coronal restoration when the periapical status of endodontically treated teeth is evaluated [63]. A systematic review concluded that although poorer clinical outcomes may be expected with adequate root filling–inadequate coronal restoration and

inadequate root filling–adequate coronal restoration, there is no significant difference in the odds of healing between these two combinations [64].

11.2 Systemic Factors

11.2.1 Demographic Factors

Age and gender have not been shown to significantly affect the outcome of root canal treatments and re-treatments [2, 3, 12]. The results of studies done on survival rates of endodontically treated tooth regarding these factors vary significantly [12].

11.2.2 Genetic Factors

Genetic disorders or genetic polymorphism might affect the host's defense mechanisms, such as innate or adaptive immunity, and result in susceptibility to diseases or altered response to treatment. Genetic disorder is an illness usually caused by one or more abnormalities in the genome. Gene polymorphism is due to certain point mutations in the genotype.

There is paucity of studies between the relationship of genetic polymorphism and posttreatment apical periodontitis [65–68]. Two genetic conditions, carriage of allele H131 of the FcrRIIa gene and a combination of this allele with allele Na^2 of the FcrRIIIb gene, have been reported to be associated with posttreatment apical periodontitis [67]. The individuals with rare allele (allele 2 or T) of IL-1ß were reported seven times more likely to have posttreatment apical periodontitis compared with individuals homozygous for the common allele (allele 1 or C) [65]. Single nucleotide polymorphisms (SNPs) of other inflammation-associated genes, matrix metalloproteinases (MMPs) 2 and 3, also show susceptibility to the development of periapical lesions and healing response [69].

11.2.3 Systemic Diseases and Medications

An early study suggested that osteoporosis, avitaminose C, steroid therapy, and diabetes may delay healing and, as a result, negatively affect the outcome of endodontic treatment [70]. From this list, scientific evidence exists at least for steroid therapy and diabetes to have an effect on the outcome of endodontic treatment. A recent systematic review did not find general medical health to significantly affect the outcome of root canal treatment [3]. However, there are evidence suggesting that there are few systemic health-related problems that may affect the outcome of endodontic treatment.

Diabetes Mellitus Diabetes has numerous complications that are of concern to oral health professions [71]. Increased susceptibility to infection, neuropathy,

and delayed healing of the diabetic patients may affect the outcome of endodontic treatment.

Most studies have shown that diabetes is associated with increased prevalence of apical periodontitis [72–74]. In contrast to these studies, one study did not find an association between apical periodontitis and diabetes in treated teeth [75].

Fouad has suggested that diabetic patients with preoperative periapical lesions are less likely to be determined successful 2 years or longer postoperatively [76]. A study on endodontic treatment outcome showed that a history of diabetes was associated with a significant reduced successful outcome [77]. A prospective study on the factors affecting the survival of nonsurgical root canal treatment found that diabetic patients have a higher chance of having an endodontically treated tooth be extracted [27]. This study is in line with another prospective study that also found that the risk of tooth extraction in endodontically treated teeth is significantly associated with diabetes [78]. It is interesting to note that in Ng's study, most of the tooth loss was due to persistent postoperative pain, possibly due to neuralgia, and not delayed healing [27]. In Wang's study, most of the teeth were extracted due to restorative concerns and tooth fractures [78].

Hypertension One study found that the prevalence of apical periodontitis and endodontic treatment was not significantly different in hypertensive patients compared with controlled subjects without hypertension [79]. However, few other studies have found that tooth extraction is significantly associated with hypertension [78, 80]. Although diabetes and hypertension may exist simultaneously, one study provided data that showed hypertension and diabetes are independent risk factors for tooth extraction 2 years after nonsurgical root canal treatment [78].

Smoking Few studies have shown that the prevalence of apical periodontitis and endodontic treatment is significantly higher in smoker hypertensive patients compared with nonsmoker patients [81, 82]. Another study has also reported that smoking is significantly associated with endodontic disease and prognosis [83]. However, more evidence-based studies are required to determine the significance of this factor on the outcome of endodontic treatment.

Human Immunodeficiency Syndrome (HIV) HIV virus has been detected in dental pulp [84] and periapical lesion [85] of HIV-positive patients. Therefore, its role in pathogenesis and healing of periapical lesions is of a concern. It has been reported that conditions associated with impaired nonspecific immune responses reduced the success of root canal treatment [86], but most of the available evidence does not support the fact that the success of root canal treatment in HIV-positive patients is less than HIV-negative patients. One study reported that root canal treatment on HIV-positive patients was associated with no short-term (3 months) complications [87]. In an outcome study, the authors did not find any difference between the outcomes of endodontic treatment of patients with HIV/AIDS compared with the

patients without HIV/AIDS [88]. Another study reported that there is no statistically significant difference between the two groups of patients (HIV-positive and HIV-negative patients) with respect to the degree of periradicular healing after 1 year after endodontic treatment [89].

Systemic Steroid Therapy The negative effect of steroid therapy on treatment outcome has been attributed to delayed healing and compromised immune system [70]. A prospective study on the factors affecting the survival of nonsurgical root canal treatment found that patients receiving systemic steroid therapy might have a higher chance of having an endodontically treated tooth be extracted [27].

Bisphosphonate Therapy Bisphosphonates are usually used in the management and treatment of bone diseases, such as osteoporosis and Paget's disease, and to prevent bone complications and to treat malignant hypercalcemia in certain types of cancer. There are an increasing number of reports of bisphosphonate-associated osteonecrosis of the jaws that have substantial implications for the patient and for the treating dentist, few of which are a result of endodontic treatment [90].

Most of the knowledge on the effect of bisphosphonates on endodontic outcome has been gathered through case reports. According to the American Board of Endodontics Position Statement (this statement can be found at http://www.aae.org/uploadedfiles/publications_and_research/guidelines_and_position_statements/bisphosonatesstatement.pdf), patients taking IV bisphosphonates are in a higher risk than patients taking oral bisphosphonates. In the former cases, conservative nonsurgical root canal therapy is an appropriate treatment in cases where the tooth may otherwise be extracted. Case reports have shown that conservative root canal treatment is successful in similar cases [91].

11.2.4 Geriatric Patients

It has been shown that age is not a determining factor in the success of endodontic treatment [2, 3]. However, this finding may be confounded by the smaller number of older patients compared to younger patients included in those studies. In general it is important to understand and consider the systemic (such as oral pain as a result of side effects of medications), local (such as root canal calcifications), biologic, and anatomic differences in the dental tissues between older and younger patients. Such differences, if not taken into consideration, may lead to misdiagnosis and mistreatment. However, these differences generally do not contraindicate treatment, which when performed correctly will be successful in the elderly patient [92]. It is also important to understand that usually the periradicular tissues will heal as readily in elderly as in young patients [7]. However, wound healing may take longer for the older patients than the younger patients because of aged stem cells and old micro-environmental cues [93].

11.3 Summary

Throughout this chapter the factors involved in endodontic outcome were reviewed. These factors were classified based on certain criteria such as location (local or systemic) and time (preoperative, intraoperative, and postoperative). However, there are other ways to classify these factors. For instance, they can be classified based on whether they affect primary or secondary treatments (re-treatments). Although most factors should influence both, there is not enough evidence to support the effect of some factors on re-treatment cases. Based on this review, there is some evidence to show that the following seven factors may also affect re-treatment cases: tooth type, periapical status, use of rubber dam, apical extent of instrumentation, apical extent of root filling, quality of the root filling, and quality of the restoration. The only factor that affects only the re-treatment cases is the one that is related to the previous treatment.

Another way to classify these factors is based on whether they influence the outcome of the treatment or the survival of the treated tooth. Positive outcome is different than survival, although there is some overlapping. Positive outcome discusses healing or nonhealing, or success or failure (based on the terminology used), but survival discusses the odds of the treated tooth to survive in the oral cavity. Among the factors discussed, the following factors seem to influence the survival of the root canal-treated tooth: tooth type, proximal contacts, periodontal status, type of restoration, and few systemic factors.

After identifying the factors that have determining effect on the outcome of the treatment or the survival of the tooth, the following guidelines are emphasized to achieve the highest possible success in root canal treatment:

1. Case selection: Review of the medical history and taking into consideration all medical conditions that may affect treatment outcome. Also, one should consider the type of tooth, the periodontal condition (probing, attachment loss, crown-to-root ratio), restorability of the tooth (preferable a crown), and whether the tooth is part of a bridge or not.
2. Informing the patient: It is paramount that the patient is fully informed of all factors that may affect the outcome of the treatment. For instance, a central incisor with normal periapex and no bone loss will most likely have a better survival rate than a molar with poor crown-to-root ratio. As another example, a primary treatment on a vital premolar will most likely have a better outcome than a re-treatment on another premolar with large periapical lesion. The situation will be complicated if the patient has a preexisting medical condition, such as diabetes. Adapting patient's level of expectation to the reality of each treatment is one of the most important elements in the quality of service rendered.
3. Proper treatment: The most important factor in the success of endodontic treatment is infection control and prevention of secondary infection. Proper use of the rubber dam, adequate cleaning and shaping, and obturation, all fall into this category. If the case is carefully selected, but the treatment is not rendered properly, failure will be expected.

4. Proper restoration: The last but not least is properly restoring the tooth in a timely manner. If the tooth is not properly and timely restored, even with the highest-quality root canal treatment, failure will be expected. Therefore, reevaluating the treated cases in few months is important to make sure the tooth is properly restored. The restoration phase should also be discussed with the patient prior to the initiation of endodontic treatment so that the patient is aware, is able, and can plan the restorative phase of the treatment appropriately.

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Criteria for Outcome Assessment of Nonsurgical Endodontic Treatment

12

Nadia Chugal, Sanjay M. Mallya, and Bill Kahler

What's in a name?
That which we call a rose by any other name would smell as sweet.

William Shakespeare

Abstract

Robust criteria for outcome assessment of nonsurgical endodontic treatment are essential determinants for any measure of success. Strindberg (1956) established strict criteria for clinical and radiographic evaluation of the endodontically-treated tooth at follow-up examinations. The absence of clinical symptoms, and the presence or absence of periapical radiolucency became the principal outcome measures of endodontic treatment. Subsequent studies have considered additional parameters that influence outcome such as microbiologic status prior to obturation, histopathologic data, and the effects of different techniques and materials. The "periapical index" (PAI) introduced the concept of a "continuum" that exists between success and failure where lesions could be considered as "healing." The Toronto study introduced a novel outcome category of "functional" for teeth that were asymptomatic regardless of the PAI score. The American Association of Endodontists (AAE) has proposed that

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endodontically-treated teeth are considered (1) healed, (2) nonhealed, (3) healing, or (4) functional. More recently, technological advances in radiology and the application of high-resolution cone beam computed tomography (CBCT) have increased diagnostic accuracy of radiographic changes in the apical periodontium. However, the use of this technology has been limited in outcome studies. Microbiological studies indicate the importance of disinfection of the root canal system on endodontic outcome. Therefore, the absence of clinical symptoms and presence or absence of radiographic apical periodontitis, as determined by periapical radiography, remain the principal outcome measures of endodontic treatment. The aim of this chapter is to discuss the development of the criterion for outcome for nonsurgical endodontic treatment from the strict view of success and failure while adequately considering newer concepts of healing and functionality.

12.1 Introduction

With completion of endodontic treatment and placement of permanent restoration, the professional obligation to our patients does not end. One of the most exciting aspects of endodontics is actually following up the patients and evaluating how the treatment performed affected the end result, i.e., the resolution of patient symptoms, restoration of normal periradicular structures, function, and ultimately tooth retention. Outcome assessment of endodontically treated teeth has been extensively studied. The terminology used to assess outcomes is varied and may be confusing to the practicing dentist. It is the intent of this chapter to clarify some of those terms and to present outcome assessment with the needs of a primary care dentist in mind. The knowledge gained from the outcome studies should be applied to the case assessment before the commencement of endodontic treatment. This information must be part of preoperative discussion, treatment planning, and informed consent.

Methods used to evaluate the outcome of endodontic therapy include clinical observation for resolution of clinical symptoms and signs, radiographic evaluation of periapical status, and histopathologic findings of biopsy specimens. Symptoms include spontaneous pain and/or pain to percussion, palpation, or biting, following endodontic treatment. The signs include swelling or draining sinus tract after endodontic treatment [1–3].

High pretreatment root canal-associated pain prevalence drops moderately within 1 day and substantially to minimal levels by 7 days after root canal treatment [4]. The frequency of persistent all-cause pain 6 months or longer after root canal therapy of permanent teeth is approximately 5 % and may include pain from an adjacent tooth, referred pain from a nonodontogenic structure, or deafferentation pain [5]. This remaining pain may also be an indicator of persistent infection [3]. Histopathologic analysis is not possible for routine nonsurgical endodontic

Table 12.1 Therapeutic results at 4-year and final follow-up examinations [6]

	Success (%)	Failure (%)	Uncertain (%)
No radiolucency	89.16	8.04	2.80
Yes radiolucency	68.40	29.00	2.60
Overall rate	80.79	16.49	2.71

A significant difference exists in outcome rates between cases with preoperative periapical radiolucency compared to those with normal periapex ($p < 0.05$)

treatment. Therefore, radiographic evaluation of periapical status remains the primary means to assess endodontic treatment outcomes.

A landmark study on endodontic outcome assessment was published in 1956 – a classic study by Strindberg that laid the foundation for conduct of future endodontic outcome studies [6]. The study was a human clinical prospective cohort study of 344 patients, which included 539 teeth and 779 roots, all treated by a single operator. All pertinent medical, dental, and treatment data were systematically collected, recorded, and analyzed. The follow-up period was 6 years, every 6 months for the first 2 years and yearly thereafter. The retention rate of the treated patients (75 %) was remarkably high. The highlights of this study are that it:

1. Established criteria for evaluation of endodontic outcome, commonly referred to as Strindberg's criteria
2. Presented success rates for orthograde (conventional) endodontic treatment (Table 12.1)
3. Related the outcome of endodontic treatment to the preoperative periapical diagnosis
4. Defined the duration and frequency of follow-up: every 6 months for the first 2 years and yearly thereafter up to a minimum of 4 years postoperatively

Outcome studies that followed evaluated the result of endodontic treatment using Strindberg's criteria or its modification [7–10]. Others expanded on the range of variables being investigated, such as microbiologic status prior to obturation [11–13], the effect of intracanal medicaments [14–16], sealers [17], technical aspects of endodontic treatment [8, 9, 18, 19], and the effect of restoration [20–24].

12.2 Strindberg's Criteria

Following the publication of his landmark study, and to this day, Strindberg's criteria continue to be widely used to evaluate the outcome of endodontic treatment. The outcome assessment is based on comparative analysis of clinical presentation and radiographic evaluation of the treated tooth at the time of treatment and follow-up examination. Determination of endodontic outcome was expressed as success, failure, or uncertain and was based on the following criteria that became known as Strindberg's criteria:

I. *Success*
Clinical
- No symptoms

Radiographic
- Contours and width of the periodontal ligament (PDL) are normal (Fig. 12.1).
- PDL contours are widened mainly around excess root filling (Fig. 12.2).
- Lamina dura is intact (Figs. 12.3 and 12.4).

II. *Failure*
Clinical
- Symptoms present

Radiographic
- Unchanged periradicular rarefaction (Fig. 12.5)
- Decrease in periradicular rarefaction, but no resolution (Fig. 12.6)
- Appearance of new rarefaction or an increase in the size of initial rarefaction (Fig. 12.7)
- Discontinuous or poorly defined lamina dura

III. *Uncertain*

Radiographic
- Ambiguous or technically unsatisfactory radiograph which could not be interpreted with certainty (Fig. 12.8).
- Periradicular rarefaction less than 1 mm and disrupted lamina dura.
- The tooth was extracted prior to recall due to reasons not related to endodontic outcome.

These criteria were accepted as a standard by which endodontically treated teeth are evaluated. It soon became evident that Strindberg's criteria were very rigid. For example, only teeth with complete absence of clinical signs and symptoms and normal radiographic presentation are classified as "success" (Figs. 12.1, 12.2 and 12.3).

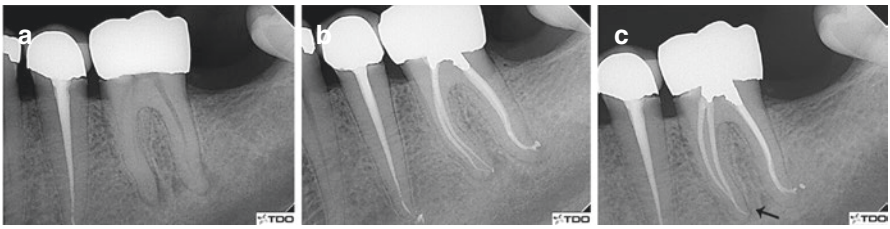

Fig. 12.1 Strindberg's criteria for success: reestablishment of the normal apical periodontal structures. (**a**) Pretreatment periapical radiograph demonstrating widening of the periodontal ligament space and loss of the adjacent lamina dura around the mesial and distal roots of the mandibular first molar (*white arrows*). (**b**) Periapical radiographs made after the completion of endodontic treatment. Trabecular bone around the mesial root apex is slightly radiolucent (*white arrow*), and the bony contours of the lamina dura are not established around the root apex. Note reduction of radiolucency around the distal root apex. (**c**) Follow-up periapical radiograph taken at the 1-year recall visit. Trabecular bone around both roots is of normal density. The lamina dura around both root apices is also formed (*black arrow*) (Images courtesy of Dr. Charles Maupin)

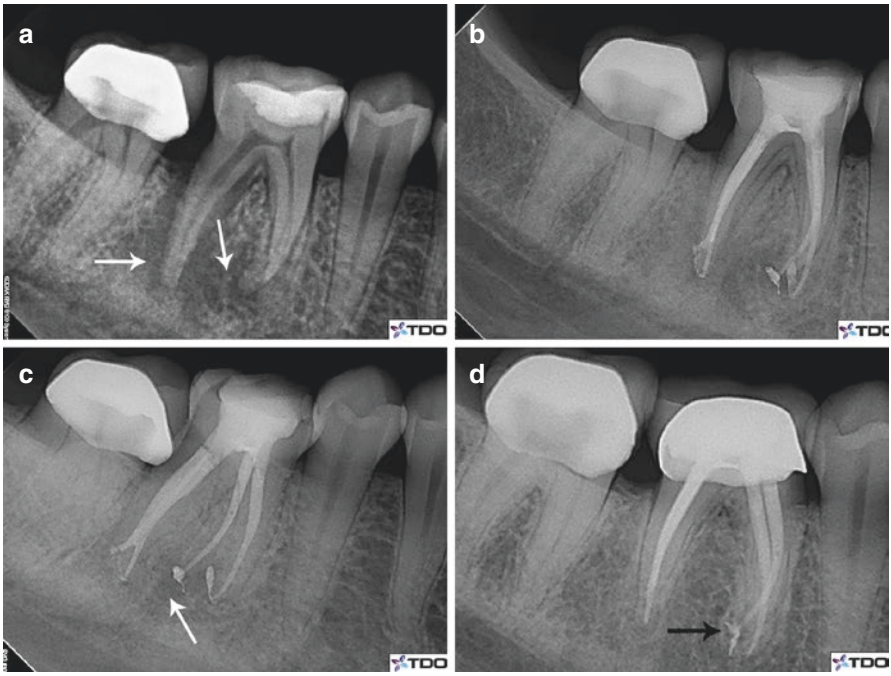

Fig. 12.2 Strindberg's criteria for success: altered periodontal ligament space contours around excess endodontic material/root filling. (**a**) Pretreatment periapical radiograph demonstrating an irregular radiolucency that encompasses almost the entire length of the distal root and the apex of the mesial root (*white arrows*). Note multiple mesial roots and pulp canals. (**b** and **c**) Periapical radiographs made at the completion of endodontic obturation following 4 months of dressing with calcium hydroxide. The radiographs were taken with different horizontal angulations to separate the buccal and lingual pulp canals in the two roots. Note persistence of the radiolucency around the mesial root apex, but considerable resolution with partial osseous healing around the distal root. (**d**) Follow-up periapical radiograph made at a recall visit, 3.5 years after completion of endodontic therapy. Trabecular bone around both roots is of normal density. The lamina dura around both root apices is also formed. Minimal widening of the periodontal ligament space is seen adjacent to the excess endodontic filling material (*black arrow*) (Images courtesy of Dr. Charles Maupin)

In contrast, an asymptomatic tooth with the appearance of broken or poorly defined lamina dura is classified as uncertain (Fig. 12.8), and clinical judgment is required for its subsequent management.

12.3 Radiographic Evaluations Have Been Inconsistent

Absence of clinical symptoms and absence of periapical radiolucency are currently the principal outcome measures that denote successful endodontic treatment. However, radiographic examination has its limitations. Radiographs provide us with a static image of the degree of mineralization in the tooth and its surrounding periodontal structures. However, for changes in bone to be radiographically apparent, there must be sufficient demineralization (or remineralization) within the lesion.

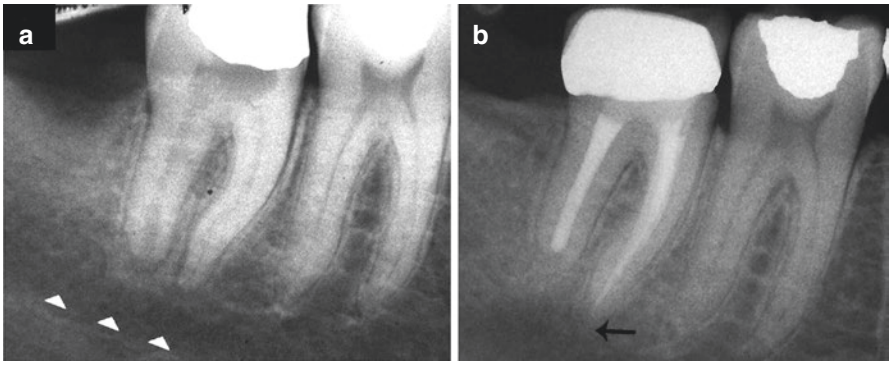

Fig. 12.3 Strindberg's criteria for success: normal lamina dura. (**a**) Pretreatment periapical radiograph showing disruption of lamina dura and widening of the periodontal ligament space around the mesial root apex of the mandibular second molar (*white arrow*) and resorption in the distal root canal. An incidental finding is the proximity of the root apices to the mandibular canal lumen (*arrow heads*). (**b**) Periapical radiographs made 1 year after completion of endodontic treatment, following 15 months and two exchanges of calcium hydroxide dressing. Note normal trabecular architecture around the mesial root apex with an intact lamina dura (*black arrow*). The distal root is shortened, but with normal architecture of the adjacent trabecular bone, suggestive of arrested resorption. As described in Strindberg's original manuscript, teeth with root resorption but no periradicular pathological changes are categorized as success (Images courtesy of Dr. Nadia Chugal)

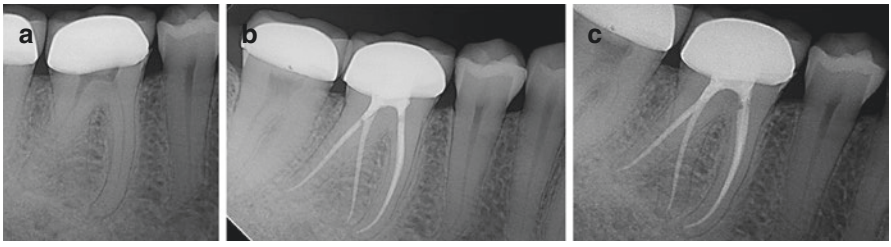

Fig. 12.4 Strindberg's criteria for success: normal lamina dura. (**a**) Pretreatment periapical radiograph showing a mandibular molar with three roots. The periodontal ligament space around all roots is discernible. (**b** and **c**) Periapical radiographs made immediately following obturation and 1 year after completion of endodontic treatment. Note that there are no interval changes in the periodontal structures (Images courtesy of Dr. Charles Maupin)

A classic study examined the sensitivity of conventional radiography to detect experimental lesions in bone and showed that periapical lesions confined to the cancellous bone are not predictably detected [25]. Furthermore, radiographic evaluations tend to be subjective and influenced by observer bias [1, 26–29]. Indeed, multiple evaluators that reviewed the same radiographs differed in their scoring/interpretation, with six evaluators agreeing only 47 % of the time [26]. Importantly, radiographic assessment is also not very reproducible – when the same radiographs

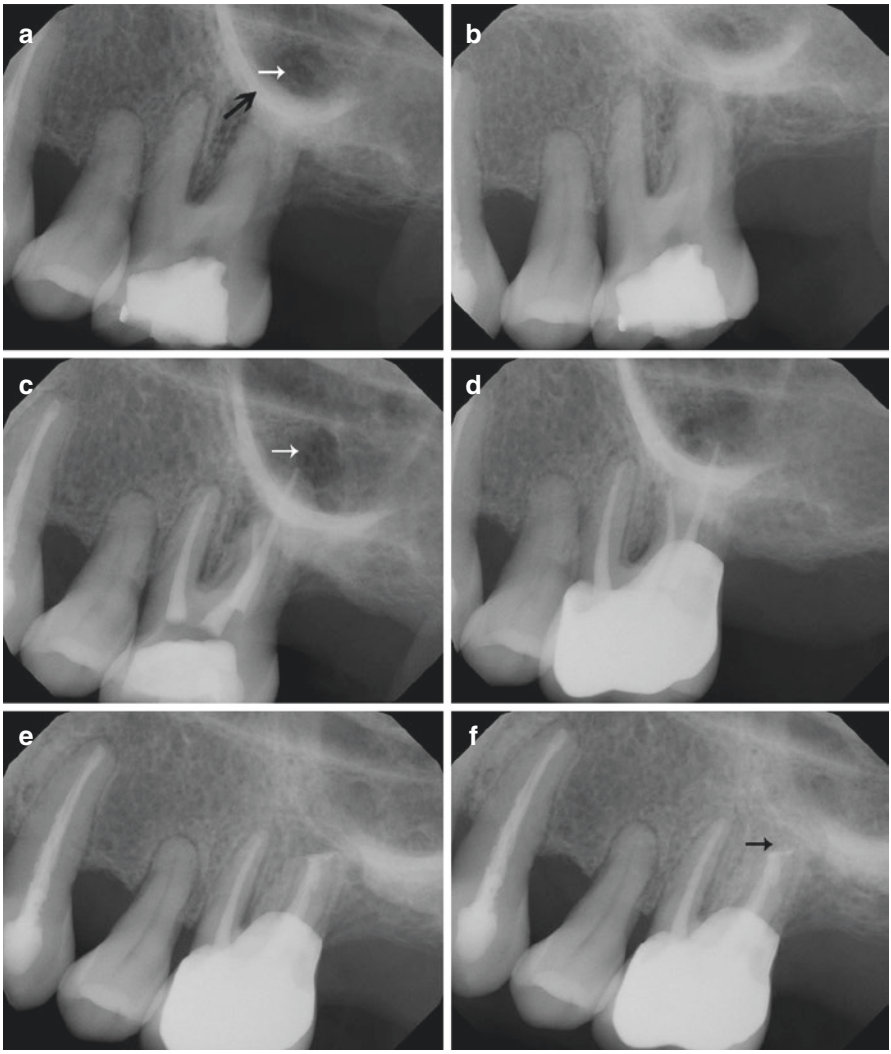

Fig. 12.5 Strindberg's criteria for failure: little or no reduction in periradicular rarefaction. (**a** and **b**) Pretreatment periapical radiograph showing a periapical radiolucency around the palatal root of the maxillary first molar (*white arrow*). Note the superimposition of the zygomatic process of the maxilla (*black arrow*) that can be avoided by changing the vertical angulation as in panel **b**. (**c** and **d**) Follow-up periapical radiographs after completion of endodontic treatment show persistence of the periapical radiolucency (*white arrow*). Nine months after completion of endodontic treatment, the tooth became symptomatic again. The AAE classification would categorize this radiographic appearance as "nonhealed" (symptomatic). (**e** and **f**) Periapical radiographs made 1 year after surgical management of the palatal root of the maxillary first molar. Note complete resolution and osseous healing around the palatal root (*black arrow*) (Images courtesy of Dr. Alexis Moore and Dr. David Han)

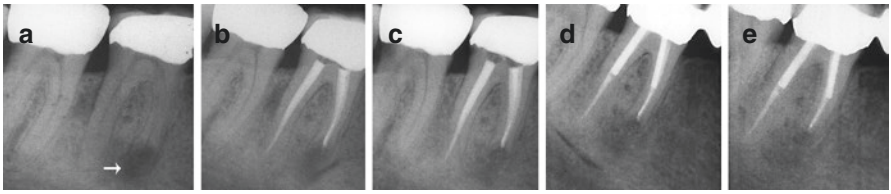

Fig. 12.6 Strindberg's criteria for failure: decrease in size but no resolution of periradicular rarefaction. (**a**) Pretreatment periapical radiograph showing a periapical radiolucency around the mesial root of the mandibular first molar (*white arrow*). Note external resorption of the mesial root apex. (**b** through **e**) Sequential periapical radiographs after completion of endodontic treatment show an increase in the radiodensity of the periapical bone. However, the area of rarefaction is persistent and, in the appropriate clinical context, may be categorized as a treatment failure. The AAE classification would categorize this as "nonhealed" (if symptomatic) or "healing" (if clinically asymptomatic) (Images courtesy of Dr. Nadia Chugal)

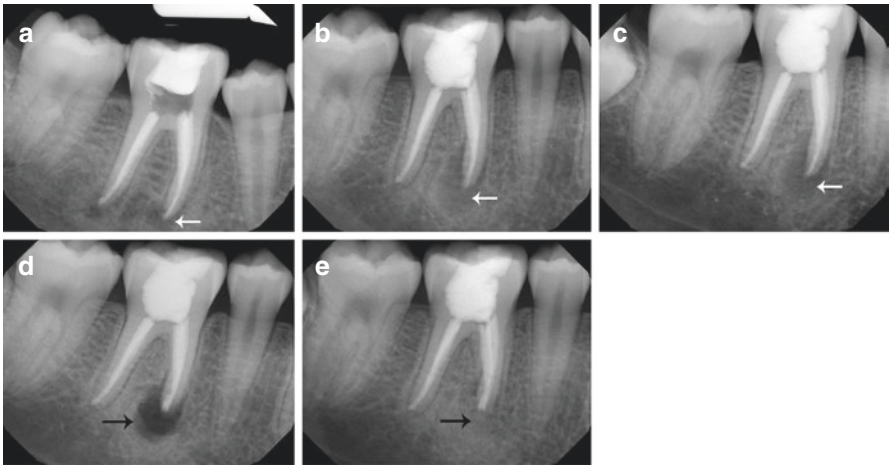

Fig. 12.7 Strindberg's criteria for failure: increase in the size of the initial rarefaction. (**a**) Pretreatment periapical radiograph showing disruption of the lamina dura and widening of the periodontal ligament space around the root apices of the mandibular first molar, particularly evident around the mesial root (*white arrow*). The surrounding trabecular bone is sclerotic, suggestive of a chronic inflammatory process. (**b** and **c**) Follow-up periapical radiographs three and a half years after completion of endodontic treatment show persistence and an increase in the size of the periapical radiolucency (*white arrow*) and, in the appropriate clinical context, (accompanied with increasing clinical symptoms of pain) is categorized as a treatment failure. (**d**) Periapical radiograph made after completion of endodontic surgery. Note radiolucent bony defect around the mesial root apex (*black arrow*). (**e**) Osseous healing and resolution of the periapical radiolucency (*black arrow*) (Images courtesy of Dr. David Han)

were evaluated 6–8 months later, the intraexaminer agreement ranged from approximately 72 % to 88 % depending on the radiographic feature being examined [27]. This variability between evaluators, and within the same evaluator, may explain the large variations in the outcome rates among clinical and radiographic studies [30]. These data underscore the need to calibrate evaluators and minimize inconsistencies

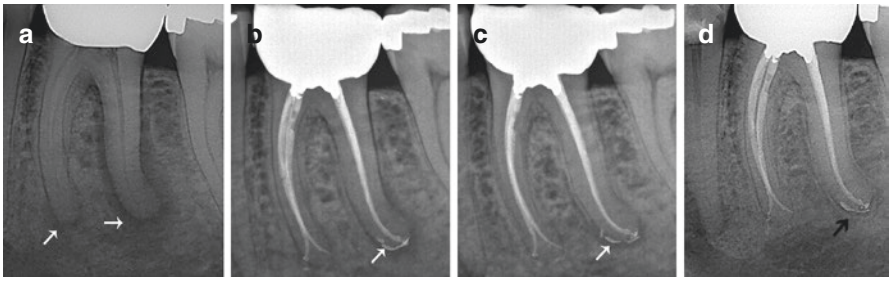

Fig. 12.8 Strindberg's criteria, uncertain outcome: periapical rarefaction less than 1 mm and with broken lamina dura. (**a**) Pretreatment periapical radiograph showing periradicular rarefaction around the mesial and distal roots of the mandibular first molar (*white arrows*). (**b**) Periapical radiograph made immediately after obturation, following 4 months in calcium hydroxide intracanal dressing. Note reduction in periapical radiolucency during this 4-month period. Slight excess of endodontic filling material is noted at the distal root apex (*white arrow*). (**c**) Periapical radiograph made 6 months post-obturation. The periodontal ligament space at the distal root apex is wide (*white arrow*), with absence of the lamina dura. As an asymptomatic tooth, this radiographic appearance would be categorized as an uncertain endodontic outcome. In contrast, the AAE classification would categorize this as "healing" (clinically asymptomatic). (**d**) Periapical radiograph made 18 months posttreatment. The periodontal ligament space at the distal root apex is minimally wide. Note presence of an intact lamina dura around the root (*black arrow*) signifying resolved periapical radiolucency and a successful radiographic outcome. The AAE classification would categorize this as "healed" and "functional" (clinically asymptomatic) (Images courtesy of Dr. Charles Maupin)

in radiographic evaluation when designing studies evaluating endodontic treatment outcomes. Importantly, the inherent observer variability in radiographic analyses emphasizes the need to select those radiographic outcome measures that are robust to be used in clinical practice.

12.4 The Periapical Index (PAI) Scoring System

In clinical practice, the principal end points to assess endodontic treatment outcomes are clinical findings and the status of apical periodontal bone as assessed by periapical radiography. These radiographic assessments are based on subjective evaluation of changes in radiodensity of the periapical lesion with osseous healing and with the reestablishment of the apical periodontal structures. Currently used criteria for endodontic outcome assessment are Strindberg's criteria and the American Association of Endodontic (AAE) classification, and both of these require radiographic assessment as one of the key end points analyzed.

For widespread application of such criteria, clinicians should be trained to reproducibly identify radiographic features of apical periodontitis. Equally important, research studies that examine endodontic treatment outcomes should use reliable and reproducible criteria to define success and failure. To address this issue, a scoring system for apical periodontitis, as depicted on conventional two-dimensional periapical radiographs was developed [31]. This scale provides clinicians and

researchers with a reliable and reproducible tool to assess endodontic outcomes and to reasonably discriminate between subpopulations of success and failure.

The periapical index is a structured scoring system for categorization of radiographic features of apical periodontitis. It is based on a visual scale of periapical periodontitis severity and was built upon a classical study of histological-radiological correlations [32]. It is a five-point ordinal scale as listed below:

1. Normal periapical structures
2. Small changes in bone structure with no demineralization
3. Changes in bone structure with some diffuse demineralization
4. Apical periodontitis with well-defined radiolucent area
5. Severe apical periodontitis, with exacerbating features

The PAI therefore provides more objective criteria for radiographic evaluation of periapical status of teeth that have undergone endodontic treatment. Consequently, it has been used in a number of endodontic outcome studies for the assessment of periapical status [33–46].

Recently, cone beam computed tomography (CBCT) has found considerable applications in endodontic diagnosis and treatment planning [47]. The CBCT-PAI (CBCT periapical index) was developed to apply standardization in approaches to assess the severity of apical periodontitis by CBCT. This index is a six-point scale that includes a score (0–5) plus two variables that assess expansion and destruction of cortical bone. The CBCT-PAI scale is as listed below:

0: Intact periapical bone structures
1: Diameter of periapical radiolucency 0.5–1 mm
2: Diameter of periapical radiolucency 1–2 mm
3: Diameter of periapical radiolucency 2–4 mm
4: Diameter of periapical radiolucency 4–8 mm
5: Diameter of periapical radiolucency 8 mm
E: Expansion of periapical cortical bone
D: Destruction of periapical cortical bone

CBCT is more sensitive than conventional periapical radiography for detection of apical radiolucencies. Thus, it can be expected that the CBCT-PAI will likely reduce the number of false-negative diagnoses on periapical radiographs. However, a recent study demonstrated significant variation in the periodontal ligament space morphology of clinically healthy teeth [48]. This underscores the need to better evaluate and clearly define normal and abnormal features on CBCT imaging, before considering systematic application of this new technology to outcome assessment.

12.5 Outcome Definitions Have Been Inconsistent

Over the years, the terms “success” and “failure” came under close scrutiny due to discrepancies in clinical, histologic, and radiographic observations [2]. New modifiers and criteria were added such as “stringent” and “lenient” where strict definition of success is characterized by “clinical and radiographic normalcy” and lenient only

by "clinical normalcy" [49, 50]. Additional criteria were defined such as "strict" and "loose" [51, 52]. Strict criteria of success are defined by the absence of clinical signs and symptoms and by conventional radiographic measures of complete healing/presence of a normal periodontal ligament space. In contrast, success based on loose criteria may be defined by absence of signs and symptoms and conventional radiographic measures of complete healing or presence of a normal periodontal ligament space or incomplete healing [51, 52]. This became very confusing for the practicing dentist who had to decipher the terminology and apply it to clinical assessment of endodontic outcome.

Escalating the debate and controversy on endodontic treatment choices was the misleading comparison of endodontic treatment outcomes to the success rate of a single-tooth implant [53–55]. The term "success" was based on entirely different criteria for two treatment modalities. This comparison is also confusing to patients who have to decide whether to elect endodontic treatment or to extract the tooth and replace it with an implant.

A series of papers now known as the Toronto study [37, 39, 40, 43–45] introduced yet another set of terms that were deemed more appropriate to assess endodontic outcomes and differed from the commonly used outcome categorization of "success." The Toronto study assessment of outcome was based on the periapical index (PAI) and categorized outcomes as "healed" when the PAI score is less than 3 or "disease" for PAI scores greater than or equal to 3. Importantly, the group introduced a novel category "functional" for all teeth that were asymptomatic, regardless of PAI score. Subsequently, it was proposed that that endodontic treatment outcome should be expressed in terms of the healing of disease, and these new terms were proposed: healed, healing, disease, and functional retention [55].

12.6 The American Association of Endodontists Outcome Criteria

Typical radiographic features of periradicular inflammation that are evident on periapical radiographs include disruption of the lamina dura, widening of the periodontal ligament space, periapical radiolucency, and root resorption. With successful endodontic treatment, the periradicular inflammatory changes resolve and the osseous and periodontal structures regenerate around the tooth apex. For these changes to be radiographically apparent, there must be adequate remineralization of the bone. This emphasizes the need to consider the radiographic changes in the context of the tooth's functional status and clinical symptoms. Recognizing this, the AAE and AAE Foundation (AAEF) took the lead to review the existing criteria used in endodontics and compared these to the outcome measures used by other specialties. The organization subsequently defined new terms for outcome assessment using valid measures that are appropriate for endodontics. The rationale for new definitions was that terms such as "success" and "failure" are too vague. As an alternative to the widely used Strindberg's criteria, the new definitions were approved by the Foundation's Board of Trustees in 2004 and by the AAE Board of Directors in 2005 [56].

12.7 The AAE-Approved Definitions of Endodontic Outcomes

I. *Healed* – Functional*, asymptomatic teeth with no or minimal radiographic periradicular pathosis (Figs. 12.1c, 12.3b, 12.4c, 12.5e–f, 12.7e, 12.8d)
II. *Nonhealed* – Nonfunctional, symptomatic teeth with or without radiographic periradicular pathosis (Figs. 12.2b–c, 12.5c–d, 12.6b–e, 12.7b–c)
III. *Healing* – Teeth with periradicular pathosis, which are asymptomatic and functional, or teeth with or without radiographic periradicular pathosis, which are symptomatic but whose intended function is not altered (Fig. 12.8c)
IV. *FUNCTIONAL** – A treated tooth or root that is serving its intended purpose in the dentition

12.8 Cone Beam Computed Tomography-Based Outcome Assessment

Over the last few years, newer imaging modalities such as cone beam computed tomography (CBCT) have been used increasingly in endodontic diagnosis and treatment planning, with intent to incorporate this technology to better assess treatment decisions and outcomes [57, 58]. The AAE and the American Academy of Oral and Maxillofacial Radiology (AAOMR) jointly developed guidelines for the appropriate use of CBCT imaging in endodontics. These guidelines define clinical scenarios and two-dimensional radiographic appearances that are likely to benefit from CBCT imaging. Notably, CBCT is more sensitive than periapical radiography to detect bone lesions, and thus, its use to evaluate outcomes will undoubtedly be beneficial to identify cases that would be false negatives on periapical radiography. Despite its higher accuracy for detecting periapical disease, the AAE-AAOMR guidelines recommend against using CBCT as a routine diagnostic and outcome assessment tool [59].

The role of CBCT imaging in endodontics is best illustrated by a case presented in Chap. 3, (Fig. 3.8). This case highlights the value of CBCT as a powerful diagnostic tool that alters diagnosis and treatment plans. Note that the decision to proceed with CBCT was made only after clinical examination and two-dimensional radiography. Additional information provided by the CBCT examination was critical in elucidating the cause of endodontic failure by identifying an untreated infected canal. It is important for clinicians to recognize that CBCT imaging does not replace conventional imaging for documentation of case completion and outcome assessment. Whereas CBCT is of value in potentially identifying causes of endodontic treatment failure, the use of CBCT imaging only to monitor treatment outcome for asymptomatic teeth is unjustified (Fig. 12.9).

12.9 Outcome Rates for Orthograde Endodontic Treatment

The results of Strindberg's seminal study on outcomes of endodontic treatment at the end of the 4-year follow-up are presented in Table 12.1. These data demonstrate that success rates for endodontic treatment are significantly lower for necrotic teeth with apical periodontitis than for the teeth with a normal periapex ($p<0.05$). The

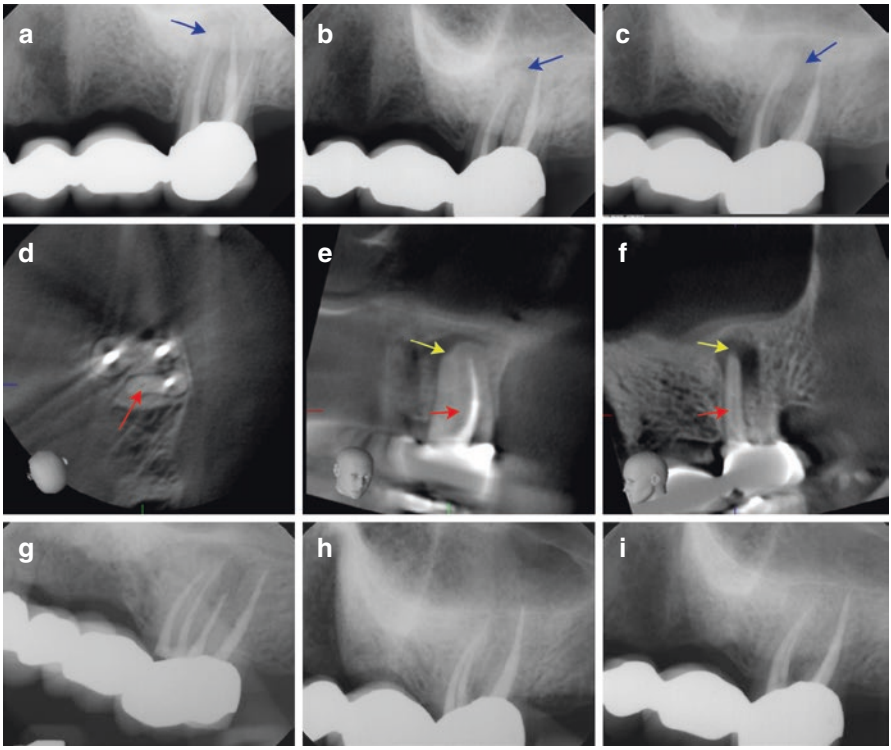

Fig. 12.9 Monitoring outcomes by radiography. The maxillary second molar was retreated (see details in Chap. 3, Fig. 3.8). (**a, b**, and **c**) Periapical radiographs taken at different horizontal angulations to evaluate endodontically treated symptomatic maxillary left second molar. Note the presence of a radiolucency around the mesiobuccal root apex. This represents a treatment failure according to Strindberg's criteria and nonhealing according to the AAE classification. (**d**, **e**, and **f**) Axial, coronal, and sagittal CBCT sections, respectively, through the maxillary second molar. Note the presence of an untreated second mesiobuccal canal (*red arrow*) that is not evident on the periapical radiographs. The extent of the lytic changes (*yellow arrows*) is better visualized on the CBCT sections, compared with the periapical radiographs. (**g**, **h**, and **i**) Periapical radiographs made at completion of endodontic re-treatment and 6-month and 30-month recall visits, respectively. The tooth continued to be clinically asymptomatic. The progressive resolution of apical periodontitis is consistent with a successful outcome (Strindberg's criteria) and/or healed classification of outcome (AAE). Note that in the absence of symptoms, conventional imaging is adequate to document this successful outcome. Additional imaging with CBCT at these follow-up stages is unnecessary and unjustified (Images courtesy of Dr. Nadia Chugal and Dr. Sotirios Tetradis)

rates for aggregate analysis and stratification on preoperative periapical diagnosis demonstrate the intimate relationship between endodontic diagnosis and outcome of treatment. Therefore, the presence of a preoperative periapical radiolucency, denoting apical periodontitis, represents a powerful prognostic indicator [6]. This finding has been repeatedly demonstrated in a number of outcome studies that followed [8–10, 37, 52, 60, 61].

An outcome study utilized microbiologic sampling prior to obturation and stratified analysis of treatment outcome based on bacteriologic findings [11]. The 4-year outcome was assessed according to Strindberg's criteria. The results showed that

teeth with positive bacteriologic culture prior to obturation, denoting residual infection, had significantly lower rate of success compared with teeth that had negative culture results (Table 12.2).

Long-term healing (8–10 years after endodontic treatment) demonstrated 96 % success rate for roots with vital pulps and 98 % success rate for necrotic teeth without preoperative periapical radiolucency [9]. However, only 86 % of roots with pulp necrosis and periapical lesion healed after root canal treatment. Thus, the prognosis for roots without a preoperative periapical radiolucency is significantly more favorable than for those presenting with periapical rarefaction ($p < 0.0001$). Another study investigated the role of infection on the prognosis of endodontic treatment 5 years postoperatively using Strindberg's criteria [13]. All teeth were diagnosed with pulp necrosis and apical periodontitis and microbiologic analysis was performed prior to obturation. This study also had an impressive 5-year retention rate of 96 %. The results showed complete healing in 94 % of teeth that exhibited preobturation negative culture and 68 % if the preobturation culture was positive ($p < 0.05$), (Table 12.3). The Toronto study arrived at the outcome rates based on PAI score. Teeth without preoperative apical periodontitis (PAI score < 3) showed healed rate of 92 %, whereas those with preoperative apical periodontitis (PAI ≥ 3) had a healed rate of 74 % [37].

A systematic review of clinical studies pertaining to success and failure of nonsurgical endodontic treatment reported an overall radiographic success rate of 81.5 % over a period of 5 years [61]. Another systematic review on the outcome of primary endodontic treatment concluded that the success rates have not changed over the last four or five decades [51]. The wide range of reported success rates in individual studies was attributed to the criteria used. When strict criteria are applied to the analysis of outcome, the average success rates ranged between 31 % and 96.2 % with a pooled success rate of 74.7 %. In contrast, when loose criteria were

Table 12.2 Correlation of positive cultures with the prognosis of endodontic treatment [11]

Culture	Success (%)	Failure (%)	Uncertain (%)
No bacteria	88.6	11.4	0
Yes bacteria	68.6	25.4	6.0

Outcome rates stratified on microbiologic status immediately prior to obturation demonstrated significant differences ($p < 0.05$)

Table 12.3 Influence of infection at the time of root filling on the outcome of endodontic treatment of teeth with apical periodontitis [13]

Culture	Success (%)	Failure (%)
No bacteria	94	6
Yes bacteria	68	32

Outcome rates stratified on microbiologic status immediately prior to obturation are significantly different for the two groups of teeth ($p < 0.05$)

applied to the analysis, success ranged from 60 % to 100 %, with pooled success rate of 85.2 %. These results show that success rates were on the average about 10 % lower when strict criteria were used [51]. Similar rates were obtained in a prospective study where the success rate of endodontic treatment was 83 % when strict criteria were used in the assessment of outcome [52].

It is evident that varied results in outcome studies may be due to many factors, including definition of success, conditions under which radiographs were taken, calibration of evaluators, criteria used, patient pool, case selection, and length of follow-up. However, common to all these studies is a significantly lower success rate for infected teeth with preoperative apical periodontitis. This emphasizes again the strong axis between diagnosis and prognosis. As discussed in Chap. 3, this places responsibility on the treating dentist to be an astute diagnostician and intervene earlier in the disease process in order to optimize treatment outcome.

Conclusion

The criteria to assess outcomes of nonsurgical endodontic treatment were initially proposed by Strindberg as "success," "failure," and "uncertain," based on specific clinical and radiographic presentations. These criteria were widely adopted, and the presence or absence of clinical signs and symptoms and the persistence or resolution of the periapical radiolucency became the principal outcome measures of endodontic treatment. However, Strindberg's criteria for radiographic categorization of outcome are stringent and standardization among observers is challenging, and thus, its application to clinical practice was limited. Accordingly, a more reproducible index, PAI, was introduced to guide clinicians to evaluate the healing of periapical lesions after root canal treatment, as depicted on conventional periapical radiographs. Interpretation of the PAI index allows for clinical decisions on transitional phases in the healing/failing process.

More recently, in categorizing the endodontic treatment outcome, the concept of a "functional tooth" was introduced. Similarly, "tooth survival" has been adopted and parallels a common outcome measure in the dental implant literature. An important distinction is that while retention of a functional asymptomatic tooth with a persistent radiographically evident periapical lesion can be regarded an important patient-centered outcome, it is also an indicator of the unsuccessful elimination of the infection as shown in histological studies. Functional and survival clinical outcomes do not imply a successful histopathological outcome. In contrast, successful histopathological outcome implies functional or survival outcome. Clinicians must clearly understand this difference, especially when interpreting the outcome literature, and be able to explain these concepts to their patients. Nevertheless, the presence or absence of clinical signs and symptoms and the persistence or resolution of the radiographic periapical lesion still remain the principal outcome measures of endodontic treatment.

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From Tooth Retention Through Root Canal Treatment to Extraction and Replacement

13

Shane N. White and Mahmoud Torabinejad

Abstract

Initial nonsurgical root canal treatment (NSRCT) is highly successful, is appreciated by patients, relieves pain, and is cost-effective. Results from systematic reviews and studies with very large sample sizes show very high tooth survival rates following NSRCT. Very few patient-associated factors decrease the prognosis for healing after NSRCT. The vast majority of cases will heal following initial NSRCT; the small minority that do not heal are generally best addressed by nonsurgical retreatment. Nonsurgical retreatment is effective and conservative, addressing bacteria remaining within the root canal system. Healing rates increase over time following nonsurgical retreatment. The very small proportion of cases that do not heal after nonsurgical retreatment are best addressed by modern apical microsurgery. Additional case-specific surgical options should be considered before extraction. Intentional replantation remains a viable alternative to extraction. Autotransplantation has a place, particularly in growing patients with an appropriate donor tooth. Root amputation is effective when disease is localized to a single root where adequate remaining tooth structure and periodontal support will remain. Valid reasons to extract and replace an unhealed NSRCT tooth include lack of remaining tooth structure, high caries risk, or high periodontal risk. Not all extracted teeth need to be replaced, but when replacement is indicated, the single-tooth implant is preferred. Single-tooth implants have

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higher survival rates, but the natural state has intrinsic value. Comprehensive case assessment, evaluation of all endodontic options, and risk assessment for caries and periodontal disease are always necessary when choosing the optimal treatment for a patient when initial root canal treatment has failed to heal.

13.1 Introduction

The principal objectives of tooth retention through root canal treatment and restoration are to provide long-term comfort, function, and aesthetics for an individual patient. The purpose of this chapter is to review prognostic considerations of the patient treatment pathways leading to endodontic options to address a tooth that has not healed after initial nonsurgical root canal treatment (NSRCT), the decision to extract, and the replacement alternatives, notably the single implant crown. Root canal treatment and implants are complementary therapies, not competing treatments, with quite distinct indications, contraindications, advantages, and disadvantages [1]. This chapter describes the flow of treatment options from tooth retention to tooth replacement.

13.1.1 High Survival Rates of NSRCT Teeth

The prognosis for healing after NSRCT is extremely good. Systematic reviews, the highest form of clinical evidence, demonstrate extremely high NSRCT tooth survival rates. Iqbal and Kim reported a 6-year survival rate for NSRCT teeth of 97 % [2]. Torabinejad et al. reported a weighted 6-plus-year survival rate of 97 % [3]. Another systematic review by Ng et al. restricted to far fewer source articles estimated an 8–10-year tooth survival rate of 87 % [4]. The endodontic literature contains several outcome studies with extraordinarily large sample sizes which show extremely high survival rates as well as low need for additional interventions following NSRCT [5–8]. Practice-based research network studies of NSRCT outcomes in community general practice also show high tooth survival rates [9, 10]. These results speak to the remarkable performance of NSRCT teeth over time.

Interestingly, the most common reasons for extraction of NSRCT teeth for extraction are decay, periodontal disease, non-restorability, prosthodontic failure, and fracture, not failure of the NSRCT itself [7, 10–16].

A cross-sectional systematic review of the prevalence of periapical radiolucency and NSRCT indicated that some disease and unmet need remain; however, billions of teeth are retained through root canal treatment [17].

13.1.2 Patient-Centered Outcomes of NSRCT

Patients choose NSRCT to retain teeth so as to preserve the natural aesthetics of their smile and for relief of pain. A recent systematic review found that the severity

of root canal-associated pain severity was moderate before treatment, dropped substantially within one day of treatment, and dropped to minimal levels in a week [18]. Likewise, the prevalence of pain drops to minimal levels in a week [18–20]. A high percentage of patients who experienced NSRCT report willingness to choose it again [21]. Overall satisfaction ratings for root canal treatment are extremely high [20, 22]. Complication rates are low [13, 23]. Costs for NSRCT and restoration are substantially lower than they are for replacement with implant single crowns or fixed dental prostheses [3, 24–26].

13.1.3 Prognostic Indicators of NSRCT Performance

It must be understood that studies on prognostic indicators using strict radiographic criteria such as those of Strindberg or Orstavik are just that, studies on prognostic indicators, not on patient outcomes [27–29]. However, these studies do help the dentist identify patients with higher or lower chances of healing following NSRCT.

Most patient factors do not influence NSRCT prognosis. For example, advanced age and HIV status do not influence prognosis [30–35]. However, diabetes and steroid therapy may decrease prognosis [30, 34, 36]. Teeth with vital pulps are associated with a slightly better prognosis than with necrotic pulps [32, 37–42]. The presence of a periapical radiolucency may also decrease prognosis; likewise, its absence may increase prognosis [38, 39, 42–45]. Treatment quality is, of course, important [34, 46].

Importantly, NSRCT may greatly benefit patients who have bleeding disorders, have received head and neck radiation, or have received high dosage of bisphosphonates in avoiding high-risk extractions or other surgical procedures, including implant placement.

Overall, patient factors affecting NSRCT prognosis are few, and their impacts are only moderate.

13.1.4 Endodontic Treatments Following Non-healing Initial NSRCT

The vast majority of teeth with NSRCT will heal without any further intervention, but additional endodontic treatments can provide a safety net [47]. These principally include nonsurgical retreatment, endodontic surgery, intentional replantation, and autotransplantation (Fig. 13.1).

Nonsurgical retreatment is generally the first line of treatment used to address failure of initial NSRCT; it has been widely studied and generally highly successful [48, 49]. Nonsurgical retreatment addresses the usual cause of failure to heal bacteria that have either remained in the root canal system or that have reentered through coronal leakage. Teeth addressed by nonsurgical retreatment tend to show increased rates of healing over time, giving a more favorable long-term outcome than surgery [50, 51].

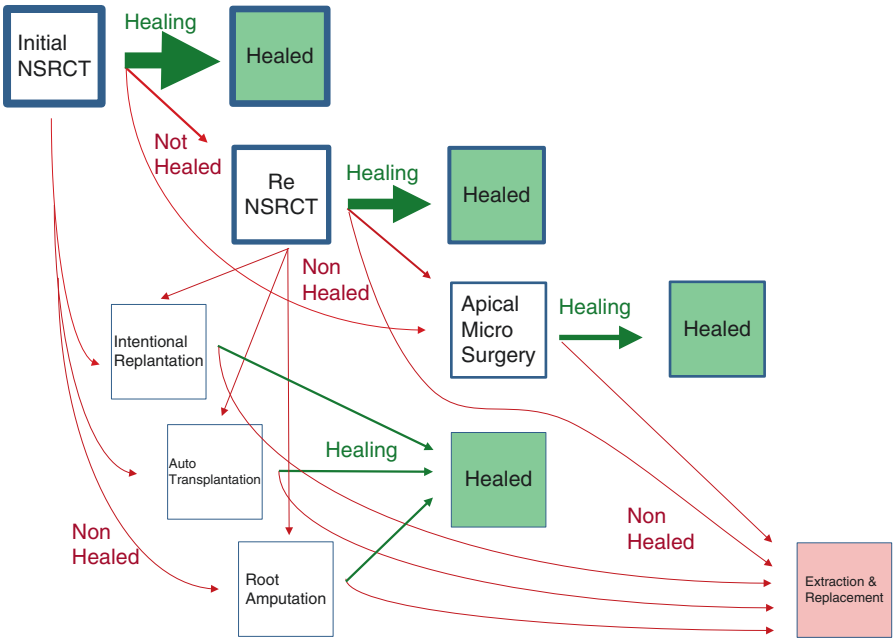

Fig. 13.1 Flowchart of main choices when initial nonsurgical root canal treatment (NSRCT) has not produced healing. The vast majority of cases will heal following initial NSRCT; the small minority that do not heal are generally best addressed by nonsurgical retreatment. The very small proportion of cases that do not heal after nonsurgical retreatment are best addressed by apical microsurgery; however, a variety of other case-specific options should be considered before extraction

Apical surgery, apicoectomy, is generally now reserved for situations where nonsurgical retreatment is not practicable or in the small number of cases where it has not been successful [52]. Recent studies of modern endodontic microsurgery, using microscopes, ultrasonic instrumentation, or current apical filling materials, have produced superior results to traditional endodontic surgery [53–55]. Apical surgery generally only addresses root apices, not the entire root canal system. Teeth addressed by surgery heal well initially, but have a tendency toward failure over time [51, 55].

Intentional replantation, the temporary extraction, treatment, and reinsertion of a tooth into its socket, is only indicated when there is no other way to maintain a strategic tooth. Intentionally replanted teeth are often successful if careful case selection is performed [56].

Autotransplantation, the transfer of a tooth from one alveolar socket to another area in the same patient, may have a reasonable prognosis [57–59]. Ankylosis and resorption are the most common failure modes of intentionally and autotransplanted teeth. Autotransplantation, sometimes simply called transplantation, may be a useful option in younger growing patients who have suitable candidate teeth.

Root amputation is effective when remaining disease is localized to a single root where adequate remaining tooth structure and periodontal support will remain [60]. Care must be taken to provide smooth cleansable emergence profile and contours.

13.1.5 Extraction and Tooth Replacement Decisions

Should a NSRCT tooth fail to heal initially, it should generally receive nonsurgical retreatment. In the small number of cases where this is not effective, endodontic microsurgery surgery can be provided. Should endodontic surgery be ineffective in producing healing, the tooth should be extracted (Fig. 13.1).

Lack of remaining tooth structure, high caries risk, and high periodontal risk are also valid reasons to extract and replace an unhealed NSRCT tooth.

Retaining substantial tooth structure in the endodontically treated tooth is more important than any restorative choice [61–75]. Restorations on teeth with substantial remaining dentin height and bulk had significantly higher survival rates than on teeth with minimal remaining dentin height and bulk; however, even those with minimum remaining dentin had an 84 % 10-year survival rate.

Caries is, of course, a concern with patients who undergo endodontic treatment, caries being the overwhelming cause of pulpal disease and root canal treatment. Caries risk assessment systems, such a CAMBRA, should be routinely used [75–77]. However, their predictive value may be limited [77, 78]. Recent caries history records may be more valuable in assessing a patient with an endodontically treated tooth.

Periodontal risk has been notoriously difficult to quantify [79]. Only the teeth with excellent and hopeless prognoses are easy to quantify [80]. Those in the middle, the fair, poor, and questionable, may go either way [80]. Patient-based risk assessments have become more predictive of which patients are at risk to disease progression, but not to which particular tooth may be lost [79].

Comprehensive case evaluation and risk assessment is always necessary to choose the optimal treatment for an individual patient's individual tooth when initial NCRCT has failed [81–83].

13.1.6 Fixed and Removable Dental Prostheses and Implant Alternatives

Should a decision be made to extract an endodontically treated tooth, the first question is whether to replace or not. Loss of a single tooth has remarkably little effect or oral function or health, but the loss of multiple teeth may be more problematic, and individual teeth may have critical strategic value [3]. Furthermore, appearance is incredibly important to patients [3].

Next, the mode of replacement must be determined. Removable partial denture provides excellent cost-benefit, but these are least preferred by patients [24].

Removable partial dentures can be stressful to abutment teeth, particularly to key abutments in tissue-supported situations. Fixed dental prostheses, bridges, have long been a preferred mode of tooth replacement; however, systematic review has shown that they have much lower survival and success rates than an implant single crown [3]. They also entail removal of healthy tooth structure from abutment teeth, unless already prepared. However, they may have a place in patients who are poor candidates for implant surgery and those who have already full-coverage preparations on their abutment teeth.

The implant single crown is the replacement of choice. Systematic reviews have shown it to have superior success and survival rates in comparison to fixed dental prostheses [3, 84]. The implant single crown has survival rates equal to a NSRCT tooth [1, 2]. It has superior survival rates to failed NSRCT teeth that have been treated using endodontic microsurgery, but that did not receive prior nonsurgical retreatment [55]. It also has superior survival rates to intentionally replanted teeth and likely to autotransplanted teeth [56]. Although the success of single-tooth implants has produced a paradigm shift in treatment planning, other options must be considered before extraction and tooth replacement. Implant single crowns have high complication rates, necessitating many additional interventions [55]. Implant placement may be contraindicated for patient reasons, continuing growth, diabetes, smoking, bleeding disorders, high dosage of bisphosphonates, and head and neck radiation; may not be possible for anatomic reasons, e.g., proximity to the inferior alveolar canal; or may be of undue complexity, e.g., some pneumatized maxillary sinuses [81–83]. The healthcare economist tells us that the natural state, a tooth, has intrinsic value [3]. The alternative to the natural must be better or less expensive, or both [2]. The implant single crown is no better than a natural tooth and is considerably more expensive than tooth retention, in both initial and ongoing costs [3, 24–26]. The preceding sections speak to the high bar set by conventional NSRCT for the alternatives in terms of survival, patient-centered measures, prognosis, and effective endodontic fallback procedures. Implant single crowns can offer predictable replacement of failed NSRCT when other treatment options have been attempted without success and are not possible or when the tooth has poor restorative, caries, or periodontal risks [1]. They should generally be considered as the first choice for single-tooth replacement.

Conclusions

Survival rates of root canal treated teeth are extremely high, and patient benefit is immense. The enormous benefit of initial nonsurgical root canal treatment is supported by an extraordinary weight of different types of evidence. The first treatment option after failure of initial nonsurgical root canal treatment is nonsurgical retreatment. Other options then include endodontic surgery, intentional replantation, and autotransplantation. Should the tooth still have unacceptable endodontic, restorative, periodontal, or carious risks, then the implant single crown is generally the best alternative. Comprehensive case evaluation and risk assessment of the individual patient and tooth is always necessary.

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