31. Lilly, John C. 1954. "Instantaneous Relations Between the Activities of Closely Spaced Zones on the Cerebral Cortex: Electrical Figures During Responses and Spontaneous Activity." Am. J. Physiol. 176:493-504

DS

30 31

Instantaneous Relations Between the Activities of Closely Spaced Zones on the Cerebral Cortex

Electrical Figures During Responses and Spontaneous Activity

JOHN C. LILLY

From the E. R. Johnson Foundation for Medical Physics, University of Pennsylvania, Philadelphia, Pennsylvania

Reprinted from THE AMERICAN JOURNAL OF PHYSIOLOGY
Vol. 176, No. 3, March, 1954
Printed in U.S.A.

Reprinted from THE AMERICAN JOURNAL OF PHYSIOLOGY
Vol. 176, No. 3, March, 1954
Printed in U.S.A.

Instantaneous Relations Between the Activities of Closely Spaced Zones on the Cerebral Cortex

Electrical Figures During Responses and Spontaneous Activity[1]

JOHN C. LILLY[2]

From the E. R. Johnson Foundation for Medical Physics, University of Pennsylvania, Philadelphia, Pennsylvania

OUR INTEREST has been centered mainly on two problems concerning the activity of the cerebral cortex: the first concerns the instantaneous pictures of the responding region's activities in the cortex after the arrival of a single afferent volley; the second deals with the role of spontaneous activity in the cortex and the specification as to where and when it occurs. The experiments reported here deal with both of these problems and allow a more detailed specification of both types of activity by means of simultaneous records from 25 electrodes placed in an area of about 0.64 cm.[2]

The separation of the afferent cortical response from the spontaneous activity as a separate entity is a result of the work of Bartley and Bishop (1), Gerard, Marshall and Saul (2), Bishop and O'Leary (3), Marshall, Woolsey and Bard (4), and Adrian (5). A surface-positive wave appearing on the cortex as a result of stimulation of a small peripheral zone has been described by them for tactile, visual, and auditory stimuli. Maps of the relations between the peripheral endorgan sheets and the responding areas of the cortex have been made for the tactile (6), the visual (7), and the auditory (8, 9) systems. All of these maps specify what cortical regions give the responses; no serious attempt has been made to see how a response behaves simultaneously at many zones in the cortex after its arrival. Does a response fire the whole region simultaneously, or does it fire the region in some sequential fashion outward from certain zones? The experiments reported here show, for the first time, that the afferent volley excites a moving 'figure.' The figure can be divided serially in time into at least three series of parts: in this paper we call these series the 'head,' the 'peak,' and the 'tail' of the activity. These parts travel through the cortical projection area in reasonably definable and reproducible ways not necessarily alike.

The investigation of the 'spontaneous' activity seen at the cortical surface in the absence of known pathology has been hampered by its unpredictable behavior; it does not have the stereotyped nature of the evoked type of activity. Previous observations by others have shown that this activity at a single locus varies in form, in amplitude, and in frequency in unpredictable ways with time. Loci near one another have relatively unpredictable and non-stereotyped phase relations with each other (10, p. 456). Attempts to relate the forms of the graphical records of this activity obtained in different cortical regions to the structure and connections of those regions have met with little success (11). The spontaneous waves are profoundly influenced by the depth of anesthesia and the type of anesthetic used, (12, 13). Analysis of the parameters of such waves at a single zone have specified other factors (carbon dioxide, blood sugar, and oxygen) which influence the components of the frequency spectrum (14). A study by Adrian and Yamagiwa (15) of the activity seen at the scalp surface in human subjects showed, by a 'triangulation' analysis, that the apparent origin of some of these waves (alpha) probably moves about in the cortex (cf. 16).

By means of the present technique (which

Received for publication September 10, 1953.

[1] This investigation was supported in part by a research grant from the National Institute of Neurological Diseases and Blindness, National Institutes of Health, U. S. Public Health Service.

[2] Present address: Research Branch, National Institute of Mental Health, National Institutes of Health, Bethesda 14, Md.

allows simultaneous recording of 25 zones within an area of 0.64 cm.^{2}) some of the past difficulties in analyzing the spontaneous activity from single zones have disappeared. For the first time a few of these waves have been found to be two-dimensional figures at the cortical surface, which grow and travel in ways which can be analyzed. In retrospect, many of the earlier difficulties with analysis of the spontaneous waves are explicable when interpreted in the light of the present findings.

The present results are from the ectosylvian region of the cat, and have been divided into several papers: This one is the first and gives the methods, some prints from the original records of typical evoked and spontaneous activities, and descriptions of the figures seen in these records. The later papers give the results of an analysis of the directions and velocities of travel of parts of these figures over the cortical surface, and the results of an analysis of a few figures as wholes, as shown by equipotential contour maps. Some material has been published in abstracts (17–21) and in two articles (22, 23).

The major task of the present paper is to show that definite single electrical forms ('figures') do exist and to show under what conditions they can be separated unequivocally as entities. As will be seen, the demonstration of these entities is limited by the present temporal and spatial resolution of the technique to some unambiguous cases.

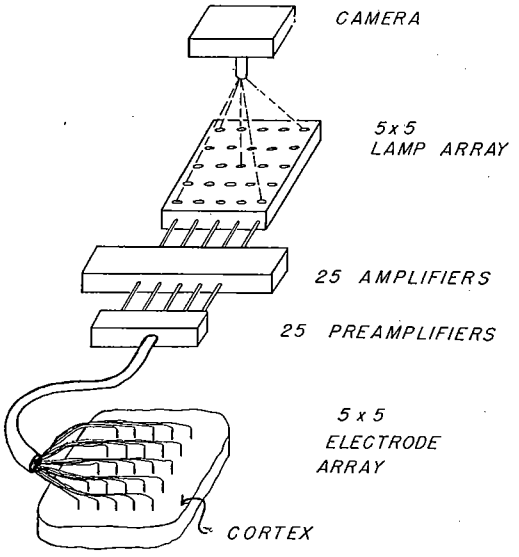

FIG. 1. Amplifiers and the recording system (see text). (Reproduced with the permission of Paul B. Hoeber, Inc.)

METHODS

The apparatus and recording technique have several novel features and hence are described in more than the usual detail. In order to record the potentials on the cortex simultaneously at 25 zones, special apparatus (fig. 1) was constructed (23). The animal is placed in a sound-deadening box in a shielded room. A square array of 25 electrodes on the arachnoid over the surface of the cortex feeds signals to 25 preamplifiers placed near the box in the shielded room. Cathode followers in the preamplifiers feed the signals to cables leading to the 25 amplifiers in a rack outside the shielded room. From the power output stages, cables lead to the recording equipment in another room. The recording is done with a camera photographing an array of 25 glow tubes (Sylvania tube 1B59) which show the signals by varying their light outputs with the signal amplitudes. The present recorder is a 16-mm motion picture camera (Bell and Howell 70-G Superspeed) electrically driven at 128 frames/sec. (This camera produces so much noise when running that it was necessary to remove it from the laboratory containing the shielded room in order to avoid stimulation of the animal).

In this apparatus the signal from each electrode in the electrode array modulates the intensity of the glow tube above and below a mean value in the corresponding position in the lamp array. The signal recorded is the difference between the potential of one electrode and the average potential of all 25 electrodes. This way of recording rejects signals common to all 25 electrodes at a given instant. Such a differential signal is seen as a brightening of a glow lamp when negative with respect to the mean, and a dimming, when positive. Thus, a wave of electrical activity under the electrodes is seen as 25 spatial parts of a surface of increased and decreased light intensity in the camera field, corresponding to 25 parts of a potential gradient surface on the cortex.

In all arrays of electrodes used to date the electrodes are arranged in a square, five on a side; the spacing between electrodes in a row or in a column is 2 mm. The first array was designed for use with exposed brains, and consists of wires in sliding glass tubes resting on the cortex under gravity (17 mg/electrode). This array has been described in detail elsewhere (23).

Subsequent arrays have been designed for implantation through the skull. This technique has several advantages (4, 24): it allows the brain to remain in a closed cavity and thus free of undue trauma, expansion, evaporation, and changed hemodynamics; and experiments can be carried on for several days to weeks on the same animal, with or without anesthesia. Experiments have been run on anesthetized cats up to 8 days and on unanesthetized monkeys up to 6 weeks without detectable deterioration of the observed

activity. The main disadvantage of this technique is the difficulty in moving the array to adjacent regions in the same animal.

The array of electrodes used in the experiments reported here consists of 25 glass tubes imbedded in a cylindrical lucite block: their openings, about 0.6 mm in diameter, flush with the surface of the lucite cylinder, touch the arachnoid (fig. 2); these tubes are connected, with plastic tubes, to 25 silver-silver chloride half-cells on a stand near the skull. Normal saline solution forms the conducting path from arachnoid to the half-cells. The lucite cylinder fits closely into a stainless steel ring. The ring has a tapered thread on its external surface which allows it to be screwed into a trephine hole ($\frac{3}{4}$-in. diameter) in the skull. The lucite cylinder has a drive device outside the skull tying it to the ring. The drive device consists of a threaded rod which drives the cylinder into or out of the ring. This latter arrangement allows the operator to vary the depth at which the array is placed in the cranial cavity.

Nembutal (30 mg/kg of body weight one-half i.p. and one-half i.m.) is used for operative anesthesia. A 1% procaine solution is used locally before cutting the superficial tissues. An aseptic procedure is generally employed.

After reflecting skin and muscle, a trephine is used to cut a $\frac{3}{4}$-in. hole over the desired region. Before the removal of the dura complete hemostasis is achieved with bone wax. Under a binocular microscope the dura is removed in the exposed region, avoiding a puncture in the arachnoid. The stainless steel ring is screwed into the bone until its lower surface presses lightly on the arachnoid. The hole in the ring is filled with Ringer's solution, and the electrode array is pushed slowly into the ring; one plastic tube is disconnected to allow the excess solution to run out. The array is pushed to a desired depth measured relative to the ring with the drive device. The usual operation takes about three-fourths of an hour. Penicillin (100,000 U) is injected postoperatively and twice during the first 48 hours thereafter. With this technique, the arachnoid is exposed to room air for only a few seconds while the ring is screwed into place.

The recording is of an intermittent type—only samples of continuous wave forms are recorded. The 16-mm motion picture camera takes 128 pictures/sec. of the glow lamp array; hence the frame cycle is 7.81 msec. For 60% of this cycle, the film is not moving and the shutter is open; thus, the film integrates the intensity of each lamp for 4.7 msec and loses about 3.1 msec of data in each frame cycle. For waves whose parts last longer than about 30 msec this loss is not serious; for more abrupt waves or transients it can be serious unless a repeating pattern can be recorded a number of times out of synchrony with the camera cycle (see below).

The original records vary in ranges of density and of signal amplitude depending on several photographic parameters. In general, a low contrast film such as Eastman Super XX shows both small and large signals. High contrast film, such as Eastman high contrast positive, acts as an amplitude selector; such film has a critical threshold, depending on the lens opening, which can be used to give an 'all-or-none' record for signals above a chosen amplitude. We have used both types and have found the low contrast film best for viewing the full signal range in motion pictures and the high contrast film best for certain types of analysis (see below).

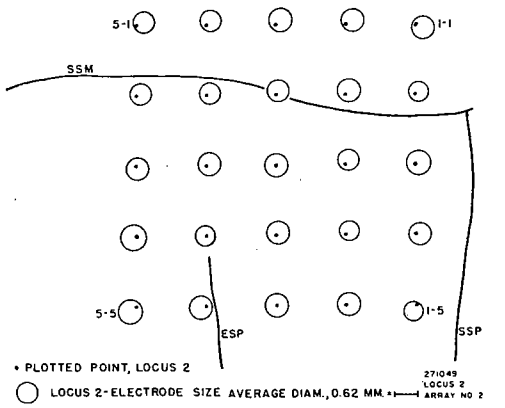

FIG. 2. Loci and sizes of the electrodes, drawn to scale. This diagram shows the diameter of each of the pores in the end of each glass tube in the array and their positions on the cortex. The extreme diameters are 0.54 and 0.70 mm. The mean diameter of all 25 electrodes is 0.62 mm. The interelectrode spacing, in a row or in a column, is 2.0 mm, which is 3.2 times the average pore diameter. The array covers about 0.64 cm² of the arachnoid surface. The numbers at the corners of the array designate each electrode by its column number first and then its row number: *column 5* is to the left, *column 1* to the right; *row 1* is at the top, *row 5* at the bottom. The marked sulci are as follows: SSP, posterior suprasylvian sulcus; SSM, middle suprasylvian sulcus; and ESP, posterior ectosylvian sulcus. This diagram gives the loci of the electrodes for the records (figs. 3 through 9). The dots ('plotted points') show the location of the light images in the subsequent records.

In general, it is difficult to reproduce in prints the full range of densities of the original records; the contrast is increased by each reproduction process from the first prints to the pictures in the journal. An example (fig. 3) shows the selection of single amplitudes by each one of several prints made with different exposures from a single original, low-contrast film. A similar selection is useful for an analysis at each instant of the distribution of a single amplitude of signal on the cortex. A later paper gives the results of such an analysis.

By a photoelectric measurement of the densities of the lamp images on the film (1000 measurements/ft. of record), all of the recorded signals can be recovered for transformation to other forms of reproduction and for other types of analysis. A rubber membrane model was used for portraying the instantaneous pictures of the potential gradients from some of our experiments

(*17* and *20*). A later paper will give some of our results in the form of contour maps of the gradients plotted on diagrams of the brain.

The clicks used to stimulate the animal are produced by an earphone driven by a 50-μsec rectangular pulse from a stimulator. The earphone is placed in front of the face about equal distances from the two ears of the cat. The amplitude of the click is adjusted to give just maximal response on the cortex at a click repetition frequency of 1.0/sec.

With this particular arrangement probably only a very short sound pulse actually stimulates the cat's ear. The observed waveform in air is a large pulse followed by damped vibrations. The pulse duration is approximately 0.5–0.8 msec, depending upon the amplitude which is considered to be at threshold value for the ear. Even though such a pulse probably has frequency components in a very wide acoustic band, most of its energy lies in the region from about 1000 cps to higher frequencies, with fairly large phase differences in the band (25). Békésy (26) has shown that a sound pulse causes a wave to travel along the cochlea; in the cat it may take 2–3 msec to go from base to apex. Such a wave may cause sequential firing of the cochlear endorgans, but this is yet to be demonstrated.

RESULTS

Because of the extremely large number of data which the method records in a few seconds on a single animal, it is rather difficult to present enough records to give a clear story and yet not so many that the reader is burdened with masses of data. A compromise was effected for this introductory paper as follows: a few prints of original records taken with a single array locus (fig. 2) in one of the three cats examined are presented. Amplitudes are shown only as above or below a certain arbitrary level at 7.8-msec intervals.

Forms in the Electrical Activity. Figures 3 through 9 show some of the forms in the electrical activity most frequently seen in the ectosylvian region of the cat's cortex (fig. 2). Examples of responses to click stimuli (figs. 4 and 7) and of forms with no intentional stimuli (figs. 3, 5, 6, 8, and 9) are presented.

Such 'instantaneous' pictures reveal that both evoked and spontaneous activity contain electrical, moving, spatially organized 'structures' changing with place and time. In order to denote such structures or forms with a specific term, I call them 'figures.' In reality such figures probably have fine details which will be seen only when a more finely grained mosaic of electrodes can be used to view them.

It is to be emphasized that these figures must have form extending inside the brain; here we see only the surface aspect of a deep electrical structure. Viewing the time-course of changes at a single electrode during the passing of a figure, the waveforms so familiar to classical electrophysiology are seen. In this paper, the term figure will be used for forms which are to be understood as only parts of the real, larger forms which extend beyond our array field.

To facilitate the discussion, a single example (fig. 4) of parts of an evoked figure relatively free of spontaneous activity is shown by itself. The anesthetic level is fairly deep in order to minimize the spontaneous activity (4, 5). The first sample of the figure occurs in *frame 8*. With more or less random placing of the stimulus in the frame cycle, the pattern in the frame which first shows activity will vary from one response to the next (fig. 7). Most of this variation is probably due to the steep, short nature of the initial rising (or falling) phase of the click response (8), and is probably not due to large variations from one response to the next. In other words, the frame cycle is long compared with the time it takes the response to reach its peak, and the recording shows only one or two parts of the rising phase. This particular sample (*frame 8*) shows two distinct regions of different response: lamps 5-2 and 5-3 have become brighter (larger images), and lamps 5-4, 5-5, 4-3, 4-4, and 4-5 have become dimmer (missing and smaller images). The first region has become relatively more surface negative; the second has become relatively more surface positive. In other words, an irregularly shaped 'hill' has appeared in the lower left hand region of the array with a deep 'valley' beside it to the upper left.

It can be seen (fig. 2 and *frame 8* of fig. 4) that this 'hill and valley' part of this electrical figure is confined to an area below the middle suprasylvian sulcus and anterior to a line extending upward from the posterior ectosylvian sulcus posterior to *column 4* of the array. This is the first area which shows activity in this response.

Frame 9 shows an increase in amplitude of the hill and the valley with little change in distribution. The brighter lights in the posterior ectosylvian region (fig. 2, mainly lamps

3-3, 2-2, 2-3, 2-4, 2-5, 1-2, 1-3, and 1-4) may not be significant, due to the differential action of the amplifier (see METHOD above, 23).

Frame 10 shows a change in distribution: the valley has spread across the middle suprasylvian sulcus to electrodes 5-1 and 4-1; the hill has moved downward leaving electrode 4-3.

In *frames 11–15*, the hill retreats from the lower left hand edge of the array (5-5). The valley (5-2 and 5-3) disappears in *frame 13* and returns briefly in *frame 14*. The negative region (5-1 and 4-1) across the middle suprasylvian sulcus, shows some oscillation and becomes quiescent by *frame 16*. Except for electrode 3-4, most of the action is over by *frame 16*.

The activity showing in lamp number 3-4 was purposely not discussed. This activity is probably an artifact signal at 60 cps (power-line frequency), and hence this lamp probably does not participate in this response. This conclusion is reached on the following grounds: In the frames of the record where no response appears, there are groups of alternating 'on-off' images, separated by two sets of frames of less regularity (*frames 6–9*, and *frames 20* and *21*). Of the three groups of alternating ons and offs (*frames 1–4*, *10–19*, and *22–25*), the middle group (*frames 10–19*) is 180° out of phase with the two end groups (*1–4* and *22–25*). The two sets of frames of less regular patterning are separated by 16 frames, or $\frac{1}{8}$ second, or 1 cycle of 8 cps. These features are predictable from simple theory: 128 samples/sec. of a sine wave of a constant peak amplitude and of a frequency of 60 cps should show a waxing and waning of amplitude and a phase shift of 180° at the difference frequency (8 cps, between the first harmonic of 60 cps (120 cps) and the sampling frequency (128 samples/sec.)).

(In other records, (fig. 7, *response forms 2* and *8*) it can be shown that electrode 3-4 can participate in some responses in the absence of 60 cps artifact; however, it does not participate in every such response (fig. 7, evoked *forms 3*, *4*, and *7*)).

From this record (fig. 4), I deduce that an acoustic projection area (or areas) lies under 7 electrodes: 5-2, 5-3, 5-4, 5-5, 4-3, 4-4, and 4-5. With less confidence, it can be said that the posterior boundary of this area lies just posterior to these electrodes. This boundary problem will be discussed later.

A single example (fig. 5) of a spontaneous figure traversing the array is presented to facilitate later discussion. *Frames 1–13* show the typical quiet background; entrance begins in *frame 14* at electrode 4-5 lying almost on the posterior ectosylvian sulcus. By *frame 16*, it has spread to include at least 3 more electrodes: 5-5, 3-4, and possibly 4-4; it then spreads farther into the array (up to *frame 19*). Up to this point the figure has been activating additional electrodes: at *frame 21*, electrode 5-5 begins to recover and does so by the time of *frame 22*. Up to this loss of electrode 5-5 from its form the figure has had the shape of a positive 'ridge' extending up from the region around the upper end of the posterior ectosylvian sulcus, dorsally and posteriorly into the posterior ectosylvian gyrus. From *frame 21* its growth continues until the maximum extent is reached in *frame 24* (underlined). This maximum area includes only 2 electrodes (4-4 and 4-5) of the above single responding figure (fig. 4); it does not go beyond the middle suprasylvian sulcus; it remains stable for at least 16 msec (*frames 23* and *24*); its shape is that of a 'mesa' extending downward out of the array along the posterior ectosylvian gyrus. In *frames 25–35*,

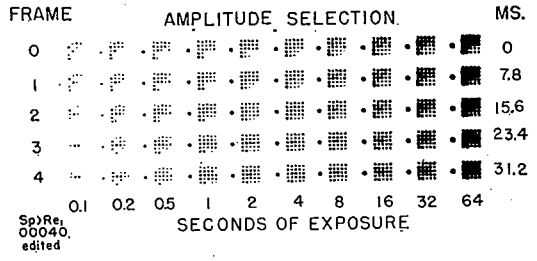

FIG. 3. Five parts of a spontaneous figure showing the selection of different amplitudes which results from printing and reproduction.

The original record was a positive (reversal) set of images on Eastman Super XX Panchromatic film. The exposure intervals are given under each print. The scale to the left shows the frame numbers; the scale to the right gives the corresponding number of msec after the time of the first frame.

Later records in this paper are prints exposed to be like those shown here at 2 sec. This exposure depends on the film used for the recording, the exposure it received, and the development processes (see text).

Fig. 4

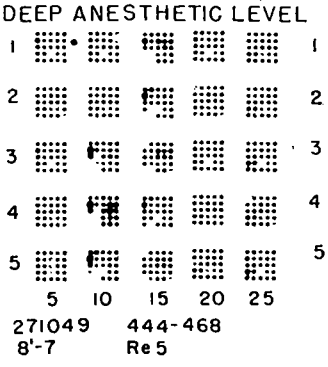

Fig. 5

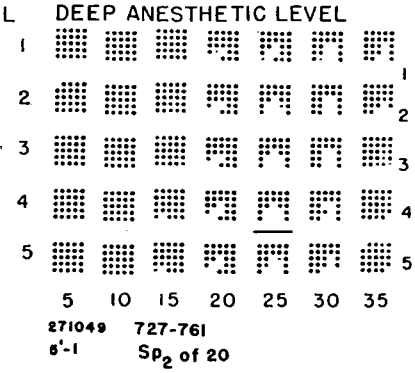

Fig. 6

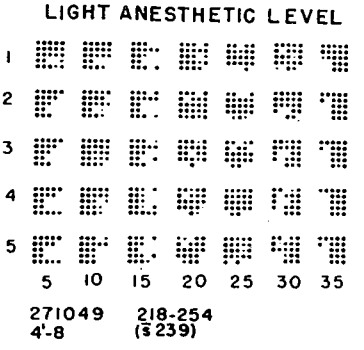

FIG. 4. Example of an evoked form. The time sequence of the frames in this and the later records is from the top of the record to the bottom, in columns arranged from left to right. The numbers increase in the direction of increasing time. The signal light for the occurrence of the stimulus shows at the left of *frame 6* (the first frame in the second column); a click stimulus occurred during this frame. The response form can be seen to develop by the time *frame 8* is reached and to change during *frames 9–15*. This response shows 2 directions of relative potential change—the positive direction shows as missing images; the negative direction, as enlarged images. A small oscillation can be seen in image no. 3-4, not related to the response. This same response is shown again (fig. 7) at a slightly reduced exposure, with its preceding and following ones in a sequence of responses.

FIG. 5. An example of a spontaneous figure at a deep anesthetic level. This record was taken at a slightly lighter depth of anesthesia than that for the single response (fig. 4). In contrast to the response, this form has only positive parts in it. No click stimuli occur in this record. The form enters the array at electrode no. 4–5, in *frame 14* near the posterior ectosylvian sulcus (fig. 2). Spreading over the posterior ectosylvian region, it reaches its maximum extent in *frame 24* (*underlined in black*). Retreating from its area of maximum extent, it leaves the region of the array at electrode 1-5 near the posterior suprasylvian sulcus. This type of form is characteristic of the posterior ectosylvian region. A long sequence of such forms is shown later (figs. 8 and 9). No large forms of this kind were seen in the acoustic projection area during a 25-sec. record.

FIG. 6. Examples of spontaneous figures seen at a light anesthetic level. The anesthetic level is lighter than that for the single spontaneous figure (fig. 5). No click stimuli are given during this record. During a 10-sec. record (1280 frames) of such activity each electrode is as active as each of the others, *i.e.*, there are about equal numbers of 'ons' and 'offs' for each lamp image. *Frames 1–7*, and *8–16* show 2 figures moving in the posterior ectosylvian region. A third figure, in *frames 25–35*, moves in the acoustic projection region. This record shows the tendency of spontaneous figures to move within restricted areas at this anesthetic level.

new electrodes are activated and old ones recover; the mesa apparently shrinks and moves downward and to the right; it leaves the array at the lower right hand edge (electrode 1-5).

This spontaneous figure is typical of a large group recorded in this region (figs. 8 and 9). The variations of other figures from the above history will be presented later.

It suffices here to add that few if any of this type of figure at this deep level of anesthesia show relatively positive parts which move across either the middle or the posterior suprasylvian sulcus; despite the large peak amplitude of these forms, no spread across the sulcus is seen. Thus we can be fairly sure that dimming of a group of lamps signifies a localized figure in these cases (but not, presumably in other cases, fig. 7).

A more crowded series of spontaneous figures occurs at a much lighter level of anesthesia (fig. 6). At this level the forms occur more frequently and in more regions and travel more rapidly. Most of the time the array sees at least one and sometimes two figures. To the eye, watching the lamp array, there is a dramatic continual entering and exiting of lively figures, in contrast to the rather sluggish show of single figures at the deeper level (fig. 5).

Certain ambiguities in interpreting the extent of figures can occur at this relatively light level of anesthetic, at this electrode spacing, and at this camera speed. The simultaneous presence of more than one figure in the array at a time makes the boundary of any one figure doubtful; any active electrode in the region between two figures cannot be

assigned unequivocally to one or the other figure. A possibly coincidental bit of activity across a sulcus may place doubt in our judgment of the extent of a given figure.

For example, (*frame 1* of fig. 6) a single peak is developed at electrodes 3-4 and 2-4. By *frame 2*, either the peak has spread to 8 electrodes, or at least one other peak has moved in and apparently coalesced with the first. Since the camera is not running fast enough to show the transition from the small area of activity in *frame 1* to the large area of *frame 2*, we cannot tell whether or not another peak has moved into this region. For example, electrode 1-2 becomes active and yet it is across a sulcus (fig. 2). In 4 frames, *2–5*, lamp 1-2 may appear, by continuity of appearance, to belong to the figure starting in *frame 1*; it may or may not belong; with the present technique this case is equivocal.

At this light level, in a record about 10 seconds long (1280 frames), each electrode showed about equal numbers of 'ons' and 'offs.' This observation implies that all of this particular field is about equally active on an average taken over long time periods. Whether this activity may be considered as single figures traveling rapidly across the whole field or whether it is several figures dancing in small zones within the field is a moot point. Below, evidence will be presented that under deeper anesthesia, at least, spontaneous figures have definite regions in which they grow and travel; at this lighter level it is not possible to describe the regions so definitely.

Evoked Figures. In order to determine the typical form of the response figure, a series of 8 responses (selected from a consecutive group of 17 occurring in 17 seconds) is shown (fig. 7). The partial figures presented here are strikingly similar in all 8 responses from the frame labeled 15.6 msec through the 46.8-msec frame. This pattern is essentially that discussed above for the single response (fig. 4). Presumably this reproducibility stems from the rather constant conditions (anesthetic level and other physiological variables) existing during the short, 17-second interval of recording. In addition, the rate of change of the figures during the above phases is slow enough so that the recording cycle can pick up similar samples within similar intervals ($\pm$3.9 msec). The differences between the responses will now be discussed.

Spontaneous figures of large amplitude and of large area occur before *responses 6* and *7*. In spite of this activity, at 15.6 and at 23.4 msec, the responses are all very similar. However, in the frames at 7.8 msec, *responses 3* and *4* each show an additional phase attributable to the response. In *response 6*, in this phase it cannot be decided how much of the figure is due to the preceding spontaneous figure. *Response 3* shows a missing 5-5 image; *response 4*, a missing 5-5 plus a slightly enlarged 5-2 and 5-3 and a missing 5-5 in the preceding frame. One possible explanation for these features is that these are early phases of the fast-developing part of the response caught by correct phasing between the click occurrence and the camera cycle. If these data are looked at in this way, the active 5-5 is the first event after the click and the active 5-2 and 5-3 the second event after the click. Continuing this approach, the third event is a missing 5-4 (*response 4*, frame at 7.8 msec); the fourth, a missing 4-3 (*response 1*, frame at 15.6 msec); and the fifth, a missing 4-4 and 4-5 (*response 1*, frame at 15.6 msec). These five events thus lead to the pattern seen in the responses in the frames labeled 15.6 msec: brightened 5-2 and 5-3, missing 5-4, 5-5, 4-3, 4-4, and 4-5. In frame 23.4 msec this pattern is increased in amplitude without fundamental changes except those due to the differential amplifiers' action.

These events can be interpreted as follows: a relatively positive wave, the 'head' of the activity, possibly starting outside the array field, reaches 5-5 first, spreads to 5-4, then 4-4, and 4-5. A short interval after this head-wave reaches 5-5, a relatively surface negative wave reaches 5-2 and 5-3, possibly from a source outside the array to the left of these two electrodes. This second head-wave then reaches electrode 4-3 with its electrical sign reversed causing a missing image. (Such sign reversals in the acoustic region are described by Hawkins (27); since here we are interested in changes which signal active regions, it makes little difference whether the changes become relatively positive or negative).

Later, the head-wave penetrates to electrode 3-3 and still later to 3-4, in both cases

for a time of only about one frame cycle or less (frame at 31.2 msec, *response 2* and then *response 8*). However, this distance of travel is seen only in these two cases, neglecting those responses showing 60 cps artifact. In several responses of this series not shown here, 3-3 is seen to be reached in 31.2 msec, and 3-4 in 46.8 msec for an interval less than one frame cycle. This completes the building up phase of the evoked figure—the traveling head-wave.

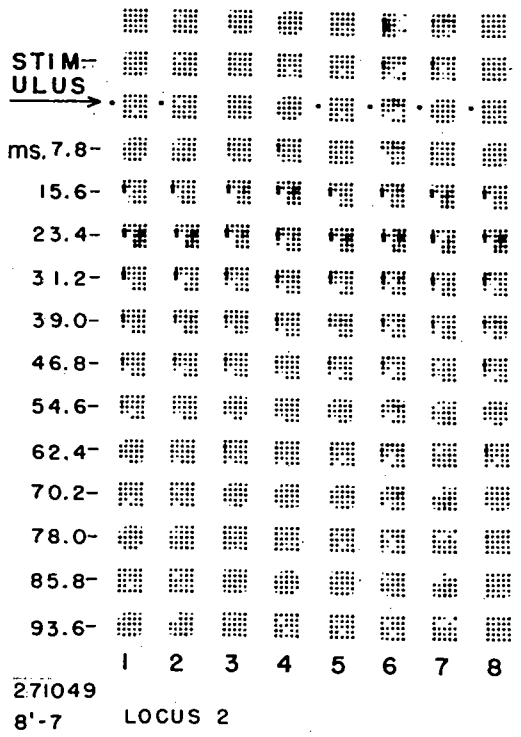

FIG. 7. Response forms to click stimuli at a deep anesthetic level. These sequences were in a continuous record of 17 responses to click stimuli occurring once per sec.; the responses are in the same order as that in which they occurred; 113 frames between each pair of responses are not shown. The numbers *1–8* at the bottom denote the number of each response. The click occurred during the frame shown by the arrow that is either during the signal light image to the left of this frame (*responses 1, 2, 5, 6, 7* and *8*) or between this frame and the preceding one (missing signal light, *responses 3* and *4*). The scale on the left shows the approximate number of msec (±3.9 msec) after the stimulus that each frame occurs. A large spontaneous figure can be seen in *sequence 6* before, during, and after the response. Smaller spontaneous forms are present in *sequences 7* and *8*; still smaller ones are in *sequences 2, 4* and *5*. In *responses 1* and *5*, an artifact of 60 cps can be seen in lamp 3–4. *Response 5* has been shown enlarged (fig. 4).

In the interim, the 'tail' of the activity has appeared at electrode 5-4 (returning image in frame at 23.4 msec, *response 4*; frame at 31.2 msec, *responses 3, 4, 6,* and *7*; frame at 39.0 msec, *response 1*; frame at 46.8 msec, *responses 2* and *5*). This tail-wave may strike 4-3 with 5-4 (frame at 31.2 msec, *responses 3, 4,* and *6*), or before 5-4 (frame at 31.2 msec, *responses 1* and *5*; frame at 39.0 msec, *response 2*) or after 5-4 (frame at 46.8 msec, *response 7*). (This latter case and that of *response 6* is doubtful; the activity after that of 5-4 in the sequence is probably due to the fact that a spontaneous figure is present before *responses 6* and *7* begin; this may cause either a change in the mean potential surface (which we cannot detect) on which the response appears or a modified pattern of excitability in this region).

In summary, the present view of the typical evoked figure in this region in this cat is as follows: there are at least two origins which fire first after the arrival of the afferent volley at the cortex, a dorsal and ventral one. Separate head-waves start from these loci, spreading out until they join as a single wave posteriorly; this is the relatively rapidly traveling part of the figure. Within our limits of experimental error, the velocity of this head-wave can be estimated as about one m/sec. Traveling 2 or 3 mm posteriorly, this wave slows down to 0.1 m/sec. and penetrates farther posteriorly into the posterior ectosylvian gyrus (electrodes 3-3 and 3-4). Thus a large region becomes active and stays active until a tail-wave starts moving out of the same region at about 0.1 m/sec. (More detailed results of analyses of these figures and those of another cat are given in a later paper).

Spontaneous Figures. In order to show the variations occurring in the forms of spontaneous figures, a series of 27 slow, spontaneous figures occurring during a period of 25 seconds free of intentional stimuli are presented (figs. 8 and 9). The level of anesthesia is slightly less than that for the evoked figures (fig. 7). At this level, large figures appear, on the average, about once/sec. and stay in the array up to a maximum time of about 200

msec. While in the array field, all of these forms grow in area and travel over the cortex; none have been seen which grow and die in place without traveling. In general, these figures are less restricted, less regular, and more fluid in their origins and subsequent behavior than are the responses.

These figures have positive and negative features: the positive peaks are the most prominent and constant feature of their structure. In the following discussion attention will be concentrated on these peaks, leaving the hollows for a later paper covering the full range of amplitudes of these forms.

The 27 large figures (figs. 8 and 9) on analysis show the following behavior: *a*) Origins, or zones of entry: one or more of the following 10 electrodes were at the place of origin or of entry for the number of forms given in parentheses after the electrode number (the order chosen is that of decreasing frequency of occurrence): 2-3 (11), 4-5 (11), 3-4 (8), 3-5 (8), 2-4 (4), 2-5 (4), 1-5 (3), 1-3 (2), 4-4 (2), 5-5 (2). *b*) Zones of traverse: the following 15 electrodes were touched at least once by the following numbers of figures: 1-5 (23), 2-3 (21), 2-4 (25), 2-5 (24), 3-3 (22), 3-4 (26), 3-5 (23), 4-5 (26), 5-5 (16), 4-4 (12), 1-4 (6), 1-3 (5), 5-4 (3), 4-3 (2), 5-3 (1). *c*) Zones of exit: one or more of the following 7 electrodes were the last to recover from the following numbers of forms: 3-5 (9), 1-5 (8), 2-5 (7), 4-5 (6), 5-5 (4), 3-4 (3), 2-4 (3). *d*) None of these figures touch upon the two top rows of electrodes.

In summary, the most frequent behavior is as follows: the figures originate, or else enter the array, in a narrow zone including 4 electrodes and extending from electrode 4-5 to 2-3, including electrodes 3-4 and 3-5; they expand and travel over a region touched by 8 electrodes (1-5, 2-3, 2-4, 2-5, 3-3, 3-4, 3-5, and 4-5); and they leave the array at its lower edge at 4 electrodes (electrodes 4-5, 3-5, 2-5, and 1-5).

It can be seen that these figures, like the evoked ones, are relatively surface-positive 'hills' (missing images) and negative 'valleys' (figs. 8 and 9). From the original records it can be seen that these hills start as low, small structures and gradually increase their height and area; while growing, the sides tend to remain steep, creating an appearance of a traveling 'mesa.'

Relating these results to the cortical surface (fig. 2), it can be seen that all of the electrodes most frequently touched by these forms are in the posterior ectosylvian gyrus, with one exception, no. 4-5, near the anterior edge of the posterior ectosylvian sulcus (ESP). (Presumably, this means that these figures continue on the anterior side of ESP in this region; additional evidence of such a crossing is seen in the participation of electrode 5-5 in 16 of the figures at least once during their growth and travel in the array). These forms originate, or enter this array, in a band extending from around the upper end of the posterior ectosylvian sulcus dorsally and posteriorly toward the middle suprasylvian sulcus (SSM) about 2 mm from its junction with the posterior suprasylvian sulcus. From this band of origin, they travel, or spread, over the posterior ectosylvian gyrus, and, finally, move ventrally down along this gyrus out of our observation region. In none of the sequences do these figures move across the middle suprasylvian sulcus.

A more detailed analysis of the velocities and directions of travel of the action and of the recovery waves, the durations of activity at each electrode, and the amplitudes of these spontaneous forms will be given in a later paper; it suffices for our present purposes to give the above evidence of their existence.

DISCUSSION

In this introductory paper, some evidence is presented that responses and spontaneous activity in the cortex have an organized aspect heretofore not demonstrated in electrophysiology. The results given above show, for the first time, that stimulation of an end-organ gives rise to certain kinds of specific complex traveling figures in and around the cortical projection area. In addition, it is demonstrated that the spontaneous activity consists of figures that grow, travel, and die away on the surface (and presumably, in the depths) of the cortex. This latter finding is new but possibly not unexpected; there is no previous literature known to the author which demonstrated that the spontaneous

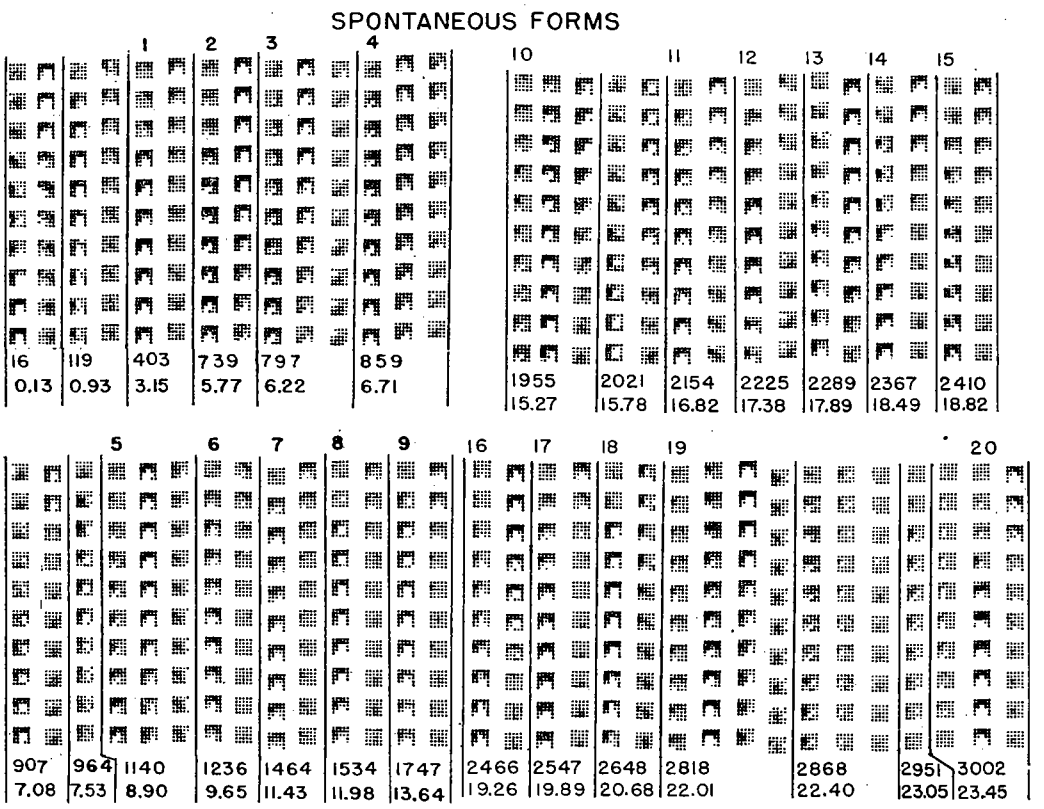

FIG. 8 (*left*). Large, slow spontaneous figures in the posterior ectosylvian region. These records (and fig. 9) are selected parts of a continuous record of a duration of 25 sec. No clicks were given during this period. Those parts of the long record (3200 frames) were selected which showed figures of large amplitude and of large area. (Forms which were smaller than these were sometimes seen in the relatively quiet records between these forms.) An inkwriter record of the activity at one electrode shows each of these figures to be a predominantly surface-positive, single wave like ones commonly seen on the cortex under fairly deep barbiturate anesthesia. The top row of numbers (*1–9*, fig. 8, and *10–20*, fig. 9) refer to 20 forms which are analyzed in a later paper. Each selected sequence of frames has a beginning frame number denoting its position in the series of 3200 frames; this number is in the first row at the bottom of each sequence. The corresponding time of occurrence of the beginning frame is given (in seconds after an arbitrary zero time) by the numbers in the lowest row. For example, the sixth sequence is no. *4* in the analyzed group of 20 and begins at *frame 859* which is 6.71 sec. after the beginning; 30 frames are shown of this form's build-up and travel; it ends on *frame 888*. A frame-by-frame analysis of each lamp in all frames shows that these figures most frequently enter the array at electrodes 4-5 and 3-4, or 1-4 and 1-5 (figure 2); they reach a maximum area of about 20 mm.^{2}, and leave the array at electrodes 4-5, 3-5, 2-5, and 1-5. (see text).

FIG. 9 (*right*). Spontaneous figures (continued). This figure is a continuation of the previous series (fig. 8).

'waves' (seen with single electrodes) are parts of figures.

The meanings of electrical 'waves' and 'figures' in terms of electrical mechanisms, neuronal activity, neuronal structure, and physiological function are, as yet, indefinite; some present views on this question are given below.

Previous records by others using graphical recording, (1–6, 8, 10–12, 13, 15 and 27) show many of the characteristics of cortical responses and other waves under anesthesia. The above evidence in the cat's acoustic cortex shows that these waves are parts of surface figures varying with place as well as time. (Additional evidence has been obtained to show that such waves are parts of figures in the anesthetized visual cortex of rabbits and of cats and in unanesthetized sensorimotor cortex of monkeys; these data are to be reported elsewhere). To date, within our limits of temporal and spatial resolutions, we

have found no large-amplitude waves which were not parts of organized figures; we have seen no instances of large waves appearing at one electrode without later participation by many others. This result suggests that all cortical waves may be parts of 3-dimensional spatial organizations varying with time and place.

Electrical figures as seen at the cortical surface can be the result of many different neuronal processes. Out of the many possible processes, three outstanding ones are considered to explain the figures of the responses and of the spontaneous activity seen in our results. A volley from some deeper structure may arrive as a compact group of impulses at one small zone of cortex and initiate a purely cortical figure growing and traveling by purely cortical laws of neuronal connection, of excitibility relations, and of timing of impulses. Or, by temporal dispersion arising from subcortical fiber and nuclear delays, a volley may arrive at many zones of cortex as a preformed figure exciting the different areas and the different strata of cortex non-simultaneously; this figure excites a new figure varying in time and place by purely cortical laws. Or, a figure may enter a subcortical nucleus which has intimate feedback connections with the observed cortex and the generation of the cortical figure be a function of the activities traveling between, and in, both nucleus and cortex.

Though, at present it cannot be decided which of the three mechanisms predominates, if any single one does, there is evidence from the literature that all three exist. Adrian (28) showed, and Burns (29) confirmed and extended the observations, that stimulation of a small cortical zone can give rise to two types of response, a decrementing surface negative one extending a few millimeters over the surface, and a non-decrementing surface positive one traveling without decrement to the edges of the observed region. Further, Burns demonstrated that a small bridge of cortical tissue connecting an isolated slab of cortex to the rest of the brain allowed spontaneous waves to enter and move across the whole extent of the isolated region. These data suggest that if activity arrives at a small zone of cortex, a typically cortical figure of activity can be generated and will spread to other regions.

Ades and Brookhart (30) have shown records of the electrical responses to a click stimulus along the acoustic pathway; their records show these responses have an increasing latency and an increasing duration as the activities come up to cortex from the cochlear nucleus. They show that either one of two mid-line commissures are adequate to excite fully the cortex at a particular site. These results suggest that temporal dispersion and lateral spread, and, possibly, a fast feedback are operating between the geniculate and the cortex.

Chang (31) presents presumptive evidence for a relatively slowly-operating feedback system between geniculate and cortex in the acoustic region. The evidence centers on multiple discharges and their time relations in an excitibility cycle for the geniculate-cortex part of the acoustic system.

More specifically, the response figures shown above are probably at first compact bundles of impulses arriving in the early part of the response at the zone first fired in cortex and, later, spread in cortex by cortical connections and by feedback with geniculate to wider regions. We have shown (22) that as the repetition frequency of the clicks is increased from 1/sec. to about 10/sec. the amplitude of the response of the initially responding part of cortex is not changed; but that the amplitude of response of cortical zones farther away decreases with increased frequency. Probably the feedback paths and the intracortical connections have long refractory periods (31) and are distributed in the primary projection area in a grossly radial fashion around the initial response zone.

Some evidence that feedback connections enter into the spontaneous activity of projection (but not in non-projection) nuclei is presented by Morison, Finley and Lothrop (32). They found an interdependent fast activity between thalamic projection nuclei and cortex which was depressed in the thalamus by cutting the connections with the cortex; however, the 5–10/sec. bursts of spontaneous activity in the internal medullary lamina which were contemporaneous with bursts in non-projective cortex were not

depressed by cutting cortical connections. These findings suggest that feedback is not an essential process in the spontaneous figures we showed above in the posterior ectosylvian gyrus; these data further suggest that these spontaneous figures may be generated by other figures in deeper structures traveling in advance of the cortical figures.

SUMMARY

Using apparatus which records the electrical activity from 25 implanted electrodes on the cerebral cortex, definite patterns distributed in space and in time were found and are called "figures." Examples of figures evoked in the anesthetized auditory cortex by click stimuli and of a special type of spontaneous figure found in the posterior ectosylvian region are presented. The stereotyped nature and courses of the response figures are shown; the variable nature and courses of the spontaneous figures are also demonstrated.

The author wishes to express his thanks to Professors Detlev W. Bronk and Britton Chance for fostering the growth of this research; to the Coyle Foundation for a grant (1946) which made the initiation of the research possible; and to the extramural grants program of the National Institutes of Health of the U. S. Public Health Service for continued support (1949 through 1953). The electronic designs were carried out largely by John P. Hervey, and modified by John Busser. The author is particularly indebted to Dr. William W. Chambers for his aid and his encouragement; to Ruth B. Cherry for her help with the analyses of records, and to many colleagues past and present in the Johnson Foundation for helpful discussions.

REFERENCES

1. BARTLEY, S. H. AND G. H. BISHOP. *Am. J. Physiol.* 103: 159, 1933.
2. GERARD, R. W., W. H. MARSHALL AND L. J. SAUL. *Arch. Neurol. & Psychiat.* 36: 675, 1936.
3. BISHOP, G. H. AND J. L. O'LEARY. *Am. J. Physiol.* 117: 292, 1936.
4. MARSHALL, W. H., C. N. WOOLSEY AND P. BARD. *J. Neurophysiol.*, 4: 1, 1941.
5. ADRIAN, E. D. *J. Physiol.* 100: 159, 1941.
6. WOOLSEY, C. N., W. H. MARSHALL AND P. BARD. *Bull. Johns Hopkins Hosp.* 70: 399, 1942.
7. TALBOT, S. A. AND W. H. MARSHALL. *Am. J. Ophth.* 24: 1255, 1941.
8. WOOLSEY, C. N. AND E. M. WALZL. *Bull. Johns Hopkins Hosp.* 71: 315, 1942.
9. TUNTURI, A. R. *Am. J. Physiol.* 141: 397, 1944.
10. ADRIAN, E. D. AND B. H. C. MATTHEWS. *J. Physiol.* 81: 440, 1934.
11. GARVIN, J. S. AND L. V. AMADOR. *J. Neurophysiol.* 12: 425, 1949.
12. FORBES, A. AND B. R. MORISON. *J. Neurophysiol.* 2: 112, 1939.
13. BEECHER, H. K. AND F. K. MCDONOUGH. *J. Neurophysiol.* 2: 289, 1939.
14. GIBBS, F. A., D. WILLIAMS AND E. L. GIBBS. *J. Neurophysiol.* 3: 49, 1940.
15. ADRIAN, E. D. AND K. YAMAGIWA. *Brain* 58: 323, 1935.
16. GOLDMAN, S., W. F. SANTELMANN, JR., W. E. VIVIAN AND D. GOLDMAN. *Science* 109: 524, 1949.
17. LILLY, J. C. *Electroencephalog. & Clin. Neurophysiol.* 2: 358, 1950.
18. LILLY, J. C. AND W. W. CHAMBERS. *Federation Proc.* 9: 78, 1950.
19. LILLY, J. C. Proceedings, 18th International Physiol. Congress, Copenhagen, 1950, p. 340.
20. LILLY, J. C. *Federation Proc.* 10: 84, 1951.
21. LILLY, J. C. AND R. CHERRY. *Am. J. Physiol.* 167: 806, 1951.
22. LILLY, J. C. *1950 Milbank Mem. Fund Symposium on the Biol. Aspects of Mental Health and Disease. New York*: P. Hoeber, 1952.
23. LILLY, J. C. The 1949 AIEE-IRE Conference on Electronics in Nucleonics and Medicine (S-33), Amer. Inst. of Electr. Eng., 33 W. 39th St., N. Y., 1950, 37–43.
24. CLARK, S. L. AND J. W. WARD. *Arch. Neurol. & Psychiat.*, 38: 927, 1937.
25. BERANEK, L. L. *Acoustic measurements.* New York: Wiley, 1949.
26. VON BÉKÉSY, G. *J. Acoust. Soc. Am.* 21: 245, 1949.
27. HAWKINS, J. E., JR. *Am. J. Physiol.* 133: 321, 1941.
28. ADRIAN, E. D. *J. Physiol.* 88: 127, 1936.
29. BURNS, B. D. *J. Physiol.* 112: 156, 1951.
30. ADES, H. W. AND J. M. BROOKHART. *J. Neurophysiol.* 13: 189, 1950.
31. CHANG, H. T. *J. Neurophysiol.* 13: 235, 1950.
32. MORISON, R. S., K. H. FINLEY AND G. N. LOTHROP. *J. Neurophysiol.* 6: 243, 1943.