

2

HIGH FREQUENCY COMPONENTS IN BRAIN WAVE ACTIVITY¹

JAN TRABKA, M.D.

Neurosurgical Clinic, Medical Academy, Krakow (Poland)

(Received for publication: February 13, 1961)

INTRODUCTION

The first report concerning EEG potentials at higher frequencies than those usually examined in clinical practice was published by Gozzano (1935). The next work was done by Lion *et al.* (1950), who found potentials of amplitudes up to 70 μ V (peak to peak), ranging between 200–1400 c/sec in human subjects, by using surface electrodes. Renshaw *et al.* (1940), with the aid of bare silver wire, several tenths of a millimeter in diameter, inserted 1 mm into the hippocampus, observed components that had durations as short as 10 msec. In this paper interest will be directed towards the 200–500 c/sec frequency spectrum of the electrical activity of the brain. In the first part, greatest emphasis will be placed on the experimental conditions that have made possible the detection of these components. The second part will be a discussion of results obtained by the application of computer methods to the processing of pertinent data. It was hoped that computer methods, mainly autocorrelation analysis, could be used to throw some light on the nature of these faster frequencies of the brain output.

Granted that synchronization of brain potentials may result in the appearance of oscillations over a wide range of frequencies, it would seem that the range of about 250 c/sec might be especially represented because of some observed properties of the electrical time constants of nerve tissue. Thus, a time constant of 4 msec has been calculated for the motor neuron by Rall (1957). (For frequencies much higher than this, it appears likely that the shunting effect of brain tissue would make detection much more difficult,

or impossible, unless microelectrodes are employed.)

MATERIALS AND METHODS

Experiments were performed on five cats with chronically implanted electrodes, under normal conditions and also when the animals were under barbiturate narcosis (intraperitoneal injection of pentobarbital: 40 mg/kg). The gross electrodes were made of stainless steel wire 300 μ in diameter, covered with three coats of Epoxylite insulator, and terminating in a loop. The insulating material was removed from the tip of the loop. All electrodes were bipolar with approximately 2 mm between points. With the aid of a stereotaxic instrument, the electrodes were placed subdurally, the pia being intact. (Electrode positions have not yet been confirmed observationally as the animals are still living.)

The impedance properties of the electrodes and the input to the cathode follower, including cables, were measured in two ways by an impedance bridge. First, measurements were made with the implanted electrodes and the cables connected. Using a sinusoidal 1 V signal at 15 kc the impedance showed a wide variation of 0.6–5.0 k Ω . The capacitance varied between 1.5 m μ F and 4.0 m μ F. The second step was to measure the electrical constants of the electrodes alone. The impedance of the electrodes, immersed in Ringer's solution, was measured in a similar way, using a sine-wave of 200–500 c/sec. The value of the resistance remained at approximately 10.0 k Ω while the capacitance varied between 40 m μ F at 500 c/sec and 50 m μ F at 200 c/sec.

The input capacitance of the cathode follower seemed to be negligible; it equalled 150 μ μ F in the push-pull connection.

Accepting even the most unfavorable values of resistance and capacitance, the frequency

¹ This work was carried out in Dr. Mary A. B. Brazier's Laboratory at the Massachusetts General Hospital, Boston, U.S.A., during the tenure of a Fellowship from the Rockefeller Foundation.

response of the recording system extended up to 15 kc/sec, and was therefore quite adequate for the purposes of the experiments. The brain signals, recorded bipolarly, after passing through the cathode follower, were delivered to an a.c. preamplifier (Grass P5). In order to get the full amplitude frequency response, ranging between 200 and 500 c/sec, the preamplifiers had to be set a 35 c/sec for the lower band limit, and 2000 c/sec for the upper. An upper frequency limit of 2000 c/sec gave an inherent maximum noise level of 6.0 μ V (peak-to-peak), measured with a short circuit input and with maximum amplification. In that case, the output from the P5 contained a great number of unwanted oscillations below 200 c/sec, which though distorted, were of high enough amplitude to prevail in the record and mask the frequencies that were being looked for. A Variable Electronic Filter (Spencer-Kennedy, model #302), was therefore used to select the desired frequency band of 200–500 c/sec.

The balanced output of the P5 was passed through the filter and connected to a dual-beam cathode ray oscillograph. The calibrating sine-wave was 200 c/sec. The display on the oscillographic screen was photographed by a Grass Kymograph Camera using Kodak Linograph Ortho S.P. 763 film. The film speed was 500 mm/sec. If there arose a need for three traces on the oscilloscope screen, an electronic switch was used. In some experiments, a 16 channel Grass EEG machine was used to make a simultaneous ink record of the narrower pass-band that this instrument permits. A Grass Photo-Stimulator was used to produce flashes at a rate of 1/5 sec and Tektronix Waveform Generators (Type 162) and Pulse Generators (Type 161) were used to produce clicks at the same rate. A Grason-Stadler Noise Generator was used to give the sound of a white noise background.

Further study of some recordings was carried out in order to determine whether or not in the frequency range of 200–500 c/sec there exists some intrinsic, steady and persistent rhythm in the electrical activity of the brain, which cannot be detected in the raw trace of the high frequency components (HFC). This problem of isolating an intrinsic rhythm hidden in the seemingly random fluctuations of the EEG trace has been considered

previously in the frequency band generally used in EEG (Brazier and Casby 1952; Brazier and Barlow 1956; Brazier 1960a). Autocorrelation analysis of EEG recordings was carried out by the above workers, and was also used for the present investigation. In brief, autocorrelation provides a method for comparing the HFC with itself displaced in time, the comparison being made at a large number of delay periods. Thus, if there is a repetitive event in the HFC, the correlation of the HFC recording with itself will be strongly positive when it lags itself by a delay time equal to the repeating period of this event, and at all multiples of this period. By this means, it is possible to detect repetitive activity from a randomly fluctuating component even though the latter, relatively speaking, is of sufficiently high amplitude to obscure the repetitive activity in the unanalyzed trace of the HFC. If no repetitive component is present, the autocorrelation will not show recurring positive peaks.

The theoretical basis for examining brain oscillations in this statistical manner, *i.e.*, consideration of them as "time series", has been explained by Brazier (1960 a, b) and Barlow (1959). The electronic details of the correlator employed for the analysis of the HFC recordings have been discussed by Barlow and Brown (1955).

For autocorrelation analysis, the brain oscillations within the selected frequency band of 200–500 c/sec, after preliminary amplification (Grass P-5) were further amplified by 100 times (Hewlett-Packard Amplifier Model 450A) prior to their being recorded onto magnetic tape (Ampex Frequency-Modulated tape recorder).

Several parameters were required for processing the HFC data:

1. The recording speed of the FM magnetic tape was 6"/sec; the tape was played back at 30"/sec; then the signals were re-recorded onto a loop of magnetic tape at 30"/sec. During correlation, the tape was played back at a speed of 60"/sec. These various recording and playback speeds resulted in a total speed-up factor of 10.

2. The incremental delay time (τ) for each step was 0.25 msec.

3. The maximal delay time (τ max) was 50–60 msec.

4. The sample length (T) of the HFC records that were processed was 45 sec — the maximum

that could be used due to technical limitations of the correlator for the processing of these particular recordings.

RESULTS

I. Analysis of photographic recordings

The resting records of the fast frequency components (HFC) of the visual, auditory and sensorimotor cortical areas appeared similar (Fig. 1). They were composed of bursts of 200–300 c/sec oscillations of 5–20 μ V amplitude and varying duration. They did not form any recognizable patterns and were mixed randomly with a much lesser amount of faster rhythms in the 300–400 c/sec range with amplitudes of 10–15 μ V that occurred mostly in short trains. This clear-

cut prevalence of the slower potentials in the record appeared to be the feature that allowed the brain output to be distinguished from that of the white noise generator which had an equal distribution of each particular frequency (Fig. 2). It would be valuable to confirm this impression, gained by visual inspection, by making an amplitude distribution histogram and comparing it with the Gaussian curve, as was done by Lion and Winter (1953). These slower oscillations, revealed in the HFC record, were irregular in shape and occasionally had the faster rhythms superimposed on them. The authenticity of the HFC in the brain output as a real biological phenomenon was checked by the following tests:

A. Simultaneous and parallel recording from the

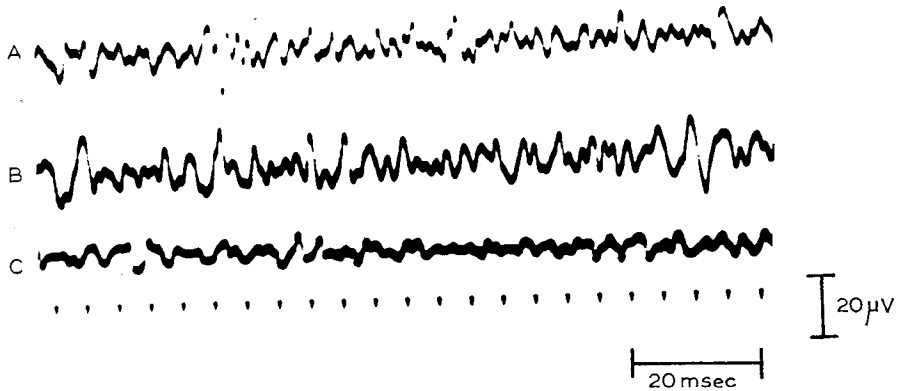


Fig. 1

High frequency components: *A*: recorded from the left visual cortex (cat #410); *B*: recorded from the left auditory cortex (cat #410); *C*: recorded from the left sensorimotor cortex (cat #417).

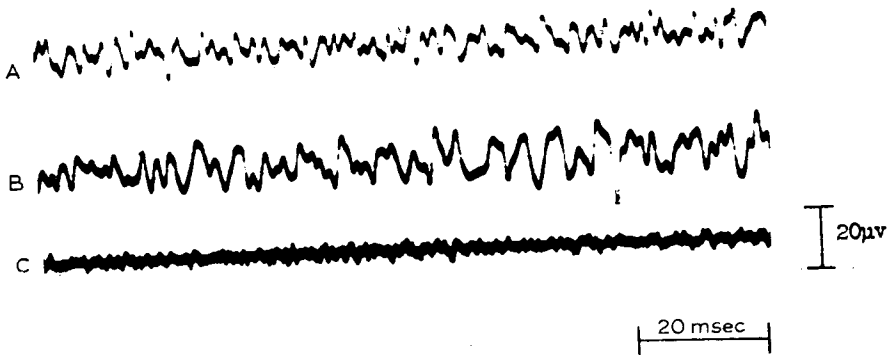


Fig. 2

High frequency components: *A*: recorded from the left visual cortex (cat #410); *B*: recorded from the left auditory cortex (cat #410); *C*: output from the white noise generator through filters with a frequency bandwidth of 200–500 c/sec. (Although the amplitude of the filtered noise here is rather low, its difference in frequency content from that of traces *A* and *B* is nonetheless evident.)

auxiliary circuit, the so-called "dummy subject".

- B. Observations of the HFC behavior under conditions of pentobarbital (nembutal) narcosis.
- C. Examination of the HFC when influenced by external stimuli such as flashes, clicks and claps.
- D. Relation between certain events in the HFC record with phenomena revealed in the concurrently running EEG traces.

These four categories are elaborated below.

that of the signals picked up from the "dummy". The oscillations from the auxiliary circuit were more regular and usually about 500 c/sec.

B. In the experiments performed while the cats were barbiturized, considerable changes were observed in the general pattern of the HFC. For controls, an EEG ink-writer trace was kept running, simultaneously with the HFC record, as changes in this lower frequency band are familiar guides to depth of narcosis. The auxiliary circuit was also used at times for comparison.

Four characteristic samples of the HFC

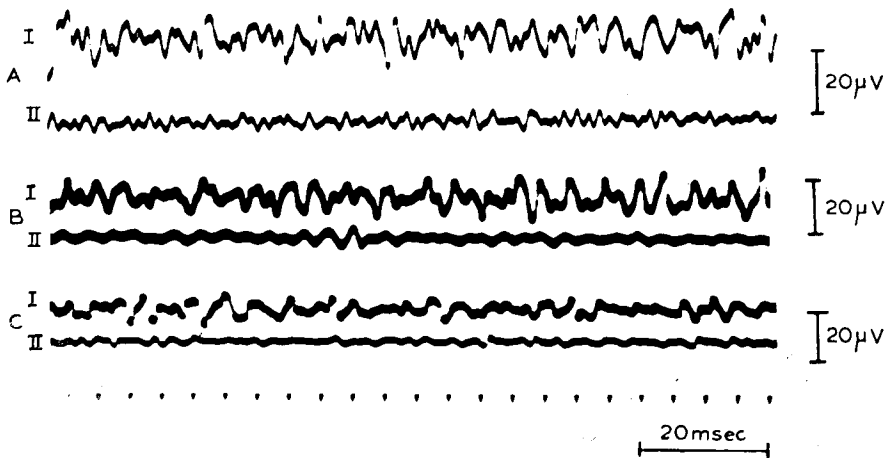


Fig. 3

High frequency components: *A*: I. Recorded from the left auditory cortex (cat #410); II. Recorded from a dummy subject (10 k Ω) through filters with a frequency bandwidth of 200–500 c/sec. *B*: I. Recorded from the left visual cortex (cat #414); II. Same as *A* II. *C*: I. Recorded from the left sensorimotor cortex (cat #417); II. Same as *A* II.

A. Lest one be misled by external electromagnetic disturbances, an auxiliary circuit was built up and situated close to the animals examined. Moreover, the electronic qualities of the input circuit were reproduced as nearly as possible, by using the same gauge insulated wire, the same length of cable and a 10 k Ω resistor as the "dummy". As a control test, a voltage-time graph of this auxiliary circuit was displayed simultaneously with the HFC record (Fig. 3). Filter settings and all gains were the same for both circuits. This test revealed the remarkable difference in amplitude and frequency distribution between the "dummy" record and that from the live subject. The amplitude of the HFC of the cats was three to five times greater than

record, made during different stages of narcosis will be discussed below (see Fig. 4A and B).

1. Shortly after drug administration (about 7 min), the slower oscillations of the selected frequency range (200–300 c/sec), usually the most remarkable in the unanesthetized preparations, disappeared, and concurrently with barbiturate a rhythm in the range of 400 c/sec became prevalent (Fig. 4A, B).

2. After a further 10 min lapse of time, while slow waves began to appear in the EEG the amplitude of the remaining fast rhythm decreased abruptly from 20 μ V to 5 μ V, close to the inherent noise level (Fig. 4B, C).

3. During later periods of narcosis (Fig. 4B, D), the HFC records did not undergo any further

change, and were in fact difficult to distinguish from the trace of the "dummy" (compare Fig. 3). The only differential feature was that on the background of the very much flattened HFC records one could still get some evoked response (Fig. 5, C).

C. Evoked responses to flashes and clicks

remarkable contrast with the background activity because of amplitudes as high as $50 \mu\text{V}$. They showed a great amount of polymorphism though in every case one could clearly discern the first component, the so-called "primary response", followed by a series of waves forming an oscillatory response (see Fig. 6).

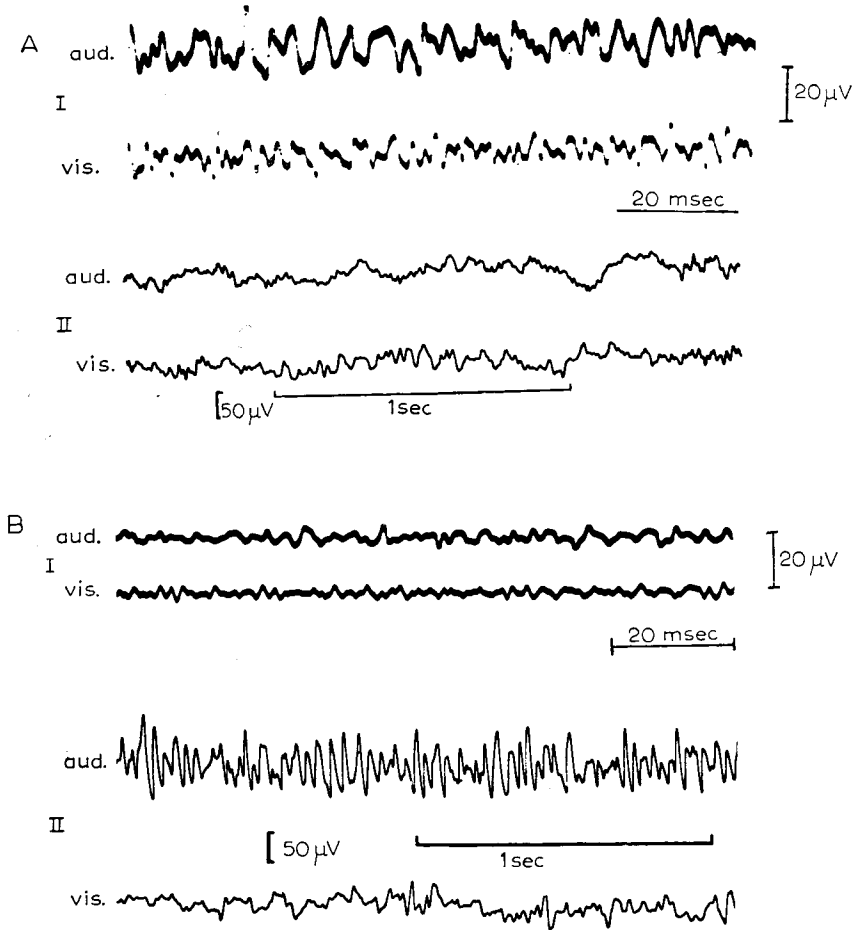


Fig. 4A

A: Resting record of: I. The faster components of the brain output (cat #410); II. The EEG taken simultaneously with A I.

B: 7 min after injection of nembutal: I. Same as A I; II. Same as A II.

were observed in the HFC records of the visual cortex and the auditory cortex. These activated HFC records were made under normal conditions and when the cats were in a state of pentobarbital narcosis.

1. In the records of the unanesthetized cats, the evoked responses, if detectable at all, were in

The "primary responses" consisted of polyphasic, usually triphasic, waveforms of rather consistent configuration. The latency of responses, evoked by flashes ranged from 9–11 msec. The oscillatory response consisted mainly of two or three serial waves lasting from 4–16 msec, at a frequency of about 250 c/sec. In the unanesthe-

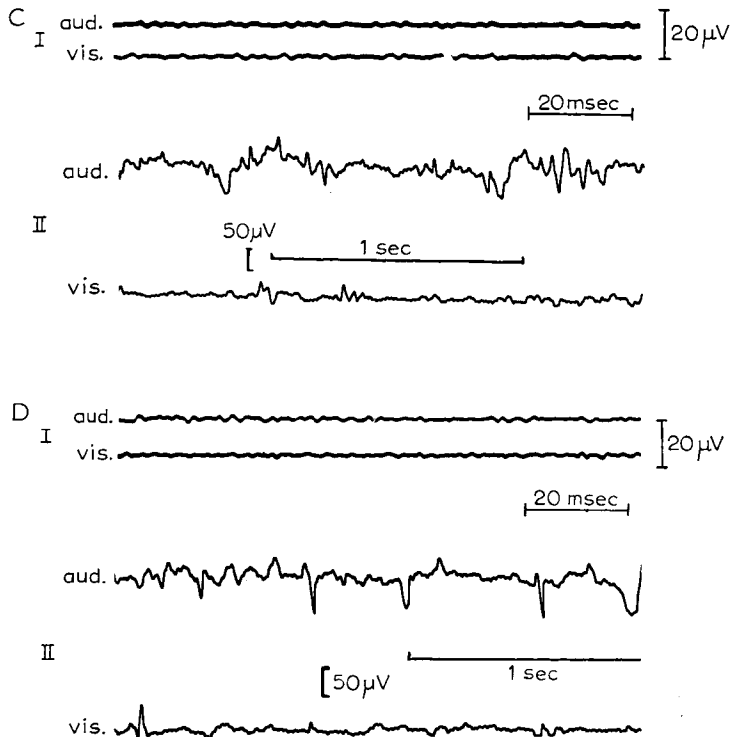


Fig. 4B

C: 17 min after injection of nembutal; record of: I. The faster components of the brain output (cat #410); II. The EEG taken simultaneously with C I.

D: 90 min after injection of nembutal: I. Same as C I; II. Same as C II.

tized state, only 72 per cent of the flashes evoked patterns of distinct change as picked up from the visual region. From the auditory projection responses to click were observed still less frequently. When detected, they demonstrated a latency of 12–14 msec.

Evoked brain potentials, induced by external stimulation were found mostly in the 200–300 c/sec band, and attempts to reveal them in a faster frequency band, of 300–500 c/sec, failed.

2. During pentobarbital narcosis, the evoked patterns showed considerable changes which particularly affected the “oscillatory response”, while the “primary responses” remained almost unaltered. Light pentobarbital anesthesia seemed greatly to improve conditions for the detection of these evoked phenomena: *i.e.*, (a) each click was followed by a prominent evoked pattern; (b) these patterns were more conspicuous in the records of the barbiturized cats than in those of the unanesthetized cats.

2 min after drug injection, evoked patterns were observed on the faster background activity

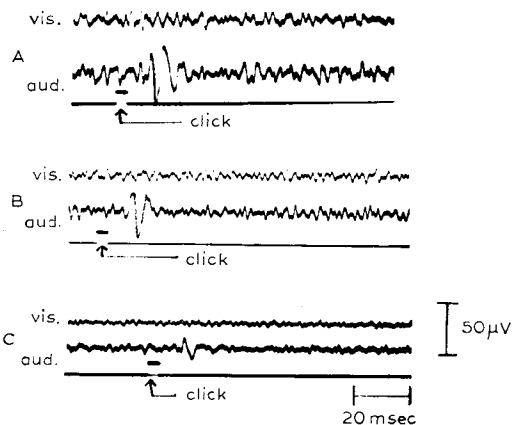


Fig. 5

Evoked responses recorded from the left auditory cortex of nembutalized cat (#410). A: 2 min after drug injection. B: 10 min after drug injection. C: 45 min after drug injection.

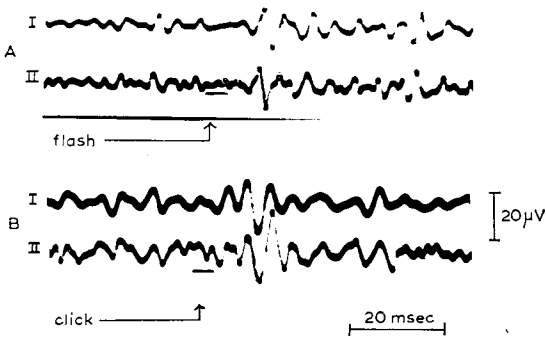


Fig. 6

A: Evoked response, from the left visual cortex of an unanesthetized cat (#414), passed through filters with a frequency bandwidth of: I. 200–300 c/sec; II. 200–500 c/sec.

B: Evoked response, from the left auditory cortex of an unanesthetized cat (#410), passed through filters with a frequency bandwidth of: I. 200–300 c/sec; II. 200–500 c/sec.

of lower amplitude, with the oscillatory responses having a very rhythmical series of potentials of 25 μ V amplitude and 12 msec duration (Fig. 5, *A*). During the course of narcosis these oscillations tended to disappear, and 10 min after injection, the regular series, previously consisting of 2–3 components, became reduced to a single, irregularly shaped wave following the primary response (Fig. 5, *B*). 45 min after narcosis had been induced, the after-discharges completely disappeared from the complex evoked pattern and there remained only a diphasic discharge as the primary response (Fig. 5, *C*).

3. In order to rule out the possibility of artifactual (instrumental) evoked responses, several test experiments were undertaken.

(*a*) The frequency response of the filter was examined in the following way: the output from a cortical area was passed, simultaneously, through different filter settings. With one filter set, as usual, at 200 c/sec as the lower limit and 500 c/sec as the upper, and the second filter set with a frequency band of 200–300 c/sec, the general shape of the evoked patterns, passed through these two filters looked quite similar (Fig. 6).

(*b*) The ringing effect of the filters was checked by a mock-up experiment. A square wave pulse (4.8 V peak-to-peak, 4 msec duration) was delivered to the external calibration circuit of the

preamplifier. The output of that circuit, presumably having approximately the same parameters as the brain signals, was passed through the filter with the same settings used for passing the brain oscillations from the auditory cortex of the barbiturized cat. The electrical pulses, designed to stimulate the evoked patterns, also drove the click generator. With this arrangement, the mock-up evoked patterns did not change with time, and they appeared simultaneously with the stimulus monitor marks (Fig. 7, *A* II) while the biological evoked responses had a definite latency and showed great variety in shape, depending on the depth of narcosis (compare Fig. 7, *A* I and Fig. 6, *B* II).

(*c*) In experiments in which the clicks were

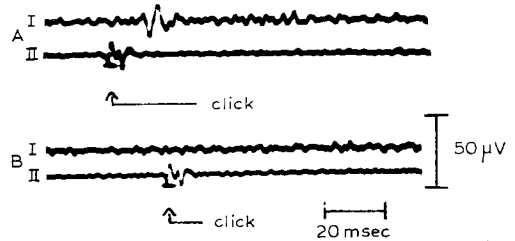


Fig. 7

A: I. Evoked response, to 1/sec click, recorded from the left auditory cortex of a nembutilized cat (#410). II. Artificial signal from the monitoring system.

B: Same as *A*, with exception that the click was masked by background noise.

completely masked by a loud background noise, there were no observable changes in the brain HFC record (compare *A* I and *B* I of Fig. 7). Similar results were obtained when the click intensity was put down to zero.

(*d*) Instead of using clicks, the animals — usually in anesthetized state — were stimulated by claps. These claps were used to trigger the Tektronix units via an amplified microphone pick-up, and at times, the trigger circuit was adjusted so that one clap stimulus produced two or three stimulus monitor marks in the record. If the described evoked patterns were really instrumental pick-up, then each stimulus monitor would cause some change in the HFC trace. That this did not occur is demonstrated in Fig. 8.

D. Finally, by comparing some bioelectrical phenomena running concurrently, but in two

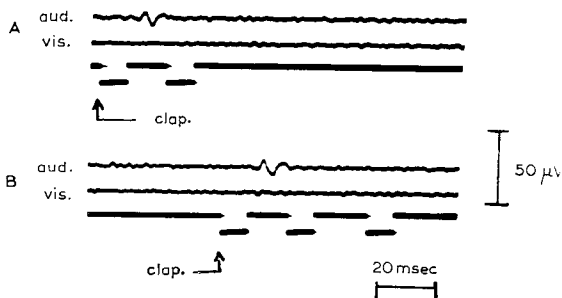


Fig. 8

Evoked responses, to randomly delivered claps, recorded from the left auditory cortex of a nembutalized cat (#410). A: One clap marked by two monitoring pulses. B: One clap marked by three monitoring pulses.

different time scales, (500 mm/sec for the HFC record, 60 mm/sec for the EEG), attempts were made to find the relation between the HFC trace and the EEG record (Fig. 9). The signals were taken, during click stimulation, from one pair of electrodes located in the auditory region. These experiments were done only when the cats were in a state of light narcosis because the evoked responses may be detected 100 per cent of the time under these conditions and reliable identification of features was made easier. Thus it appeared that the different shapes of the evoked responses, usually complex in the HFC record, corresponded with the uniform sharp discharges found in the EEG record.

II. Autocorrelation analysis of magnetic-tape recordings

Autocorrelograms made of the output of the white-noise generator were used as a basis for comparison with the HFC data (Fig. 10). Following the positive peak at zero delay, the autocorrelogram of the noise generator reached a negative peak at a delay of 1.25 msec, then it reached the second positive peak at a delay of about 4 msec. Finally, at a delay of about 6 msec, it returned to and stayed at the baseline value.

The autocorrelogram results of the HFC records may be divided into two groups:

1. Those that were somewhat similar in their behavior to the one for the noise generation that no persistent rhythm was suggested (these were obtained in the majority of cases (Fig. 11 and 12).
2. Those which showed some evidence of persistent rhythms (Fig. 13). The average

frequency of these rhythms, determined from the autocorrelograms, was between 240 and 280 c/sec. For large delays the value of the autocorrelation factor (i.e., the amplitude of the envelope of the pen excursions relative to that for zero delay) was from 1/5 to 1/2. Usually these oscillations in the correlogram were present out to the maximum delay (about 60 msec).

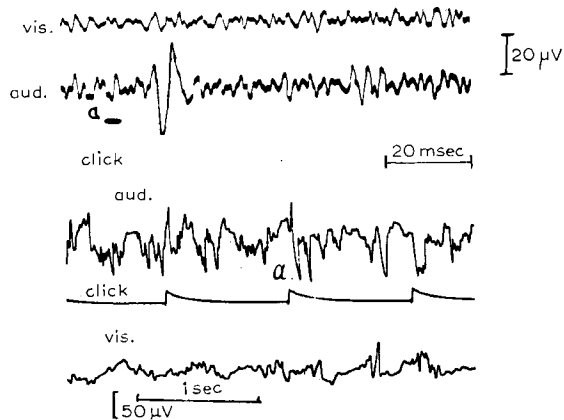


Fig. 9A

The evoked response (a) occurring simultaneously in the HFC and EEG records 10 min after nembutal administration.

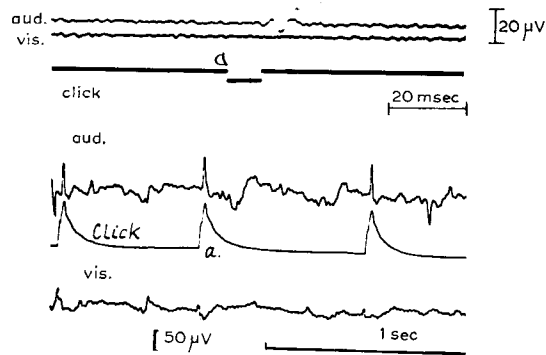


Fig. 9B

The evoked response (a) occurring simultaneously in the HFC and EEG records 30 min after nembutal administration.

In several instances, the possibility existed that the rhythms were artifacts deriving from pick-up of higher harmonics of the 60 c/sec frequency of the a.c. supply in the laboratory (Fig. 13). In fact, some autocorrelograms revealed clearly a component of 60 c/sec or of its harmonics; these results indicated that there had

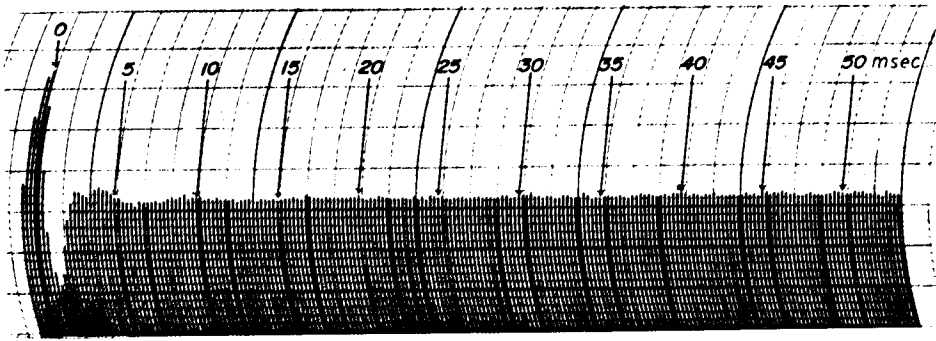


Fig. 10

Autocorrelogram of output of noise generator. The numbers in this and in the subsequent figures refer to the correlation time scale (*i.e.*, delay) in msec.

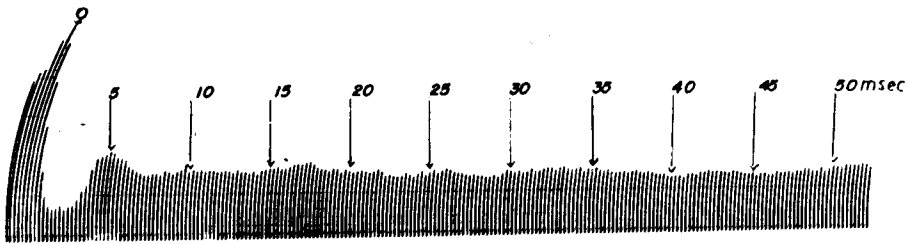


Fig. 11

Autocorrelogram of the left auditory cortex (cat #410).

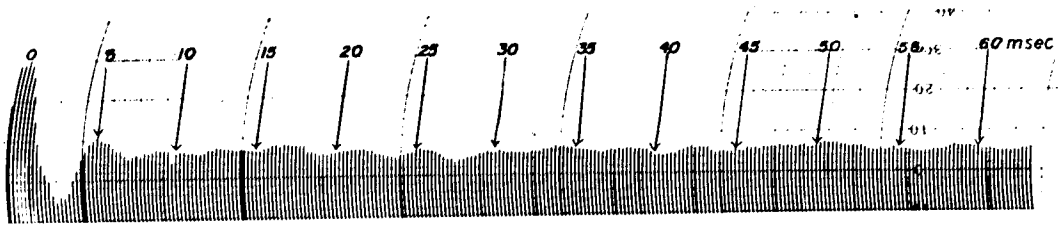


Fig. 12

Autocorrelogram of the left auditory cortex (cat # V-16).

been electrical pick-up of this nature in the physiological recordings (Fig. 14). In other instances, however, the rhythms could not be clearly attributed to 60 c/sec pick-up.

DISCUSSION

From the experimental results, one may infer that the HFC, especially those in the range of 200–300 c/sec are present in the brain output.

Leaving the problem of the origin of the HFC as quite unknown for the time being, one may assume that if the neuronal cells generate these fast frequency oscillations, their detection is not prevented by properties of the nervous tissue itself. Freygang and Landau (1955) found

the transverse resistance of the cortical layers to be $222\Omega/\text{cm}$, although several other experimental results showed the resistance values of particular structures of the nervous system to be much higher (Tasaki 1955; Coombs *et al.* 1955; Frank and Fuortes 1956). For the frequencies discussed here, brain tissue cannot be treated only as a homogeneous resistive medium, for the element of capacitance should also be considered. For example, the time constant value of 4 msec calculated for the motor-neuron by Rall (1957) may be quoted. Assuming that the time constants for the exponential decay of the membrane potential difference for other neurons measure much the same, then the potentials at about

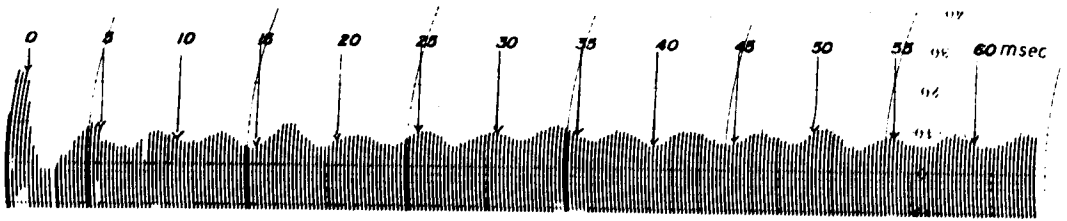


Fig. 13

Autocorrelogram of the left auditory cortex (cat # V-19). The recurrent positive peaks have an average separation of 5.2 msec, which corresponds to a frequency of 240 c/sec.

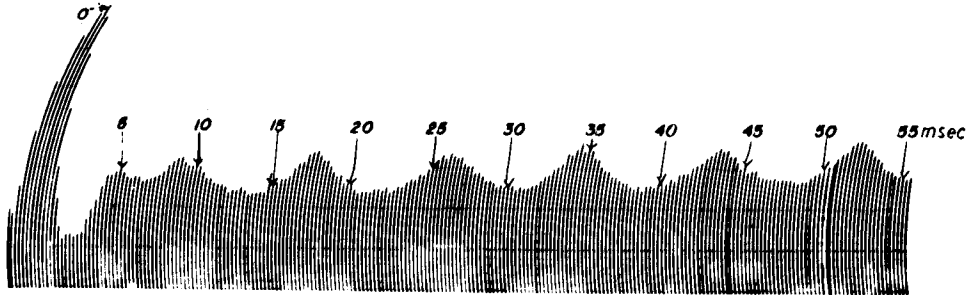


Fig. 14

Autocorrelogram showing prominent 60 c/sec pick-up. The recurring positive peaks have an average separation of 8.3 msec, corresponding to a frequency of 120 c/sec, the second harmonic of 60 c/sec.

250 c/sec are still possible. All the values adduced here are only relative because they are a dynamic characteristic, and are continuously changing in the course of time (Brown 1959¹).

As proof of the biological nature of the HFC four types of experiments were done; however, the main support for the brain as the source comes from the study of evoked responses which merits further discussion. First of all the time characteristics, localization, and amplitude distribution of the evoked patterns which appeared in the HFC records, cover the definition generally accepted in the EEG dimension (Chang 1959).

A. The responses have a definite latency for a given sensory system (12 msec for the auditory and 9–11 msec for the visual system).

B. They appear only in the circumscribed projection area of the cortex.

C. They have a definite pattern, easily reproducible under similar conditions, and consist of two major components, the primary response and the after-discharge, which behave differently in various stages of pentobarbital narcosis. The after-discharges observed in the

¹ BROWN, G. *Impedance variation within the lateral hypothalamus of the cat*. Unpublished.

HFC records appear to be more sensitive to the drug, therefore more changeable than the primary responses. After the transient period, during which time they are very prominent and show great variation in pattern, they show a gradual reduction in the number of rhythmic waves and in time duration, from 14 msec down to 4 msec, until they are entirely blocked. Meanwhile, the primary response continues; even after 1½ h they still follow the stimuli and have a steady, diphasic shape, lasting about 3–4 msec.

In the analysis of magnetic-tape recordings of the HFC by means of autocorrelation, the percentage of results that showed evidence of truly periodic rhythms was relatively small (about 10 percent), and hence it seems quite reasonable to think of these apparently positive results rather as artifacts. In fact, some autocorrelograms clearly revealed components of 60 c/sec or of its harmonics. These latter results indicated that there had been electrical pick-up of this nature in the physiological recordings (Fig. 14).

Thus the autocorrelation analysis did not show definite evidence of any steady, persistent, time-locked (*i.e.*, truly periodic) rhythms in the

frequency range of 200–500 c/sec. But this finding does not necessarily mean that the brain, with respect to its electrical activity, works in an entirely random fashion as does the noise generator. And, indeed, from a rational point of view, one may claim that all biological electrical sources have some organized, ordered way in their operation. The negative results may mean that the frequency range examined was not the appropriate one, or perhaps much longer recordings than 45 sec should be examined in order to detect any persistent rhythm of the cortex.

The existence of these faster frequency components calls for further and deeper investigation, and stronger confirmation, as they may prove to be of great importance in frequency analysis of brain output. They may also serve as a bridge between the vast knowledge of the slower oscillations (0.5–30 c/sec) and that of the single unit firings.

SUMMARY AND CONCLUSIONS

The bioelectrical activity of the brain in the frequency range 200–500 c/sec (for which the term high-frequency components or HFC is used) has been examined from recordings from five cats with chronically implanted subdural electrodes. The special techniques for recording of this data are described. Four kinds of experiments are described which established the physiological origin of the potentials recorded:

1. Simultaneous recordings from the cats and from a "dummy".
2. Observation of the changes in the behavior of the high-frequency components under pentobarbital narcosis.
3. Study of responses evoked by sensory stimuli.
4. Comparison of the traces of the high-frequency components with the EEG recorded simultaneously on an ink-writer.

These experimental and control recordings established the existence of brain potentials in the frequency range 200–500 c/sec, more especially in the range 200–300 c/sec.

Further study of some recordings was carried out by means of autocorrelation analysis, in an attempt to determine whether there were any components in the above frequency range which were steady, persistent and time-locked (*i.e.*,

truly periodic). The results of this part of the investigation were negative.

I want to express my acknowledgement to Dr. Mary A. B. Brazier and Dr. John S. Barlow for help and advice, and to thank the Rockefeller Foundation which provided me the Fellowship in the Neurophysiological Laboratory of the Massachusetts General Hospital. I should also like to thank Professor K. S. Lion of the Department of Biology at the Massachusetts Institute of Technology, for his helpful advice, and Professor W. A. Rosenblith of the Research Laboratory of Electronics for the opportunity to use the correlator in the Laboratory of Communications Biophysics at the Massachusetts Institute of Technology. The technical assistance of Miss Margaret Magavern and Mrs. Mildred Riley is gratefully acknowledged.

REFERENCES

- ADEY, W. R. Studies of hippocampal electrical activity during approach learning. In: J. F. DELAFRESNAYE (Editor), *Brain mechanisms and learning. UNESCO symposium, Montevideo 1959*. Blackwell Scientific Publ., Oxford, 1961: 577–588.
- BARLOW, J. S. Autocorrelation and crosscorrelation analysis in electroencephalography. *IRE Trans. med. Electron.*, 1959, ME 6: 179–190.
- BARLOW, J. S., BRAZIER, M. A. B. and ROSENBLITH, W. A. The application of autocorrelation analysis to electroencephalography. *Proceedings first national biophysics conference*. Yale Univ. Press, New Haven, 1959: 622–626.
- BARLOW, J. S. and BROWN, R. M. An analog correlator system for brain potentials. *Techn. Rep. 300, Res. Lab. Electron., Mass. Inst. Technol.*, 1955, 41 p.
- BRAZIER, M. A. B. Some uses of computers in experimental neurology. *Exp. Neurol.*, 1960a, 2: 123–143.
- BRAZIER, M. A. B. Long-persisting electrical traces in the brain of man and their possible relation to higher nervous activity. *Electroenceph. clin. Neurophysiol.*, 1960b, Suppl. 13: 347–358.
- BRAZIER, M. A. B. and BARLOW, J. S. Some applications of correlation analysis to clinical problems in electroencephalography. *Electroenceph. clin. Neurophysiol.*, 1956, 8: 325–331.
- BRAZIER, M. A. B. and CASBY, J. U. Crosscorrelation and autocorrelation studies of electroencephalographic potentials. *Electroenceph. clin. Neurophysiol.*, 1952, 4: 201–211.
- CHANG, H. T. The evoked potentials. In: J. FIELD, H. W. MAGOUN and V. E. HALL (Editors), *Handbook of physiology, Sect. 1*. American Physiological Society, Washington, 1959, 1: 299–314.
- COOMBS, J. G., ECCLES, J. C. and FATT, P. The electrical properties of the motoneurone membrane. *J. Physiol. (Lond.)*, 1955, 130: 291–325.
- FRANK, K. and FUORTES, M. G. Stimulation of spinal motoneurons with the intracellular electrodes. *J. Physiol. (Lond.)*, 1956, 134: 451.
- FREYGANG, W. H. and LANDAU, W. M. Some relations between resistivity and electrical activity in the cerebral *Electroenceph. clin. Neurophysiol.*, 1962, 14: 453–464

- cortex of the cat. *J. cell. comp. Physiol.*, **1955**, *45*: 377-392.
- GOZZANO, M. Ricerche sui fenomeni elettrici della corteccia cerebrale. *Riv. Neurol.*, **1935**, *8*: 212-261.
- LION, K. S. and WINTER, D. F. A method for the discrimination between signal and random noise of electrobiological potentials. *Electroenceph. clin. Neurophysiol.*, **1953**, *5*: 109-111.
- LION, K. S., WINTER, D. F. and LEVIN, E. Electrical activity of the brain measured in the frequency range above 200 c/sec. *Electroenceph. clin. Neurophysiol.*, **1950**, *2*: 205-208.
- RALL, W. Membrane time constant of motoneurons. *Science*, **1957**, *126*: 454.
- RENSHAW, B., FORBES, A. and MORISON, B. R. Activity of isocortex and hippocampus: Electrical studies with microelectrodes. *J. Neurophysiol.*, **1940**, *3*: 74-103.
- TASAKI, T. New measurements of the capacity and the resistance of myelin sheath and the nodal membrane of the isolated frog nerve fiber. *Amer. J. Physiol.*, **1955**, *181*: 639-650.