I

On the Electroencephalogram of Man

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(With 17 figures)

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As *Garten*[1], who in all likelihood can be regarded as one of the greatest experts in electrophysiology, has rightly emphasized, one cannot be far from the truth if one ascribes to each living plant or animal cell the ability to produce electrical currents. Such currents are called bioelectric currents, because they accompany the normal manifestations of life of the cell. They are, I presume, to be distinguished from currents artificially produced by injuries which were designated under the terms of demarcation currents, alteration currents or injury currents[T2]. It was to be expected as a matter of course that bioelectrical phenomena should be demonstrable also within the central nervous system, since it represents such an enormous cell aggregate and in fact this demonstration was made relatively early.

Caton[2] as early as 1874 published experiments on rabbit and monkey brains, in which non-polarizable electrodes were either applied to the surface of both hemispheres, or in which one electrode was placed on the cerebral cortex and the other on the surface of the skull. The currents were recorded with a sensitive galvanometer. Distinct current oscillations were found which became accentuated especially upon arousal from sleep and when death was imminent, but after death decreased and later completely disappeared. *Caton* already was able to demonstrate that strong current oscillations occurred in the cerebral cortex when the eye was exposed to light and he surmised that perhaps these cortical currents could be used for the purpose of localization within the cerebral cortex.

In 1883 *Fleischl von Marxow*[3], using non-polarizable electrodes and a sensitive galvanometer, first observed that in various animals, when records were taken from two symmetrically placed points on the surface of the cerebral hemispheres, only slight or no deflections at all occurred at first, but that with peripheral stimuli, *e.g.*

[1] *Garten*: Die Produktion von Elektrizität. *Wintersteins* Handbuch der vergleichenden Physiologie, Volume 3, 2nd half, p. 105[T1].

[2] *Caton*: Brit. med. J., **2**, 278 (1875); abstract in Zbl. Physiol., **4**, No. 25 (1890). According to *Bechterew*: Die Energie des lebenden Organimus, p. 102. Wiesbaden, 1902.

[3] *Fleischl von Marxow*: Gesammelte Abhandlungen, p. 410. Leipzig: J. A. Barth, 1893; and Zbl. Physiol., **4** (1890).

by exposing the eyes to light, one could obtain clear-cut deflections when the electrodes were located in the region of *Munk's* visual centers. Chloroform administration abolishes the occurrence of deflections on the galvanometer in response to peripheral stimulation. If one allows the animal to wake up from the narcosis, current oscillations in response to peripheral stimulation reappear in the cerebral cortex. He succeeded in recording these currents not only from the exposed cerebral cortex, but also from the dura mater and even from the calvarium divested of its periosteal covering. He stressed that one has to exercise great care to prevent cooling of the cerebral cortex and adds: "It may even become possible, by taking records from the scalp, to perceive the currents generated in our own brain by various mental acts".

A. Beck[1] also worked on the cerebral cortex of the dog, using non-polarizable clay electrodes and *Hermann's* galvanometer. He made the important observation that a current of variable strength is present *at all times*, when any two points on the cortical surface are interconnected. The oscillations of this current do not coincide in time with respiration or the movements of the pulse and are also independent of movements of the animal. This current disappears during narcosis. Upon stimulation of peripheral sense organs, *e.g.* of the eye by magnesium light, a strong current oscillation occurs in the contralateral occipital lobe, thus making it possible to define the dog's visual area by means of these potential oscillations.

In 1892 *Beck* and *Cybulski*[2] published additional studies carried out in monkeys and dogs. Using a sensitive galvanometer, they again found that when two points of the cerebral cortex were connected, a current of varying strength was present all the time. A relationship of its oscillations with pulse and respiration could not be demonstrated. They took great pains to show in particular that the currents originate in the cortex itself and are not conducted from elsewhere. Thus, *e.g.*, passing strong currents through the scalp, while the cerebral electrodes remained applied, did not elicit any movement of the galvanometer needle. Upon local stimulation of the cerebral cortex a local alteration of the cortical currents took place. Upon stimulation of the forelimb a current oscillation was induced in the area of the cruciate sulcus; upon illumination of the eye a similar change occurred in the occipital lobe. These electrical changes in the cerebral cortex were easiest to elicit in monkeys and were all the more pronounced, the closer the stimulus resembled those stimuli that usually affect the animal under normal conditions. Thus, *e.g.* a slight touch of the hand influences the galvanometer more strongly than pinching of the skin. The authors believe that these electrical phenomena in the cerebral cortex correspond to the simple mental states[T3].

Gotch and *Horsley*[3] performed experiments on cats, rabbits and monkeys. They used non-polarizable clay electrodes and *Lippmann's* capillary electrometer. They interconnected various parts of the cerebral cortex. At rest currents were almost

[1] *Beck, A.*: Die Bestimmung der Lokalisation der Hirn- und Rückenmarksfunktionen vermittels der elektrischen Erscheinungen. Zbl. Physiol., **1890**, No. 16.

[2] *Beck* and *Cybulski*: Weitere Untersuchungen über die elektrischen Erscheinungen der Hirnrinde der Affen und der Hunde. Zbl. Physiol., **6**, 1 (1892).

[3] *Gotch* and *Horsley*: Zbl. Physiol., **1889**; J. Physiol., **1890**.

totally absent, but upon each peripheral stimulation a current oscillation took place.

Danilevsky[1,T4] in 1891 observed current oscillations in the cerebral cortex of dogs in response to peripheral stimulation.

Upon *Bechterev*'s suggestion *Larionov*[2] in 1899 and *Trivus*[3] in 1900 used the current oscillations originating in the cerebral cortex to localize the auditory and visual areas of the dog, without being able to make any significantly new observations in the course of these studies.

Tcheriev[4] carried out similar studies in 1904. He became convinced that these currents were in all probability dependent upon the movement of the blood in the cerebral vessels and that they were therefore not caused by the state of activity of the central nervous system.

In 1912 *Kaufmann*[5] experimented on 24 dogs and took records with non-polarizable electrodes and a *Wiedemann* galvanometer. He was able to demonstrate unequivocally the physiological origin of the electrical phenomena and to refute *Tcheriev's* view. He succeeded in recording these currents also from the surface of the skull bone. He likewise saw *at all times* spontaneous oscillations of the cortical current and succeeded in demonstrating changes occurring upon peripheral, *e.g.* visual stimulation.

Pravdich-Neminsky[6] in 1913 recorded the cortical currents in the dog for the first time with the string galvanometer and observed the influence of peripheral stimuli which, however, were at first limited to electrical stimulation of the sciatic nerve.

In 1919 *Cybulski*[7] in collaboration with a coworker also studied the action currents of the cerebrum in dogs and monkeys by means of the string galvanometer. They could only confirm *Beck's* and *Cybulski's* earlier observations.

Finally, in 1925 *Pravdich-Neminsky*[8] published a larger study in Pflügers Archiv. He points out that such continuous phenomena as the spontaneous oscillations of the cerebral cortical currents had not been observed by all investigators, but only by *Beck*, *Danilevsky* and *Kaufmann*. His own investigations were carried out in dogs. Records were taken with non-polarizable clay electrodes and the large *Edelmann* string galvanometer. In addition to the "electrocerebrogram", the cerebral pulsations and the blood pressure were also recorded. *Neminsky* also became convinced that *Tcheriev* was incorrect in asserting that a simple physical relationship exists between the electrical phenomena in the brain and the friction of the blood

[1] *Danilewski*: Zbl. Physiol., **5**, No. 1 (1891).
[2] *Larionow*: Über die corticalen Hörzentren. Schriften der Klinik für Nerven- und Geisteskrankheiten, St. Petersburg, 1899.
[3] *Triwus*: Die negativen Stromschwankungen in der Hemisphärenrinde des Gehirns. Thesis, St. Petersburg, 1900.
[4] *Tschirjew*: J. Physiol. et Path. gen., **4**, 671 (1904); Arch. Anat. u. Physiol., **1913**, Physiol. Abt., p. 414, especially p. 442 and 447.
[5] *Kaufmann*: Elektrische Erscheinungen in der Grosshirnrinde. Rev. Psych. Neur. u. exper. Psychol. (Russian), **17**, 403 (513) (1912). Abstract Z. Neur., **6**, 1130 (1913).
[6] *Prawdicz-Neminski*: Elektrische Gehirnerscheinungen. Zbl. Physiol., **1913**, No. 18, 915.
[7] *Cybulski*: Zbl. Physiol., **1919**, 406.
[8] *Prawdicz-Neminski*: Zur Kenntnis der elektrischen und der Innervationsvorgänge in den funktionellen Elementen und Geweben des tierischen Organismus. Elektrocerebrogramm der Säugetiere. Pflügers Arch., **209**, 362 (1925).

on the walls of the cerebral vessels, etc. In the electrocerebrogram recorded with the *Edelmann* string galvanometer, he was able to distinguish waves of first and second order. Of those of the first order there were 10–15 in one second, of those of the second order, there were 20–32 in one second. *Neminsky* was also successful in recording such oscillations from the dura, as well as from the bone of the skull, just as from the cortex itself.

Most of the authors cited here considered these "cortical currents" as the expression of the activity of the cerebral cortex of the animal, because they increase with functional involvement of the cortical centers and disappear during narcosis or at death. It is useful to distinguish between the *current present at all times*, which can be recorded from the cerebral cortex, and its *alterations under the influence of peripheral stimuli*. The latter current oscillations are particularly sensitive and disappear easily upon cooling of the cortex and for otherwise not wholly explainable reasons. Whether the interpretations given by the authors are in fact correct, is still by no means established. *Garten*[1] expressed the opinion that the electrical phenomena in the central nervous system, in accordance with the complicated structure of the latter, may be explained in a variety of ways. According to him, if an action current is observed, the first question that arises is whether this action current originates from the myelinated nerve fibers, or whether it is caused by excitation of many unmyelinated fibers of the grey matter, or by excitatory processes of the ganglion cells in the cortex or in deep-lying nuclei. *Garten* adds: "The conditions will become especially complicated in studies on the *cerebral cortex*, because there we have to expect simultaneously action currents of very different systems which at times may be active and at other times may be at rest".

I myself worked in 1902 with *Lippmann's* capillary electrometer. Using boot-shaped clay electrodes[T5] and *Fleischl von Marxow's* procedure, I attempted to record currents from symmetrical locations in the two cerebral hemispheres of the dog. In five experiments, in one cat and four dogs, it was possible to carry out the experiment as designed without technical flaws, but several other experiments failed. In these five experiments oscillations of the electrometer, which did not depend upon external stimuli, were found when the electrodes rested on the brain surface of the unanesthetized animal. Once they were also recorded from two points on the dura which still covered the two cerebral hemispheres. On the other hand, in contrast to *Fleischl von Marxow's* observations, it was possible in only one of these five experiments to demonstrate the occurrence of current oscillations upon stimulation of peripheral sense organs; upon stroking the dog's forepaw a very pronounced current oscillation occurred each time on repeated occasions. Because at that time I was particularly interested in the effect exerted by peripheral stimuli upon these currents recorded from the cerebral cortex, I abandoned the experiments.

Subsequently, in 1907 I performed once again an experiment on a dog, with the capillary electrometer, without, however, being able to observe the hoped for current oscillations upon stimulation of peripheral sense organs.

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[1] See footnote 1 on p. 37.

Then, in 1910 I tried with the small *Edelmann* string galvanometer to obtain currents from symmetrical points of the cortex, using non-polarizable boot-shaped clay electrodes. Even though at rest, *i.e.*, without the influence of external stimuli, one saw at all times exceedingly small oscillations of the string, larger deflections again failed to occur in any of the dogs investigated, either upon touching the paw, or upon illuminating the eye, or even under the influence of strong auditory stimuli, although the animals were not anesthetized.

Then last year, at a time when my observations on man, which I shall report below, were already available, I again performed three experiments on dogs[1]. In these I used the large *Edelmann* string galvanometer and the double-coil galvanometer of Siemens and Halske, the latter with particularly sensitive inserts[T6]. The dogs used in these experiments had received 1.5 grams[T7] of Veronal by mouth about five hours before the experiment; then in addition, one hour before the beginning of the preparatory operation, they received 0.03–0.05 grams of morphine subcutaneously. In accordance with *Einthoven's* suggestion for the recording of the electrocardiogram in the animal, and in order to avoid cooling of the cerebral cortex, I substituted freshly amalgamated tiny zinc plates for the non-polarizable clay electrodes which I had used before. The zinc plates were introduced into the subdural space through a slit in the dura. They measured 12 mm in length and 4 mm in width; their four corners were rounded off to avoid injuries; to them was soldered the well insulated connecting wire; they had a surface area of 25 sq.mm. After they had been inserted through the slit in the dura, through which they were just able to pass, they were advanced into the subdural space far enough to come to rest in the laterally sloping region of the skull. Thus their surfaces were firmly applied to the pia-arachnoid covered cortex and they were pressed against the dura and the bone by the pulsating brain. The trephine opening, which was kept as small as possible, was enlarged with a *Lüer's* rongeur only to the extent necessary to permit easy introduction of the tiny zinc plates, and was then completely filled with the wax customarily used in brain operations in man. The well insulated wire was led through this mass of wax. The wire itself was surrounded by wax, and the skin was then closed with a few sutures over the trephine opening. Thus, the brain was in no way exposed to drying or cooling.

In accord with the above findings quoted from the literature it was found that when these electrodes were applied over two areas of the same hemisphere, or also when they rest upon the right and left hemisphere, a current exhibiting considerable oscillations is present at all times.

Figure 1[2] shows a record of the continuous cerebral current oscillations[T9], which were recorded from the right and the left hemisphere of an approximately four year old female dog by means of the tiny amalgamated zinc plates and the large *Edelmann* string galvanometer. The legend of the figure gives additional details con-

[1] In all investigations carried out since 1924 to be reported here, Privatdozent Dr. med. *Hilpert* always helped me by word and deed, for which here too I express to him my most sincere thanks.

[2] All figures are reproductions of original records at a *reduced* size.

cerning the type of recording, the resistance and other similar items. One recognizes in Figure 1 larger oscillations of longer duration and smaller ones of shorter duration.

Using exactly the same arrangement, the current oscillations that can be picked up from the cortex of the two hemispheres were recorded with the coil galvanometer of Siemens and Halske which for my purposes is much more sensitive. Figure 2 shows

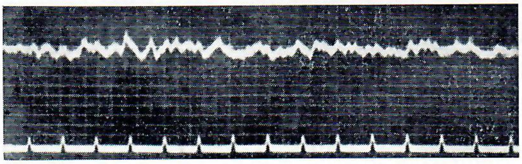

Fig. 1. Four year old female dog; amalgamated tiny zinc plate electrodes in the subdural space, right and left. Large *Edelmann* string galvanometer. Platinum string of 10,800 Ohm. Condenser inserted in the circuit[T8]. Resistance in the electrode circuit = 360 Ohm, 10 mm = 0.001 Volt. At the top: curve recorded from the brain; at the bottom: time in 1/5ths sec.

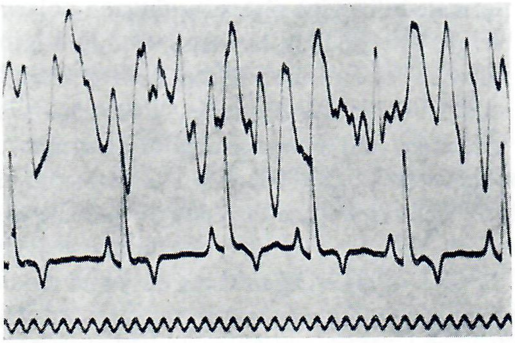

Fig. 2. The same female dog as in Figure 1 and the same cerebral recording. Siemens and Halske double-coil galvanometer. At the top: the curve recorded from the cerebrum; below: the electrocardiogram, recorded with amalgamated small zinc rods, inserted under the skin; at the bottom: time in 1/10ths sec. Condenser inserted into the circuit.

a small segment of a long curve recorded in this fashion from the same female dog. Having two galvanometers made it possible also to record the electrocardiogram simultaneously. In the figure the latter is written in the middle, whereas the curve of the cerebral oscillations appears at the top. In contrast to the record taken with the string galvanometer, the time signals here indicate tenths of a second. In accordance with *Einthoven's*[1] proposal, the electrocardiogram was recorded with freshly amalgamated small zinc rods which were inserted under the skin of the thorax. It is quite evident that the oscillations recorded from the surface of the two hemispheres do not coincide with those of the electrocardiogram. Thus, it is hardly possible that the cerebral record represents a distorted electrocardiogram, a question to which later in a different context we shall have to return once again.

[1] *Einthoven*: Die Aktionsströme des Herzens. Handbuch der normalen und pathologischen Physiologie, Vol. 8, 2nd half, p. 790, 1928.

The deflections of the current oscillations recorded from the brain surface are very much larger when they are derived from the two hemispheres than when one records from two points in the same hemisphere, *e.g.* from the area of the cruciate sulcus in front and from the occipital lobe posteriorly. A bilateral ligation of the common carotid arteries had no influence upon the amplitude of the deflections of the electrical curves recorded from the brain. Certainly, the blood flow in the brain of the dog is thereby, as we know, by no means interrupted, even though the blood supply is at first probably somewhat reduced in its amount. Also, total exsanguination through the opened and incannulated femoral artery in another dog led to no decrease, but to a transient increase in the amplitude of the deflections of the continuous current oscillations recorded from the surface of the cerebral cortex. As shown by *Mosso*[1], it is possible to arouse dogs by an injection of 0.01–0.02 grams of cocaine hydrochloride, even from deep chloral-induced sleep. In one dog, put to sleep by the above described combination of Veronal and morphine, a considerable increase of the current oscillations recorded from the brain surface was obtained by intravenous injection of a large dose of cocaine hydrochloride given into the jugular vein. However, the amplitude of the deflections of the electrocardiogram also increased simultaneously.

I was of the opinion that the procedure which I had devised prevented drying and cooling of the cerebral cortex, but on the other hand I also believed that, owing to the continuous cerebral movements, the fairly large electrodes were certainly not resting uniformly and always under the same pressure on the surface of the cerebral cortex. Since this might give rise to some experimental artefacts[T10], I decided to convince myself in some other way that the oscillations of the curves recorded from the surface of the cerebral cortex were not merely caused by the movements of the brain. It was because of these considerations that I had ligated the carotid arteries, but, as mentioned before, I did not, of course, thereby entirely abolish the circulation within the skull, nor the movements of the brain. Therefore this experiment does not disprove at all that the oscillations of the cerebral curve are caused by the movements of the brain. Furthermore, one may take exception to the experiment involving exsanguination through the femoral artery on the ground that a total exsanguination does not occur and that a certain amount of blood is retained for a fairly long time, precisely to maintain the cerebral circulation. Furthermore, the ensuing cerebral anemia by changing the brain volume and thereby altering the contact areas between the electrodes and brain surface could distort the cerebral record *in such a manner* that it would be impossible to draw reliable conclusions from it. The records which I showed above in Figures 1 and 2 undoubtedly exhibit some distortions of the cerebral current oscillations. This is because the cerebral circulation, which is also greatly influenced by the respiration through the intermediary of the veins, causes the subdurally placed tiny zinc plates to rest on the brain surface at one moment more firmly and at the next less so. This is of course associated with changes in resistance and with changes in the height of the deflections of the current oscillations

[1] *Meyer* and *Gottlieb*: Die experimentelle Pharmakologie, p. 28, Berlin, 1920.

which are thereby induced. Although sufficiently incontrovertible observations by other authors already existed, I was nevertheless time and again haunted by the worry that the continuous oscillations, which can be recorded from the brain surface, could perhaps be caused merely by the movements of the brain after all?[T11] I therefore made a transection of the upper cervical cord in the four year old female dog whose curves were shown above in Figures 1 and 2, after first having given an intravenous injection of 0.05 grams of muscarine into the femoral vein. The respiration stopped and shortly thereafter the heart was beating also only between long pauses.

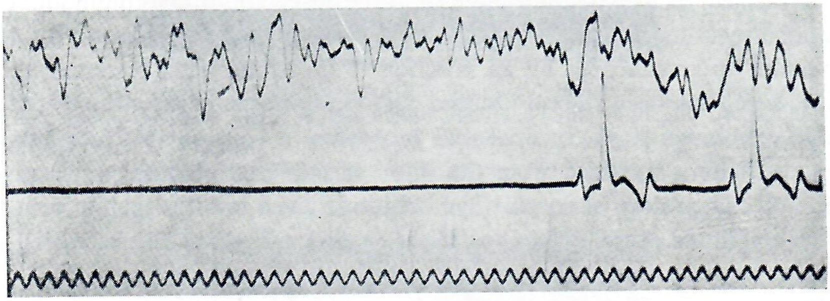

Fig. 3. The same female dog as in Figures 1 and 2 with exactly the same recording conditions as in Figure 2. At the top: the curve recorded from the cerebrum; in the middle: the electrocardiogram; at the bottom: the time in 1/10ths sec.

Figure 3 shows a segment of the record thus obtained. In the middle there is again the electrocardiogram, recorded in the manner indicated above. At the beginning of the strip of record shown here, the heart had already stopped for a fairly long time. Again after a fairly long time two heartbeats occur. These are separated by a brief pause which nevertheless is longer than the normal one; then a prolonged cardiac arrest again sets in. It is evident from the curve that the current oscillations, written at the top and recorded from the two hemispheres of this female dog, continue during the cardiac arrest. They have undergone some changes insofar as they have now become much more regular and also of lesser amplitude. The respiration stops completely and thus its influence upon the cerebral circulation mediated by the venous system is also eliminated. One notices during the two heart beats that the cerebral record at once becomes again more irregular, as in Figure 2. Thus, in spite of the total failure of circulation and respiration and in spite of the fact that the cerebral movements caused by the blood vessels are thereby eliminated, the oscillations of the cerebral record persist. This indicates, as other authors had also emphasized, that the cerebral current oscillations cannot be merely the mechanical consequence of the movements of the brain and more generally of the cerebral circulation. The form of the cerebral record obtained in Figure 3 is in all likelihood the more accurate one, whereas the curves in Figures 1 and 2 are distorted by just those cerebral movements to which the filling of the arteries and the veins, and thus the respiration, contribute. As was pointed out, the contact area between brain surface and electrodes is altered by the movements of the brain. It is true that the oscillations of the cerebral record are not produced by these, but they are distorted by them. In my opinion one can, *e.g.* in Figure 2, scarcely fail to recognize the similarity existing between the oscillations of the curve recorded from the surface of the cerebral cortex and a venous pressure curve. Later we must return to this question again. In any case, the experiment illustrated in Figure 3 proves that even after the arrest of respiration and the elimination of the cerebral circulation, it is possible to record from the surface of the brain regular current oscillation which therefore can neither be caused merely by movements of the brain, nor by the friction of the blood in cerebral vessels. This, therefore, confirms the opinion of the above mentioned authors. Because a condenser was inserted in the circuit[T8] in all cerebral recordings which I made with the string galvanometer and with the double-coil galvanometer, only the rapidly alternating current oscillations appeared in the records. In general these briefer oscillations exhibit two different lengths. One can distinguish between waves of somewhat larger amplitude and greater duration, with an average of 90–100 σ and those of shorter duration and smaller amplitude of 40–50 σ. Therefore these findings also essentially agree with *Pravdich-Neminsky's* reports, who distinguishes between waves of the first order, of which there are 11–15 in one second, and shorter waves, of the second order, of which there are 20–32 in one second. According to my observations, the amplitudes of the current oscillations recorded from the brain surface in the dog reach an average magnitude of 0.0002–0.0006 V for the longer 90–100 σ duration waves, and one of 0.00013 V for the largest of the briefer and essentially smaller second order waves with a duration of only 40–50 σ.

I have not carried out experiments on the influence of peripheral stimuli again, because what mattered to me now was the investigation of the current oscillations present *at all times* that can be recorded from the surface of the cerebral cortex. I need hardly point out that by post-mortem examination of the dogs it was verified that the tiny electrode plates inserted into the subdural space really were placed as intended, and that no alterations visible to the naked eye were produced in the subdural space or on the surface of the arachnoid and pia. In particular, not the slightest hemorrhage could be demonstrated. It goes without saying that the table upon which the dog was lying during each galvanometer recording was insulated from the surroundings by glass legs.

There exist no investigations on electrical events in the brain of *man*, neither do I know of any publication of records which would correspond to those to be reported here. After several fruitless attempts, I was able on July 6, 1924 to make the first pertinent observations in a young man aged 17. This young man had undergone a palliative trepanation over the left cerebral hemisphere performed by *Guleke* because of a suspected brain tumor. Because the signs of increased intracranial pressure after an initial remission recurred, the original trephine opening was enlarged posteriorly, whereupon the signs of increased intracranial pressure receded. About one year after the second operation I attempted to demonstrate currents in the area of the trephine opening, where the bone was missing, by using non-polarizable boot-shaped clay electrodes and the small *Edelmann* string galvanometer. The experiments were initially unsuccessful, and only when the two clay electrodes were placed 4 cm apart in the vicinity of a scar running vertically from above downwards through the middle of the enlarged trephine opening, was it possible with large magnifications[T12] to obtain continuous oscillations of the galvanometer string. This could be achieved either by inserting a platinum thread with a resistance of 5200 Ohms or a quartz thread with a resistance of 3200 Ohms. No oscillations could be demonstrated with the clay electrodes in the region of the trephine opening away from the very firm scar. This was the first result which intimated that probably in man, as in rabbits, dogs and monkeys, continuous electrical currents can be recorded from the surface of the intact cerebral cortex. [See Plate 3.]

Since I had at my disposal only the small *Edelmann* string galvanometer and it was only possible therefore to observe, but not to record, the very small movements of the string, I decided to obtain first of all a large *Edelmann* string galvanometer. Fortunately, after some time, I was successful with this also. But the very first attempt to use it was again unsuccessful. On March 20, 1925, using non-polarizable brush electrodes, I could not obtain current oscillations of any kind from the surface of a fairly markedly protruding cerebral herniation in a young woman aged 20 in whom a large palliative trepanation had been performed in the region of the right frontal and parietal lobes. It is true that the resistance was enormously high; according to the measurements made with the *Edelmann* instruments, it amounted to 44,000 Ohms in the electrode circuit.

Later I succeeded in obtaining a double-coil galvanometer which was brought on the market by Siemens and Halske, and which proved to be of great value for my investigations. I am certainly not sufficiently trained in physics to give an expert opinion on the merits and disadvantages of a Siemens coil galvanometer, but I refer to *Schrumpf's* and *Zöllich's*[1] work which is concerned with the usefulness of the string and coil galvanometers for the recording of cardiac currents. From this work, it seems to me, one can conclude that the coil galvanometer is more sensitive than the string galvanometer and thus quite definitely deserves preference for many physiological investigations. When comparing Figures 1 and 2 above, the different magnitudes of the deflections of the current oscillations which, under otherwise identical conditions, can be picked up from the cortical surface of the dog, are immediately evident. If in the large *Edelmann* string galvanometer the string tension is calibrated at a value of 10 mm = 0.001 V, as is customary for the recording of cardiac currents, the insert[T6] which I used in galvanometer 1 for the recording of cerebral records is, by comparison, several times more sensitive and its deflections are about 7½ times as large as those obtained with the string galvanometer at the indicated string tension. One disadvantage of the coil galvanometer is that with the model put on the market by Siemens and Halske it is impossible to measure simultaneously the resistance in the electrode circuit. However, if, as in my case, one has available an *Edelmann* system at the same time, this resistance measurement can be carried out with ease. [See Plate 5.]

In the investigations in man, to be described next, I used, instead of non-polarizable electrodes, needle electrodes, which were zinc plated according to

[1] *Schrumpf* and *Zöllich*: Saiten- und Spulengalvanometer zur Aufzeichnung der Herzströme. Pflügers Arch., **170** (1918).

Trendelenburg's[1] proposal and, except for their tips, were insulated from their surroundings by a coat of varnish. Needle electrodes have also often been used by others for the recording of action currents, thus, *e.g.* by *Straub*, for the recording of cardiac currents, by others for the recording of muscle action currents, etc. Several descriptions of needle electrodes have been made. *Straub* inserted ordinary sewing needles to which copper wires had been soldered, at a flat angle under the skin. *Mann* and *Schleier*[2] used nickel silver electrodes. I have used zinc plated steel needles. According to *Gildemeister's*[3] and *Paul Hoffmann's*[4] explanations, the use of non-polarizable electrodes for the recording of currents from the human body is not required at all in circumstances in which one is concerned with the recording of current oscillations with a rapid time course. These needle electrodes, which of course are by no means completely non-polarizable, have in addition the great advantage of bypassing the skin. The latter, according to the studies carried out by *Einthoven*, and especially by *Gildemeister*, creates very complicated electrical conditions, which are not easily comprehended. These zinc plated electrodes were inserted through the skin into the subcutaneous tissue and whenever a bone defect was present they lay between the dura and the skin, *i.e.* epidurally[5]. It is known from the animal experiments reported in detail above, that one can also record the so-called "cortical currents" from the dura and from the bone shorn of its periosteum. The puncture sites located in the vicinity of the existing bone defects were treated with iodine. The zinc plated needle electrodes, insulated except for their tips, were sterilized by keeping them for several hours in a 10% formalin solution and then transferred into a sterilized physiological saline solution to wash off the last remnants of formalin which would irritate the tissue. Under careful observation of all the rules of asepsis, the needles, just like a hypodermic needle, were inserted in the region of a skin fold elevated from its base and were pushed in, parallel to the skin surface, until the tip was placed securely in the subcutaneous tissue, *i.e.* in the epidural space. The very fine needles could cause no injury with this method of insertion. The double-coil galvanometer was used predominantly for the recording of the current oscillations obtained in this manner from the epidural space with the needle electrodes, firstly because of the larger deflections and the better monitoring of the curves which could always be seen, even during the recording, and secondly, because of the advantage of having these curves written in black on white.

In a 40 year old man in whom 5 months earlier a large gliosarcoma had been removed by *Guleke*, a marked protrusion had again formed in the operative area where the bone had been completely removed. At the same time general signs of increased intracranial pressure had developed again. In this man a record was taken

1 *Trendelenburg, W.*: Zur Methodik der Untersuchung von Aktionsströmen. Z. Biol., **74**, 113 (1922).
2 *Mann* and *Schleier*: Z. Neur., **91**, 551 (1924).
3 *Gildemeister*: Passive elektrische Erscheinungen im Tier- und Pflanzenreich. Handbuch der normalen und pathologischen Physiologie, Vol. 8, 2nd half, p. 657.
4 *Hoffmann, Paul*: Ruhe- und Aktionsströme von Muskeln und Nerven. Handbuch der normalen und pathologischen Physiologie, Vol. 8, 2nd half, p. 703.
5 In many early postoperative cases there probably remained some remnants of periosteum, which were left behind at the palliative trepanation.

from two points within the bone defect located over the left hemisphere. A double-coil galvanometer and the above mentioned zinc plated electrodes were used; these were inserted subcutaneously and lay 4.5 cm apart. The man lay comfortably on his back on a couch which was insulated from the surroundings by glass legs. He remained completely still during the recording. A curve was recorded of which Figure 4 repre-

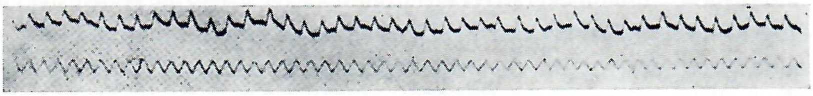

Fig. 4. 40 year old man. Large left-sided bone defect extending from the forehead to the parietal region. Double-coil galvanometer. Condenser inserted into the circuit. Subcutaneous needle electrodes in the area of the bone defect, 4.5 cm apart. Above: oscillations of the curve recorded epidurally; below: time in 1/10ths sec.

sents a small segment. During the recording the condenser was inserted into the circuit and the very sensitive galvanometer 1 of the double-coil galvanometer, connected to the needle electrodes, was set on maximal sensitivity. Galvanometer 2 was also switched on and set on maximal sensitivity in order to exclude with certainty the recording of any currents intruding from outside. In Figure 4 shown here, the completely stable line of galvanometer 2 cannot be seen; to save space the time marking indicating tenths of a second was moved somewhat closer to the curve obtained with the needle electrodes. From Figure 4 it becomes readily evident that the current oscillations recorded from the epidural space are composed of two types of waves alternating regularly with each other. The large waves have an average duration of 90 σ, the smaller ones one of 35 σ. In this record one can furthermore recognize slight pulsatory fluctuations and establish that six large and six small waves of the curve recorded from the dura correspond to *one* pulsatory fluctuation of 0.75 second duration. No influence of respiration is evident in the record, which is several meters long and of which only a small segment is reproduced here. Thus, when recording with needle electrodes placed in the epidural space in the area of a bone defect, we immediately obtain continuous current oscillations, which in their time course also approximately correspond to the two wave types found in the dog. I would like to mention again that, in spite of the large bone defect, a considerable increase in intracranial pressure existed at the time of the recording. A few weeks later the man succumbed to his recurrent brain tumor after displaying signs of increasing brain compression.

In another case, a bilateral temporal *Cushing*-type decompressive trepanation had been carried out by *Guleke* in a 19 year old girl, because of a large tumor in the pituitary region which could be recognized on X-ray plates from shadows caused by calcifications. Six weeks after the operation the two trephine openings, where the bone had been completely removed, were markedly protruding. On both sides, at the upper margins of the right- and left-sided trephine openings, zinc plated needle electrodes were inserted subcutaneously and a record was taken with galvanometer 1 of the double-coil galvanometer. Simultaneously, by means of lead foil electrodes, arranged in a manner to be discussed in more detail later, a record was obtained with galvanometer 2 from both arms and thus the electrocardiogram was also written continuously. Figure 5 represents again a segment from the long record obtained in this manner. In both galvanometers of the double-coil galvanometer a condenser was inserted again. At the top in Figure 5 one sees the current oscillations recorded with

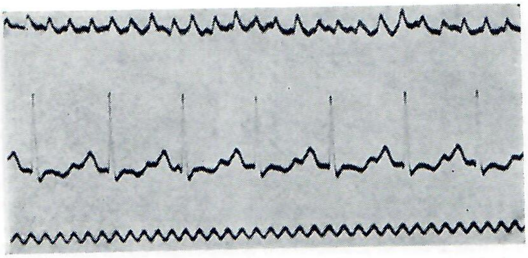

Fig. 5. 19 year old girl. Bilateral bone defect in the temporal area after palliative trepanation. Double-coil galvanometer. Condenser inserted into the circuit. Needle electrodes subcutaneously, right and left, in the upper parts of the bone defects. Electrocardiogram recorded from both arms by means of lead foil electrodes. At the top: curve recorded epidurally; in the middle: electrocardiogram; at the bottom: time in 1/10ths sec.

the needle electrodes epidurally from the bilateral bone defects; in the middle the familiar curve of the electrocardiogram and at the bottom, time recorded in intervals of tenths of a second. Again one is immediately struck by the correspondence between this figure and Figure 4. Here too we see the large and small waves which alternate regularly. The larger waves have a length of 90–100 σ, the smaller ones one of 40–50 σ. In many places one recognizes here also a slight influence of the brain pulsations upon the electrical oscillations, but this is by no means as pronounced as in Figure 4. A relationship between the electrocardiogram and the cerebral record certainly does not exist. There is a pronounced similarity between Figures 4 and 5. In this instance too, in spite of the bilateral decompressive trepanation a considerable increase in intracranial pressure still existed at the time these curves were recorded.

In these epidural recordings with needle electrodes it also depends entirely upon the local conditions whether the curves one obtains are more or less distinct. A small displacement of the needle in the subcutaneous tissue often works wonders. Particularly large deflections and a beautiful display of the waves of the cerebral curve were obtained in the following examination:

In a 15 year old girl a large tumor in the white matter of the left frontal lobe was suspected because of the clinical signs. She underwent an extensive palliative trepanation in the left anterior half of the skull which was performed by *Guleke*. In the course of this operation the bone had been removed. About 8 weeks after the operation needle electrodes were introduced into the subcutaneous tissue at two points 6 cm apart within the large left-sided bone defect. The resistance in the electrode circuit was measured with the *Edelmann* instrument and found to be 1600 Ohms. *Siemens*-type lead band electrodes were attached to both arms for the recording of the electrocardiogram. The needle electrodes in the epidural space were connected to galvanometer 1, set at its maximal sensitivity which wrote on the top of Figure 6; the arm electrodes were connected to galvanometer 2, writing in the middle. The lower curve of Figure 6 indicates time in tenths of a second. A condenser was inserted into the circuit. The curves are brought somewhat closer together to save space, but the time relationships have been strictly preserved. The electrocardiogram written

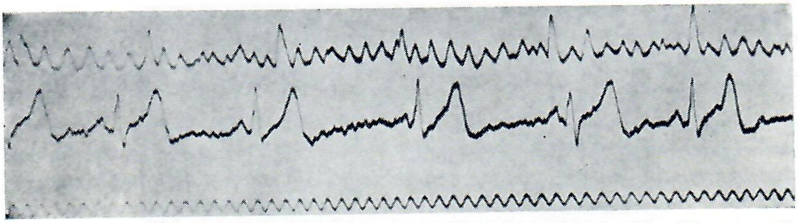

Fig. 6. 15 year old girl. Large palliative trepanation over the left frontal lobe. Double-coil galvanometer. Needle electrodes subcutaneously inserted 6 cm apart in the area of the bone defect. Resistance = 1600 Ohms. Electrocardiogram recorded from both arms by means of Siemens-type lead band electrodes. At the top: curve of the epidurally recorded oscillations; in the middle: pathologically altered electrocardiogram; at the bottom: time in 1/10ths sec.

in the middle is undoubtedly altered pathologically and also shows irregularities in the sequence of heart beats. Even before the operation the patient's pulse rate had been 51; after the operation at the time of this recording it measured 54 beats per minute and thus certainly had considerably slowed down; furthermore, the pulse was markedly irregular. The curve of the epidurally recorded current oscillations, written at the top, shows very large deflections, but also again discloses the regular alternation of large and small waves, exactly as in Figures 4 and 5 discussed previously. The relation between the time course of the first- and that of the second-order waves is also about the same. The larger waves have an average duration of 90 σ, the smaller ones one of 35–40 σ. In the upper curve one is impressed by occasional strikingly large waves; no relationship exists between these and the deflections of the electrocardiogram or with the pulsations in the areas of cerebral protrusion. The time course of the latter can be computed from the electrocardiogram. In this case too there was a considerable increase in intracranial pressure, as is evident from the slowing of the pulse. The trephine opening bulged out markedly.

In the three cases just reported here we have before us the same waves of the cerebral record. What is striking is the regularity with which in all three the large and small waves alternate with each other, a large wave always being followed by a small one, then again a large one, and so forth.

In other cases with epidural recordings I did not obtain curves that were regular *to such a degree*. In a 30 year old woman a tumor in the area of the right precentral convolution was suspected because of the clinical findings. At operation, at the expected site and a depth of 1.5 cm, *Guleke* found a cyst which was emptied of its content. The findings were interpreted as indicating a glioma with cystic degeneration. Because removal of the tumor was impossible and subsequent X-ray irradiation was planned, the bone at the site of trepanation was completely removed. Four weeks after the operation, by means of subcutaneously inserted needle electrodes, a record was obtained from two points 6.5 cm apart within the right-sided large bone defect. The resistance in the needle electrode circuit measured 1500 Ohms. With lead foil electrodes a record was taken from the arms to galvanometer 2 of the double-coil galvanometer, while galvanometer 1 was connected to the needle electrodes. A curve

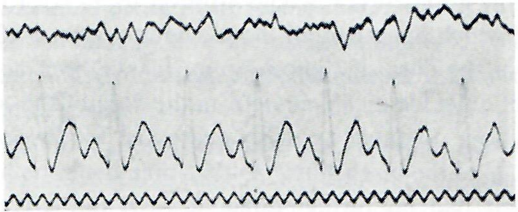

Fig. 7. 38 year old woman with large right-sided bone defect in the region of the motor area. Double-coil galvanometer. Condenser inserted into the circuit. Subcutaneously inserted needle electrodes within bone defect, 6.5 cm apart. Resistance = 1500 Ohms. Electrocardiogram recorded from both arms with lead foil electrodes. At the top: curve recorded from the epidural space; in the middle: electrocardiogram; at the bottom: time in 1/10ths sec.

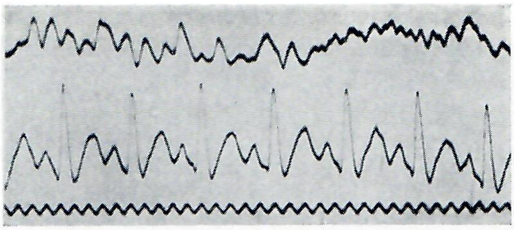

Fig. 8. 38 year old woman. Exactly the same recording conditions as in Figure 7; recorded on the same day.

was obtained of which a small segment is shown in Figure 7. The current oscillations recorded from the epidural space with galvanometer 1, set at its maximal sensitivity, appear at the top; in the middle is the electrocardiogram; at the bottom, time in tenths of a second. This record, as all the preceding ones, was taken with a condenser inserted in the circuit. One finds here too the same larger and smaller oscillations, known from the preceding records, of which the larger ones in this case last for 90–100 σ, the smaller ones for 40–50 σ. But the consistently regular sequence, characterized by a large and small wave always following upon each other, is missing here. A little to the right of the middle of the figure, for instance, there appear seven consecutive small waves. The curve generally shows much more variety than the strips of records displayed in the preceding figures.

The same is shown in Figure 8, which reproduces a segment of a curve recorded in the same patient under the same conditions and on the same day. I would like to attribute the greater variety of form of the epidurally recorded current oscillations to the fact that there was no significant increase in intracranial pressure in this case. This is in agreement with other records obtained in the same manner which are not shown here. At the time at which these investigations were performed, the site of trepanation was exactly at the same level as the remainder of the skull and was in no way bulging. Neither could any other signs of intracranial pressure be demonstrated in this patient. Yet these investigations also confirm the presence of two wave types, a longer and a shorter one, similar to those also demonstrated by *Neminsky* in his animal experiments.

According to my experience, it would however be an error to assume that these current oscillations, which appear in all the previous curves, could only be obtained with recordings from the dura of the cerebrum. I have been able to record a very similar, although not quite identical, curve from the dura of the cerebellum. A young man, aged 22, had been operated upon six years ago by *Guleke* because of a cyst located in the left half of the cerebellum. At that time the bone had been completely removed. The patient had no further difficulties. In the left occipital region the cerebellar hemisphere, covered only by the dura, protruded under the skin. Needle electrodes were inserted subcutaneously 5 cm apart in the area of the left-sided bone defect and were connected to galvanometer 1 of the double-coil galvanometer. Galvanometer 2 was connected with lead foil electrodes applied to the two arms. A condenser was inserted in the circuit.

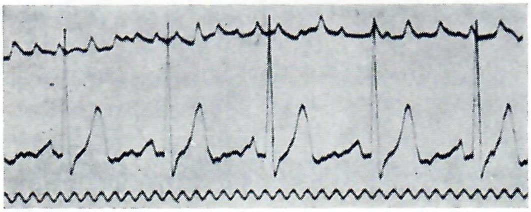

Fig. 9. 22 year old man. Bone defect over the left cerebellar hemisphere. Double-coil galvanometer. Condenser inserted. Subcutaneous needle electrodes, 5 cm apart, within the bone defect. Electrocardiogram with lead foil electrodes from both arms. At the top: curve recorded epidurally from the cerebellum; in the middle: electrocardiogram; at the bottom: time in 1/10ths sec.

Figure 9 shows a small segment of a long curve which was obtained in this manner. At the top are written the current oscillations which were recorded with the needle electrodes from the dura of the cerebellum. In the middle is the electrocardiogram; I retouched its largest deflections in a few places with a pencil. At the bottom the time is recorded in tenths of a second. Again one sees the two types of waves with exactly the same durations as could be recorded from the dura of the cerebrum. The only thing that distinguishes this cerebellar curve from that of the cerebrum is the fact that here, even without any increased intracranial pressure, the curve is again very regular—upon a large wave there always follows a small wave—and that the waves occur somewhat less frequently. I am, however, unable to decide whether this really represents a fundamental difference or whether it is just a fortuitous finding.

By means of subcutaneous needle electrodes placed within the bone defect I recorded the current oscillations from the dura of the cerebrum in still some other cases, without however obtaining anything different from what is evident from the curves reported and discussed here. However, I wish to reiterate what was stated above, that an apparently insignificant displacement of a needle tip in the subcutaneous tissue often greatly influences the quality, *i.e.* the height of deflections, of the curves one obtains. In still other cases, which will not be described here further, I was able to observe several times that the curves recorded with needle electrodes, which a few weeks after the palliative trepanation had been quite well developed, deteriorated with increasing intracranial pressure while the tumor was growing into the trephine openings, as was verified later by post-mortem examination. This fact too, like many others, seems to me to favor the idea that the current oscillations originate locally in the underlying brain tissue.

As a general result of these recordings with epidural needle electrodes I would consequently like to state that it is possible to record continuous current oscillations, among which two kinds of waves can be distinguished, one with an average duration of 90 σ, the other with one of 35 σ. The longer waves of 90 σ are the ones of larger amplitude, the shorter, 35 σ waves are of smaller amplitude. According to my observations there are 10–11 of the larger waves in one second, of the smaller ones, 20–30. The magnitude of the deflections of the larger 90 σ waves can be calculated to be about 0.00007–0.00015 V, that of the smaller 35 σ waves 0.00002–0.00003 V.

Before I carried out the epidural needle recordings from two points within a skull defect, as reported in abridged form above, I had performed a great number of investigations in which I took records by connecting a galvanometer to the skull defect and to the exactly corresponding spot on the contralateral, intact half of the skull. At the beginning of these investigations non-polarizable electrodes were used, and specifically at first boot-shaped clay and brush electrodes which, however, because of their high resistance, turned out to be unsuitable. Conditions were more favorable with the non-polarizable funnel electrodes described by *Piper*[1]. The resistance of these electrodes amounted to 530–2500 Ohms, depending upon the size of the funnel used, the local conditions in the area of the skull defect, and those on the contralateral side of the head. Although very beautiful records were obtained with these electrodes, the greatest misgivings with regard to their use are justified, especially when they are applied to the head, because of the possibility of corroding the skin with the concentrated zinc sulfate solution. There is also the danger that, in spite of the greatest care, small droplets of fluid may happen to come into contact with the conjunctiva of the eye. For this reason these electrodes were only very rarely used and then actually only for the purpose of obtaining curves for comparison. Because one deals with rapidly alternating current oscillations, non-polarizable electrodes, as explained above, were not necessary at all. I therefore changed over to metal electrodes, which can be used much more conveniently and also without any danger[2]. Dry metal surfaces applied to the skin also have a very high resistance. This resistance is much less when a moist pad is used under the electrodes. It is well known that the resistance to be expected decreases with increasing size of the electrode

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1 *Piper*: Elektrophysiologie menschlicher Muskeln, p. 20. Berlin: Julius Springer, 1912.

2 *Schellong*: Über exakte und nichtexakte Registrierung des menschlichen Elektrokardiogramms. Klin. Wschr., **1926**, 541.

surface, with increasing concentration of the salt solution used for moistening, and with increasing temperature of the skin upon which the electrodes rest. I first used round copper plates with an underlying flannel pad of slightly larger size, soaked in a 20% sodium chloride solution. These had a resistance of 240–1200 Ohms when locally applied in such a manner, that, as mentioned, one electrode was placed on the skull defect and the other on the exactly corresponding spot on the other side of the head. Furthermore, I used large thin platinum sheets[1], also together with an underlying flannel pad soaked in 20% sodium chloride solution; these, depending upon local conditions, showed a resistance of 400–1400 Ohms when applied. Silver electrodes were also used with a resistance of 450–3000 Ohms. In spite of the pieces of flannel lying under the electrodes, and even when sometimes cotton wool soaked in 20% sodium chloride solution was added, it was difficult to achieve a close fit of the metal plate electrodes, because of the uneven surface of the skin, especially within the confines of a skull defect. I therefore changed over to lead plate electrodes. Each of these was cut out of a lead plate exactly according to the size of the skull defect, and was fitted to the surface by bending and otherwise manipulating it in the appropriate manner. These electrodes, depending upon the size of the skull defect and the local conditions, had a resistance of 500–7600 Ohms. Lead band electrodes, folded several times in a zig-zag line, applied over the defect and over the exactly corresponding spot of the contralateral half of the skull, had about the same resistance. However, I was really not fully satisfied with any of the arrangements just discussed, because difficulties always arose in attaching the electrodes and one could never be sure that they would be firmly applied to the skin, even when using rubber bands or a rubber swim cap pulled over the head. Finally, the idea occurred to me to use very thin lead foil, similar to the tin foil used for the packaging of chocolate, etc. These pieces of lead foil could always be cut according to the form of the skull defect. A piece of flannel, larger by a few millimeters than the lead foil and soaked in 20% sodium chloride solution, was laid on the skull defect under the lead foil; also the latter was again covered with such a piece of flannel. A lead foil of the same size with the same base and cover was applied to the corresponding spot on the other side of the head. These pieces of lead foil were then fixed with thin rubber bandages of the kind used for other medical purposes. These were wound around the skull several times. This prevented any displacement of the electrodes and pressed them as firmly as possible against the skin over the surface of the cranium and over the skull defect. Drying of the electrodes, which is a factor of utmost importance in the change of resistance, was thereby also completely avoided, and it was possible to obtain perfectly uniform curves over a considerable length of time. The resistance, which in this case could be considerably reduced by the use of lead foil electrodes of the largest possible size, measured only 380–500 Ohms. Moreover, I also wish to mention at this point that I preferred to record the electrocardiogram in the same manner with lead foil electrodes. Instead of the lead band electrode which comes with the Siemens and Halske double-coil galvanometer, a lead foil electrode was used. First, a flannel

[1] *Gildemeister*: Über die Polarisation der Elektroden, die zu elektrisch-physiologischen Zwecken gebraucht werden. Z. biol. Techn. u. Meth., **3**, 28 (1915).

band soaked in a 20% sodium chloride solution was wrapped around the forearm, then a lead foil of corresponding size was wound around it once and on top of it was wrapped another moist flannel band. Everything was then covered with a rubber bandage. In this fashion, without any drying, an always uniform electrocardiogram could be obtained for hours. This is an arrangement which modified somewhat the recording conditions of the electrocardiogram described by *Einthoven*[1]. Instead of lead foil he used zinc plated wires. The arrangement proposed here which I used many times is even more convenient than the use of zinc plated wire which has to be wound around the arm in many turns.

I have no desire to report the details of my numerous investigations in people with skull defects, but I do want to discuss two observations somewhat more thoroughly.

In the 19 year old patient of whom before, on page 49, Figure 5 was shown, records were taken from the areas of the bilateral bone defects using lead foil electrodes in the above described manner. A curve was thus obtained of which a small segment is shown in Figure 10. Unfortunately, the record was not entirely perfect.

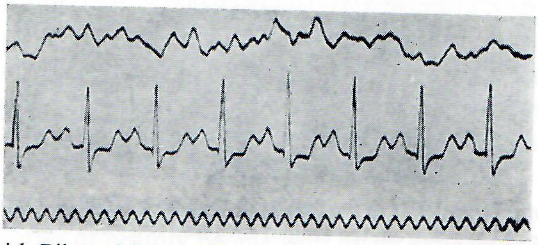

Fig. 10. 19 year old girl. Bilateral bone defect in the temporal region after palliative trepanation. Double-coil galvanometer. Condenser inserted. Recording from the two areas of trepanation with lead foil electrodes. Resistance = 500 Ohms. Electrocardiogram with lead foil electrodes from both arms. At the top: the curve recorded from the skin over the bone defects; in the middle: the electrocardiogram; at the bottom: time in 1/10ths sec (compare with Figure 5).

At the top of the figure is the curve recorded with the lead foil electrodes placed over the bilateral bone defects and connected to galvanometer 1 of the double-coil galvanometer. Below there follows the electrocardiogram which was recorded from both arms to galvanometer 2, also by means of the above described lead foil electrodes. At the bottom, time is indicated again in tenths of a second. The resistance of the lead foil electrodes over the skull defects measured 500 Ohms. When we compare Figures 5 and 10 it is evident that Figure 10 is a somewhat distorted rendering of the curve of Figure 5. But here too one sees again the longer and the shorter waves, even though by far not everything stands out as sharply as in the epidural needle recording from the same girl reproduced in Figure 5. In any case, however, the curve proves that when one records from the skin over skull defects, one can obtain a tolerably good record which also contains the characteristic details of the two wave types.

I shall report here still another observation. It is that of a 43 year old lawyer, who in 1914 had been wounded by a shrapnel fragment in the region of the forehead

[1] *Einthoven*: *l. c.* p. 790 [see footnote on p. 42].

on the right side of the midline and who presented a markedly pulsating bone defect in this area of about the size of a five mark piece. After the skin in this region and at the occiput had been well scrubbed with alcohol and ether, the somewhat depressed bone defect was filled with a cotton wad soaked in a 20% sodium chloride solution; on the top of it, a layer of flannel, then a thin lead foil and on top of it again a second layer of flannel was laid. Exactly the same type of electrode was placed on the occiput in the midline somewhat above the external occipital protuberance. The two electrodes were fixed by a rubber bandage firmly wound around the skull and further reinforced by a second bandage. The electrodes were thus protected against drying. The record was then taken with galvanometer 1 of the double-coil galvanometer and a curve was thus obtained of which a small segment is represented in Figure 11. The electro-

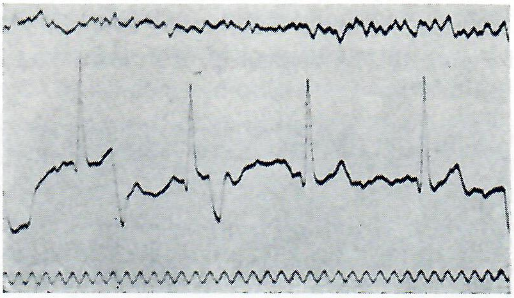

Fig. 11. 43 year old man. Bone defect in the forehead. Double-coil galvanometer, condenser inserted. Record from the bone defect and from the occiput with lead foil electrodes. Electrocardiogram from both arms with lead band electrodes according to Siemens. At the top: the curve recorded from the bone defect and from the occiput; in the middle: the electrocardiogram; at the bottom: time in 1/10ths sec.

cardiogram was also recorded from both forearms, in this case by means of Siemens lead band electrodes. At the bottom, time is indicated in tenths of a second. As always a condenser was inserted in the circuit. Dr. G. remained fairly quiet during the recording. As all other persons in whom records were taken, he lay on his back on a comfortable couch, which was insulated by glass legs against its surroundings. The top curve of Figure 11 again shows exceedingly well the larger and smaller waves, which till now we have observed in all other records.

The two segments of curves shown here, recorded from the skin of skull defects, or from the skin of a skull defect in the frontal region and from an area of skin on the occiput, show a marked similarity with the current oscillations recorded epidurally. In all instances in which such curves were recorded from the defect and from the area contralateral to it, one always obtained the same results. In 101 sessions I recorded in a total of 38 persons with skull defects, 23 men and 15 women, 506 curves, most of them measuring several meters in length. The statements made above are based on the careful analysis of these records. Thus not only with needle electrodes, placed in the epidural space, but also from the skin over a skull defect and the corresponding area of the other side, it is possible to obtain continuous oscillations of the electrical current with two characteristic wave types, the larger with a slower time course and the shorter[T13] with a more rapid one.

From the beginning *this* was my hope: that it would become possible to record from the human scalp with an intact skull the oscillations of the electrical current which can be obtained in animals from the surface of the brain and in humans with bone defects from the epidural space, and thus to fulfil what *Fleischl von Marxow* had said: "It may even become possible by taking records from the scalp to perceive the currents generated in our own brain by various mental acts", a statement already referred to above. As early as 1920, in a medical student who had lost almost all his hair and who, upon my request put himself most obligingly at my disposal, I had attempted to obtain current oscillations from various places on his scalp, especially from corresponding areas on the right and left half of the head, but also from the frontal and parietal regions on one and the same side of the head. I used *Piper's* funnel electrodes and subcutaneously inserted needle electrodes, which were connected to the small *Edelmann* string galvanometer which was then available to me in addition to the *Lippmann* capillary electrometer. However, I was completely unsuccessful. Now, of course, I was incomparably better prepared for these investigations. The large *Edelmann* string galvanometer was available to me and especially also the Siemens and Halske double-coil galvanometer. Above all, however, I had already recorded many curves from people with skull defects and thus I knew fairly precisely *what* one had to expect. I pursued right from the start not only purely scientific, but also practical aims, because I hoped that I might be able to utilize these observations for diagnostic purposes. I shall return to this point later again. I recorded curves in a whole series of healthy people with intact skulls and I shall now discuss the results of these investigations in the light of some characteristic examples.

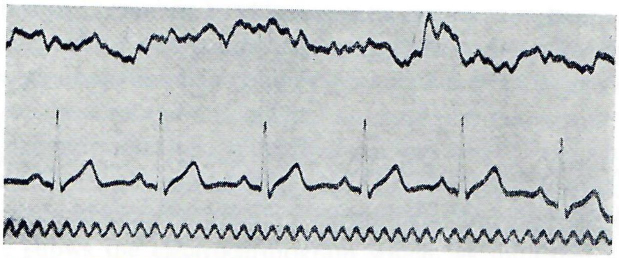

Fig. 12. Klaus at the age of 16. Double-coil galvanometer. Condenser inserted. Subcutaneous needle electrodes on the forehead and occiput. Resistance = 700 Ohms. Electrocardiogram with lead foil electrodes from both arms. At the top: the curve recorded from the scalp; in the middle: electrocardiogram; at the bottom: time in 1/10ths sec.

In 14 sessions I have recorded 73 tracings in my son Klaus, who at the time of these studies was 15 to 17 years old. Whenever these investigations were carried out, his hair was cut as short as possible. Figure 12 shows such a record obtained from my son Klaus. Zinc plated needle electrodes were inserted subcutaneously in the midline of the skull anteriorly within the hair line of the forehead and posteriorly about two finger breadths above the external occipital protuberance. In this examination the resistance of the needle electrodes was 700 Ohms when measured with the *Edelmann* instrument. They were connected with galvanometer 1 of the double-coil galvanometer, while the electrocardiogram was being recorded from both arms with lead foil electrodes through galvanometer 2. As in all previous investigations a condenser was inserted in the circuit. In Figure 12, in the top curve, one recognizes immediately and distinctly the already familiar larger waves with an average duration of 90 σ and the smaller oscillations lasting on the average 35–40 σ. The middle curve represents the electrocardiogram. At the bottom, time is indicated in tenths of a second. The amplitude of the deflections of the electrical oscillations recorded with the needle electrodes amounts to 0.00012–0.0002 V when measured in a simultaneously recorded string galvanometer curve.

I also wish to emphasize that curves differing markedly in quality were obtained when recording with needle electrodes from the intact skull, even in the same person, *e.g.* in my son Klaus, and that even the smallest displacements of the needle in the subcutaneous tissue often exert an unexpected and above all unintended effect upon the quality of the curves. Using subcutaneous electrodes records were also taken in Klaus from both parietal regions, as well as crosswise or ipsilaterally from one frontal to one parietal eminence and with various other combinations. However, the fronto-occipital recordings taken with needle electrodes, in which the latter were applied exactly in the midline of the skull, yielded by far the largest deflections.

In Klaus records were taken with every other possible type of electrodes: silver, platinum, lead electrodes, etc.; also, different arrangements of these on the skin surface of the head were used. However, time and again it was found that the best arrangement was that with electrodes placed on the forehead and occiput. Of Klaus' many records, I only want to show in Figure 13 another small segment of a curve obtained in this manner. In this instance lead band electrodes were applied to the forehead and occiput and were fixed with rubber bandages. From these lead band electrodes records were taken with galvanometer 1 of the double-coil galvanometer; galvanometer 2 was set at its maximum sensitivity and was used as a control to make

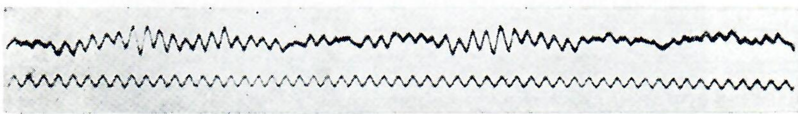

Fig. 13. Klaus at the age of 15. Double-coil galvanometer. Condenser inserted. Recording from forehead and occiput with lead band electrodes. At the top: the record obtained from the scalp; at the bottom: time in 1/10ths sec.

sure that no outside currents were entering the galvanometer circuit to disturb the examination. At that time I was still very distrustful of the findings I obtained and time and again I applied such precautionary measures. The record of galvanometer 2 ran as a completely straight line, without any oscillation; it is not shown in Figure 13. In the reproduction the second curve indicating time in tenths of a second is moved closer to the cerebral record in order to save space. The curves are recorded with a condenser.

With this type of recording also the larger and smaller waves familiar to us are seen very beautifully, even though the latter are somewhat less distinct than when recorded with needle electrodes.

I also had a whole series of records taken from my own scalp, both with needle electrodes and with other types. In these I used the most diverse placement of electrodes. These curves also confirm essentially what has already been reported here. I have 56 of my own curves. These were recorded by *Hilpert* in 11 sessions. The records from my *scalp* just as those of my son Klaus, were not as beautiful as those of people who had large areas of baldness or, even better, had no hair at all. Taking this into account, I selected a series of people for examination, from whom I then took records.

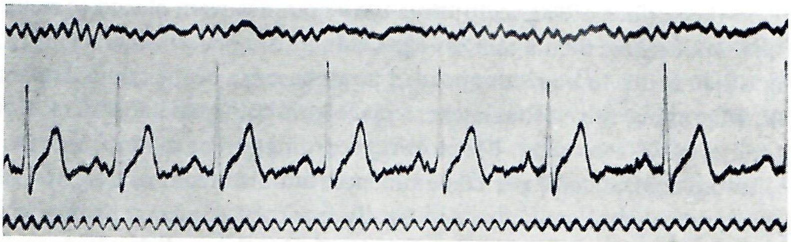

Fig. 14. 36 year old bald-headed man. Double-coil galvanometer. Condenser inserted. Record from forehead and occiput with lead foil electrodes. Resistance = 140 Ohms. Electrocardiogram with lead foils from both arms. At the top: the curve recorded from the scalp; in the middle: the electrocardiogram; at the bottom: time in 1/10ths sec.

Figure 14 is a segment of such a record. It was obtained from a 36 year old healthy man with extensive baldness of the head in whom, especially in the frontal and occipital region, there was a complete lack of hair. In the manner previously described a large lead foil electrode was placed on the forehead and another on the occiput; they were fixed to the head by means of rubber bandages. From these lead foil electrodes on the forehead and occiput a record was taken with galvanometer 1 of the double-coil galvanometer. With this arrangement the resistance for the two fairly large lead foil electrodes measured only 140 Ohms. The top curve of Figure 14 shows the current oscillations recorded in this manner from the forehead and occiput; the middle one shows the electrocardiogram which, as indicated above, was also recorded with lead foil electrodes from both arms through galvanometer 2. At the bottom, time is indicated in tenths of a second. As always a condenser was used. Even though the top curve unfortunately shows a somewhat thick tracing, one nevertheless recognizes in it the characteristic larger and smaller waves of the current oscillations which are sufficiently well known to us from the epidural recordings.

In a 37 year old healthy man without skull defect and with extensive baldness, I took records from the frontal and occipital region successively with *Piper's* non-polarizable funnel electrodes, with subcutaneously inserted zinc plated needle electrodes and finally with the repeatedly described lead foil electrodes. I did this in order to convince myself that, in spite of the differences between these electrodes and the different resistances which they offer, one can nevertheless obtain from the skull curves which in all essential points correspond to each other and readily display the larger and smaller waves which were discussed repeatedly.

In all, I have obtained 231 records in 48 sessions from 13 men, aged 16 to 65, these being predominantly employees of the clinic under my direction, and in one 36 year old woman. The reason why only *one* woman was examined is that the dense hair, especially at the occiput, prevents the attachment of the electrodes or causes such an enormous resistance that successful records can only be obtained by bypassing the skin with subcutaneous needle electrodes. The only woman in whom I performed such investigations had a circumscribed loss of hair and thus the electrodes lay conveniently on the completely hairless surface of the scalp.

I wish to point out again that I tried all conceivable arrangements of electrode positions on the surface of the scalp; thus the electrodes were placed sometimes over both frontal eminences, then again on each side in the planum temporale, a type of recording which is not to be recommended at all because of the subjacent temporalis muscle. Furthermore, the electrodes were placed on both parietal eminences which is a very good type of recording. Moreover, recordings were made from one frontal eminence to the contralateral parietal eminence, but also from one frontal eminence to the ipsilateral parietal eminence and finally from the forehead to the occiput. As already emphasized the latter turned out to be the best recording arrangement, even though it also has many disadvantages to which later we shall have to return once again, when considering the sources of artefacts[T14]. Of the various electrodes, the lead foil electrodes which can remain attached without discomfort for a fairly long time proved to be most satisfactory, along with the subcutaneous needle electrodes which, although somewhat uncomfortable to the subject being examined, can always be used even when there is considerable growth of hair.

In many investigations I also tried to record with one electrode placed on the skull and the other elsewhere on the body, because I believed that perhaps one could in this manner display the current oscillations originating from the skull with that much larger amplitude and all the more beautifully. All these investigations, however, were unsuccessful. In all these experiments the electrocardiogram interfered in a troublesome way. Thus, *e.g.*, when one electrode was located in the midline of the skull on the forehead or at the vertex, and another electrode of equal size was placed on the chest, the back, in the lumbar or sacral region, or was applied as a band around the whole chest, I always obtained the electrocardiogram more or less distinctly. Likewise electrocardiogram curves appeared immediately when a record was taken between the scalp and both palms placed upon the same electrode surface, or both soles of the feet. Also with an arrangement in which one electrode was placed on the vertex and the other on the left leg or foot or on the left arm or hand, the electrocardiogram showed up. Also when recording from the left side of the head and the left arm, the electrocardiogram appeared in a more or less distorted form. Only in a record from the vertex and the right forearm or right hand did I obtain a more composite curve in which, it is true, the presence of the electrocardiogram was clearly recognizable, but in addition other oscillations could also be demonstrated, such as *e.g.* the longer ones of the cerebral current oscillations. In any case, the result was that this curve was not suited for my purposes either. One can actually speak of an *ubiquity* of the electrocardiogram which renders impossible all recordings of this kind. We shall have to point out later that electrocardiogram curves can appear occasionally even when records are taken from various points on the skull. I have therefore, for the time being, abandoned all attempts to find other recording arrangements than those indicated above and I returned time and again to that of recording with lead foil electrodes from the forehead and occiput on the intact skull.

If now I consider the *sources of artefact*[T14] which, under certain circumstances can lead to a distortion of the curves recorded from the skull, I can say that gross experimental errors are easy to avoid, such as those resulting from mutual contact of the electrodes wires, even though they are insulated by some material wrapped around them, or from their contact with or rubbing against areas of the skin on the head. Large movements of the connecting wires too, probably by displacements at the points at which they are screwed in can cause a distortion of the curve by so-called wobbling contacts, owing to the great sensitivity of the galvanometer. These, however, are usually easy to recognize and therefore avoidable.

More important are the movements to which the electrodes placed on the skin surface or in the subcutaneous tissues are subjected. If the electrodes are located in the region of the bone defect, obviously the dura and the skin stretched over it pulsate very vigorously, because of the propagated cerebral movements. Therefore one can often recognize very distinct cerebral pulsations in curves recorded with needle electrodes placed in the epidural space. In Figure 4 such pulsations are apparent and when this curve was discussed, it was already pointed out that pulsatory fluctuations can be recognized, and that in this case six larger and six smaller waves occur for each cerebral pulsation. *Sommer*[1] in particular already drew attention in an excellent way to the origin of these fluctuations. He emphasized that from the changes in the contact areas of the electrodes, caused in turn by differences in pressure, time-related fluctuations of current intensity result. Even with the small needle electrodes used for recording the current oscillations in Figure 4, this can still be clearly recognized, as was emphasized above. Of course, this is much more evident with plate electrodes placed on the skin. This was also the reason why later instead of the metal plates I used pieces of lead foil which by means of a tightly drawn rubber bandage were pressed as firmly as possible upon their base. In the course of successive cerebral pulsations, the influence of respiration also becomes always more or less distinctly apparent, because it determines to a large extent the filling of the cerebral veins. The variations in pressure in a pulsating area of the brain caused by respiration also change the size of the areas of contact of the surface electrodes, or of those introduced into the tissue, and in this manner also alter the deflections of the galvanometer. This is evident in Figures 1 and 2 taken from a dog and reproduced earlier, in which amalgamated tiny zinc plates had been introduced into the subdural space over both cerebral hemispheres. The above mentioned effect of the pressure changes

[1] *Sommer-Fürstenau*: Die elektrischen Vorgänge in der menschlichen Haut. Klin. psych. Krkh., **1**, 197 (1906).

caused by the filling of the arteries and veins, and the concomitant changes in contact areas between electrodes and brain surface, are of course so prominent there that the curve recorded from the brain surface in many places actually resembles a venous curve. Undoubtedly, the current oscillations which were recorded from the brain surface with this arrangement were markedly distorted by the manner of recording, but for the considerations under discussion there this was not disturbing. These oscillations recorded from the brain surface are not generated by the pulse or the respiration, nor by the brain movements caused by these two factors; they are merely markedly altered by these processes in this kind of recording, which of course is something entirely different. But certainly any conscientious investigator will automatically be forced to ask himself the following question: "Are these current oscillations recorded from the brain surface with their two wave types perhaps only distorted pulsations of the brain after all, being thus caused by the movements of the blood in the cerebral vessels, in the arteries, capillaries and veins?"

It is true that each cerebral pulse corresponding to a heart beat does not represent a simple single upward movement of the investigated point on the brain surface, but that it is most often composed of three fairly large individual oscillations. *Mosso* and numerous other investigators have already referred to this. These three oscillations are not all equally pronounced and with accurate recording of the brain movements one can easily demonstrate still a few more, so that one could end up by bringing together the six larger waves of the current oscillations which correspond to each cerebral pulse (page 48). I believe, however, that all theoretical considerations are of no value with regard to such questions and it is better to examine them experimentally.

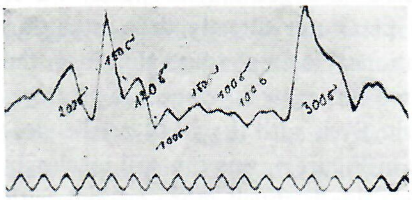

Fig. 15. 43 year old man. Bone defect on the forehead. At the top: oscillating movements of the skin of the bone defect, recorded with a *Marey* capsule and transmitted pneumatically to a *Marey* write-out capsule with an optical recording system. At the bottom: time in 1/10ths sec (compare with Figure 11).

In Figure 11 (page 56) a segment of a curve was shown which had been obtained from a pulsating bone defect and from the occiput in the 43 year old lawyer. The location of his bone defect was such that it was easy to record the movements of the overlying skin with a *Marey* recording capsule which covered the whole extent of the bone defect and was connected through a tube to a write-out capsule with an optical recording system. In this manner a curve was obtained of which Figure 15 represents a segment. At the top the oscillating movements of the skin over the bone defect are recorded by means of pneumatic transmission and optical write-out. At the bottom, as usual, time is indicated in tenths of a second. It is evident that at the onset of every brain pulsation a large wave occurs which rises above all others and which is then followed by a series of smaller oscillations. The magnitudes of the individual oscillations are very different, and so are their lengths. For simplicity's sake I directly entered the time values of these oscillations on the original record. In any event it is clear that the time relationships of these oscillations differ from those of the first and second order waves of the current oscillations recorded from the brain surface. If one compares the record of the pulsations within the bone defect as it is reproduced here with the curve of the current oscillations of the same man, as they were shown in Figure 11, one sees immediately that the pulsatory fluctuations of the bone defect do not at all stand out individually as large high-rising waves above the current oscillations recorded from the area of the defect. On the contrary, this curve of current oscillations is a uniformly continuous one in which large and small waves alternate more or less regularly. From the known delay existing between the movement of the heart and the pulsation of the brain it is easy to calculate the time of onset of each pulsation from the simultaneously recorded electrocardiogram. This applies also to the curve recorded from the skull and one can thus demonstrate unequivocally that the onset of a cerebral pulsation is by no means distinguished by a particularly large wave of the current oscillations.

This method of pneumatic transmission to a rubber membrane upon which a mirror is glued writing out the motions as an optical lever, may nevertheless be criticized with regard to the accurate reproduction of the *time*-relationships, and therefore in the same man I used still another method of recording the timing of the motions of the pulsating skin area. Using an *Edelmann* pulse telephone I recorded these movements with the aid of the galvanometer. The recording head of the pulse telephone was brought to the middle of the pulsating bone defect; the glass cylinder was

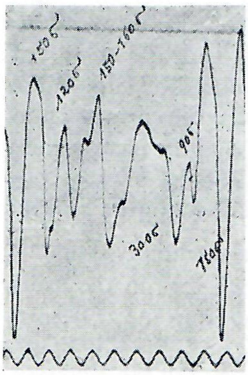

Fig. 16. 43 year old man. Bone defect on the forehead. At the top: recording of the oscillating movements from the middle of the bone defect obtained with the *Edelmann* pulse telephone and galvanometer 2 of the double-coil galvanometer. At the bottom: time in 1/10ths sec.

positioned comfortably upon the rim of the bone defect. The motions of the knob induce oscillations of the microphone plate of a telephone and the currents which are thereby generated are led to a galvanometer. In this particular case the double-coil galvanometer was used. Thus, a record was obtained of which a segment is shown in Figure 16. At the top of the record a single cerebral pulsation is shown which is included between the two deepest points of the curve. Here also, to simplify matters, I have entered into the curves the *time* values of the individual oscillations, *which alone are of importance in this record.* The lower time marker again indicates time in tenths of a second. In any case, however, it is evident from this, that the motions in the region of the defect are much more complex than it appears at first glance. I also believe that under certain circumstances these movements could perhaps exert a modifying influence upon the current oscillations recorded from a defect, even if one were to use a type of electrode such as the described lead foil which may be closely fitted to the shape of the surface to which it is applied. However, I am of the opinion that the current oscillations recorded from the skin over a skull defect cannot be caused *exclusively* by the movements of the brain, *i.e.* only by the degree of filling of the cerebral vessels. The time relationships of the single oscillations *and* the relationships of the magnitudes of the individual fluctuations of the brain movements argue most categorically against it. I can for instance not imagine through what kind of permutations the motions of the dura in an epidural needle recording could cause the regular sequence of the curve as represented in Figure 4 (page 48), such that six large waves of almost equal magnitude and also six small, again completely regular, waves should correspond to each single brain movement. But, when recording from within bone defects, one has to consider the movements of this area and the resultant variable pressure against the electrodes as an important source of artefact.

One could think that the arguments just presented are completely superfluous, since the recording of the current oscillations with the characteristic waves succeeds in people in whom apparently pulsating oscillations of the recording site are out of the question, because at the particular recording site no skull defect exists and thus there are no brain movements. This, however, would be completely wrong. Simple considerations show that the skin everywhere is subject to pulsatory oscillations as is well enough known from plethysmographic investigations. If, however, only fluctuations in the degree of filling of the blood were the cause of the current oscillations that one can record from the skull, with or without a bone defect, then one should actually also be able to record the same curves from other parts of the body, *e.g.* when taking a record from the upper arm and forearm. According to searching investigations carried out to this end by me, this is not at all the case. In fact one also obtains a curve which exhibits current oscillations, but these do not show the characteristic waves of first and second order at all. Nevertheless, one could again take exception to this by saying that the conditions on the scalp are essentially different, insofar as the skin there is stretched over a firm bony base, whereas in the arms, muscles and vessels, etc., lie under the skin. To counter this objection too, I tried to record curves from my right tibia with the double-coil galvanometer and needle electrodes which were placed subcutaneously 6 cm apart after having been inserted as far as the bone. When the galvanometer was set at its highest sensitivity, I could record photographically a few isolated small oscillations, but I did not in the least obtain a curve similar to the one I was able to record from the skull. I also said to myself that if the filling of the blood vessels produces oscillations of the electrical current which can be recorded from the skull, then the oscillations of the curves apparently originating from the brain should surely increase if the vessels of the scalp and brain were to be artificially dilated. With needle electrodes subcutaneously placed over both parietal eminences and recording through galvanometer 1 of the double-coil galvanometer, I was able to record on myself the known current oscillations discussed above. A handkerchief upon which 5 drops of amyl nitrite had just been dropped was brought before my nose. I inhaled the amyl nitrite and shortly there occurred a marked dilatation of the external vessels of the face and of the scalp; I noticed a distinct pounding of the temporal arteries. During all this time the galvanometer curve from the two parietal eminences was being written continuously. No amplitude increase of the current oscillations occurred in spite of the fact that upon inhalation, amyl nitrite causes a dilatation of the vessels of the scalp and of the brain[1]. This observation made on myself also militates against a purely vascular origin of the current oscillations recorded in man from the scalp and from the epidural space.

Then finally still, to leave nothing that occurred to me untried and to reassure myself completely on this point which caused me many worries, I carried out the following investigation on my son Klaus: I used small lead foil electrodes which were placed in the described manner on the two parietal eminences. These were laid on top of a piece of flannel and covered by a similar piece; they were firmly pressed to the skull by a rubber bandage. I thus recorded from the scalp to galvanometer 1 of the double-coil galvanometer. Exactly in the midline between the two parietal eminences the recording pin of the *Edelmann* pulse telephone was placed which, as reported above, had already been used for displaying the pulse in the area of defect

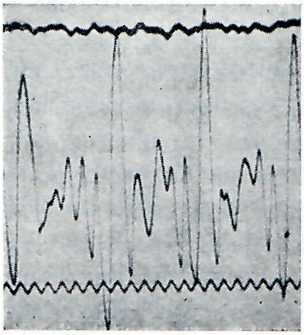

Fig. 17. Klaus at the age of 16 years. Double-coil galvanometer. Condenser inserted. Recording from both parietal eminences with small lead foil electrodes. Oscillations of the scalp between the two parietal eminences are recorded with the *Edelmann* pulse telephone. At the top: the current oscillations recorded from the scalp; in the middle: the mechanical oscillations of the scalp; at the bottom: time in 1/10ths sec.

in Dr. G. The pulse telephone was connected with galvanometer 2. Thus was obtained the curve of which a segment is shown in Figure 17. On the top is written the familiar curve of the current oscillations, as they can be recorded from the scalp; the deflections certainly are not very large, because only a small electrode surface could be used, and in addition the electrodes were lying on hair which even though it had been cropped fairly short, nevertheless did not provide a hairless scalp. However, in the top curve one can distinguish clearly enough, for our purposes at least, the waves of the first order. In the middle, the time relationships of the scalp movements are recorded by means of the pulse telephone. At the bottom, time is indicated in tenths of a second. It is immediately apparent that the mechanical oscillations of the scalp, which of course are caused by the changing degree of filling of the vessels, do not coincide *in time* with the cerebral waves. On the other hand I was nevertheless very amazed at

[1] *Meyer* and *Gottlieb*: *l. c.*, p. 308 [see footnote on p. 43].

the considerable oscillations which the scalp exhibits, even over an intact skull. One recognizes from this how advisable it is to carry out such investigations in order to guard oneself against serious errors.

I believe that in view of the results of these investigations I must reject the criticism that the current oscillations which can be recorded from the skull over bone defects or also from the intact skull and from the epidural space, and which were described in detail above, are merely the expression of movements of the brain or only of the scalp caused by variations in the degree of filling of the vessels, arteries, capillaries and veins. As I already once emphasized before, with such an assumption one could by no means explain such a regular curve, displaying oscillations which essentially are always of the same size within *one* heart beat, as *e.g.* shown in Figures 4 and 5. Neither, on the other hand, would it be easy to explain merely on the basis of fluctuations in the filling of blood vessels *such* irregular curves as those reproduced in Figures 7 and 8.

By disproving the assumption that the current oscillations recorded from the scalp or from the epidural space are caused by a changing degree of filling of the blood vessels of the scalp or brain, one has, of course, not yet refuted the other objection to which *Tcheriev* referred, that the electrical phenomena originate through friction of the blood on the blood vessel walls. Certainly, however, one could then expect a somewhat different course of the electrical oscillations and surely also a certain parallelism with the pulse wave. But in my opinion the animal experiment too militates against such an assumption. Exsanguination causes a transient increase in the amplitude of the current oscillations recorded from the brain surface of the dog; likewise the bilateral ligation of the carotid arteries does not influence their magnitude and, finally, it can be observed that in spite of the cessation of the heart beat and of respiration, as shown in Figure 3, the current oscillations persist. Just like *Kaufmann*, *Cybulski* and *Pravdich-Neminsky*, I also believe that *Tcheriev's* objection is incorrect.

But as far as man is concerned one may still have to ponder the question whether, *e.g.* with needle electrodes inserted subcutaneously into the tissue, one records streaming currents[1]. As streaming currents one designates those electrical currents which appear when a fluid in which the electrodes are placed is made to flow, starting from a state of rest. These streaming currents, however, appear also whenever in an already flowing liquid the velocity of flow changes. Thus, for example, in every artery the velocity of flow is enhanced with each systole and therefore an oscillation coincident with the pulse occurs at an electrode introduced into the artery. These streaming currents in my opinion could only be relevant to our considerations if by chance the tip of the subcutaneously introduced needle lay in a larger blood vessel of the kind that may indeed be found in the subcutaneous tissue. But certainly this could only be an exceptional situation and would be recognized because of a considerable local hemorrhage. Furthermore these currents would also again have to coincide in time with the pulse wave.

[1] *Gollwitzer-Meier* and *Steinhausen*: Pflügers Arch., **220**, 551 (1928).

Likewise the electrical phenomena described by *Helmholtz*[1] as vibration currents are in my opinion of no importance for the question under consideration. If the vibrations caused by the blood flow, or the flowing of the blood in the subcutaneous connective tissue by transmission to the electrodes were sufficient to cause these current oscillations, why then do they also not appear when one records from the tibia? Why does one not find exactly the same current oscillations consisting of waves of first and second order on the forearm, etc.? All these arguments appear to me to militate against the assumption of an exclusively vascular origin of the above described current oscillations.

I have, however, to discuss yet another source of artefact which under certain conditions could cause distortions of the current oscillations recorded from the scalp or from the epidural space. This is muscular movement. One might think that movements in the area of the M. frontalis, M. occipitalis, M. corrugator supercilii, Mm. ciliares, M. orbicularis oculi and of the other eye muscles, the muscles of the external ear and finally of the very powerful M. temporalis and M. masseter and perhaps also of the muscles of expression could be involved in the generation of these current oscillations recorded from the skull. Anyone who ever recorded muscle currents with the string or the coil galvanometer will immediately discard the notion that the curve of the presumed cerebral current oscillations, repeatedly shown above, merely represents transmitted muscle currents. Muscle currents look quite different. One could, however, be dealing with a displacement of the electrodes on the scalp. Or, in the case of needle electrodes, there could be displacements of the electrodes within the scalp or subcutaneous tissue, caused by the pulling of these various muscles. *Sommer*, in the above cited paper, demonstrated in an excellent way that in fact the area of contact between the skin and an electrode placed on it can be considerably influenced by muscle contractions, *e.g.* by contraction of the frontalis muscle, and that oscillations of an existing current can thereby be elicited. But here too, all theoretical considerations do not lead to our objective and what matters is testing by experiment.

In a series of investigations I therefore examined the effect of voluntary movements of the above muscle groups on the curves recorded from the scalp. The result was that the influence of these active muscle movements can be demonstrated both upon needle electrodes in the subcutaneous tissue and upon lead foil electrodes which are firmly pressed against the skin. With the insertion of a condenser into the circuit, this influence manifests itself mainly in a simple upward or downward displacement of the level of the galvanometer line. If however the same movements are performed several times as rapidly as possible in a repetitive manner, then in fact wave-like oscillations may appear. But they still differ markedly from the first and second order waves of the curves recorded from the scalp. Chewing movements performed rapidly in a repetitive fashion cause current oscillations of a duration averaging 400 σ; frowning causes oscillations of 450 σ. The shortest oscillations are seen with repetitive eye blinking, performed as rapidly as possible; wave-like oscillations of a duration

[1] *Wiedemanns* Annalen der Physik. **11**, 737 (1880).

of 160–180 σ then appear. Other movements, *e.g.* movements of the entire head, can also elicit wave-like oscillations; with very rapidly performed forward and backward head nodding movements these oscillations measure 250 σ, with head rotation 200 σ, etc. Speaking, tongue movements, mouth movements such as puckering of the lips, pulling the mouth to the side and other similar movements did not influence the deflections of the curve recorded from the skull, if these movements were not associated with others, *e.g.* speaking with head rotation, eye movements, etc. Naturally, the influence of these movements was most marked when metal plate electrodes were attached to the scalp; but, as mentioned before, they appeared also with the frequently used lead foil electrodes and even with needle electrodes! If one knows these effects they are easy to interpret. With lead foil electrodes placed on the forehead and occiput the influence of these movements was much more pronounced than when the lead foil electrodes were placed upon the two parietal eminences; in the latter case the influence of all the above movements could hardly be demonstrated anymore. Undoubtedly, this greater susceptibility to movements of the muscles is a disadvantage of the recording arrangement with lead foil electrodes placed on the forehead and occiput. The interpretation of the records, however, hardly ever seriously suffers because of this. I believe it to be completely impossible that the above reported current oscillations and their first and second order waves could be caused merely by these muscle movements. However, the muscle movements can under certain circumstances markedly change the current oscillations of first and second order by altering the areas of contact between electrodes and skin surface, or those between the needle electrodes and the surrounding subcutaneous tissue. They may thereby influence the form of the curve and lead to distortions. If perchance the current oscillations of apparent cerebral origin were to represent unperceived movements, then surely one should be able to record these over a bone defect just as well or as poorly as on the opposite side. Investigations in people with skull defects, however, have shown unequivocally that *e.g.* on the left side with epidural needle electrodes placed in the area of the defect, one obtains the known curve, but that on the right side with needle electrodes inserted subcutaneously against the intact skull, one does not obtain as pronounced oscillations as in the area of the bone defect, even though they are present. If these oscillations were only the result of transmitted movements, then surely they would show up equally on both sides, perhaps even better on the intact than on the other side, where at operation the fibers of the frontalis muscle, etc., had been severed or damaged in some other way. Certainly one must take muscular movements into consideration as a source of artefact when recording current oscillations from the skull. I do not, however, believe that these current oscillations are caused solely by the movements of the external muscles of the head or even by the movements of the eye muscles.

Finally, one might still consider whether the currents could originate in the human skin. Perhaps the smooth musculature, the piloerector muscle, but also the skin glands, *i.e.* the sebaceous and the sweat glands, might play a part in this[1]. Gland

[1] See *Stöhr*: Lehrbuch der Histologie, 15th ed., p. 379, Fig. 330, 1912.

currents, however, have a different course and therefore we are probably justified in excluding them from our considerations without further ado. But the situation is different for the piloerector muscles which belong to the smooth musculature. I recorded the current oscillations in the subcutaneous tissue in the area of the bone defect and thus bypassed the skin. Yet, currents originating in the skin could surely also be conducted downwards, exactly as the currents presumably originating from the cortical surface by going through the dura and also through the periosteum reach the needles in the subcutaneous tissue. I therefore coated subcutaneously inserted straight surgical needles including their tips with varnish. This covered their entire surface as far as the latter penetrated below the skin, except for a small area left bare of varnish on the undersurface of the tip. With these needles the current oscillations showed up in the same fashion. Yet, even so a conduction of the currents from the skin downwards was not excluded. But if these were really currents originating from the skin, it would be strange that they should only appear on the scalp, but not also for instance on the leg, on the calf or over the tibia, where surely piloerector muscles are also present in abundance. From the arm too where, as is well known, the skin contains hair and therefore piloerector muscles, such records cannot be obtained. This, in my opinion, militates quite categorically against the cutaneous origin of the above described current oscillations. But I believe that on two occasions, when recording with lead foil electrodes from the skin surface, I saw current oscillations which perhaps could be attributed to the influence of the piloerector muscles. In a man, who on a cold day in spite of adequate heating of the examination room felt fairly chilly, goose pimples developed; short oscillations of 17–20 σ, in addition to the usual ones of 90 and 35 σ, appeared simultaneously in the electrocardiogram *and* in the curve recorded from the surface of the skull in the area of a bone defect, as well as in that recorded from the opposite side. These short oscillations, as I said, could be demonstrated in the electrocardiogram as well as in the curve recorded from the skull, and this not only with the double-coil galvanometer, but also with the string galvanometer. I presume that these short oscillations were related to the goose pimples and that they were perhaps caused by the contraction of the piloerector muscles. Of course I am not able to prove this.

In the course of the investigations, another not insignificant source of artefact became apparent which has to be considered in detail. This is a fact which I already mentioned once before, namely the ubiquity of the electrocardiogram. I already explained above that recordings from the head and the back, the head and the chest, etc., always yielded an electrocardiogram. I even saw the electrocardiogram with a lead foil recording from the skull in which the lead foil electrodes were lying on the forehead and occiput. The main deflections of the electrocardiogram could be recognized without difficulty in this curve. I therefore, at least temporarily, arrived at the somewhat peculiar notion that the curve supposedly recorded from the dura was actually only a distorted electrocardiogram, an electrocardiogram altered by changes in the area of contact of the electrodes caused by the changing blood content of the skin and brain and, perhaps also by associated changes caused by polarization and capacitative phenomena of the skin. With needle electrodes one bypasses the skin, of course, and thus the latter with its electrical fluctuations could not induce any changes; but the objections with regard to the changes in the area of contact between electrode and tissue and to polarization remained[1]. Figure 3 obtained in the animal experiment in which current oscillations recorded from the brain surface continue in spite of the arrest of the electrocardiogram, decisively argues against the notion that the supposedly cerebral curves may only represent an altered electrocardiogram. In any case, however, the fact that a distorted electrocardiogram appeared in the course of a scalp recording, led me later to record an electrocardiogram simultaneously and in addition to the current oscillations derived from the skull in all these investigations. This circumstance was also the reason why I set such particularly great value on the possession of a double-coil galvanometer. The simultaneous recording of the electrocardiogram also has the great advantage that, from the known delay of the pulse in its propagation to the brain, one can by calculation approximately determine the time of onset of each cerebral pulsation in the curves recorded from the skull, even when these pulsations are not recognizable in the curves.

I therefore believe I have discussed all the principal arguments *against* the cerebral origin of the curves reported here which in all their details have time and again preoccupied me, and in doing so I have laid to rest my own numerous misgivings. Moreover I refer to the results of the animal experiments in dogs and monkeys, performed from *Caton* to *Pravdich-Neminsky*, which for this very reason I reported in somewhat greater detail above. I believe indeed that the cerebral curve which I have described here in great detail originates in the brain and corresponds to *Neminsky's* electrocerebrogram of mammals. Because for linguistic reasons I hold the word "electrocerebrogram" to be a barbarism, compounded as it is of Greek and Latin components, I would like to propose, in analogy to the name "electrocardiogram", the name "*electroencephalogram*" for the curve which here for the first time was demonstrated by me *in man*.

I therefore, indeed, believe that I have discovered the electroencephalogram of man and that I have published it here for the first time.

The electroencephalogram represents a continuous curve with continuous oscillations in which, as already emphasized repeatedly, one can distinguish larger first order waves with an average duration of 90 σ and smaller second order waves of an average duration of 35 σ. The larger deflections measure at the most 0.00015–0.0002 V.

To begin with I only investigated those continuous oscillations which correspond to the continuous oscillations recorded by *Cybulski*, *Kaufmann* and *Neminsky* from the cerebral cortex of the dog and the monkey. In man, as I said, such investigations have up to now been unknown. It is true that *Bissky*[2] claimed "he had discovered the physiological rhythm of the human nervous system" and had established that

[1] *Note added to proofs*: Meanwhile I obtained in the area of skull defects in several cases exactly the same curves as those reported above by using chlorided silver needles which according to *Proebster* (Über Muskelaktionsströme am gesunden und kranken Menschen, Stuttgart, 1928, p. 10) can be considered as practically non-polarizable.

[2] *Friedländer*: Die *Bissky*sche Diagnostoskopie. Umschau, **1926**, 1053.

"our nervous system and brain only reacts to a special alternating current with a certain number of oscillations per second". The frequency of this alternating current is, however, several times greater than the one that corresponds to the oscillations of first and second order found by me in man. I gather from a paper by *Schulte*[1] concerning this method of *Bissky* that the current that was used exhibited 335 interruptions per second. It is in any case evident from this that these investigations by *Bissky* bear no relationship to our findings. For, of the larger waves of the human electroencephalogram there are 10–11 in one second, of the smaller ones 20–30 in one second and therefore if one adds both together, there are about 10–30 in one second.

In contrast to *Bissky*'s vagaries serious investigators showed evidence suggesting an entirely different rhythm of the human central nervous system. Of many investigations I select only those of *P. Hoffmann* and *H. Strughold*[2]. They studied in man by means of action currents the voluntary innervation in movements at the elbow joint and found that a double rhythm of the action currents can be demonstrated. They distinguish between a rhythm A and a rhythm B. Rhythm A shows 10–50, rhythm B 150–180 current pulses per second. These investigators express the opinion that rhythm A probably originates from higher centers, whereas rhythm B may be caused by the activity of the last motor neuron. This rhythm A of 10–50 current pulses per second which is attributed to the higher centers of the central nervous system would correspond well to our 10–30 per second waves of the electroencephalogram. But in any case these objective findings by *Hoffmann* and *Strughold* already show that it is really wrong to speak of a rhythm of the human central nervous system in general. The various subdivisions of the central nervous system have different rhythms.

If we now consider the question of how the electroencephalogram originates, I would like to point out again that it is not only possible to record these current oscillations from the dura of the cerebrum, but also from that covering the cerebellum. The electroencephalogram therefore certainly does not represent a particular characteristic of the cerebrum, even though perhaps the electroencephalogram of the cerebellum may show a somewhat different form and more infrequent large current pulses. But we are completely unable to determine whether the current originates in the cortex of the cerebrum and cerebellum or in deeper parts, and I wish once more to refer to *Garten's*[3] above quoted view. It is, however, certain that the oscillations of the electroencephalogram do not, in the strict meaning of the word, represent resting currents, but they are action currents, *i.e.* bioelectric phenomena which accompany the continuous nervous processes taking place in the central nervous system. For we have to assume that the central nervous system is always, and not only during wakefulness, in a state of considerable activity. This is, *e.g.*, true for the cortex in

[1] *Schulte*: Über Elektrodiagnose seelischer Eigenschaften. Psychol. u. Med., **1**, 62 (1925), especially p. 66.

[2] *Hoffmann, P.* and *H. Strughold*: Ein Beitrag zur Oszillationsfrequenz der willkürlichen Innervation. Z. Biol., **85**, 599 (1927). Abstract: Zbl. Neur., **47**, 614 (1927).

[3] *Garten*: *l. c.* [see footnote 1 on p. 37].

which, in addition to those events connected with consciousness, a whole series of other activities take place. Indeed, one can say that the processes connected with conscious phenomena probably only represent a small part of the total cortical work. It goes without saying that the electrical manifestations which continuously appear in the electroencephalogram are only concomitant phenomena of the true nervous processes. For one has long abandoned the old notion that the electrical phenomena in themselves are of special importance for the functions of the central nervous system. Such views were still held by *Rolando* who saw in the lamellar arrangement of the cerebellum evidence that the latter had a particular significance for the development of electricity, and also by *Baillarger*, when he compared the six-layered structure of the cerebral cortex observed by him with the arrangement of individual plates in a *Voltaic* pile[1].

We see in the electroencephalogram a concomitant phenomenon of the continuous nerve processes which take place in the brain, exactly as the electrocardiogram represents a concomitant phenomenon of the contractions of the individual segments of the heart.

Naturally, in the course of the investigations various questions quite spontaneously forced themselves upon my mind, *e.g.* whether in the human electroencephalogram too, as has been found in the animal experiment, changes occur under the influence of peripheral stimuli; furthermore, the question whether one would be able to demonstrate a difference of the electroencephalogram in wakefulness from that of sleep, how it would behave in narcosis and others of this kind. Above all, however, what about the question which already preoccupied *Fleischl von Marxow* when he wrote that under certain circumstances one would perhaps be able to go so far as to observe the electrical concomitants of the events in one's own brain? Is it possible to demonstrate the influence of intellectual work upon the human electroencephalogram, insofar as it has been reported here? Of course, one should not at first entertain too high hopes with regard to this, because mental work, as I explained elsewhere, adds only a small increment to the cortical work which is going on continuously and not only in the waking state. But it is entirely conceivable that this increment might be detectable in the electroencephalogram which accompanies the continuous activity of the brain. Naturally, I have performed numerous such experiments, but I did not arrive at an *unequivocal* answer. I am inclined to believe that with strenuous mental work the larger waves of first order with an average duration of 90 σ are reduced and the smaller 35 σ waves of second order become more numerous. With complete mental rest, in the dark, with the eyes closed, one obtains the best electroencephalograms showing both types of waves in a fairly regular pattern. This information is based primarily upon investigations in healthy human individuals who had no skull defects and in whom therefore records were taken from the scalp with lead foil electrodes. In this type of investigation, *i.e.* when recording from the skin, the interference especially by the *Tarkhanov* phenomenon[2] must however be

[1] *Soury, J.*: Système nerveux central. **1**, 570 (Paris 1899).
[2] *M. Gildemeister*: Die Elektrizitätserzeugung der Haut und der Drüsen. Handbuch der normalen und pathologischen Physiologie, VIII, p. 776, 1928.

considered. The *Tarkhanov* phenomenon, which can be demonstrated particularly during the performance of intellectual tasks, can level out the larger deflections of the electroencephalogram by a compensating action, so that the amplitude of the waves of first order decreases and one gains the impression that the small waves stand out more prominently. Of course one can avoid being deceived in this manner by measuring the length of the individual wave types, but for this purpose one naturally needs very well written curves. Especially in experiments on my son Klaus I gained the impression that with exacting intellectual work, even with just a high level of attention, the smaller and shorter waves predominate. However, this can by no means be regarded as a conclusive finding, but still requires many follow-up investigations so that I would not like to commit myself to a definite answer here. I hope, however, to be able to report later on this particular question. Naturally the investigation of the influence of drugs and stimulants upon the electroencephalogram would also be of great interest so that really an abundance of problems is presented, for here in the electroencephalogram we may possess at last an objective method of investigating the events occurring at the higher levels of the central nervous system. Predominantly practical considerations were those which repeatedly for many years induced me to work on this task, especially the specific question whether, as is the case for the electrocardiogram in heart diseases, one could discover an objective method of investigating *pathological* alterations of the activity of the central nervous system. This, of course, could then also become of utmost importance from the diagnostic point of view. I already carried out a series of investigations in this direction. Here too, I cannot make any definite statements because unequivocal results are not yet available. But these studies as well as those of the problems indicated above will be continued as far as time will allow me, and I hope to be able to report on them later. In the pursuit of these questions and investigations it would of course be desirable if one could use still more sensitive instruments of the type which technology is in fact able to provide[1].

[1] Siemens and Halske, upon my inquiry, offered me such an apparatus as early as 1927; however, I had to forego its acquisition because of the costs.