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Historical Section

History and Evolution of Electroencephalographic Instruments and Techniques

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Several important themes emerge in the history of EEG instruments and techniques. The first is that leading-edge electroencephalographers often design and construct their own apparatus. Alternatively, they acquire and adapt instruments originally intended for other uses. These uses range from other areas of electrophysiology to communications, audio engineering, office machines, and military surveillance. Many of the participating technologists, or the investigators themselves, had backgrounds in these areas and brought their knowledge into emerging EEG developments. At times, EEG returned the favor as concepts, methods, and devices developed for EEG found use in other fields. As commercial systems became available and evolved to considerable sophistication, laboratories continued to seek additional capability, either by developing it directly or by acquiring and using available instruments in a novel way.

Another dominant theme is the extraordinary foresight and vision of the earliest workers. Virtually all of the major areas of EEG research and clinical practice were understood and practiced within the first 20 years after human EEG was discovered. In much of this work, standards and conventions emerge surprisingly early. For example, the first scientist to record human EEG, Dr. Hans Berger, coined and used the terms "alpha" and "beta" essentially as they are today and established the use of the 30 mm/s paper speed, which subsequently became a standard. Within 20 years, electrodes and preamplifier characteristics were achieved that equal those in use today.

EEG development has consistently taken advantage of the state of the art in technology. Many systems emerged within the same year that the technological capability first appeared. The use of sensitive galvanometers and amplifiers, photographic and inkwriting devices, electronic circuits, and digital systems appeared in EEG very shortly after they were developed. EEG pioneers have always kept a sharp eye on the latest technology and were ready to take it up and use it as soon as possible.

The development of EEG equipment was and is pivotal to the advancement of the science itself. As new capabilities emerged and new signals became evident, the interpretation of the signals could proceed. Groundbreaking work has had to proceed along two parallel lines. One was the pure electrophysiological work necessary to acquire data; the other was the interpretation and understanding of the records, the separation of the important from the unimportant. This latter task often proved to be more difficult than the former, which was not in itself trivial, either.

THE EARLIEST ROOTS: PRE-EEG

The early roots of electrophysiology can be traced to the Italians Luigi Galvani (1737–1798) and Alessandro Volta (1755–1832) and to the Englishmen George Ohm (1787–1854) and Michael Faraday (1791–1867). Their contributions led, by the mid 1800s, to the general understanding of electrical potential and current and to the recognition that living tissue had

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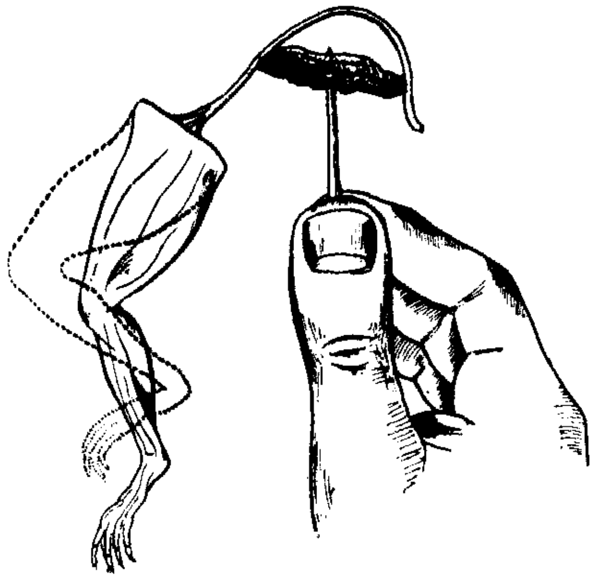


FIG. 1. A very early electrometer. In a test of Galvani's claims, Alexander von Humboldt observed an isolated frog muscle to contract when a nerve impulse is induced by dissimilar metals. (Reproduced from Sirol, 1939.)

important electrical properties, particularly in connection with muscle activity.

The earliest electrical detector was the frog nerve-muscle preparation developed by Galvani and first used to detect static electricity (Fig. 1). His work continued along the lines of studying lightning and making static generators using glass, resin, and so on. He used arrays of prepared frogs to detect both natural and man-made electrical charges. He was able to develop the concept of animal electricity, and his studies, published in his *Commentarius* of 1791, aroused considerable interest and controversy.

Volta at first accepted Galvani's work but later refuted it. His work emphasized the electrical properties of combinations of metals and chemicals, and he took issue with the concept of physiologically produced electricity. Volta's experiments, designed to refute Galvani, laid the foundation for our contemporary energy-based technology and economy. Ohm and Faraday conducted important work on the nature of potential and current, the behavior of conductors and insulators, the interactions between current and magnetic fields, and the use of coils and capacitors in alternate-current (AC) circuits.

Early electrical observations were made using static electrometers called "electroscopes," which revealed weak electrical potentials in the form of some subtle mechanical change, such as the movement of fine gold leaf or changes in the curvature of a meniscus of mercury. These devices were able to detect gross changes, such as the direct-current (DC) potentials of nerve and muscle, or the largest electrocardiographic (EKG) signals. Indeed, the EKG was studied, most notably by Waller in the 1870s, using the capillary electrometer; the study of EEG would have to wait until the development of the mirror galvanometer and the string galvanometer, which could respond with a time constant of less than several seconds.

Electromagnetism was discovered in 1820 by Hans Christian Oersted (1777–1851), who constructed a voltaic battery sufficient to bring a conducting wire to red heat and to deflect a compass needle. J. S. C. Schweigger repeated this work and introduced the concept of adding additional turns of the wire, giving the galvanometer the term "multiplier." He went on to develop both the moving coil and the moving vane galvanometers.

C. L. Nobili, of Florence, constructed a galvanometer with a double coil of 72 turns and two magnetic needles. The needles met in the middle of a "figure eight" of coil and were sufficiently sensitive to compare with the Galvani frog preparation. Nobili avoided the use of metals in his physiological work, using exclusively glass beakers and cotton thread. He continued to refine his galvanometer and in 1828 was finally able to obtain indisputable evidence of frog-related current. He arranged frogs in series and was able to both cancel and to reinforce their current.

The earliest scientists to focus on physiologically related electrical phenomena were Carlo Matteucci (1811–1868) and Emil Du Bois-Reymond (1818–1896). Matteucci studied frog muscle preparations and was the first to observe the action potential that preceded contraction as well as the reduction in measured current during the contraction. Du Bois-Reymond constructed a galvanometer with more than 4,000 turns, increasing its sensitivity. He also developed nonpolarizable electrodes made of clay and understood the importance of their use. Such electrodes were used for many years, including the first animal and human EEG recordings. He used the term "muscular current," introduced the term "negative variation" in connection with this reduction, and recognized its significance. He was important in his recognition that the limitations of the organ/instrument system could produce phenomena that were not in themselves properties of the organ itself. He observed that the galvanometer was useful in the assessment of

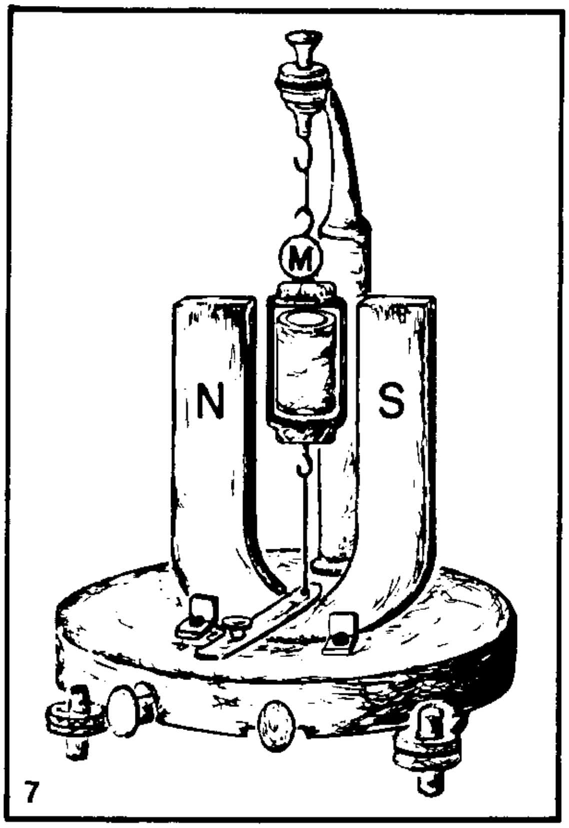


FIG. 2. d'Arsonval galvanometer (1882). A moving coil is suspended in a permanent magnetic field; current flow causes rotation. The deflection is recorded via a light beam reflected from the attached mirror. (Reproduced with permission from Grass, 1985.)

continuous current but that it would fail to represent intermittent changes. He also observed the negative variation in nerve, which was beyond the capabilities of Matteucci's instruments.

The galvanometer was significantly refined in 1858 by Lord Kelvin (William Thompson), but this design was still essentially a DC instrument. The observed potential was visualized as the movement of a small needle, deflected by the magnetic force produced by current in the recording coil. This was further refined by d'Arsonval in the 1870s to incorporate a moving coil in a strong, permanent magnetic field (Fig. 2). Because of the low mass of the reflecting mirror, this instrument could operate with a minimal coil, producing an impedance of about 5 kohms and a time-constant of about 4 s. This device continued to be refined through the 1880s and found significant use in electrophysiology. The d'Arsonval movement became the conceptual basis for the Grass and other pen oscillographs of the 20th century.

L. Hermann (1838–1914) began as a student of Du Bois-Reymond and contributed significant original thinking, particularly in the theoretical area. He doubted the existence of resting currents and extensively studied the differences between normal and injured tissue. He developed the concept of negative variation, turning it into an "action current," and showed the existence of a wave of excitation. He interpreted this as a self-propagating state that is conveyed from one section of the nerve to the next. This work led to the later development of the membrane theory of ionic action currents by J. Bernstein (1839–1917). Hermann also developed further refinements to the galvanometer, including the use of optical lenses to improve the visibility of small deflections produced by weak measured currents. This instrument was also known as the Wiedemann galvanometer, after Gustav Heinrich Wiedemann (1826–1899) who developed improvements and produced devices for other investigators.

The electrometer also was refined during this time. John Burdon-Sanderson (1828–1905) was an eminent physiologist at the University of London and a member of the Royal Society. He had a capillary electrometer produced by Fredereck J. M. Page (Fig. 3), which he initially used to record potentials from the heart of the frog. He went on to perform the earliest

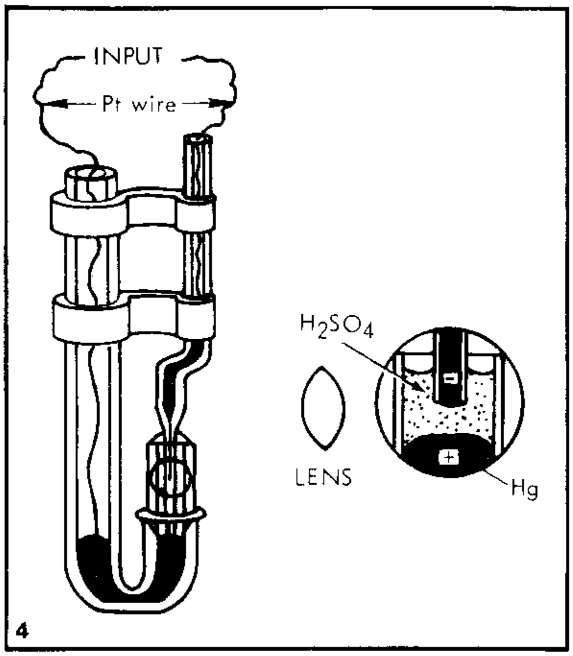


FIG. 3. Capillary electrometer of the type used in the 1870s. This drawing is after a design by Frederick Page. The measured potential is manifested in the curvature of the mercury meniscus. (Reproduced with permission from Grass, 1985.)

stereotactic studies on the brain but never recorded EEG potentials.

The capillary electrometer was improved by Gabriel Lippmann (1845–1921) and was used by Waller in 1880 to first record the EKG in dog and man. The input impedance of the capillary could be as low as 1,000 ohms, requiring the use of very large electrodes. Buckets of salt water were used for these early studies.

STIMULATION STUDIES

The earliest understanding of cerebral function and localization was derived from experience with lesions and from stimulation studies. Most notably, G. Fritsch (1838–1927) and Eduard Hitzig (1838–1907), in Germany in 1870, produced specific motor responses in anesthetized dogs in response to galvanic stimulation. This work was motivated by Fritsch's observations of contralateral muscle activity in response to the dressing of an open head wound during the Prusso–Danish War. Sir David Ferrier (1843–1928) in England, conducted subsequent work on apes and other vertebrates, producing sustained movements in response to faradic stimulation. Although stimulation and functional mapping progressed rapidly, the systemic recording of brain electrical activity was much slower in coming. This work was stimulating in another important way, however, for it made the earliest EEG researchers very aware of the electrical properties and functional organization of the brain and motivated their search for intrinsic electrical activity.

CATON: THE FIRST ELECTROENCEPHALOGRAPHER

Richard Caton (1842–1926) at the Royal Infirmary, Liverpool, was able to record electrical activity from the exposed brains of rabbits and monkeys using a mirror galvanometer. This work was first reported in 1875 and in more detail in 1877. He describes the instrumentation as follows:

> Sir William Thomson's reflecting galvanometer, etc., with Du Bois-Reymond's non-polarisable electrodes. Small light electrodes were employed, supported by small screw-clamps, fixed firmly to the skull, in such a manner that no movement of the animal's body could affect the position of the electrodes on the brain.

Without Du Bois-Reymond's high-quality electrodes, it is certain that Caton would have observed a significant amount of artifact and noise, which would have likely drowned out the EEG. Fortunately, he was acutely aware of this fact and took care to prepare and use nonpolarizing electrodes. His instrument had a frequency response from DC to 6 Hz. In order to visualize the weak signals, he amplified the waveform optically by shining an oxyhydrogen lamp on the mirror and having it reflected onto an eight-foot scale placed on the wall.

Caton initially described the general positivity of the surface of the gray matter when measured in relation to deep structures. He also stated that, "The electric currents of the grey matter appear to have a relation to its function," and used the term "negative variation" to describe the event-related potential shifts. His initial premise was similar to that of the earlier frog experiments; when any part of the gray matter was considered active, its negative shift was regarded as essentially similar to the nerve action potentials recorded by Du Bois-Reymond. Such shifts were observed in relation to rotation of the head and mastication in dogs. In rabbits, he reported that, "Impressions through the senses were found to influence the currents . . . found to be markedly influenced by stimulation of the opposite retina by light." For this work, Caton is recognized as the discoverer of EEG.

The 1877 report confirmed and extended the original 1875 report. Caton reported that he had studied over 40 cats, rabbits, and monkeys. He observed variations associated with sleep and wakefulness, anesthesia, and death. He was also able to record responses to the presentation of food, which he interpreted as related to the perception of the odor of food. He investigated responses to stimulation of the skin and observed changes due to pinching of the skin of the lips and cheeks. He was unable to record auditory responses but was able to localize responses to retinal light stimulation, which were found on the posterior and lateral aspects of the hemispheres. These early observations can therefore be interpreted as the earliest records of not only oscillating EEG potentials but also of standing DC potentials, of motor-related potentials, and of sensory evoked potentials. Caton was guided in his investigations by prior work done by Sir David Ferrier in the identification of brain areas associated with motor activity including head movement, mastication, and movements of the eyelids. Caton's studies could be further interpreted, therefore, in the context of functional topography, making him the first EEG brain mapper as well.

EASTERN EUROPEAN EEG

After Caton's discoveries, EEG work shifted to Eastern Europe, as it had earlier for brain stimulation. V.Y. Danilevsky (1852–1939) in Russia, published his thesis in 1877, in which he recorded spontaneous and evoked activity from the brains of animals. In 1891, he gave full credit to Caton, indicating that he had corroborated the Englishman's studies using essentially equivalent instrumentation.

The Polish scientist Adolph Beck (1863-1939) worked in Krakow, studying under the physiologist N. Cybulski (1854-1919). He published reports of steady potentials recorded from the spine and medulla of the frog and studied the effects of cord damage and removal of the cerebral hemispheres. He used instruments similar to his predecessors and had the same difficulty in recording oscillatory currents. However, he appreciated their significance and put special effort into studying the visual cortex. He was able to record small fluctuations in the absence of stimulation and to show that they were not related to pulse or respiration. Using dogs, he observed blocking of spontaneous activity caused by light stimulation and saw similar effects produced by stimulation of a hind leg. The latter was localized to the contralateral cruciate area. He thus added desynchronization to Caton's observations, which he also extended and refined. He succeeded in observing responses to a shout, recorded from the temporal cortex. His 1890 paper was an extremely important contribution. Since it was a doctoral thesis, it included considerable details of the experimental procedures.

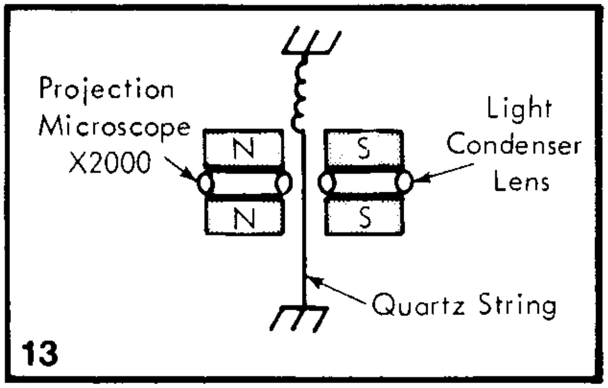


FIG. 4. Principle of the Einthoven string galvanometer. (Reproduced with permission from Grass, 1985.)

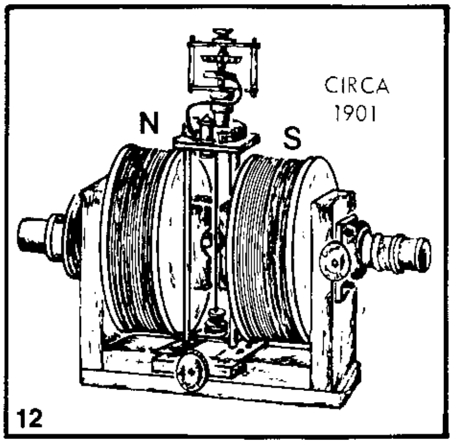


FIG. 5. Einthoven string galvanometer (1901). (Reproduced with permission from Grass, 1985.)

In his early work, Beck used Hermann's modification of the galvanometer, which allowed him to observe the divisions of the scale through a telescope. In 1908, he began to study cerebrocerebellar relationships and took up the use of the string galvanometer, which had recently been developed by Wilhelm Einthoven (1860–1927) in Holland. This instrument was the first device capable of recording physiological potentials without distortion, and it earned Einthoven a Nobel Prize in 1924. This instrument had been introduced in 1901, and it effectively replaced the capillary electrometer and the d'Arsonval galvanometer (Figs. 4 and 5). The sensitivity was as high as 1 mV/cm, and it had frequency response to 200 Hz. Resistance was between 4 and 8 kohms. The device used a gold-plated quartz filament as the moving element, which was viewed through a microscope or projected onto moving film.

After the publication of Beck's paper, the Imperial Academy of Sciences in Vienna opened a sealed report that had been provided in 1883 by Fleischl von Marxow (1846–1891). This report described observations of electrical activity from the visual cortices of various animals, resulting from illumination of the retina. He did not report any spontaneous oscillations. He showed that the responses were abolished by chloroform and by cooling. Von Marxow was a very conspicuous public figure; his report caught the attention of many subsequent researchers, including Hans Berger.

Additional work continued in the East. V. E. Larionov, working in St. Petersburg, focused on the localization of hearing and was able to differentiate the cortical responses to three tuning forks. This work was also done with the same type of galvanometer as Beck had used. The first photographic recordings of EEG signals were obtained by V. V. Pravdich-

Neminsky in Kiev. By 1912, he had worked out a method that used an Einthoven string galvanometer in conjunction with moving photographic paper. He clearly described the alpha and beta waves of the dog and saw blocking produced by sensory stimulation. His 1913 published results provide the first literature to show EEG or evoked potentials in the familiar, time-series waveform presentation. At the same time, N. Cybulski in Krakow, who had been Beck's teacher, independently developed a photographic attachment to the galvanometer. He provided EEG tracings of an epileptic seizure produced by electrical stimulation in a dog.

Until after about 1910, no investigator had a camera, or the means to produce hard copy of their observations. Indeed, Caton had to demonstrate his effects at the meeting of the British Medical Association before his report would be accepted for publication. All of his published material includes only written reports of his observations. Beck was similarly limited in his published papers, but he did include in his dissertation sketches of his preparations and graphs of the observed deflections.

After this early work, research began to occur on both sides of the Atlantic, leading ultimately to the discovery of the human EEG. This discovery did not come easily. Significant improvements in sensitivity were necessary to record the minute potentials produced on the human scalp. Several EEG pioneers had been working in electromyography (EMG) or nerve research and were thus in a position to study brain potentials when adequately sensitive instrumentation became available.

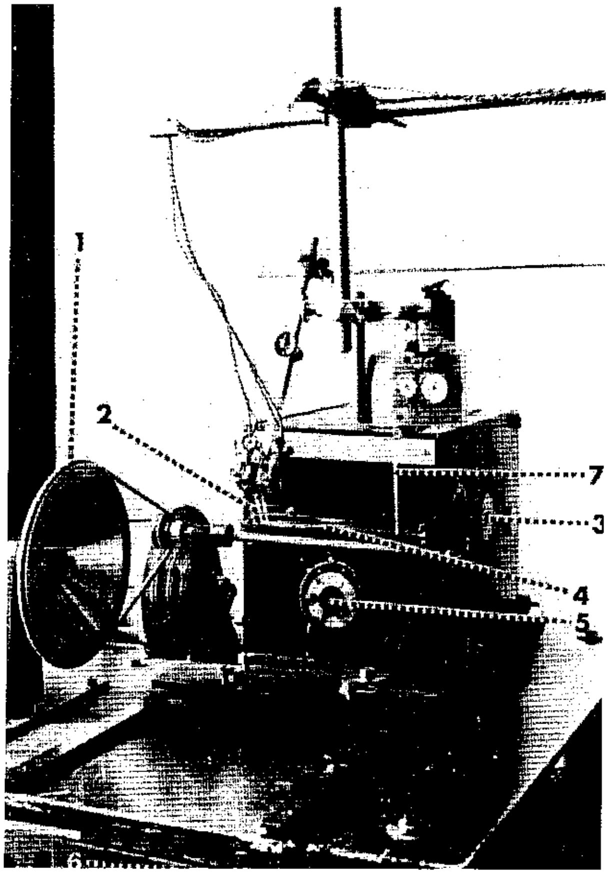


FIG. 6. Dr. Hans Berger's first string galvanometer with recording apparatus. The indicated features are as follows: (1) crank, (2) marker fibers, (3) on/off switch, (4) lens, (5) diaphragm, (6) paper box, (7) tuning fork. (Reproduced with permission from Gloor, 1969.)

BERGER: THE FIRST HUMAN ELECTROENCEPHALOGRAPHER

Hans Berger (1873–1941) became interested in the electrical activity of the brain in 1902, when he was studying temperature changes in the cortex of the dog. He had been trained in medicine and neuropsychiatry and had joined the Department of Psychiatry at the University of Jena in 1897. He had, as did Caton, an excellent understanding of neurology in general and cerebral localization in particular.

All of his early recordings were made with a Lippmann capillary electrometer. In 1902, he was able to detect the spontaneous activity reported by Caton, Beck, and Neminsky. He failed to record specific responses to sensory stimuli. His original interest was to evoke "fluctuations of electrical current," as had been described by Fleischl von Marxow. He made further recordings in 1907 but was again unable to detect effects due to sensory input. In 1910, he took up the Einthoven string galvanometer and again met with negative results to stimulation. His instrument was capable of recording EKG and nerve potentials, but its usefulness for EEG was marginal.

Later, he used the "small" string galvanometer with photographic capability, provided by Edelmann. With it, Berger was able to make permanent recordings of 1-3 min (Fig. 6). He was never able to see his recordings as they were being made. It was necessary to treat the paper photographically before the traces could be seen. He originally used silver bromide paper, 5-6 cm in width. The exposed paper ran into a metal box that was taken to a darkroom, where the paper was unrolled and developed.

In 1924, he began to record from humans (Fig. 7). On July 6, 1924, he was able to observe EEG from a 17-year-old boy who had a trepanation while undergoing

FIG. 7. One of Dr. Berger's first attempts to record the EEG in man, ca. 1924. The patient had a left-sided trepanation, and silver electrodes had been taped to the scalp. This attempt was unsuccessful. All subsequent work was done with the patient lying down. (Reproduced with permission from Gloor, 1969).

surgery for a suspected tumor. The frontoparietal surface of the cortex was exposed. As Berger described it, "Electrical activity was recorded using nonpolarizable clay cylinder electrodes and Edelmann's small string galvanometer." The electrodes were boot-shaped and were similar to those he used in 1910 to record from anesthetized dogs. He reported that the electrodes had to be positioned 4 cm apart, in the vicinity of a scar that ran over the opening in the skull. When either a 5,200-ohm platinum thread or a 3,200-ohm quartz thread was inserted in the galvanometer, the movements could be observed but were not large enough to be recorded.

In 1924, he began to use the larger Edelmann string galvanometer and was able to procure a string with a sensitivity of 1 mV/cm and frequency response to 200 Hz. Berger continued to record from human subjects but often found it difficult or impossible to make successful recordings. On March 20, 1925, he was unable to record oscillations of any kind from a protruding cerebral herniation in a 20-year-old woman. He determined that the nonpolarizable brush electrodes he was using produced a total resistance of 44,000 ohms in the electrode circuit.

Based on this experience, in 1926, he procured a Siemens double-coil galvanometer, providing a sensitivity of about 130 µV/cm. He noted that, whereas the large Edelmann galvanometer produced a calibration of 10 mm = 0.001 V, the Siemens oscillograph was "several times more sensitive and its deflections about 7½ times as large as those obtained with the string galvanometer" (Gloor, 1929). It had the additional advantage of providing black-on-white traces, instead of the light-on-dark produced by the earlier galvanometers. The input impedance of this instrument was 3–10 kohms, so he used low-impedance pad or foil electrodes applied to the surface of the head. He noted, however, that the Siemens design was unable to simultaneously measure the resistance in the electrical circuit. For this, the Edelmann device would continue to be used (Fig. 8).

The tracing from another man, aged 40, who was undergoing surgery for a "gliosarcoma," was published in the 1929 report and is the first published instance of human EEG. This recording was made using zinc-plated steel needles, insulated except for their tips, inserted into the subcutaneous tissue. Although these were not nonpolarizable electrodes, they had the advantage of bypassing the skin and its concomitant "very complicated electrical conditions, which are not easily comprehended" (Gloor, 1969). These were sterilized and inserted into the subcutaneous tissue beneath an elevated skinfold.

In the search for suitable electrodes, he experimented with nonpolarizable funnel electrodes containing zinc sulfate. Their resistance was 530–2,500 ohms. Although they produced excellent recordings, the possibility of skin corrosion was too great for their continued use. In his dog studies, he substituted amalgamated zinc plates for the clay electrodes, primarily to avoid local cooling of the brain. These plates measured 4 × 12 mm, which he fashioned with rounded corners and inserted subdurally.

He abandoned nonpolarizable electrodes for a while, reasoning that "for rapidly alternating current oscillations, nonpolarizable electrodes . . . were not necessary at all." He changed to metal electrodes, using moist, warm pads and large surface areas to reduce resistance. He increased the electrolyte concentration to further reduce resistance. Using copper plates with 20% sodium chloride in a flannel pad, he

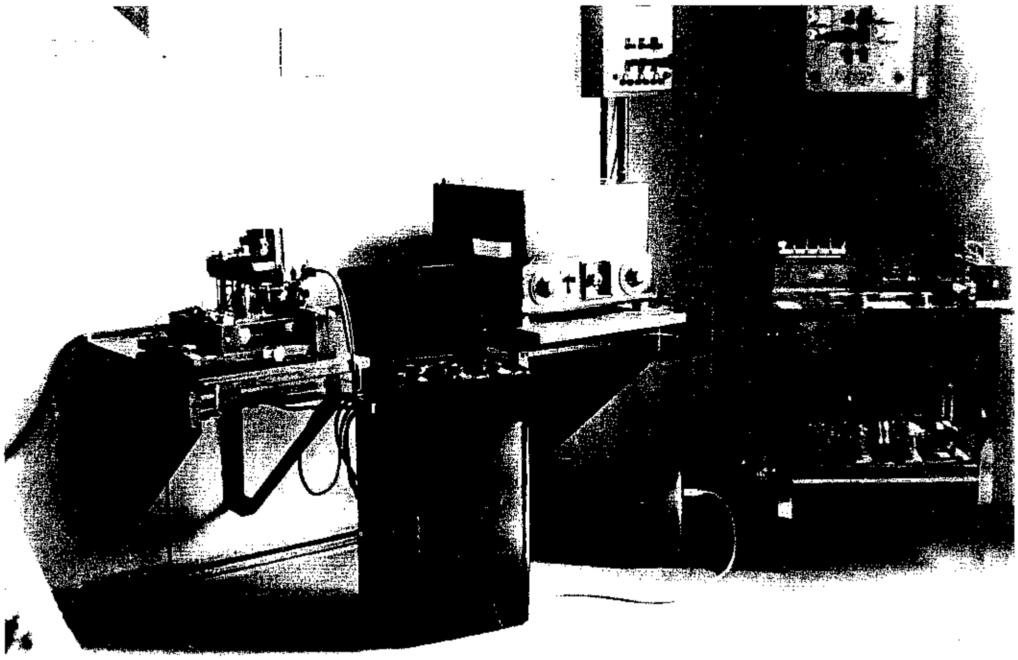


FIG. 8. Dr. Berger's EEG laboratory used between 1926 and 1931. The subject lay on a couch to the left, next to the coil galvanometer. The camera is the large box on the shelf in the middle, and to the right is the resistance measuring apparatus. (From Werner, 1963; photo courtesy of Dr. P. Gloor.)

achieved 240–1,200 ohms. He also used platinum sheets and silver electrodes in the same configuration; he had difficulty conforming these to the skin, so he tried lead foil plates, cut and fitted to the particular site. These produced resistances of 500–7,600 ohms.

Although these were acceptable electrically, Berger had to use rubber bands or a rubber swim cap in order to achieve adequate mechanical stability. He then went to using very thin lead foil, wrapped with flannel, and secured with rubber bands wrapped around the head. These achieved resistances of 380–500 ohms. At times, when recording from the scalp, he used 1-cm-diameter silver electrodes glued to the skin with adhesive tape.

He took 73 scalp EEGs from his son, Klaus, who was between 15 and 17 years old during the studies. He notes that Klaus' hair was "cut as short as possible" whenever investigations were carried out. He also selected a series of volunteers for examination, taking into account the preferability of bald areas for achieving what he called "beautiful" records (Gloor, 1969). In an extensively bald 37-year-old man, he achieved resistance for two large lead foil electrodes of only 140 ohms.

He took simultaneous recordings of EEG and mechanical oscillations from Klaus' scalp, using an "Edelmann pulse telephone." These records demonstrated that the EEG waves were not associated with the pulsatile oscillations of the scalp. He also took 56 traces from himself, using mostly needle electrodes. These were either chlorinated silver needles, platinum wires, or zinc-plated steel needles.

After 5 years working on the results of his studies, he published the first report of human EEG in 1929. His caution was understandable; even after waiting 5 years to report his successes, his report was met with widespread disbelief. His own diary indicates that he had considerable doubt about the authenticity of his observations, particularly during the time preceding his 1929 report. This report includes a description of 10-Hz alpha waves, which were subsequently called "Berger waves" by Lord Adrian. It also contains descriptions of beta waves and alpha blocking by light stimulation. These were recorded between 1926 and 1929, using the double-coil galvanometer.

In his second report in 1930, he shows very clear recordings from a 39-year-old woman with a trepanation, using chlorided silver needles inserted into the epidural space. In describing this record, he introduces the term "alpha wave" and "beta wave" to designate waves with average duration of 120 ms and 30–40 ms, respectively (Gloor, 1969). In describing the waxing and waning pattern, he reports the dura-

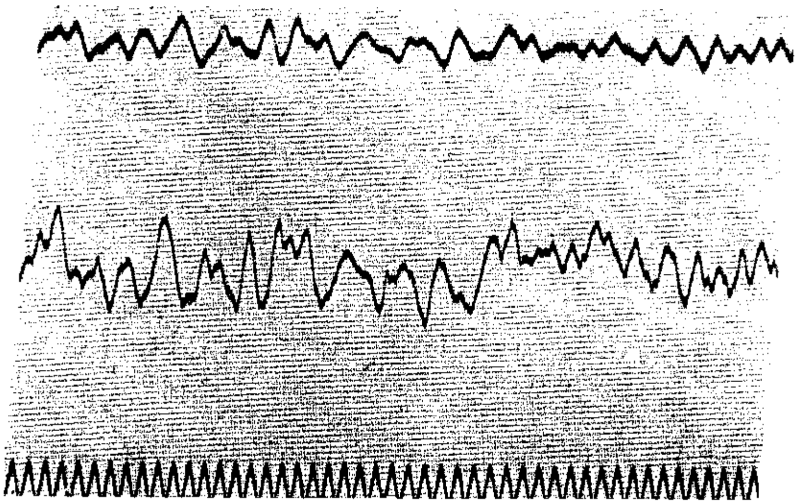


FIG. 9. Recording made by Berger in 1932. **Top trace:** EEG recorded with Edelmann string galvanometer. **Middle trace:** Same EEG recorded with Siemens double-coil oscillograph. **Bottom trace:** 10-Hz reference. Note the difference in resolution, and the offset time axis between the two traces. This represents the pinnacle of Dr. Berger's instrumentation and presents a striking illustration of the improvement in recording quality between two early electroencephalographs. (From 5th report; Gloor, 1969, p. 156.)

tion of the fluctuations over several minutes. This simple summary of time intervals probably comprises the first, albeit rudimentary, signal processing of the EEG.

Berger continued to refine his techniques. He began to use chlorided silver needles inserted into the periosteum, despite the hemorrhages and pain that often resulted. He used light, local anesthesia when possible. He also moved the subject into a separate room, with padded soundproof doors and ran cables outside to the instruments. It was with this configuration that he set about to systematically study the phenomenon of alpha blocking in a variety of situations. At the end of this report, he summarized that, in 1,133 records from 76 people, he had established normative values for alpha wave and beta wave frequencies and amplitudes, preparing him to approach pathological changes in future studies.

By the time of his third report in 1931, he had changed completely to recording with chlorided silver needles inserted into the skull, having experienced too many artifacts when using silver foil applied to the scalp. He also reports having had an opportunity to record EEGs with a Siemens oscillograph; however, no such results were published (Gloor, 1969).

In 1931, he obtained a specially constructed amplifier/oscillograph from Siemens; its effect on input impedance made it possible to measure potential directly and thus to ignore the resistance of the electrodes (Gloor, 1969). It also allowed him for the first time to accurately compare recordings taken from different subjects and from different sessions (Fig. 9). He had a brother who was an engineer with the Carl Zeiss Company of Jena. Through this affiliation, he received assistance in the acquisition and use of the sensitive instruments, including a grant from the Carl Zeiss Foundation to purchase the Siemens equipment. This optical system used paper that was 12 cm in width, moving at a speed of 1.5, 2.3, or more often, 3 cm/s. The lengths of the records varied between about 2.5 and 7.5 meters. He was able to arrange for the Edelmann galvanometer to project its tracings onto the recording paper simultaneously with the Siemens instrument, although the amplitude scales were different and the time axes were not aligned (Fig. 9).

A major drawback of this device, however, was the instability in its gain, which required Berger to make frequent calibrations, and to interpolate between them during individual recordings. Using this system, he also had to ensure that x-ray and diathermy instruments were turned off, even if in separate buildings. He also had to provide extensive shielding for power lines and noticed an increased sensitivity to motion artifact, further restricting his patient selection to those who could remain completely still.

As is true in EEG laboratories today, Berger had to attend to the overall physical environment of his laboratory to ensure successful recordings. Since he was director of the clinic, he had a small laboratory annexed to his office, and he carried out his studies between 5:00 and 8:00 p.m. At that time, the electrical machinery and equipment in the main and adjacent building were turned off. The main power to the clinic was, fortunately, fed by DC power, which avoided the AC interference that is so familiar today. Only once did Berger publish a recording contaminated with electrical artifact, and he subsequently published a correction.

In his fifth report in 1932, he reported that his silver needles were provided with a coat of baked varnish. With the new instrumentation, he was able to record potential differences as a function of electrode position and made the first statements regarding the size of the recorded alpha wave as a function of interelectrode spacing. This, then, was the beginnings of brain electrical topography.

In 1938, he reported using two silver scalp electrodes, each 70 cm^2 in area. His preferred montage consisted of one point high on the forehead and one point on the back of the head above the inion (Gloor, 1969). Occasionally, he used a large capacitor to eliminate DC potentials, providing a low-frequency cutoff of about 2.5 Hz.

In his 14th report, he summarized the advantages and disadvantages of the two types of electrodes he had settled on: chlorided silver needles and silver foil sheets. It is notable that these configurations are at the extremes for electrode size, invasion, and impedance. Thus, all subsequent electrode designs fall within the parameters that Berger explored and established. Although he preferred the clarity of the needle recordings, he had developed a preference for the foil electrodes because they were more comfortable and because they recorded potentials from a larger area of the brain. Because of his understanding of the brain as a "unitary process," he did not particularly value localized measurements (Gloor, 1969).

Throughout his work, he had at most two channels at his disposal; one being obtained on the Seimens galvanometer, the other taken with an Edelmann galvanometer, which was later improved with an amplifier. Since the gains of the two were different, and the light spots could not be vertically aligned, his double recordings are difficult to read. He never had access to a multiple oscillograph or to an inkwriting system, even though they were available while he was still active. None of his reports include any voltage calibrations. He reports that he made such calibrations, however, and used them in determining the magnitude of his recordings. He included voltage estimates in his written descriptions of the traces and always recorded a 10-Hz sine-wave oscillator waveform as a time reference. Some recordings included simultaneous cerebral plethysmographic and EKG traces, which supported his contention that the phenomena producing EEG were unrelated to mechanical or cardiac processes.

Berger had one notable colleague, the physicist G. Dietsch of the Institute of Technology and Physics at Jena, who worked with him in two main areas. Dietsch is initially mentioned in Berger's writings in connection with devising a procedure to carry out resistance measurements on the skull, which was determined to be about 40 times that of his oscillograph input. In 1932, Dietsch published a report on the Fourier analysis of human EEG. In this report, he provided the theoretical basis for calculating the frequency spectrum of the EEG and estimated the parameters and anticipated results, should one carry out the computation.

Berger's contributions to experimental and clinical EEG are substantial and have been detailed elsewhere. From a strictly biomedical engineering point of view, however, an additional set of contributions is evident, including: (1) studies of the effects of the skull on EEG voltages; (2) development of needle, cup, and plate electrodes; (3) development of electrode-restraining devices; (4) normative values for EEG background rhythms; (5) use of simultaneous EEG with EKG and blood pressure; (6) simultaneous surface and invasive recording; (7) investigations of EEG topography; (8) simultaneous EEG and movement recording in focal motor epilepsy; (9) use of signal processing to extract EEG parameters; and (10) estimation of the Fourier transform of the EEG.

Some of the climate of Berger's scientific work, plus his determination, is revealed in the following report by Dr. Nicholas Bercel, who saw Berger demonstrate the EEG in Paris in 1937.

> I was a resident in the Saltpêtrieṙe Hospital in 1938. Professor Baudoin was constructing a one-channel instrument. A year earlier I heard Hans Berger in the great hall of the Sorbonne medical school demonstrate his tracings that were, thanks to his brother who was an engineer at Carl Zeiss of Jena, optically amplified and he needed a whole wall of the hall on which to project his tracings. I have also noted that in the darkened room when he was showing his slides about half of his audience deserted him.

This account is notable in light of Caton's previous work; two important similarities arise. Both investigators had to rely on a mirror deflection with optical magnification in order to see their signals, which were at the lower range of their instruments. Also, both scientists had to demonstrate their recordings at a formal meeting of skeptical peers for their results to be accepted. In both cases, the accomplishment was considerable.

For further details of Berger's instrumentation, methods, and results, and considerable insight into the personal side of his work, see Gloor (1969).

GERMAN EEG DURING AND AFTER BERGER

Before Berger's death, important work had begun at the Institute of Brain Research in Berlin-Buch. The Department of Physiology under M. H. Fischer and the Department of Electrophysiology under A. E. Kornmuller had access to an outstanding engineer, J. F. Toennies (1902–1970), who made important advances in EEG instrumentation. Toennies built the first inkwriting oscillograph, which he called a "neurograph," for the recording of brain potentials. He had a fellowship in New York with the Rockefeller Foundation in 1932 and had developed a differential amplifier, whose design and application were reported in 1933. For this, he shares the distinction with B. H. C. "Brian" Matthews of England of being the originator of this important milestone. Toennies' report also developed the basic concepts of differential recording including impedance considerations and the effects of volume conduction. He presented simultaneous recordings from surface and invasive electrodes, providing quantitative support for his arguments.

Toennies returned to the Rockefeller Institute, where he made further contributions in the development of the cathode follower to record from high-resistance electrodes. This work opened the door to microelectrode recording, which was to bear fruit for many years.

Using Toennies' instruments, Kornmuller had much better recordings than Berger and was also able to make multichannel recordings. He placed emphasis on recording the potential differences between given regions of the brain. He conducted important work with Fischer and with Lowenbach, including the earliest published recordings of epileptic seizures and of epileptiform spikes.

ADRIAN AND MATTHEWS

In Cambridge, England, E. D. Adrian ("Lord Adrian") (1889–1977) became aware of Berger's work in 1933 and immediately endeavored to confirm and promulgate Berger's discoveries. He had already developed by 1929, with Dr. Detlev Bronk, the method of recording single neuron action potentials. For this work, he used a capillary electrometer in conjunction with a vacuum tube amplifier. This produced a recording sensitivity of 10 μV full scale and a response time of a few milliseconds. With it, Adrian conducted studies of afferent impulses in peripheral nerves responding to touch and other stimulation. With refinement, he recorded single end-organ receptor signals and single-unit action potentials in the optic and motor nerves.

He collaborated with a gifted electrical engineer, Brian Matthews, who designed and constructed instrumentation suitable for EEG. Matthews developed two such systems. One was an oscillograph with a high-frequency cutoff of 955 Hz, which recorded on moving bromide paper. In the majority of their work, however, they used an inkwriting oscillograph with a high-frequency cutoff of 64 Hz. This had been developed circa 1926 as an electrocardiograph and used a chart drive system driven by a clock motor. In addition to graphic output, they connected a large loudspeaker, which they modified, to produce sound adequate to hear the raw EEG waves.

Matthews introduced the use of differential input amplifiers to electrophysiology (Fig. 10). He developed designs using vacuum tubes, but he did not apply the concepts of feedback and stability that emerged later in the 1930s from Bell Laboratories. Adrian and Matthews set up a three-channel system, in which each channel contained a balanced differential amplifier. The electrodes fed into the grids of a balanced pair of vacuum tubes, which were capacitively coupled to an amplification stage. The push-pull input design is described in Matthew's 1931 report. This system was proven in by recording from different points on a frog and observing that EKG artifact was effectively eliminated in traces taken from the animal's liver. Through extensive animal studies, they established many of the basic principles of EEG, including the underlying nerve cell activity and volume conduction of the extracellular currents. They were concerned about the effect of the capacitor coupling and therefore conducted simultaneous recordings using a battery-coupled amplifier. They observed no discernible difference when using 1-μF coupling capacitors. They specifically looked for slow or sudden baseline shifts and found no evidence of them.

The electrodes they used were squares of copper gauze covered with lint and soaked in warm saline. These were placed over a part in the subject's hair and held in place with a head bandage. They also evaluated Berger's method of using steel needles thrust through the scalp into the skull and found that the pads gave equally good results. In contrast to Berger, they had instruments that were relatively free of input loading effects, giving them considerably more freedom in their selection and use of electrodes.

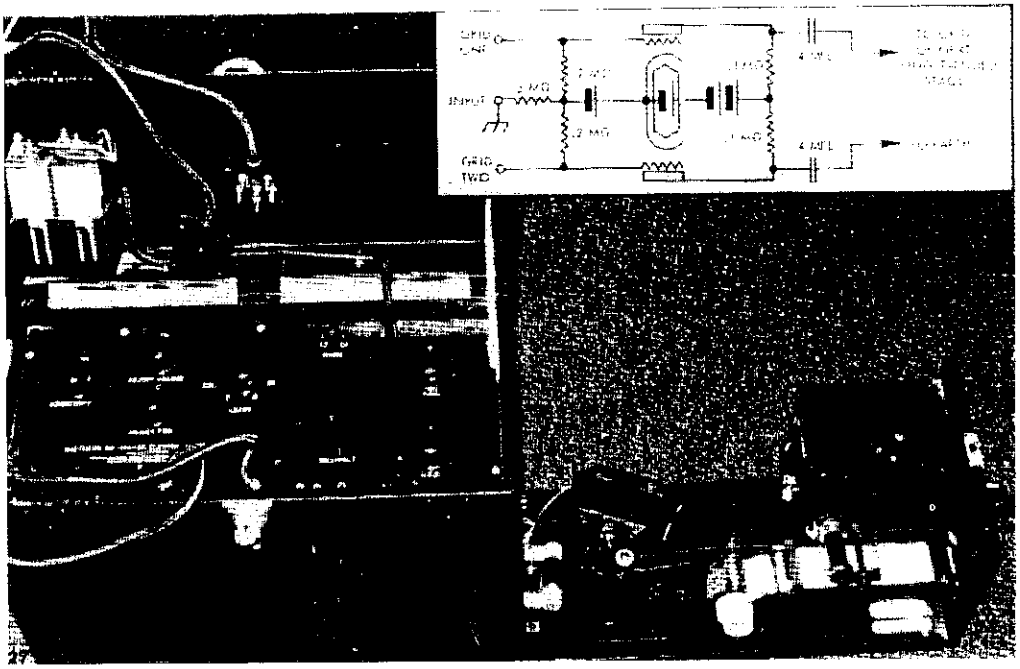


FIG. 10. Differential amplifier, 1934 design by B.H.C. Matthews, with Matthews' inkwriter. Note that this particular amplifier, although differential, was not of the "push-pull" type, and hence had a very low input impedance of 200 kohms. (Reproduced with permission from Grass, 1985.)

The use of multiple, differential channels was important for the development of the concepts underlying the EEG and neuronal physiology. Before Adrian and Matthews' observations, it was unclear how EEG related to neuronal activity, if at all. Adrian and Matthews were able to record simultaneously and independently from different areas of the brain, revealing the spatial as well as the temporal relationships between signals. They published detailed reports that showed conclusively that EEG and the "Berger rhythm" were real, of cortical origin, and unrelated to muscle, eye, or other sources of artifact.

EARLY ELECTROPHYSIOLOGY IN THE UNITED STATES

Important instrumentation development and application was conducted in the laboratory of Dr. Alexander Forbes (1882–1965), Professor in the Department of Physiology at Harvard Medical School. He was an M.D. who was trained in physics and had worked on submarine detection during World War I. He brought his knowledge of the details of vacuum tube amplifiers to the development of electrophysiological instrumentation. In the course of his work, he developed many instruments and techniques; in 1920, he was the first to use a tube amplifier in the recording of nerve action potentials. The vacuum tube had been invented by Fleming in 1904 and was first used as an amplifier by Lee De Forest in 1906. The output of Forbes' amplifier was connected to a string galvanometer; one of Forbes' greatest expenses was the replacement of strings that were destroyed by the excessive currents they occasionally had to carry.

Forbes worked with Hallowell Davis, who was to become an important figure in EEG. Forbes and Davis worked in EMG and were important contributors to the early work necessary to identify which attributes of EMG were real and which were artifactual. They designed the premier EMG instrumentation of the 1910s and 1920s. Forbes' laboratory published very detailed technical reports, including the derivation of important properties of tube amplifiers and the systematic design of high-quality instrumentation. He pioneered the consideration of effects such as frequency compensation, shielding, balancing, and gain stability. He increased the sensitivity of the system from 1 mV/cm to 50 μV/cm and the input impedance from under 10 kohms to over 500 kohms. However, his amplifiers did not have differential inputs. Frequency response was from DC to 200 Hz. Forbes continued doing electrophysiology through the 1930s, during which time Davis began to work with Dr. Frederick A. Gibbs to explore the new area of EEG.

Gasser and Erlanger, two physiologists at Washington University in St. Louis, conducted important electrophysiological work, including the development of the first cathode-ray-tube (CRT) oscilloscope. They received their first tube from Dr. A. H. Compton, who was head of the Physics Department and developed their own amplifiers to use it. Later, they acquired tubes from Bell Laboratories. Their amplifier was similar to Forbes' design. The system had an upper frequency response of several thousand hertz and a sensitivity of about 50 mV/cm. Photographic records were produced by holding sensitized paper against the display. All laboratories had to build their own CRT oscilloscopes until the early 1930s, when commercial products became available. The earliest commercial supplier was Dumont, who provided a single-trace tube that was not easily used for EEG.

As early as 1930, George H. Bishop and S. Howard Bartley recorded EEG tracings from dogs at Washington University in St. Louis. This institution was already established as a leader in the neurophysiology of peripheral nerves and was by this time equipped with CRT oscilloscopes provided by Braun. Bartley had worked with the Westinghouse oscillograph as a graduate student at the University of Kansas. He built his own amplifiers, again with transformer-coupling, but more suited to cortical potentials. This system was used for the dog studies during 1930–1933.

HUMAN EEG IN AMERICA BEGINS WITH JASPER

Herbert H. Jasper, working with Leonard Carmichael, was the first in North America to confirm Berger's reports on the human EEG. In 1933, Jasper received a grant from the Rockefeller Foundation to establish a clinical and experimental EEG laboratory at the Bradley Hospital in Providence, Rhode Island. In 1934, they made their first recordings on photographic paper with Westinghouse four-channel mirror oscillographs. Howard Andrews, a physicist and electrical engineer from Brown University, designed and constructed the EEG amplifiers. He had also designed a high-gain DC amplifier. In July 1934, Jasper and Carmichael, who was chairman of the Department of Psychology at Brown, recorded the first human EEG west of the Atlantic. Their published account describes the blocking of the alpha rhythm by light stimulation. In 1935, Dr. Jasper traveled to Paris to defend his doctorate, which included the thesis, "Electroencephalographie chez l'Homme." He then visited Berger in Jena and Kornmuller and Toennies. He also visited Grey Walter in London and Adrian in Cambridge before returning to Brown.

The instrumentation and results were published in several papers in 1935, in which the functional requirements and design details were described. Their first report appeared 1 month after Adrian and Matthews published their confirmation of Berger's work. The amplifiers had a maximum frequency response of 1 to 1,000 Hz. In-line filters were used to limit the effective response to below 100 Hz, so muscle potentials would not be a problem. The inputs were differential, battery-powered, and used the push-pull design attributed to Matthews. Both inputs of each channel were independent of ground, so that completely separate bipolar derivations could be achieved. Each input was then connected to a common ground through a large resistance. The gain of the preamplifier stage was a mere 4.5. However, with special attention to the selection and operating conditions of the input tubes, noise was kept to a minimum.

The authors also mention that, in order to avoid input grid saturation, they had to use smaller grid resistors, which had the undesirable effect of reducing the low-frequency response. For example, one study used a 2-μF capacitor and a 500-kohm resistor to couple to the electrodes. The output of each preamplifier was fed, through large capacitors, to a conventional single-ended amplifier with a ground common to all other channels. Over a 3-month period, these amplifiers had a gain stability of within 4%.

It was also necessary to design an output stage capable of driving the Duddell-type oscillograph with its film camera attachment. The oscillograph used the same basic principle as the d'Arsonval moving-coil galvanometer but had a loop of wire in place of the heavier moving coil. This provided reduced coil inertia and resistance, increasing high-frequency response to 2 kHz. However, the input impedance was low, about 8 ohms, and the sensitivity was also low. Adapting the oscillograph to the amplifiers required matching the low input impedance to the relatively high impedance of the amplifier outputs. Since transformer coupling would have introduced excessive low-frequency distortion, they designed a battery-boosted class A triode circuit to perform active impedance matching.

Jasper's group also went to considerable lengths to develop a high-quality electrode. They required nonpolarizable electrodes, plus excellent skin contact and stability. Silver disks covered with saline-soaked flannel were not sufficiently noise-free for their work. They developed a system that consisted of a T-shaped tube filled with 10% NaCl and containing a spiral coil of chlorided silver wire. The tube was firmly affixed to the scalp using a rubber headband. The subject's hair was clipped, and the skin was vigorously cleaned with alcohol. A rubber seal with a little electrode paste provided a watertight contact with the scalp; the tube included a small dome to collect air bubbles, preventing them from disturbing the recording. The resistance of these electrodes was about 200 ohms in saline, and from 1,000 to 5,000 ohms in contact with the scalp.

The liquid-filled electrodes were abandoned shortly afterward, in favor of 5-mm chlorided silver "hats" with felt-covered brims. These were attached to the head with collodion and filled with electrode jelly. The properties of these electrodes were likely as good as any scalp electrodes in use today. With these, they were able to record bilaterally from the frontal, precentral, parietal, occipital, and temporal regions. This group was particularly interested in localizing the EEG waves; electrodes were generally placed close together, usually less than 2 cm.

It is impressive how many of the principles and operational conventions used by this group are essentially unchanged today and are particularly close to techniques used in long-term scalp monitoring for epilepsy. Indeed, this work was to lead directly to the first epilepsy monitoring and EEG localization of epileptogenic foci for surgical treatment of seizures.

JASPER MOVES TO MONTREAL

Dr. Jasper collaborated with Dr. Wilder Penfield, whom he convinced to operate on two patients with epileptic seizures that he had localized based on EEG. The operations were successful, and Dr. Penfield arranged for Jasper to move to Montreal to continue his work. Jasper established the Laboratory of Electroencephalography there, and a new annex was completed in January 1939. At the opening ceremonies, a photograph of 36 attendees included most of the electroencephalographers active in North America at that time. The EEG department included a specially designed laboratory building with three electrically and sound-shielded rooms with observation windows, to permit recording from outside. One room was built on a separate, mechanically isolating foundation. EEG facilities were also provided for the neurosurgical operating room, with a glassed-in amphitheatre for observation. Dr. Andrew Cipriani, who was an electronics engineer as well as a physician, constructed all of the amplifiers, including winding the coils for the four-channel inkwriters (Figs. 11 and 12).

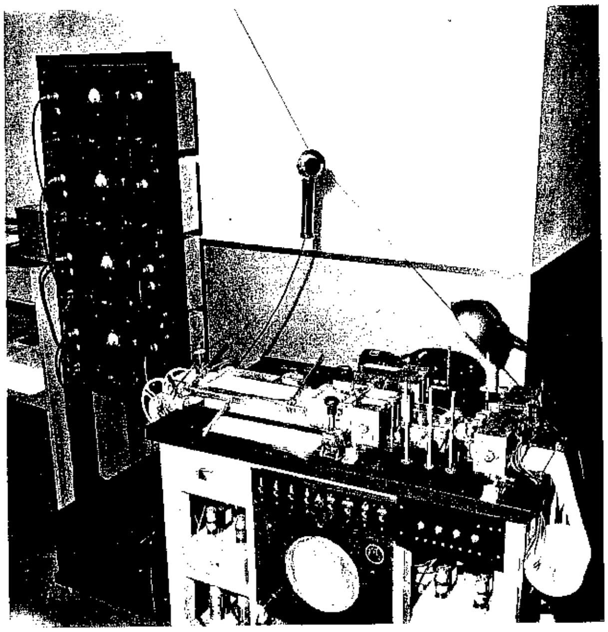


FIG. 11. Four-channel EEG machine used at Montreal Neurological Institute during the 1940s. Note the large loudspeaker, used in conjunction with EMG studies. (Photo courtesy of Drs. P. Gloor and H. Jasper.)

Jasper's laboratory carried out approximately 1,000 EEGs on over 500 epileptic patients during the year 1939. Over half of the patients were subsequently considered candidates for possible neurosurgical exploration and were admitted subsequently for more detailed study. The results of these systematic studies were published with Jack Kershman in 1940 and later in 1941 in Penfield and Erickson's *Epilepsy and Cerebral Localization.* This chapter also describes the International 10–20 System for electrode placement and the use of sphenoidal electrodes.

In 1949, Dr. Jasper and John Hunter reported a method to record EEG and clinical events simultaneously, using a movie camera. In their report, they mention a photographic method described in 1938 by Dr. Robert Schwab at Harvard that used two cam-

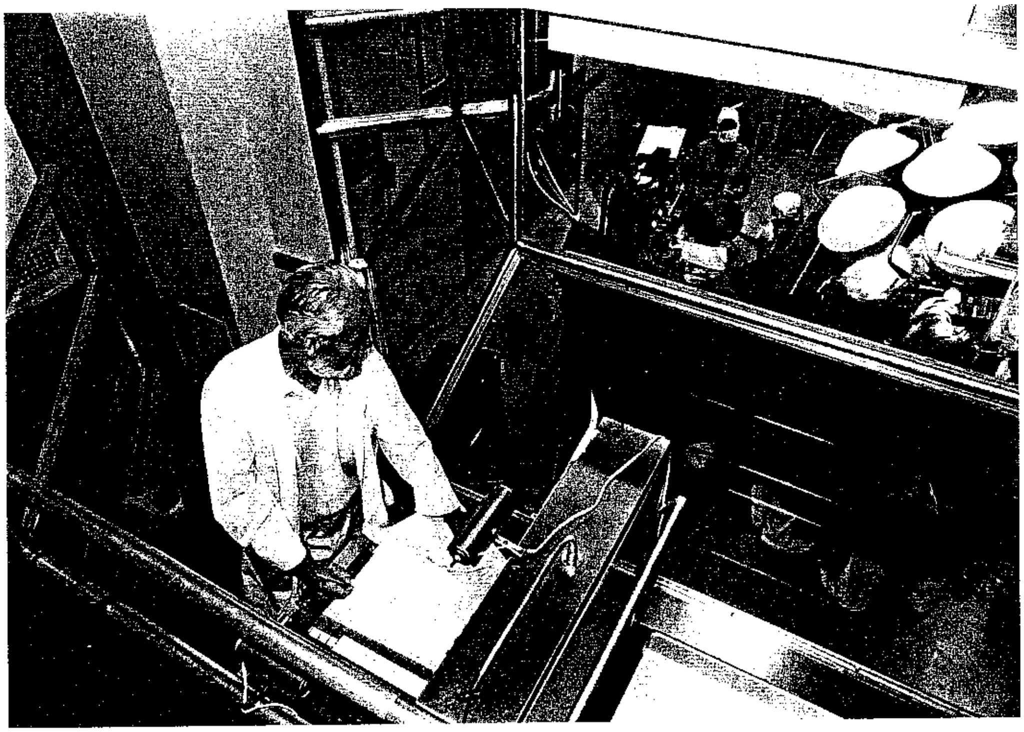


FIG. 12. Dr. Pierre Gloor recording intraoperative electrocorticograms at Montreal. The basic setup was devised by Penfield and Jasper in the early 1940s and has not been changed, save for updating the EEG equipment. (Photo courtesy of Dr. P. Gloor.)

eras with synchronizing marks to facilitate the processing of a single composite film. These systems were the forerunners of the video/EEG systems that have become indispensable in the diagnosis of epilepsy and the planning of epilepsy surgery.

ALFRED L. LOOMIS

Shortly after Jasper confirmed Berger's results, Alfred L. Loomis working in a private laboratory in Tuxedo Park, New York, became the second published American electroencephalographer. Loomis' group used silver disk electrodes attached to a headband made from rubber tubing. They had a switch box that connected 12 electrodes to six channels of amplification, comprising perhaps the first headbox. Amplifiers were of the four-stage, push-pull tube type with a frequency response of 0.3–46 Hz. The input had such high impedance and common-mode rejection that it was not necessary to provide a separate ground at all; moreover, EKG potentials were effectively rejected even if a noncephalic location was used as a ground electrode.

Each amplifier had a high-power output stage for the ink pens. In addition to the six EEG pens, the system had seven additional pens; one was an event marker, and the other six were additional outputs for "tuned" circuits. These channels allowed narrow band-limited EEG to be produced, to facilitate an accurate reading of any specific frequencies of interest.

Loomis' group put the subject in a shielded room that contained a bed, furniture, and the first stage of EEG amplification. An adjoining room contained the rest of the EEG amplification. An adjoining room contained the rest of the EEG amplification, amplifiers for heart, respiration, and movement, and communication to a third, control room, which was 66 feet away. The control room contained the recording equipment, intercoms, and other switches and controls.

Loomis' 1938 system used a roll-feeding system fitted with an ingenious paper-handling machine. As shown in Fig. 13, this system operated continuously and included a means for the operator to cut the paper every 30 s and stack the cut sheets into a neat pile. The piles were assembled using nuts and bolts to provide a record that could be reviewed by turning pages.

A later system used a steel drum 8 feet long and 44 inches in circumference, fitted with three high-speed dynamic pens, in addition to three CRT oscillographs with a camera. The drum system moved at ½ or 1

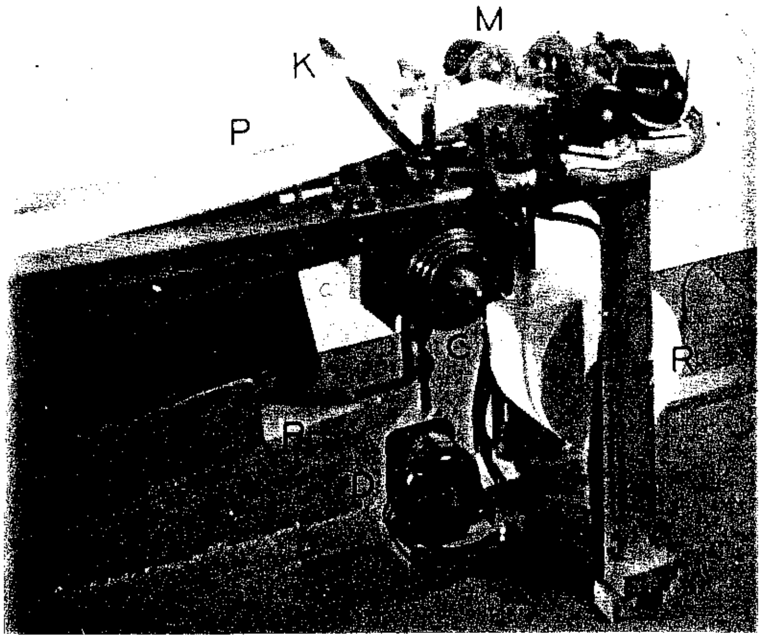


Fig. 2. Paper cutting brain potential recorder showing roll of paper R which passe nder pens activated by 6 magnets (M) and is cut by a knife (K) each 30 seconds, turne ver and laid on a pile (P). The machine is driven by synchronous motor, D. The contac heels, C, are so arranged that stimuli can be sent to the subject at predetermined times

Loomis et. al. (1938) [redacted]

FIG. 13. Automatic continuous EEG system designed by Alfred L. Loomis. This design allowed an operator to produce neatly stacked sheets of EEG traces and also controlled a stimulator. (Reproduced with permission from Loomis et al., 1939.)

revolution per minute, providing a paper speed of 1.46 inches per second. The pens were attached to a threaded bar, so that the entire assembly moved slowly across the paper, providing a spiral record. Every record also contained a calibration wave. The system was able to provide sound, light, or other stimuli upon each rotation of the drum, providing records that were automatically aligned with the stimuli. A considerable amount of automation and control was provided, significantly easing the burden of making detailed recordings during a long sleep session.

Loomis produced sleep records that included summaries of the amount of various brain rhythms throughout the night. These had to be hand-generated and provided an important precursor to modern, automatically generated sleep studies.

DAVIS, GIBBS, HARVARD

A group in the Department of Physiology at the Harvard Medical School, led by Hallowell Davis, became the third American laboratory to report human EEG recordings. In early, unpublished work, Davis worked with Howard Simpson and A. J. "Bill" Derbyshire to produce EEG traces on a Dumont CRT oscilloscope, confirming Berger's observations of the alpha and beta waves.

In December 1934, Dr. Frederick A. Gibbs and Erna L. Gibbs joined Davis' laboratory. By then he had a single-channel inkwriting recorder from Western Union that traced recordings on ½-inch paper tape (Fig. 14). They used it under the direction of Davis and William Lennox, who was taking care of epilepsy patients and had research support from the Rockefeller Foundation. They immediately began to record epileptic seizures using the EEG. A second petit mal patient to be recorded was Dr. Davis' 30-year-old secretary, who had been hired partly because of the scientific value of her unusually long seizures. In these patients, electrodes were placed in the frontal and parietal areas, with an ear reference. The primary intention of the reference was to obtain a sweat-free surface for improved stability. Later, recordings were also made using a needle in the vertex for the active site and a crown made of wire and saline-soaked cotton bandage for the indifferent site.

The Gibbs' worked with an engineer in the Physiology Department, E. Lovett Garceau, to pursue the design of a single-channel, portable EEG system using the Western Union Morse code inkwriting

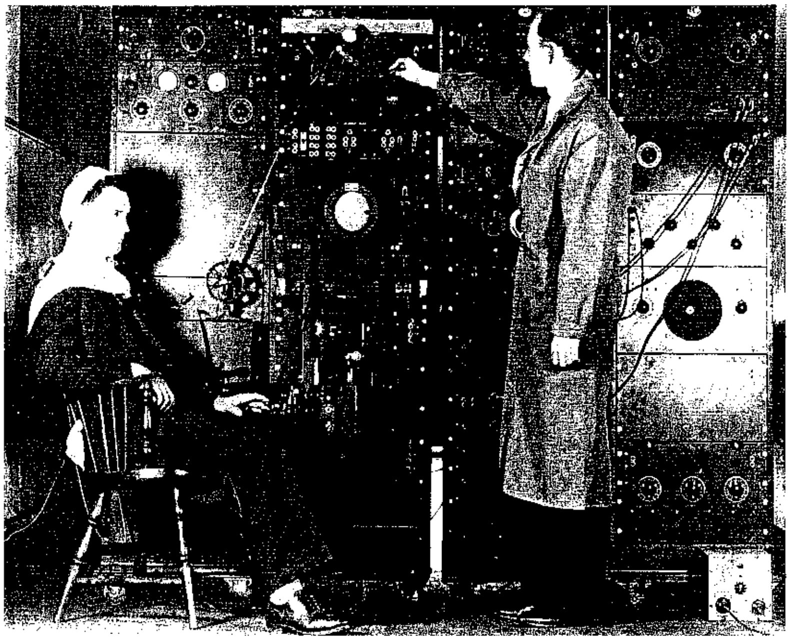


FIG. 14. EEG laboratory of Dr. Hallowell Davis at Harvard Medical School in 1933. Donald B. Lindsley is the subject, and A. J. (Bill) Derbyshire adjusts the Western Union undulator, which recorded one channel of EEG on ½-inch paper tape. (Photo courtesy of Dr. D. B. Lindsley.)

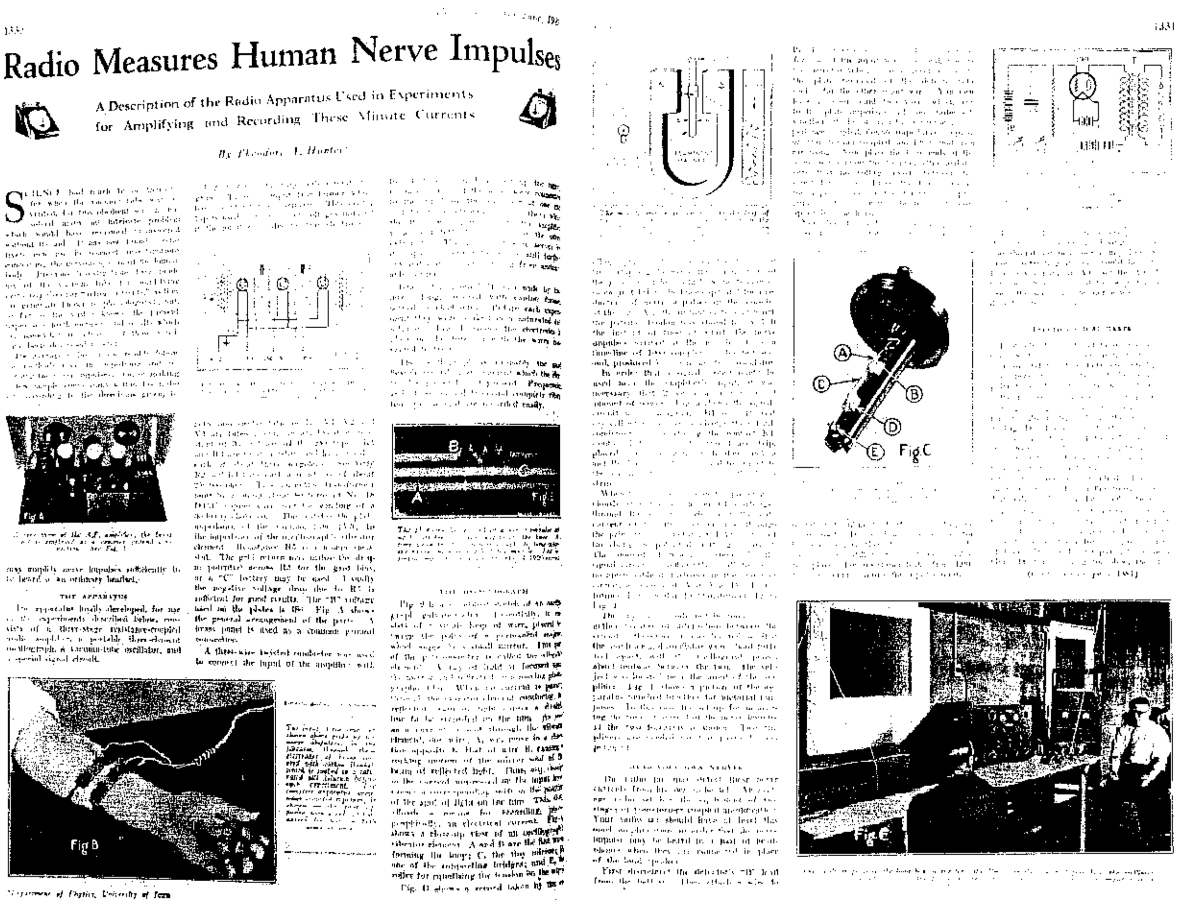
"undulator." Garceau had previously worked in the cable telegraph recording field. This writer, which was used by other laboratories as well, was originally designed to produce on/off Morse code via a pen deflection. It had to be modified to produce a continuous output range. This design was very nonlinear and failed to provide consistent results, so they sought other means. Albert M. Grass (1910–1992) was an engineer in the Mechanical Engineering Department at MIT, participating in the design of seismographic equipment for the detection of earthquakes. In May 1935, the Gibbs' contracted him to build a three-channel amplifier for availability by September 1, for $1,000, again using the Western Union inkwriter.

During that summer, Dr. and Mrs. Gibbs traveled to Leningrad and Moscow to attend the International Congress of Physiologists. They visited Berger in Jena in 1935 and showed him the petit mal pattern they had recorded. Berger was delighted with their work but reported that he had met with scientific and political opposition from Kornmuller at the Kaiser-Wilhelm Institute. Berger's equipment had been confiscated by the state, and he was stunned and saddened during the Gibbs' visit. He had enough recorded material, plus clinical material, to allow him to continue writing and publishing through 1938. However, even by 1935, the state of the art in EEG instrumentation had gotten well beyond his grasp. Systems with amplification, inkwriting, and other enhancements were already in use. The Gibbs' met with Toennies during this trip and saw his "neurograph." Dr. Gibbs made a sketch of this instrument and conveyed it, with Toennies' consent, to Albert Grass in August 1935. They also saw the system developed by Matthews in Adrian's laboratory.

In 1939, the Loomis and Davis laboratories published a collaborative report on an attempt to record DC EEG changes during sleep. Both the electrodes and the instrumentation required considerable innovation. Although DC potentials could be recorded with a tube amplifier and galvanometer, they chose to use a mechanical interrupter using silver contacts to design a chopper-based amplifier with an operating rate of five switches per second. They rejected the use of silver chloride electrodes due to the difficulty of achieving a robust connection to the patient. Instead, they used either 6-mm copper bowls filled with copper sulfate or zinc bowls in zinc chloride and filled with zinc sulfate. With this system, they achieved electrode resistances of 15,000–30,000 ohms, producing stable recordings for periods in excess of 4 h.

THE SPREAD OF AMERICAN EEG

The fourth American human EEG laboratory was established by Dr. Lee Travis at the University of Iowa. He was aware of Berger's work in 1933, before it was confirmed by Adrian. Among the EEG pio-



Radio Measures Human Nerve Impulses

A Description of the Radio Apparatus Used in Experiments for Amplifying and Recording These Minute Currents

By Theodore A. Hunter

FIG. 15. *Radio Age* article (1928) written by Theodore A. Hunter, describing early instrumentation used by Dr. Lee Travis. (Reproduced from Hunter, 1928.)

neers trained by Travis were Herbert Jasper, Donald Lindsley, Charles Henry, and John Knott. His original equipment was built by Theodore Hunter, a local electrical engineer, for the original purpose of recording muscle potentials. This work was well underway in the 1920s. Hunter was an accomplished radio afficionado and brought his talents into the EEG area. Indeed, an early report of his amplifier appeared in a radio magazine (Fig. 15), and EMG activity was broadcast on the University radio station in 1928.

The original Hunter design had transformer-coupled input and output, providing a low-frequency cutoff of 60–70 Hz, virtually eliminating all EEG signals of interest. In 1935, Hunter and Paul E. Griffith designed and built a system capable of recording EEG. It was modified from circuits obtained from Andrews and Jasper at Brown University, again with a battery-powered input stage. The two-channel system used a Westinghouse oscillograph and continuous-roll, four-inch or 35-mm sensitized paper carried by a hand-cranked camera attachment. These were developed in 100-foot rolls, presenting significant paper handling and storage problems. They were processed in 25-foot lengths to avoid tearing and were immersed in large stone jars containing the chemicals. Trousers and shoes were frequent casualties of the caustic solutions. A modified Morse code undulator was later adapted from Davis and Garceau as a penwriter (Fig. 16). It had a bandwidth of a mere 2–20 Hz and had the same nonlinearity problems that others had experienced. It was later replaced by modified audio speaker voice coils with pens attached.

A reference oscillator on a third channel was always used to compensate for unavoidable variations in the paper speed. Later, the paper drive used a geared-down one-quarter horsepower motor to provide a stable time reference. While this was effective for its intended purpose, it was also known to consume any neckties that happened to become caught in its gears.

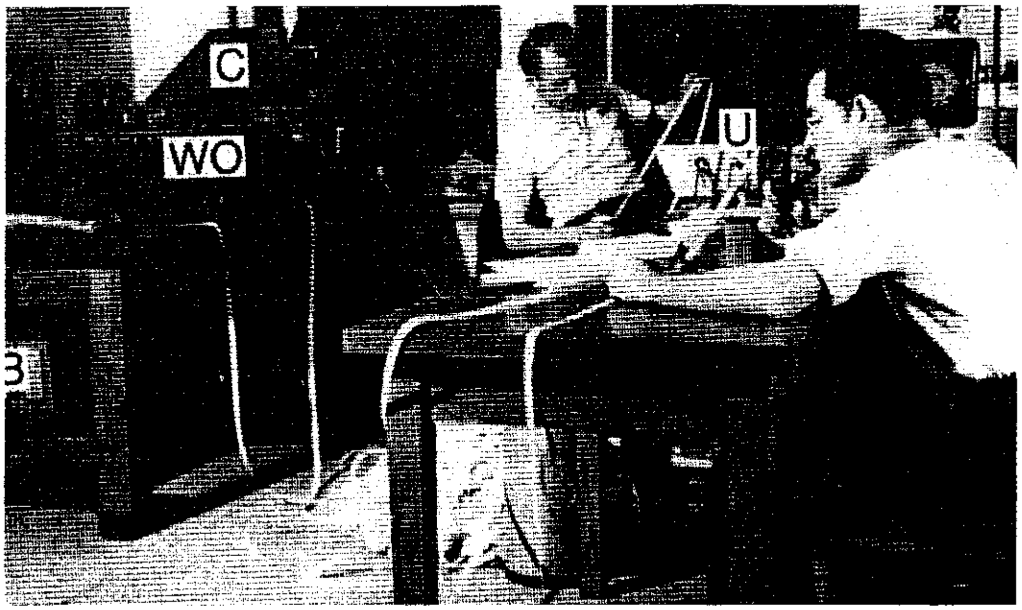


FIG. 16. East Hall (now Seashore Hall) EEG Laboratories, University of Iowa, 1937. Charles Henry (left) and John Hadley as graduate students, analyzing one-channel sleep study from inkwriting "undulator." Travis' 1920 oscillograph and recording camera are on the table at the left. (Reproduced with permission from Knott and Kimura, 1985.)

The first published report from the laboratory appeared in 1936, describing the EEG of normal speakeres and of stutterers. This work was carried out by Dr. John R. Knott (1911–1993). It constituted the first published quantitative, albeit manual, analysis of the frequency and voltage characteristics of the EEG.

The EEG amplifier was enclosed in a copper-lined wood box and hung from the ceiling by door springs to avoid microphonic interference. As an example of the difficulty of separating physiology of instrumentation, Peter Seaba reports that, during early sleep recordings, the investigators noted a decrement in the recorded EEG, which was apparently "fixed" by tapping on the amplifier box. Years laters, Dr. Knott realized that the decrement was a normal transition into the rapid eye movement stage, and the tapping had the effect of arousing the subject, not curing any electrical problem.

EEG AT THE MAYO CLINIC

At the Mayo Clinic, Dr. C. L. Yeager began EEG work as a fellow in 1935. Having heard of Berger's work, he immediately sought an EEG capability. Working with a biophysicist, Dr. E. J. Baldes, he arranged for a system to be built by an engineer from Minneapolis, based on Matthews' design. The input stage contained batteries and had a 25-foot cable connecting it to a main three-stage amplifier. Leakage from the lead–acid battery ultimately destroyed the circuits.

The output was a piezoelectric Rochelle salt galvanometer that controlled a small mirror. This galvanometer was made by the Brush Instrument Company of Cleveland and was also used in other EEG systems. A discarded EKG photosensitive-paper camera was found in the basement and was interfaced to the oscillograph. The first recordings were taken in a 4 × 4 × 4-foot shielded cage in which the subject sat on a stool. Dr. Yeager's EEG was recorded with this system in 1936. This one-channel system was used for about 1 year, until the Grass four-channel EEG became available.

In the late 1940s, Dr. Reginald G. Bickford began a collaboration with Dr. A. Faulconer, Jr., of the Department of Anesthesiology to study EEG patterns under various conditions of anesthesia. For this project, a two-channel recorder was designed and built specifically for a small, cart-based monitor. A later version of this system provided automated control of the drug, comprising the first closed-loop anesthesia control system based on the EEG. The system converted the integrated voltage output of the EEG into pulses that could operate a relay that controlled the administration of the agent. Dr. C. W. Mayo used this system for more than 50 lengthy operations.

The Mayo laboratory also produced other ingenious devices. Dr. Bickford devised an electronic photostimulator that was reported in 1951 and replaced the previously used rotating disk stimulators. A wave synthesizer was also designed, which produced clinically interesting simulations of EEG patterns, built up from simple sinusoidal frequencies. Dr. Donald Klass, working with Ted Karau, developed a plastic head filled with saline and with embedded electrodes, which provided a physical simulation of the volume conduction of currents in the brain. An electrical dipole could be introduced into the saline, manipulated as desired, and the resultant fields measured from the surface using a conventional EEG machine. Another important first occurred on April 27, 1963. Dr. Charles D. Ray and Dr. Bickford of the Mayo Clinic transmitted an EEG from the American Academy of Neurology meeting in Minneapolis to W. Grey Walter's laboratory in Bristol, England, using a telephone hookup.

EEG ELSEWHERE

In 1937, H. Blake and R. W. Gerard at the University of Chicago reported on long-term sleep studies conducted with a system designed in collaboration with F. F. Offner. The EEG system later became one of the first commercial units. During this study, recordings were made throughout the night, and the subject was scored based on movement, response to a sound, and the presence or absence of 1-Hz and 10-Hz waves. Results were summarized in graph form, comprising one of the first attempts at systematic sleep staging.

By the mid-1930s, commercial EEG systems began to appear. As a result, it was no longer necessary to design or construct apparatus on a per-laboratory basis. Many laboratories made important contributions to EEG methodology and practice using systems that were either "clones" of previous designs or using commercial systems. As such, they are not included in this report, which is focusing on instrumentation development in itself. Their absence here does not imply that their contributions were not significant. Even as standard EEG machines became available, researchers and clinicians continued to push the envelope of technology and practice, incorporating existing designs into ever more sophisticated systems. For example, C. W. Goodwin at Yale designed an improved differential amplifier in 1941, which provided DC and AC amplification with gains up to 1 million, from 0 to 10,000 Hz.

The *Journal of Neurophysiology* began in 1938. The depth and breadth of the first year of reports is impressive. Within the 52 papers contained in these 6 issues, virtually every technique and application of current EEG was anticipated. This year included groundbreaking work on single-unit studies, sleep EEG, behavioral effects of drugs and surgery, autonomic control, voluntary control, thermal effects in the brain, corticothalamic and corticocerebellar relationships, electrical brain stimulation, EEG localization, effects of fever, poisoning, blood chemistry and blood pressure, normative values for EEG rhythms, EEG correlates of postural control, frequency analysis, and EEG correlates of psychiatric drugs. These reports appeared within 10 years of the first publication of the observation of human EEG, chronicling tremendous growth and innovation.

COMMERCIAL EEG BEGINS

Albert Grass produced the first three amplifiers comprising the Grass Model I in September of 1935. These units were provided to the Boston City Hospital for use by Gibbs and Lennox. A second unit was provided to Davis' laboratory at Harvard Medical School. The first Grass inkwriters were produced in early 1936. The pen deflection circuit used the same basic principle as the d'Arsonval galvanometer, in that a current-carrying moving coil was caused to rotate due to a magnetic field. The design also drew from the knowledge of the European designs, particularly Matthews' and Toennies', that the Gibbs' learned during their trip in the summer of 1935.

The commercial version of the Grass Model I had three channels of differential amplification and an inkwriter that recorded on rolls of paper (Fig. 17). In 1936, several of these machines were sold to laboratories in the Boston area. The basic design included a large table top, an inkwriter on the right, and a paper takeup roll on the left. The amplifiers had five stages of vacuum tubes, including a final inkwriter driver. The first three stages were powered by a combination of automobile and dry-cell batteries, the last two by an AC power supply. Batteries remained in these designs until the 1950s, when stable, low-ripple, low-noise power supplies became available.

At the time of its introduction, the Model I was the only commercially available system with a bandwidth of 1.0–10,000 Hz. It was used in conjunction with CRT displays for high-frequency microelectrode nerve studies by dozens of non-EEG physiologists. This system also introduced many of the basic controls, such as filter and sensitivity, chart speed, calibration, and montage selection.

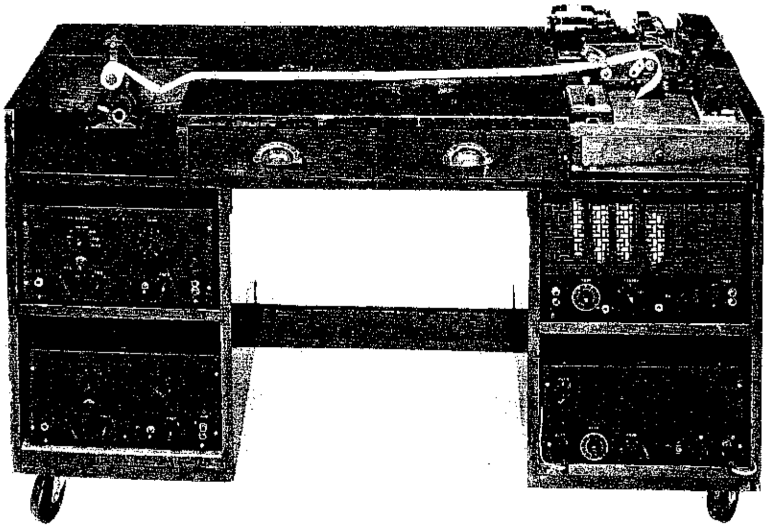


FIG. 17. Grass Model I EEG (1935). This machine was built for Dr. Hallowell Davis, who designed the console with his wife Pauline. Note the essential elements that persist to the present day: rugged console with wheels, inkwriter on right, table-top for paper, paper takeup on left, knee space for the operator, and supply drawer. (Photo courtesy of Mrs. Ellen R. Grass.)

During 1936 and 1937, the paper roll became recognized as the weak point in the system. Records often spilled onto the floor, and the unwinding, winding, and cutting of records for viewing or collating was tedious and manually tiring. Moreover, the paper had no lines or other markings, making records difficult to read in a quantitative fashion.

Albert Grass found that folded paper was being used in billing machines. This paper was produced preprinted and precollated, with perforations and punched holes to facilitate its use in books and ledgers. It was used in printing machines that were hand-cranked and moved the paper by pinwheels. During 1937 and 1938, Grass was able to find a manufacturer to design a press to make EEG paper. The paper speed of 30 mm/s, which had been Hans Berger's preference, was standardized in 1937 by Davis, Gibbs, and Grass. By 1938, 60 channels of the Model I had been built.

The Grass Model II appeared in 1939. It used the specially produced folded paper and initially had four-channel and six-channel capability. This system had essentially the same gain and response characteristics that were to be used from then on. The first units were used to retrofit the Brown University system that had been built by Andrews. Dr. Donald B. Lindsley, who had trained with Travis, came to Bradley Hospital in 1938, after Jasper had moved to Montreal. He inherited the four-channel system, and contracted with Grass to improve the output capability. In 1939–1940, Grass modified this system to use the new inkwriter.

The Model II became the mainstay of EEG during World War II. Approximately 1,000 channels were produced, in four- and six-channel configurations (Fig. 18). The priorities for these machines were ruggedness, reliability, and the ability to operate in front-line hospitals. Some machines were transported in water-tight containers and were actually floated ashore from supply ships. They were used to select pilots and to evaluate physically and mentally injured soldiers. Many machines continued to be used in hospitals after the war.

The Grass Model III was conceived in 1939 when new materials and technology became available. Its development, however, had to wait until after the war. The "console" Model III was introduced in 1946, and included the first 8-channel (Fig. 19) and 16-channel EEGs ever made. About 5,000 systems were made and shipped worldwide. By this time, EEG was firmly established as a clinical discipline, and research and clinical studies experienced a post-war boom.

Another early EEG manufacturer was Franklin Offner, who began producing systems in 1935. He worked for Dr. Ralph Gerard at the University of Illinois, before forming the Offner Electronics company in Chicago. The original output was the Brush type OS-1 piezoelectric writer, the same type that was used in the Mayo Clinic's first system. This writer gave linear response from 1 Hz up to 1,000 Hz. However, it was initially very sensitive to temperature and had to be redesigned. An early Offner recorder was used by Jasper and Andrews at Bradley Hospital.

Offner and Grass took different approaches to design. While the Grass company produced primarily

FIG. 18. Dr. Donald B. Lindsley recording a four-channel EEG at Northwestern University circa 1946. This shows typical EEG instrumentation as used during World War II. (Photo courtesy of Dr. Lindsley.)

FIG. 19. Dr. John R. Knott operating an eight-channel Grass Model III in 1947. This was the first "off-the-shelf" EEG instrument. (Reproduced with permission from Knott and Kimura, 1985.)

AC-coupled amplifiers, Offner focused on chopper-based DC amplifiers. While this provided superior low-frequency response, the chopper design introduced high-frequency noise. Although this was not a problem in normal use, there were times that the chopper would interact with, for example, EKG artifact, producing a beat frequency. In one episode, Dr. John Knott thought he had discovered a new EEG rhythm, only to discover that he was looking at one such beat frequency.

At this time, electrode selectors appeared. The first Grass electrode box offered 10 positions; in 1940, this was expanded to 16. Electrode selection was widely used, particularly to create and modify various bipolar montages useful for localizing focal activity. In 1949, Dr. Reginald Bickford, working with Dr. Warren Gilson at the Mayo Clinic, developed a sophisticated electrode selector switch with a visual display, incorporated into an eight-channel Grass Model III. Its value in reducing operator fatigue was significant. The technical problems inherent in a high-quality multichannel selector are not trivial. For many years until the introduction of digital EEG systems, it was the most intricate and precise mechanical component in an EEG machine and often the one most prone to reliability problems.

EEG DURING AND AFTER WORLD WAR II

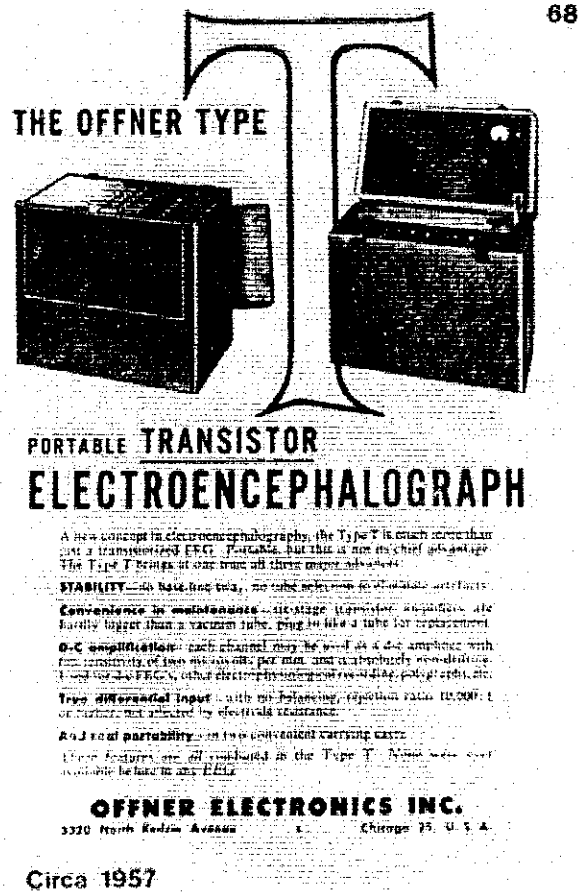
During World War II, EEG research and development essentially ceased. However, the considerable gains that had been made during the previous decade were put into service to support the war effort.

During World War II, EEG found considerable use in neurological and psychological studies, particularly in association with head injuries. Dr. Reginald G. Bickford, who had studied with Grey Walter at Cambridge and later became an EEG pioneer at the Mayo Clinic, developed a portable EEG unit that could be rushed to the site of a plane crash, providing immediate and continuing monitoring of the pilot's condition. He also recorded with implanted intracranial depth electrodes during surgery on patients who had suffered penetrating head injuries.

In the 1950s, Offner produced the "Type T," including the first transistorized EEG amplifiers (Fig. 20). The transistor had been invented in 1947 at Bell Laboratories. Offner produced a portable system contained in two suitcase-sized boxes, with covers and handles. Among the advantages gained from transistors were low heat dissipation, high efficiency, lower operating voltages, and small size. Moreover, it set a new standard for EEG instrumentation. Any of the eight amplifiers could be used as a stable DC amplifier, with a sensitivity of 2 μV/mm. They boasted differential inputs with common-mode rejection of 10,000:1, making electrode resistance much less of a concern.

As transistor technology developed, so did the knowledge of how to use them. Within a few years, transistors were used in very reliable, stable high-gain designs and became indispensable for high-quality EEG equipment.

One of Offner's reasons for supporting DC operation was a commitment to recording non-EEG signals as well, such as pressure and EKG. The machines were provided with plug-in "couplers," allowing the user to insert modules with desired input characteristics and to change them in the field. Although all channels used a full-range DC amplifier, the addition of low-cost couplers could suit the channel to any desired measurement. Modules were available with capabilities well beyond those required for EEG, facilitating the creation of specialized or research-oriented systems. Indeed, some of these units found use in other fields such as geology, seismology, and the monitoring of riveting and other construction operations. Offner's product line thus differed from Grass in that Grass offered an integrated, complete EEG system, whereas Offner provided a more flexible, general-purpose solution.



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THE OFFNER TYPE T

PORTABLE TRANSISTOR

ELECTROENCEPHALOGRAPH

OFFNER ELECTRONICS INC.

3320 North Kedzie Avenue · Chicago 25, U. S. A.

Circa 1957

FIG. 20. Advertisement for the Offner Type T (1947), the first portable EEG machine and the first to use transistorized circuitry. (Reproduced with permission from Grass, 1985.)

During the 1940s and 1950s, many EEG instrument companies appeared in the United States, Europe, and Japan. Commercial systems provided a standard configuration including a large console with a paper feeder and reading table, controls above and/or below the table, and leg room for the operator. In addition to Grass and Offner in the United States, Medcraft Electronics Corp. produced EEG machines out of Long Island, New York. Other suppliers included Artex and Alvar in France, Marconi and Ediswan in England, Toennies and Schwarzer in Germany, and van Gogh in Holland.

Within 20 years of Berger's first publication, EEG had become a formal laboratory or department in many institutions. By the mid-1950s, nearly every teaching hospital was equipped for EEG. By 1960, systems were found in many other hospitals and in

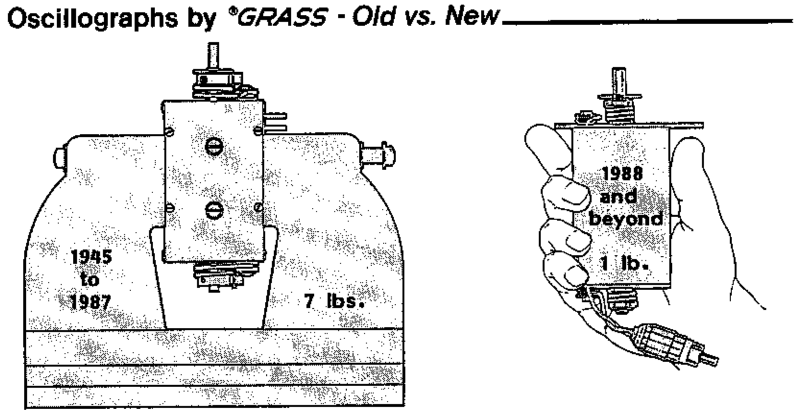

FIG. 21. Some of the earliest concepts are still with us. The original Grass pen oscillograph, designed in 1945 based on the d'Arsonval galvanometer from 1882, was redesigned in 1988 to reduce weight. (Reproduced with permission from a 1989 Grass Model 9 brochure, SO42D89.)

private practices. Specialized units began to be formed, such as pediatric or adult EEG laboratories, sleep laboratories, and epilepsy monitoring units.

The EEG business also became a bona fide industry, and EEG manufacturers took on a life of their own. In the mid 1960s, Offner Electronics, Inc., was sold to Beckman, who kept the product line under the name "Accutrace." Later, in the mid 1980s, Beckman reorganized its electronic instrument division in connection with its cardiopulmonary division and spun those areas off into the Sensormedics Company. The remaining EEG product line stayed with Beckman and was later sold to Teca. Teca did not continue with this product line but chose to discontinue it and pursue digital EEG systems. Thus ended the lineage of Offner's original analog-based designs. During the 1970s and 1980s, there continued to be turnover and change in EEG providers, with some new companies appearing, and others forming partnerships or buying other manufacturers. Among the more notable vendors were Nihon Kohden in Japan, Nicolet in Madison, WI, and Telefactor in Conshohocken, PA.

The Grass Instrument Company continues to improve their product line without abandoning their roots in simple, rugged, equipment suitable for a wide range of uses. It is beyond the scope of this report to describe the evolution of their products, which have included, most notably, the Models 6 and 8 EEG, Model 7 Polygraph, and Model 12 Neurodata Acquisition System. The basic, pen-based approach has gone unchanged, even as Grass amplifiers become used in computer-based systems (Fig. 21). In 1989, Grass was the only entirely American supplier of clinical EEG systems and has recently added functions such as programmable montages, LED displays, and chart annotation.

Many vendors specialized in particular capabilities, such as intensive monitoring for epilepsy, polysomnography for sleep, portable systems, telephone access, and operating-room and intensive-care monitoring.

OTHER EEG ENHANCEMENTS

In 1947, C. C. Breakell at the Whittingham Hospital in England obtained a license from the Postmaster General for the use of a 158.75 MHz frequency for the telemetry of EEG signals. The successful development of a transmitter and receiver was reported in 1949, and applications in portable and long-term monitoring were discussed.

The challenge of EEG recording has resulted in developments stemming from the audio and instrumentation recording fields. In 1964, for example, two engineers working for Ross Adey at UCLA developed a frequency modulation multiplexing scheme for recording multichannel EEG on single tracks of tape. This system was applied to the recording of depth EEG for the localization of epileptic foci in surgical patients. This laboratory also pioneered developments in radiotelemetered EEG, which was originally applied to conditioning studies in chimpanzees. Up to 14 channels could be monitored for extended periods of time; when applied to patients, it yielded some of the first invasive recordings of the progression of a spontaneous clinical seizure.

Television and related technologies have also found considerable use in monitoring. In 1954, Gastaut and Bert recognized the value of recording EEG in conditions "as close as possible to those of life itself," particularly for the diagnosis of epilepsy. J. R. Stevens et al. reported the first use of radiotelemetry for long-term epilepsy monitoring in 1969, and this

FIG. 22. Dr. E. S. Goldensohn at the Neurological Institute of New York in 1962 with the first split-screen closed-circuit video/EEG TV system that he devised for epilepsy monitoring. (Reproduced with permission from Goldensohn, 1991.)

was also reported by R. S. Porter and J. K. Penry in 1971. The first use of split-screen video/EEG recording was reported in 1966 by E. S. Goldensohn and R. Koehle of the Neurological Institute of New York (Fig. 22). This system was employed for teaching and for clinical use as early as 1963. The images were originally filmed directly from the TV screen; later, videotape was used.

Clinical seizure monitoring for epilepsy was refined by J. R. Ives, P. Gloor, and others at the Montreal Neurological Institute (Figs. 23–25). As early as 1973, computerized telemetry was used to acquire the

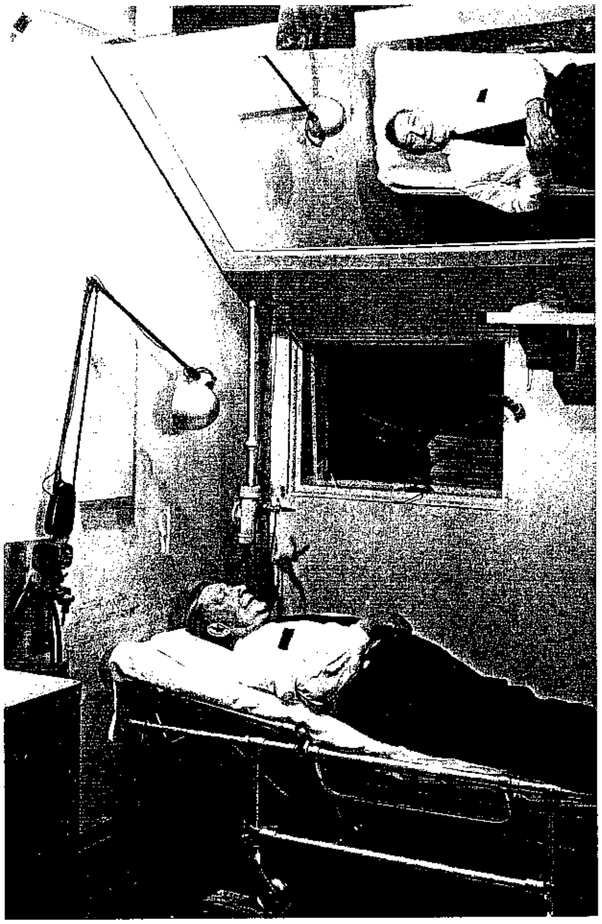

FIG. 24. Patient lying underneath the mirror used for cinematographic recording in Montreal. (Photo courtesy of Dr. P. Gloor.)

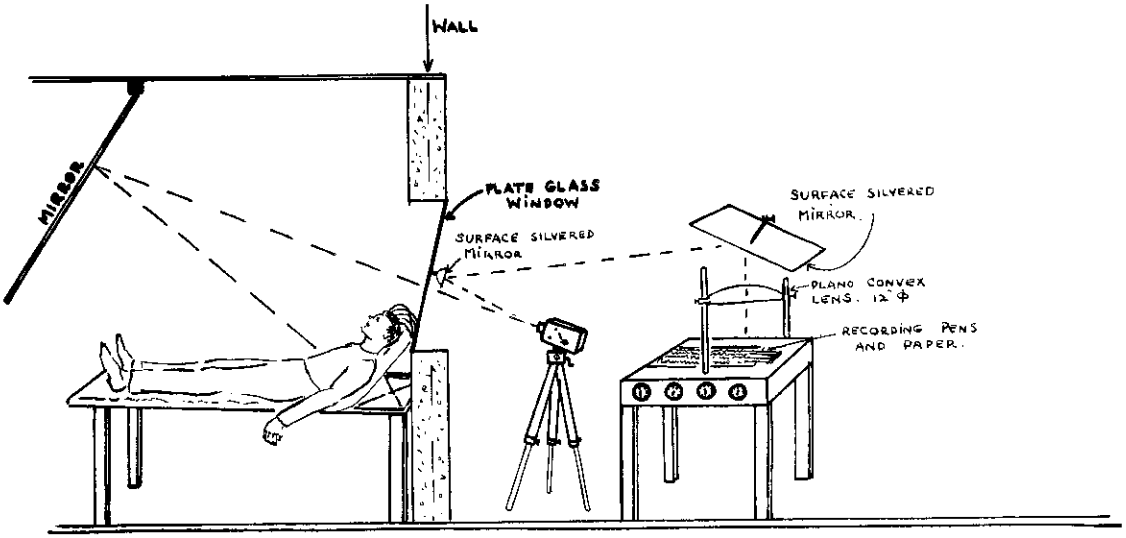

FIG. 23. System used at Montreal in the 1950s to record EEG combined with video for seizure monitoring. Most seizures were induced with Metrazol to minimize the total monitoring time. (Photo courtesy of Dr. P. Gloor.)

FIG. 25. Recording end of the Montreal seizure monitoring system. Note the camera and lens behind the operator, Miss L. Prisko. (Photo courtesy of Dr. P. Gloor.)

sample EEGs from patients subject to unpredictable attacks. Initially, the computer was used to provide a 4-min delay in the EEG, allowing time to capture a seizure without losing important preictal information. They were able to transmit an entire 16-channel EEG with timing information on a single channel, by sampling the EEG at 200 samples per second and multiplexing the additional information into the digital signal. The EEG remained analog, however, as the multiplexer retained all amplitude information. The signal was demultiplexed at the remote end and fed to a computer, where it was then digitized and stored. Permanent records could be made in response to either a button press by the patient or by staff or by the automatic detection of an EEG seizure pattern, which would cause a tape to be made. The video information was handled separately, but synchronization with EEG was assured through the use of a common clock that could write the time on each of the records.

The Telefactor Corporation has produced an entire line of products based on the use of videotape for the storage and integration of video and EEG information. Although an auxilliary computer can be used for signal processing, the basic system is built around video technology, taking advantage of the ability of videotape to store large quantities of information at low cost. These systems also have the advantage of assuring synchrony of the video and EEG information, since they are stored in the same medium.

Other enhancements have been developed to enhance the basic EEG machine, leading it toward more automation and control. For example, Ives described a device in 1984 that could be used to write time codes on an unused EEG channel, turning the signal into a scribe that produces legible characters. Similar features, using matrix printers, provide complete annotations on several commercial machines. Such enhancements move the traditional EEG machine toward computerized functions. Ironically, EEG machines based on digital computers, which can provide such functions quite easily, have difficulty providing the traditional capabilities such as a scrolling display or convenient handwritten annotations.

DIGITAL EEG BECOMES COMMERCIAL

With the introduction of digital technology, EEG systems began to split into several directions. Despite the speed and reliability of microcomputer systems, it took several decades for a digital system to equal the performance and user-interface characteristics of the paper-based systems that had been used since the 1930s. Computer-based EEG is a very active and dynamic business. It is beyond the scope of the present report to properly treat the historical details of EEG computerization, which have included both commercial and private laboratories.

Digital implementations do provide certain immediate advantages that have lent them to special applications. Among the capabilities of a digital design are signal storage, retrieval, numeric processing, and novel, stable displays. The situations that can exploit these capabilities are recording and display of signals too fast to see, sleep staging and scoring, event-related potential estimation, frequency analysis, topographic mapping, and dipole localization. For over a decade, the emergence of digital EEG systems occurred without directly displacing analog pen-based systems.

The EEG industry continues to be an active and competitive business. Companies continue to differentiate themselves based on features, performance, and cost. Although paper-based EEG is said to be obsolete, it is not yet clear that any particular digital or computer-based approach provides the technology of choice for all applications. It is only within the last 2 years that digital EEG systems have approached the real-time response and user-interface characteristics of traditional analog-based systems. For example, to emulate a moving sheet of paper on a high-resolution bit-mapped display, the computer must move the entire screen at least 20 times per second. This implies a bit block transfer rate in excess of 15 million pixels per second, which requires special graphics acceleration hardware. Similarly, the ability to quickly place annotations on the record requires either a very simple and powerful graphic user interface or the ability to use a light-pen or similar device. Several emerging commercial EEG machines now use digital technology to emulate the behavior of a paper-based system. They are near the limits of the commonly available technology and are very close to providing everything electroencephalographers have had for 40 years, plus the advantages of computerization.

Computerized systems have thus moved from an initial strategy of "acquire and do" to that of emulating the traditional clinical EEG machine. The technical limits that were originally encountered in the analog world no longer apply; solid-state devices with digital control have taken care of that. However, new limits now encumber the designer. Current systems engineers must grapple with megabytes, megahertz, bits-per-second, disk access rates, and so on.

As digital EEG systems exploit the available technology, new capabilities come to the forefront. For example, the use of large amounts of data storage leads to systems especially suited to long-term monitoring. Similarly, the emergence of network-based computers can provide an EEG laboratory with immediate, simultaneous, remote access to records from a wide range of locations. The consideration of voltage and frequency specifications has given way to concerns about data storage and processing speed. Modern systems are evaluated in terms of how many hours of EEG they can store online and how many times real-time they can play back recordings. Standard features include montage reformatting, signal processing, quantitative analysis, and sophisticated algorithms for summarizing and mapping EEG characteristics.

Recent developments in computerized monitoring have placed a greater emphasis on the issues of system design, computer software, and multiuser architectures. Such systems may have more in common with distributed, computerized communications or operations-support systems than they do with the strip-chart recorders that preceded them. As has occurred in the past, it is anticipated that the developments of leading-edge laboratories will find their way into commercial systems, as the underlying concepts become increasingly important for broad-based systems.

Acknowledgment: This report is respectfully dedicated to Dr. John R. Knott (1911–1993) and Dr. Albert M. Grass (1910–1992). Dr. Donald B. Lindsley and Mrs. Ellen R. Grass provided valuable early input, and graciously reviewed the draft manuscript. I wish to thank the following individuals for their generous correspondence and commentary: Dr. Nicholas Bercel, Dr. Thomas W. Billinger, Dr. Richard C. Burgess, Dr. John Cadwell, Dr. Pierre Gloor, Dr. Eli S. Goldensohn, Dr. Charles E. Henry, Dr. Herbert H. Jasper, Dr. Donald W. Klass, Mr. George H. Klem, Mrs. John R. Knott, Dr. Ernst Niedermeyer, Dr. John Peters, Mr. Peter J. Seaba, and Dr. Harold W. Shipton.

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