THE ELECTROENCEPHALOGRAPHIC HERITAGE

Albert M. Grass

The Electroencephalographic Heritage Until 1960

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Dr. Alexander Forbes, one of the first electrophysiologists in United States, while Professor at Harvard Medical School, had a favorite topic to get a conversation going with a new group at tea time or over lunch. He would ask: At what time in history would they have preferred to live if they had a choice? Almost inevitably each answered: In the age that they individually lived. From there Forbes would tell endless stories from the change in downtown Boston from horse drawn street cars to electric cars, to his efforts with the Navy to first use the vacuum tube as an amplifier to detect submarines in World War I, and the past came alive. Then, we weren't so sure that it would not have been better to live in his time - he was such a good story teller. I am very glad to have lived in my time because not only did I live and work with all the kinds of instruments except the capillary electrometer, but saw and took part in the development of those from 1935 on and had the pleasure of knowing all the persons who made EEG what it is. It is hoped that by the selection of these few instruments from the past the reader can see how we got from there to here. I have limited the "here" to the early 1960s because anything later would probably be within the time frame of the reader's experience. Also, I didn't want this article to appear more biased than it does because of my own intimate experiences.

Within the 100 years or more selected, and for the purposes of EEG, one can consider the 50 years before Berger, the 25 years after Berger, and then the next 25 years to the present (not described here) as three vastly different periods because of the development of instruments made possible from corresponding changes in the developments in physics - specifically electromagnetic theory, electron theory and the electron tube and finally the transistor with off shoots of memories, microprocessors, and digital techniques.

Until the last few years the definition of "Electroencephalograph" has been described as "an electrical-brain-writer". We came to think of an EEG as a multichannel device to economically record continuous "spontaneous" electrical brain potentials between pairs of electrodes for hours at a time. With the advent of many possible ways of displaying electrical brain activity now in existence or in people's minds, it appears that the definition may need to be broadened less it become obsolete.

In the same way, usage of the term "Evoked Response" has come to mean those potentials on the surface of the head which are synchronous responses to various peripheral stimulii that are displayed by summation and averaging techniques. Lest we forget, scientists were evoking responses in nerve and muscle by stimulation for the last hundred years or more. Long before Berger, the anatomy of the brain was being charted by peripheral stimulation by recording electrodes on and in the brain of animals.

In fact, when looking at some of Dr. Forbes' unpublished string galvanommeter records taken in the 1920s, I think I saw background potentials that were probably spontaneous EEG potentials, but at that time were probably considered noise and artifact while he was searching for responses in the brain of animals to remote stimulii. Such EEG potentials were ignored for three years after Berger published in 1929.

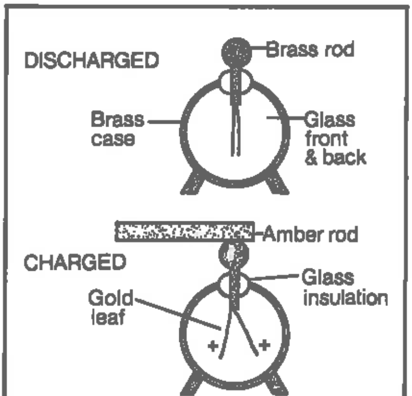
When Dr. Gibbs started to look for clinical uses of brain waves for the diagnosis of epilepsy, I can remember some research electrophysiologists taking the position that there was no sense in doing it and that clinicians should wait until the anatomy and understanding of the brain's nervous system had been defined. Dr. Forbes himself published a paper that criticized the Grass-Gibbs Fourier Transform because no-way were sine waves per se existent in the brain. Forbes and others could not be convinced that the Fourier Transform does not pretend to define the components of the original EEG as sine waves, but merely states that the composite signal can be represented by a series of sine waves of certain amplitudes and frequencies. Such was the understanding of mathematics by biologists at the time. It took another 30 years before the next generation schooled in spectrum analysis brought it out of the closet and made use of it. It should be recognized that the present digital spectrum analysis called the Fast Fourier Transform (FFT) makes still further assumptions departing from Fourier Theory, but it is still practical for EEG in that it can be made to display an approximation to theory nearly instantaneously. Now we see that the merge of "clinical EEG" and "Evoked Responses" of the early electrophysiologists defining a whole new meaning to "Electroencephalograph". It remains now to correlate single neuron responses to the summation of all electrical brain activity.

This bit of history is limited to the instrumentation for "brain waves". However, since the EEG instrument was the only recording device with such high sensitivity, it got used for many physiological variables as transducers got developed to convert pressure, movement, flow, volume, oxygen, CO_2, etc. to electrical potentials. Since the EEG measured only changes in potential above 0.1 Hz, a means was needed to make absolute DC measurements so these variables could have specific values associated to the amplitude scales. Circuits were designed to modify the instrument to record DC for the physiologists.

Thus, application demanded that the polygraph be designed as a separate instrument from EEG to replace the Smoked Drum Kymograph (Figure 31). Now that EEGers are widening the scope of their measurements, there is a convergence of the EEG and the polygraph in the same instrument as for sleep. A monograph could be written about the history of polygraph and transducer development alone.

Confining the history of EEG to the few items illustrated herein from hundreds of contributions to choose from, inherently means many significant contributions to improvements, standards, safety and convenience are deleted. However, it is difficult to decide when to stop. I hope those who consider their pet contribution should have been included will understand.

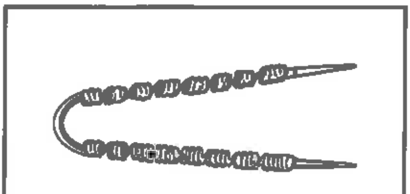
In the beginning of EEG in the United States, most of us were twenty-five to thirty-five years old with boundless energy and curiosity. EEGers from all over the country were on a first name or nickname basis so close had our common interests brought us together. I have chosen to describe the people mentioned in that way so as to try and establish the flavor of the 1930s and 1940s. It is hoped this bit of history will let the reader understand what has gone on before and why. I wish I could tell it as well as Forbes.



1

Static Electroscope

In the late 1500s, William Gibert devised the "Electroscope", the first man made device to detect electricity. This was a pivoted metallic needle which deflected when approached by a rod of amber rubbed with silk to produce a charge (known to ancient Greeks). Ben Franklin (1700s) demonstrated that two linen threads, hung close together and touched by the amber rod, would separate because each carried like charges (which repel). Madame Curie devised the gold leaf electroscope (shown) to indicate the intensity of radioactive material which had been shown to discharge the charged electroscope.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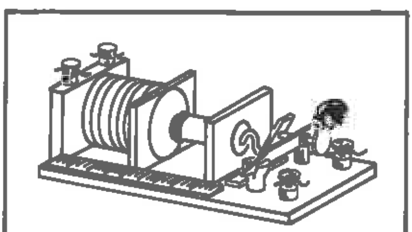
Battery stimulator (circa 1850)
Claude Bernard

Alternating discs of copper and zinc were connected in series and the whole instrument was soaked in vinegar (acetic acid) just before use. It provided a constant DC voltage of about 10 to 20 volts as it was applied to the preparation--probably a frog. It could stimulate nerve but not muscle leading Bernard to false conclusions.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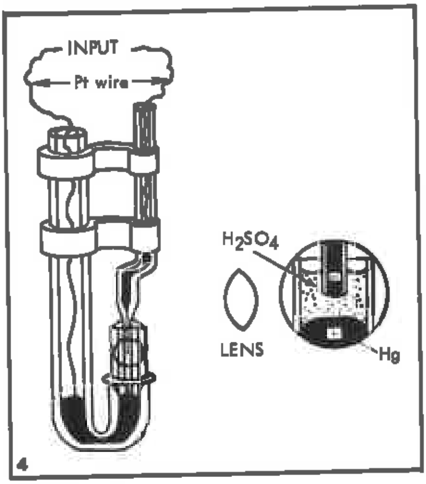
Induction coil (circa 1850)
du Bois-Reymond

du Bois developed the inductorium (used for the next 100 years) which is basically a variable transformer. When DC battery voltages were applied intermittently to the primary by "make-break" contacts, which in turn were actuated by the magnetic flux induced by the coil, pulsating AC high voltages were produced on the secondary for Faradic stimulation of both nerve and muscle. Recording with a crude static electrometer du Bois was able to demonstrate DC resting potentials in both excised nerve and muscle.



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Capillary Electrometer (circa 1873) Lippman

An electrometer operates according to the laws of static electricity. The capillary electrometer relied upon the change in curvature of a tiny meniscus of mercury within a glass capillary when an electric potential was applied between the mercury in the pool and that in the capillary. The meniscus changes were observed with a microscope and/or photographed with a shadowgraph moving film camera. Although it was "sluggish" and the frequency response very poor, Waller is credited with demonstrating the first EKG in 1880. Caton is also credited with using it to demonstrate brain potentials in 1875. The capillary continued to be refined up until 1912 (Lucas). One is at the Harvard University museum.

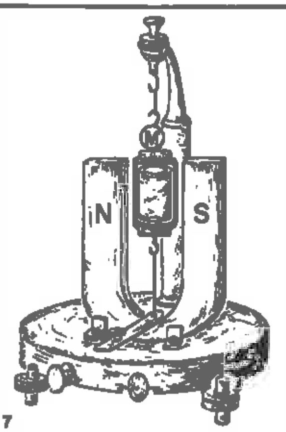

5


6

Waller (circa 1880)

Waller demonstrated the electrocardiograph of man and dog using the capillary electrometer. The input impedance of the capillary was very low, probably well below 1000 ohms. In order to provide enough current from heart potentials to cause a good deflection, the electrode impedance had to be even lower. Buckets of salt water increased the contact area and obtained electrode impedances probably well below 100 ohms.

For many electrophysiologists the inductorium and the capillary electrometer were their stimulator-record instruments from 1880 to 1910 when the string galvanometer became the instrument of choice.



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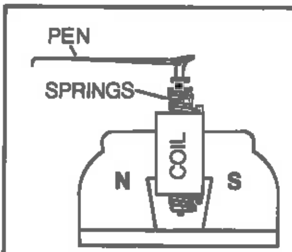
The d'Arsonval Galvanometer (1882)

When d'Arsonval introduced the mirror reflecting moving-coil galvanometer, it had immediate application for very slow potentials. A large U-shaped electromagnet creates a magnetic field. A soft iron core is placed in the center of the field creating air gaps near each magnetic pole. A rectangular coil of fine wire (resistance about 5 KΩ), is suspended by wire in the gaps. A concave mirror (M) to reflect a light beam is attached to one-end.

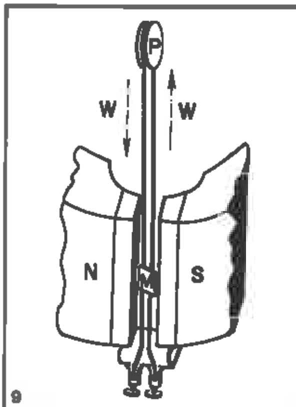
As current flows through the coil, it rotates. The attached mirror deflects light beam proportionately. Current in the wires of the coil near the North Pole are opposite in direction to the current in the wires near the South Pole which causes the rotational force. When the current reverses, the rotation reverses. The relatively large mass of the moving coil gave early designs a time constant of about 4 seconds.



8

Grass EEG Ink Writing Oscillographs 1946

Figure 8 is out of sequence in this series by over 60 years but placed here to show its heritage as one of the most important aspects of analog-time display of Electroencephalography. Note the similarity with d'Arsonval's. The pen has replaced the mirror. Geometry is changed to accommodate the magnetic material which is hundreds of times stronger than was available a hundred years ago. Response is increased by 1000 times to give a rise time of 4 milliseconds.



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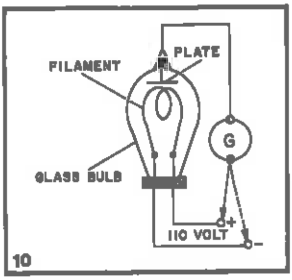
The Duddell Oscillograph (circa 1897)

The Duddell Oscillograph is, in basic principle, much the same as the d'Arsonval, except that the relatively large moving coil is replaced by a single loop of wire. Effectively, this reduced magnet size, narrowed the air gap, reduced coil inertia and resistance to only a few ohms, improved the rise time, and increased the high frequency response to 2 kHz. Sensitivity was very low.

Used by Travis, Jasper, Lindsley 1930s. Required amplifiers and photography for EEG recording.



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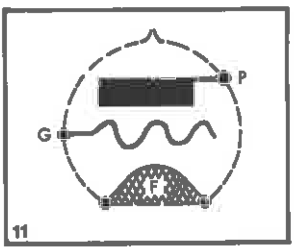
Diode 1883
Thomas A. Edison

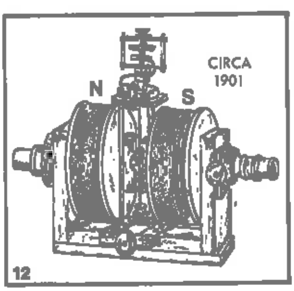
When Edison was experimenting with the construction of the "electric lamp", trying to find materials for a filament that would last more than a few hours, he eventually used carbon in a loop configuration as shown. Edison was an advocate of DC and had the equipment to produce and measure it. Although he had no known use in mind, he put a second element in the vacuum of the lamp and demonstrated that when this second element (plate) was made positive with respect to hot filament, current (G) would flow. Electron theory had yet to be developed.



11

Electron Tube 1907: facilitated the first electronic amplifiers - Lee Deforest

Lee Deforest capitalized on Edison's discovery of DC current flow from a hot cathode (F) to a positive plate (P) by inserting a grid (G) of sparsely spaced fine wires with which he controlled the flow of electrons by changing the voltage between the grid and the cathode. When the grid was more positive, plate current would increase and when negative, current would decrease. Very little grid voltage and even less grid current could control large plate currents and thus large power. The source of power was the plate battery; later a power supply. World War I exploited the vacuum tube for many uses including radio communications and submarine detection amplifiers. Beginning in 1960 the transistor replaced the tube in instrumentation.



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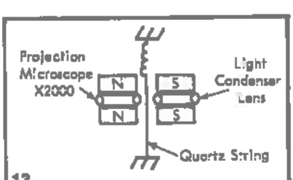
Einthoven String Galvanometer 1901

Einthoven's String Galvanometer provided an instrument sensitive enough to directly record the EKG without distortion. For this achievement, Einthoven received the Nobel Prize in 1924.



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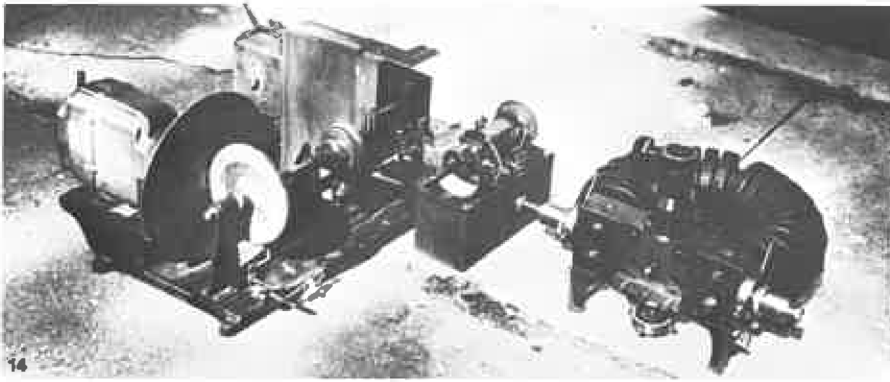
Sensitivity was 1 mV/cm and frequency response to 200 Hz. Visualization of the string movement was possible through a hole drilled in the magnet. A microscope magnified the image, and an optical system projected it onto moving film. The string was a gold plated quartz filament. Resistance was 4 KΩ to 8 KΩ.



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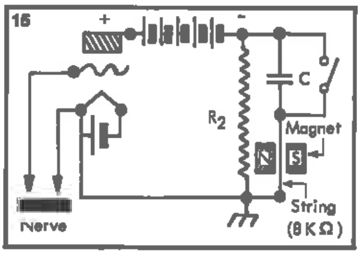

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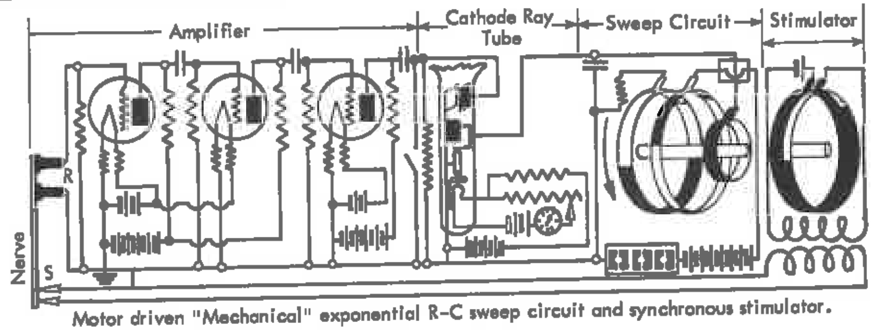
String Galvanometer Amplifier 1920
Alexander Forbes

Dr. Forbes obtained the string galvanometer made by Hindle in U.S.A. in 1910 and used it at Harvard Medical School, Physiology until his demise in the 1960s. His training in physics and as a navigator/sailor of re-known qualified him to work on submarine detection devices during World War I at Submarine Signal Company (now Raytheon Company) where he learned the intricacies of vacuum tube amplifiers. Immediately when the war ended he started work on an amplifier to drive his string galvanometer.

Up until his contribution the only means of "amplification" was by microscope or by projection of images of mechanical displacements. Forbes also developed a high speed, moving film camera to photograph the image of his string to provide time axis.

His 62 page paper in the American Journal of Physiology in 1920 is a classic study in which he explored every state of the art at that time to produce this amplifier, to increase its sensitivity from one millivolt per centimeter to 50 microvolts per centimeter and its input impedance from 4K-8K to 500 KΩ. Frequency response of his string was from DC to 200 Hz. All this brought nerve physiology and cortical potentials nearer to the recording ranges that we know today. It would have been suitable to see EEG with electrodes from the surface of a man's head. Like all other early electrophysiologists he used silver-silver chloride electrodes to gain stability, low polarization, low impedance and good low frequency response.



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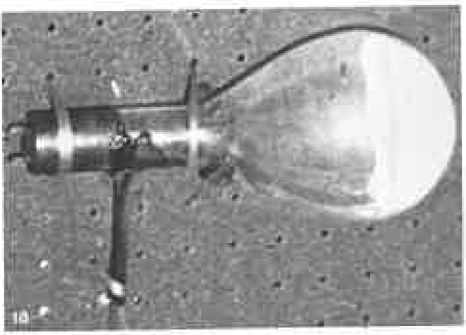
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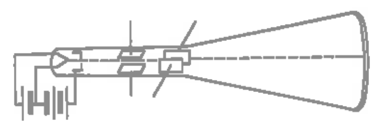
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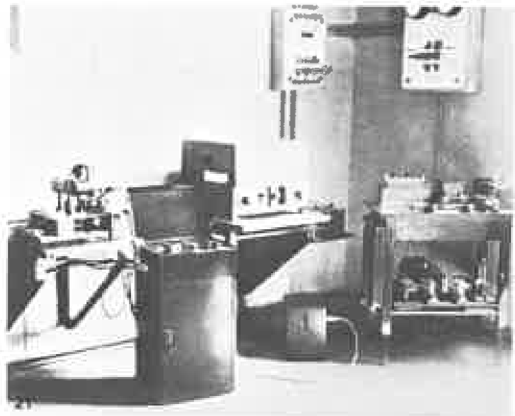
Cathode ray oscilloscope 1922
Gasser and Erlanger

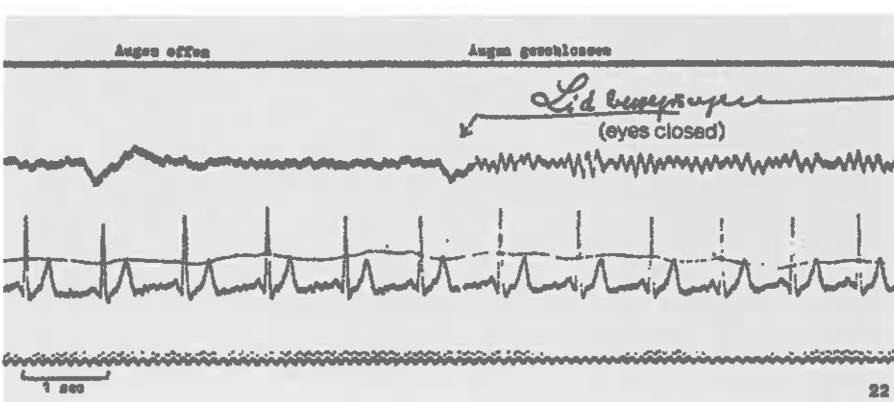
These two physiologists got together at Washington University, St. Louis and developed the first cathode ray oscilloscope and even built their own tube. Unfortunately they never could get their tubes to stay working. Eventually they got one from the Bell Telephone Labs who were also starting to develop a tube (Johnson, 1921). One of their trial tubes is at the Washington University and is shown in Figure 18. The amplifier circuit they used was similar to Forbes in that it used cascaded amplifier stages and did not have a differential input. It had a frequency response of several thousand cycles and for the first time fairly accurately recorded a single nerve potential. Sensitivity was probably about 50 millivolts/cm. The circuit diagram shows not only the amplifier with gain of 450 but also motor driven potentiometers that provided the time axis voltage and a synchronous stimulus pulse by make-break contacts (on the same shaft) that provided a pulse for the primary of an induction transformer. Photographs of the trace were taken by holding photosensitive paper against the face of the tube. With sufficient repetitive responses, a record was obtained. This instrument was not suitable for EEG because of its low sensitivity.

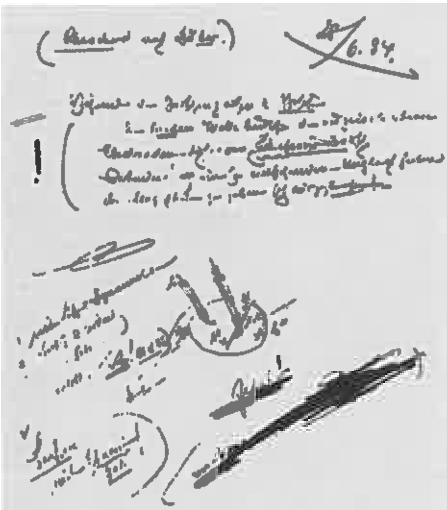
It was not until the early 1930s that commercial CROs became available. Most physiology labs built their own.



First Reported Human EEG 1929
Berger 1877-1941

Berger, like many others of his time, worked first with the Lippmann Capillary Electrometer and about 1910 changed to a string galvanometer to study electrical activity in animals - EKG and nerve physiology. In 1924 he was able to get a string with a sensitivity of 1 mV/cm and frequency response to 200 Hz. He began recording on humans about then and found that if he recorded from persons with skull defects, he could put needles near the cortex and thus get potentials large enough to record. He did not get an amplifier until 1931, long after he reported human 10 Hz alpha waves in 1929. Sensitivity was enhanced by a double coil galvanometer by Siemens in 1926 which gave a sensitivity of about 130 microvolts per centimeter. We do not find any of his records with voltage calibrations. It was on this device he was able to record the EEG (21) shown here. Records were always on photographic paper with lengths only one to three minutes. Since the input impedance of his instruments was 3 KΩ to 10 KΩ, he used non-polarizable pad electrodes (24) of very low impedance on the surface of the head. On occasion he

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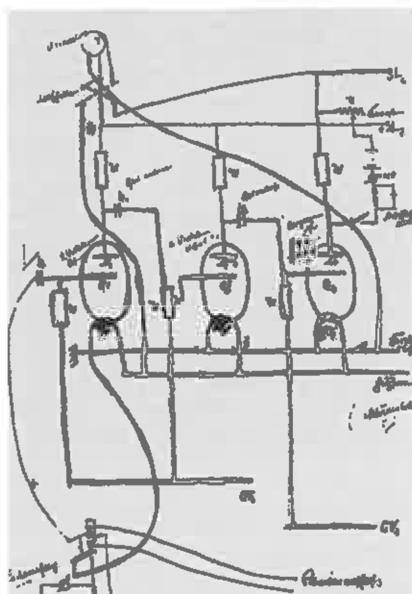
also used a large capacitor to keep out DC potentials and was aware that this limited all responses below 2.5 Hz. When he was able to get an amplifier (1931) by Siemens (25) he was more impressed by its high input impedance than he was by the increased sensitivity it provided him.

Berger was such a quiet, unassuming man that it is little wonder that his published treatise on human brain waves lay unrecognized until 1933 when Adrian found it. It was nearly as much a job to discover Berger as it was brain waves.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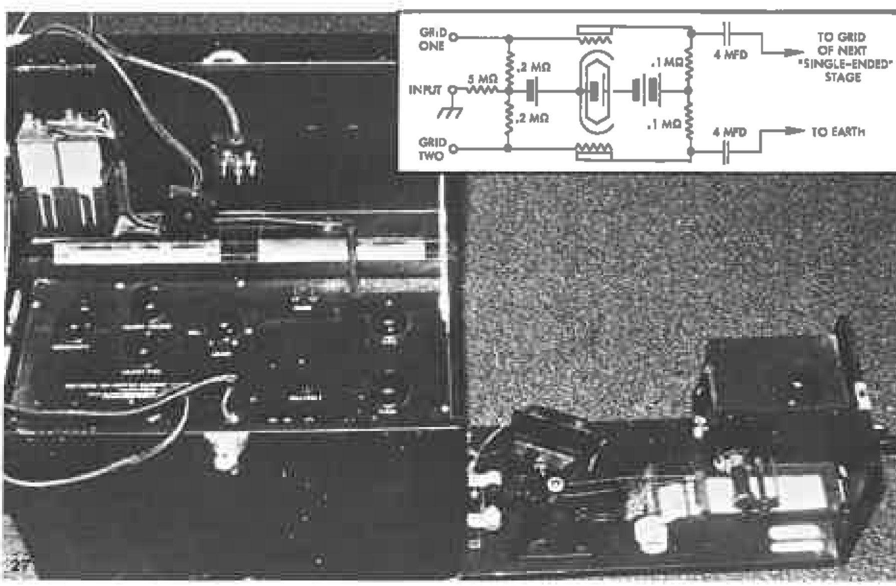
Instruments - England 1920s-1930s: Matthews

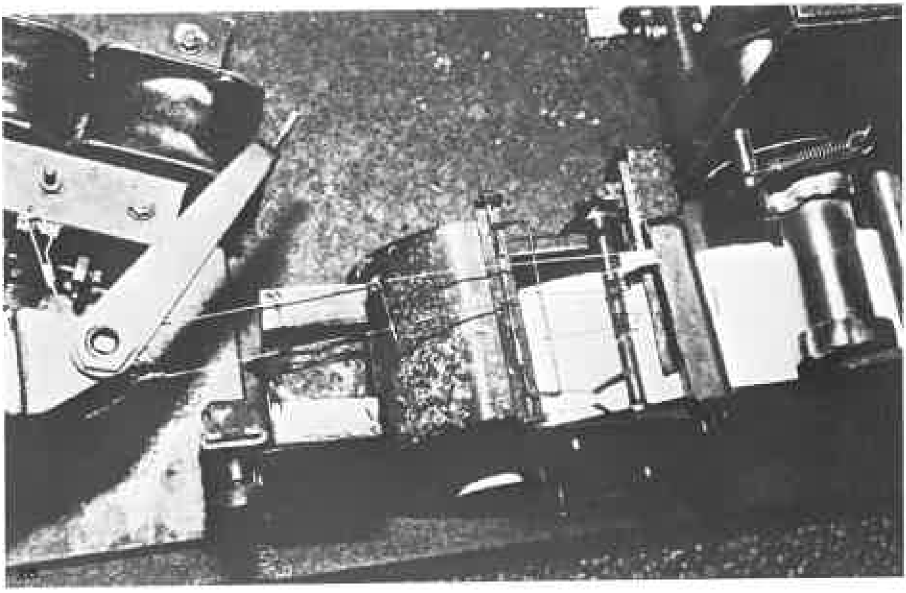
Brian Matthews (later Sir Brian) was the prominent English physicist-engineer who worked with the physiologist Adrian (later Lord Adrian) as instrument builder par excellence. A Matthews mirror galvanometer (1923) with frequency response above 2 kHz is shown. It did require a vacuum tube amplifier to be useful for physiological potentials.

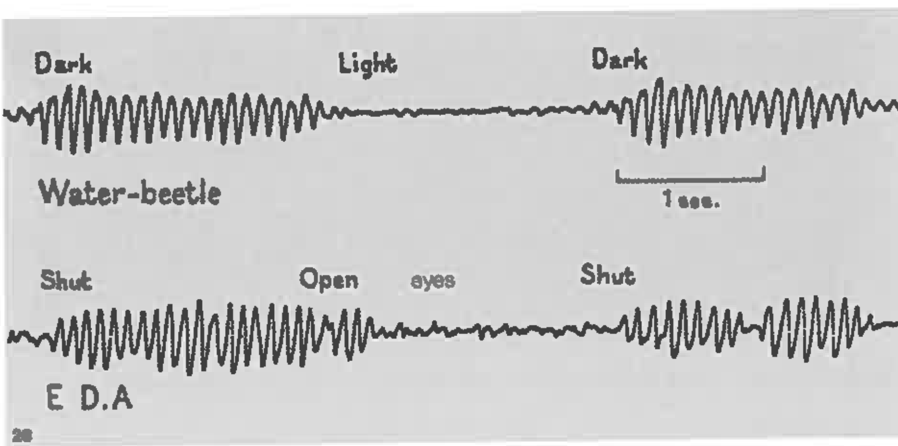
Another development of Matthews was the direct inkwriting electrocardiograph (circa 1926). It also made use of a three stage capacity coupled amplifier. Its main contribution was the pen motor which consisted of the electromagnetic driving coils coupled by a mechanical leverage to amplify displacement of a low inertia long pen. The chart drive system was driven by a spring wound clock-type motor (28).



Differential Amplifier 1934: Matthews

One of Matthews contributions was the application of the input differential amplifier to electrophysiology. This is not the classical differential amplifier with a large common mode resistor in the common cathode return to ground or to negative. The latter is believed to have been described by Bell Labs also in the early 1930s. The large common resistor tends to automatically equalize the amplification of the two input tubes and improve common mode discrimination ratio (CMR). EEG amplifiers with successive stages of this latter design were first introduced by Grass and did much to eliminate interference, crosstalk, power supply problems and physiological artifacts.



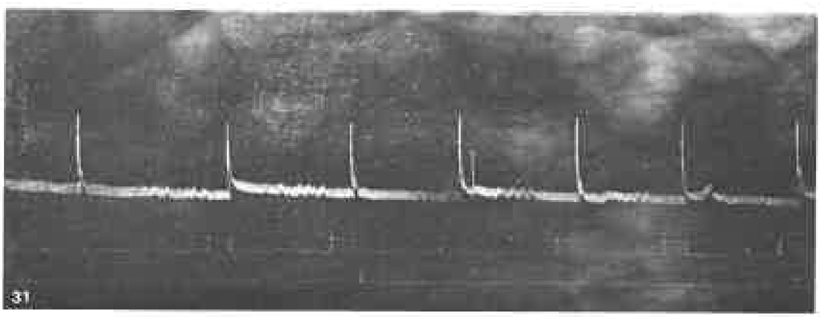


Inkwriter records by Adrian and Matthews on the Matthews Inkwriter in 1933. Comparison of brain waves from a water-beetle preparation in darkness and light (upper record) and from human subject (Adrian) with eyes closed and open (lower record). In both the rhythm is abolished during visual activity.

Adrian came to U.S.A. and reported he had verified 10 Hz brain waves on humans as reported by Berger, 1929. He called it the Berger Rhythm. At the ANA meeting at Atlantic City on June 4, 1934, Adrian was instrumental in assuring that Hans Berger got credit for the discovery.

Computers Massachusetts Institute of Technology 1927-1930

One of the first analog computers and certainly the most advanced and precursors to vacuum tube digital computers were two developed under Dr. Vannevar Bush at M.I.T. in the late 1920s. The early one was 100% mechanical and the second was combined electrical/mechanical (no vacuum tubes). The latter is included here to show the state of computer art at that time and the originality and bearing on subsequent designs that led to the first step of our present computer technology.



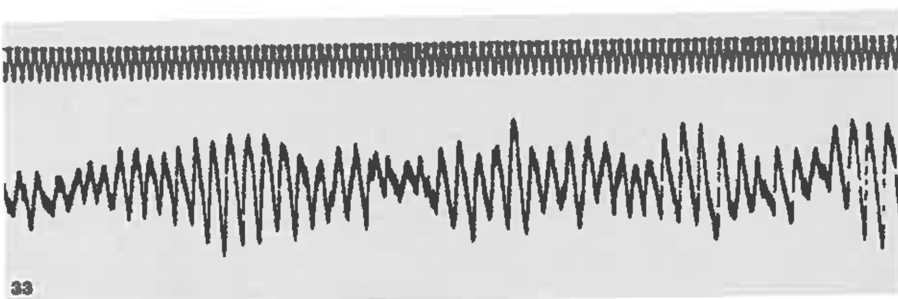
Smoked Drum Kymographs vs the Physiologic Polygraph to 1950s

Before stable DC amplifiers, transducers and polygraphs, time related physiologic measurements were recorded on the "smoked drum kymograph". This consisted of glossy paper whose surface was coated with smoke from a kerosene flame then placed on a vertical cylindrical drum which was rotated by a spring wound clock motor for a time axis. Forces, displacements, pressure, stimulii, etc., were directly translated by strings, springs, pulleys, levers, pivots, and diaphragms to bamboo straws positioned and pivoted to act as styli to scratch a line of smoke off the paper when activated by the physiological event. This pre-polygraph procedure had little application outside experimental physiology. The record was made permanent by coating the paper by dipping in varnish. This record was made by Mrs. Ellen Grass in 1934 for her degree in physiology.

Lee Travis
Iowa City (circa 1920s)

Travis was one of the best educators in our field, as indicated by his Ph.D. graduate students who have been in or near EEG since then. They include: Herb Jasper, Don Lindsley, John Knott, Chuck Henry, all of whom added to the foundation of EEG as a clinical procedure. In the late 1920s Dr. Travis built amplifiers and adapted them for listening to sounds created from electrical muscle responses. He later recorded responses on mirror oscillographs and then on an ink-writer. Unfortunately his early amplifiers were transformer coupled and thus did not have adequate low frequency response for good EEG.

EEG at Brown University 1934
Jasper



Sample of the first human EEG tracing taken at the Bradley Hospital, Providence, Rhode Island, by Jasper and Carmichael July 9, 1934. Record, which shows prominent alpha rhythm was made with a Westinghouse, galvanometer-type mirror oscillograph Duddell type. Time line 25 Hz. Frequency response: from 1 to over 1 kHz good amplitude linearity amplifiers by Andrews. Required photography.

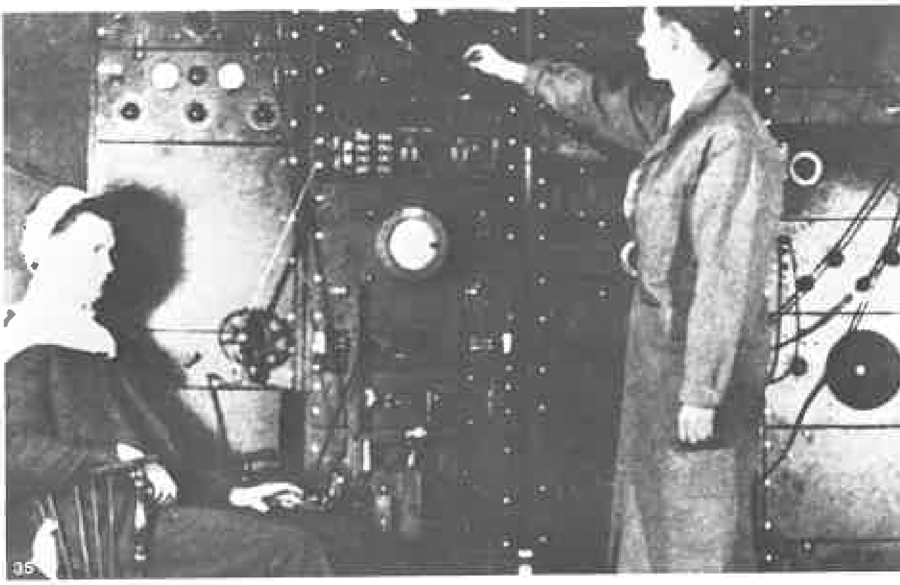
EEG at Harvard 1933-1935
Davis, Lindsley, Derbyshire, Simpson

Hallowell Davis, (student of Alexander Forbes) in the early 1930s had Lovett Garceau, engineer, build the acoustic lab (35) with the apparatus shown here for creating sound stimuli and recording the auditory responses on a CRO. It also had a one channel Western Union Morse Code inkwriter which subsequently was used to record EEG by such notables as Davis, Gibbs, Lindsley, Derbyshire, among others, during the 1934-1935 era. In the course of doing her thesis on hearing, Ellen Grass (né Robinson) came to the medical school to work under Davis in 1935. One of the first EEGs in U.S.A. was recorded in the Davis' lab.

Some Early Publications on Brain Electrical Activity
Lindsley

Dr. Lindsley lists the following persons who published on "brain activity" up to 1933 to 1934 when Adrian and Matthews in England confirmed the EEG in man to which Berger is now known to have dedicated his work beginning in 1924 and published in 1929. This list is far from all inclusive. From 1934-1935 on when Gibbs, Davis, and Lennox identified the spike and wave as specific to twelve petit mal patients, clinical EEG was established and instruments specifically dedicated to EEG became available.

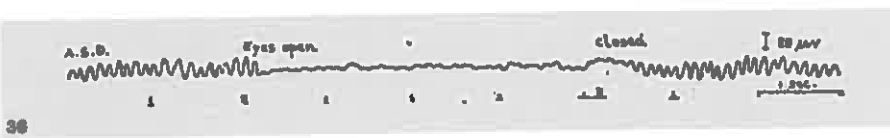
Caton (1875)
Fleischl von Marxow (1890)
Beck (1890)
Danilewsky (1891)
Gotch and Horsley (1891)
Beck and Cybulski (1892)
Larinow (1898)
Trivus (1900)
Tchiriev (1904)
Kaufman (1912)
Prawdicz-Neminski (1913)
Cybulski and Macieszyna (1919)
Prawdicz-Neminski (1925)
Berger (1929)
Bartley and Newman (1930)
Bartley and Newman (1931)
Travis and Herren (1931)
Travis and Dorsey (1931)
Davis and Saul (1931)
Adrian (1931)
Adrian and Buytendijk (1931)
Bishop and Bartley (1932)
Travis and Dorsey (1932)
Fischer (1932)
Kornmüller (1932)
Perkins (1933)
Bartley (1933)
Gerard, Marshall, and Saul (1933)



35

Davis' Lab, Harvard Medical School 1934

Donald B. Lindsley was a subject for Gibbs, Davis, and Lennox (1935). The operator of the apparatus in this particular picture is A. J. (Bill) Derbyshire, who has spent much of his professional life in EEG work. The electrodes on Dr. Lindsley's head consist of a crown made of wire and saline soaked cotton bandage for ground (G_2) and a hypodermic needle in the vertex for (G_1).



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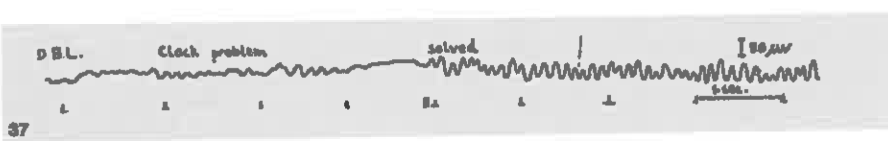
Ink record taken on Derbyshire on above apparatus showing eyes open – eyes closed.



37

Ink record of Lindsley when asked to describe the angle the clock hands made when hands of clock were at 10:15. Eyes were closed.

Letter from Gibbs to Grass 1935

Aug 27 1935
Bad Homburg v.d. H.
Germany

Dear Albert,

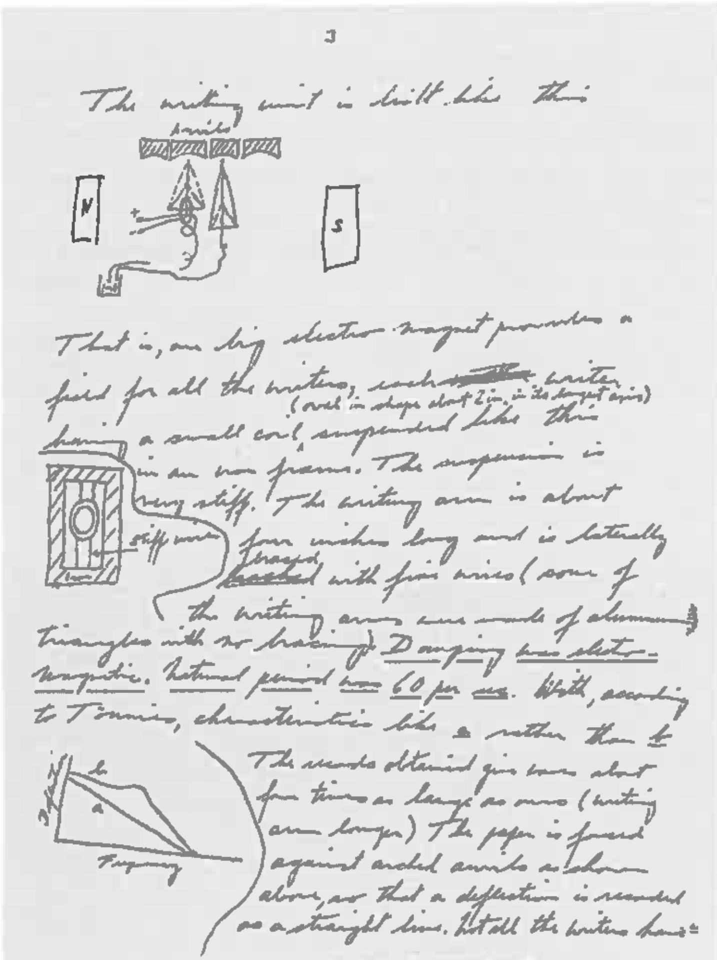
I have talked to the man who was supposed to have built a pre-amplifier to replace the push pull input described by Matthews and have found that he has nothing of the sort. He has some new circuits that may be useful for other purposes and he is going to send them to me; they will be published this winter in the Brit. Journal of Physiology.

We went to the Kaiser Wilhelm Institute in Berlin and saw the apparatus that a fellow named Tönnies has built for them. It is called a "polyneurograph" and was designed for the same sort of work we plan to do. It is essentially five ink

38 ("Push-pull" early name for "differential amplifiers")

Clinical Electroencephalograph 1935: Grass-Gibbs

In late May of 1935 Dr. Frederic Gibbs contracted with Albert Grass while at M.I.T. to build three channels of EEG amplifiers to drive the Western Union Morse Code inkwriting undulator to be delivered by September 1, 1935 at a cost of $1000.00. Dr. and Mrs. Gibbs were going to spend the summer visiting Berger and others in Germany working on EEG. These amplifiers were to be ready when he returned. They were ready. Subsequently, in early 1936, the first Grass ink writers were produced. These two pages from a letter from Dr. Gibbs in August 1935 show some of the things he saw and heard in Europe including the Matthews differential amplifier circuit and a design for inkwriters by Toënnes. Such long visits were a vital link for science at that time.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The writing unit is built like this

That is, one big electro-magnet provides a field for all the writers, each writer (oval in shape about 2 in. in its longest axis) having a small coil suspended like this in an iron frame. The suspension is very stiff. The writing arm is about four inches long and is laterally braced with fine wires (some of the writing arms are made of aluminum triangles with no bracing). Damping was electro-magnetic. Natural period was 60 per sec. With, according to Tönnies, characteristics like a rather than b

The records obtained give waves about four times as large as ours (writing arm longer) The paper is forced against arched anvils as shown above, so that a deflection is recorded as a straight line. But all the writers have

(Innovative but not practical)

39

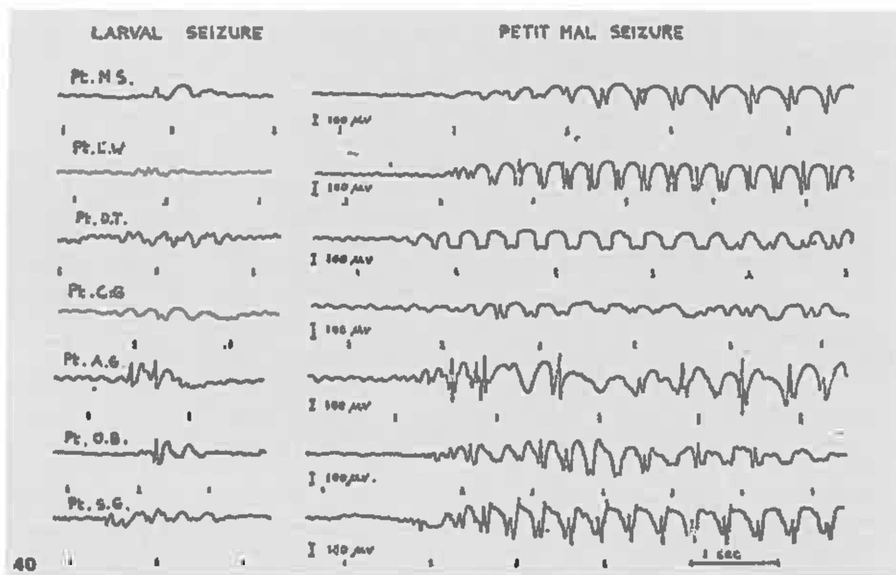
This letter is five pages long and part of it is documented here to show that it took a whole summer by boat travel, (without benefit of air travel or workable telephones) to explore what was being done in Germany and England. Gibbs did it and thus the work of Berger, Kornmüller, and Fischer in Germany and Adrian/Matthews in England was brought back to U.S.A. and expanded by Gibbs and others to get clinical EEG off to a flying start here. But remember in Europe the dark clouds of World War II were approaching and free scientific work there was getting to be impossible. Berger became a victim of the war.

Please note Adrian came to U.S.A. in 1934 and reported at the ANA that he had verified Berger's work. Lennox and others of the Neurology Department at Harvard where Gibbs worked were members of the ANA.

Gibbs-Lennox-Petit Mal 1935

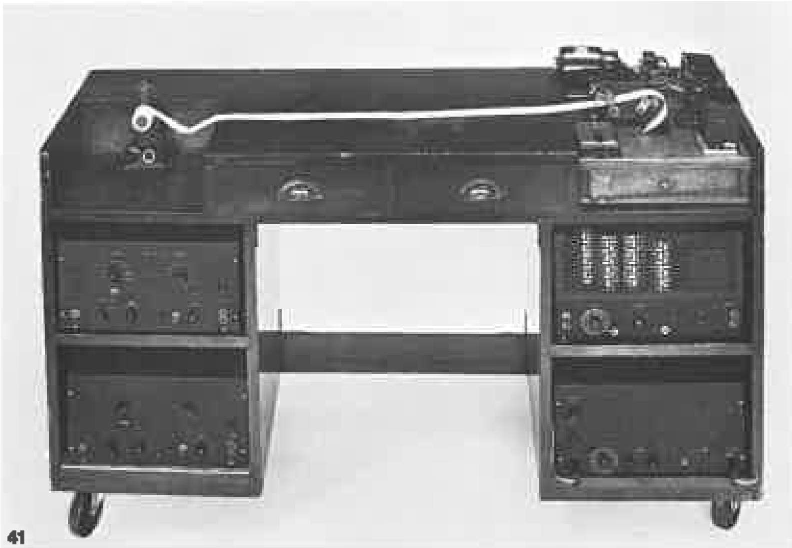
In 1934 Dr. Gibbs came to Boston from Johns Hopkins via the Johnson Foundation, University of Pennsylvania. Motivated to learn about epilepsy, he sought out Dr. William Lennox, world renowned epileptologist, and to find out about recording equipment that Davis had at the Department of Physiology at Harvard. There he saw the advantage of instant recording inkwriters for recording EEG as described previously. He contracted with Garceau, Davis's engineer, for a single channel "portable EEG" using a Western Union Undulator built in World War I for recording Morse Code - i.e. DOT-DASH. The portable "EEG" failed to work consistently. Gibbs, frustrated, came to M.I.T. for advice and found Albert Grass in 1935.

Gibbs, Davis, and Lennox reported in December of 1935 single channel ink records on twelve petit mal patients, grand mal patients, sleep, overventilation, and effects of some anaesthetics, confirming in man what others had published on animals. The availability of immediate ink recordings, even with poor quality, to view while the patient was still hooked up to relate "cause and effect" of artifacts and observed conditions of the patient was what gave the Gibbs' a decided advantage over others in the U.S.A.



Records from Seven Petit Mal Patients

As can be seen above the Undulator records were distorted badly. Not only were they non-linear in amplitude (actually amplitude sensitivity increased with amplitude until the magnets stuck) but frequency response was barely "out" to 24 Hz - I won't use the word "linear" here. Worst of all they were not consistent as can be seen on Traces 3 and 4. It is amazing that misinterpretations did not abound.



41

Grass Model I Electroencephalograph 1935

Regretfully, we do not have a picture of the first three channel EEG built for Dr. Gibbs. The amplifiers were completed and driving the recording heads of three undulators by October 1935. New linear moving coil pen writers were designed and installed early in 1936.

In 1936, Model I EEGs were made for Davis, Schwab, and others in the Boston area. Sixty channels of Model I were made by 1938. The picture shown here was built for Hal Davis and his wife Pauline as a two channel EEG. Hal and Pauline designed the "console". The principle of the design was to have a long table top to view the record, the ink writer on the right, and a roll paper take-up device on the left. Knee space was provided. Remember control consoles for any kind of instrument were not yet considered. The basic design is included in EEGs today.

The circuits consisted of five stages of cascaded differential vacuum tube amplifiers (see Matthews). The last stage was a power stage to drive the inkwriter. The first three stages were powered by automobile storage batteries, the last two by an AC power supply. The advent of stable regulated power supplies with low noise and 60 Hz ripple had to wait for another twenty years for transistors before all batteries could be eliminated.

Model I did more than establish basic parameters to record EEG. Being the only available high sensitivity amplifier with a bandwidth of 1.0 Hz to 10,000 Hz it was used for such things as single nerve cell response using microelectrodes by Renshaw, for CRO amplifiers for dozens of famous basic physiologists including Cannon, Rosenbleuth, Morison. Furthermore, the kinds and values for control of filter and sensitivity, chart speeds, calibration, and even master electrode montage selectors were established and are essentially the same in 1984 for EEG.

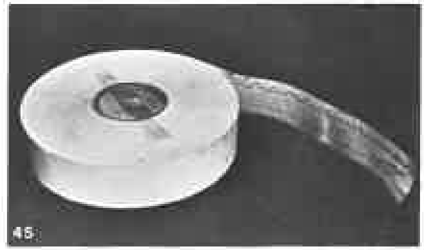
42

Fred and Erna Gibbs brought their three channel "set of boxes" and writer to every mental hospital in Massachusetts, and with Dr. Lennox examined every variety of mentally disturbed patient. For the AMA annual meeting in Kansas City, June, 1936, the EEG was transported in Dr. Gibbs' car and demonstrated with live epileptic patients. The AMA honor award was given to Drs. Gibbs, Lennox, Davis, and Erna Gibbs and Albert Grass for the demonstration.

Roll versus folding chart paper 1937 Grass

Rolls of chart paper -no lines- were the means for EEG recording with ink, in the beginning. Access to the record within the roll required spilling records all over the floor or as Dr. Henry is doing, winding from one mandrel to another. At the Loomis lab they developed a "guillotine" which cut the paper in about one meter long sheets, then bound it all together with nuts and bolts. The motivation to do something about roll paper was far greater than to develop amplifiers, stimulators, etc.

Grass came across folded paper then used in billing machines (46). It was called "register paper" because it involved several precollated folded, perforated sheets with punched holes in the side (like todays computer paper) driven by pin wheels and hand cranked. It was a giant step at the time to find a printing press manufacturer to help design a press to make EEG paper. This was done in 1937-1938 and was improved in the early 1950s to break the ground for making a high speed offset printing press for Grass EEG paper. The EEG paper speed of 30 mm per second was standardized for U.S.A. in 1937 by Davis, Gibbs, and Grass. Figure 43 shows Dr. Charles Henry, 1937; Figure 44 Dr. and Mrs. Gibbs, 1937. Figure 46 shows the piece of the original register paper on which a frequency response was run. The sine waves were created by the output of a photoelectric cell from light passed through a narrow slit and passed by an "off center" circular disc driven by a high speed motor. The shadow of the disc fell on the photocell. Electronic oscillators with frequencies below 100 Hz had not yet been developed.



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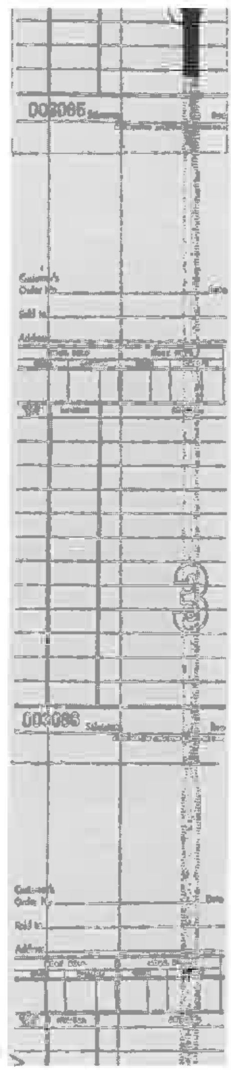

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Model II EEG 1938-1946: Lindsley's Labs

Dr. Lindsley came to Brown, Bradley Hospital, Providence, after Jasper moved to Montreal. He inherited the four channel photo recording Duddell mirror oscillograph made by Westinghouse and amplifiers by Andrews. These were modified by Grass to drive the Grass inkwriter for Model II, year 1939-1940.

About 1000 channels of Model II, four and six channels were made, all with essentially the same technical response characteristics as produced in 1984 -- most going to the armed services during World War II. Reliability and ability to work well in front line hospitals was the main priority. Shipped in water tight containers, some were thrown overboard in the Pacific and floated to shore. They were also used in the selection of pilots and on men physically and mentally injured in battle, in post-War hospitals. Most pre-War EEGers in U.S. and Canada were enlisted in these war programs. This photo of Lindsley was taken about 1946 at Northwestern University and shows a typical EEG as used in the war.

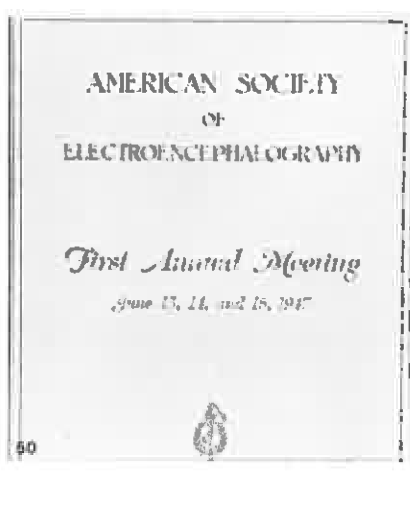
Jasper–Penfield, Montreal Neurological Institute, Canada 1939

First conference on the use of EEG during brain surgery.

FIGURE 1-5.—Participants and invited guests at the opening of the Electrophysiological Laboratories in The Montreal Neurological Institute, February 24–26, 1939. First row; left to right: Robert S. Schwab, S. Humphreys, Herbert Jasper, A. Cipriani, Garret Hobart, N. Fraser, W. V. Cone. Second row: L. F. Nims, David P. C. Lloyd, Joseph G. Hughes, Stanley Cobb, E. Newton Harvey, Alfred L. Loomis, Alexander Forbes, Hallowell Davis. Third row: Colin Russel. (unidentified), Margaret Rheinberger, E. J. Baldes, G. E. Hall, Theodore C. Erickson, John E. Goodwin, Theodore J. Case, Molly R. Harrower-Erickson, Mrs. Robert S. Schwab, Arthur Elvidge. Fourth row: Howard L. Andrews, Joseph Evans, Donald Y. Solandt, (unidentified), John Kershman, J. Roy Smith, Donald B. Lindsley, Choh-Luh Li, Simon Dworkin.

American EEG Society First Meeting 1947

The American EEG Society was organized post-World War II and held its first formal meeting in Atlantic City in conjunction with the American Neurological Association in 1947 -- Herb Jasper was the first president; Fred Gibbs was the next. The first seeds for a society exclusive for EEG were planted in the informal meetings held from 1936 on in Boston, Providence, Hartford, New York City and Montreal. New discoveries were discussed monthly. These meetings were the basis of the Eastern EEG Society and eventually AES.


AMERICAN SOCIETY
OF
ELECTROENCEPHALOGRAPHY

First Annual Meeting

June 13, 14, and 15, 1947

50

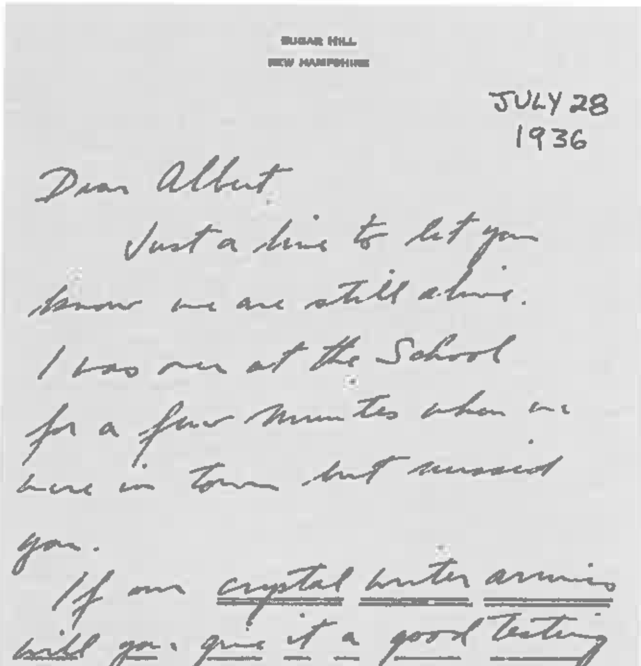
51

Circa 1950 52

Model III EEG, 1946
Fred and Erna Gibbs

Model III Grass EEG was conceived in 1939 when the materials and technology became available but development time for such mundane products had to wait until the end of the war. About 5000 Model III, 8 channel and Model IV, 16 channel were made and shipped worldwide. These were the first 8 and 16 channel EEG instruments ever made. With the post-War boom in neurology and the founding of the American Academy of Neurology, clinical applications of EEG really took off. Papers on new findings in EEG were profusely published in whatever journal would accept them. The EEG journal, sponsored by AES, with Herb Jasper, chief editor, was published in Canada. It eventually became an international journal and moved to Holland. The original Gibbs EEG Atlas was published in 1941 and was followed in 1950 with the updated three volume edition. Electrocorticography started by Penfield and Jasper (circa 1939) at Montreal Neurological Institute had now become an accepted procedure and spread to Chicago, Phoenix and all points of the compass. Other EEG instrument manufacturers in the U.S.A. at the time were Offner, Medcraft and Rahm. Offner worked with Gerard in Chicago and also started production in the mid 1930s with his own company.

Concept of Fourier Transform of EEG: Letter from Gibbs to Grass 1936



SUGAR HILL
NEW HAMPSHIRE

JULY 28
1936

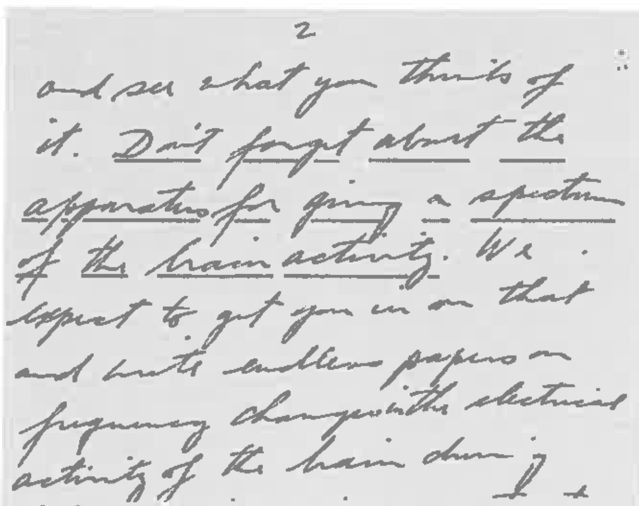
Dear Albert

Just a line to let you know we are still alive. I was over at the School for a few minutes when we were in town but missed you.

If our crystal writer arrives will you give it a good testing

(refers to Offner's Crystal Oscillograph)

53



2

and see what you think of it. Don't forget about the apparatus for giving a spectrum of the brain activity. We expect to get you in on that and write endless papers on frequency changes in the electrical activity of the brain during

(refers to plans for Fourier analyzer for EEG)

54

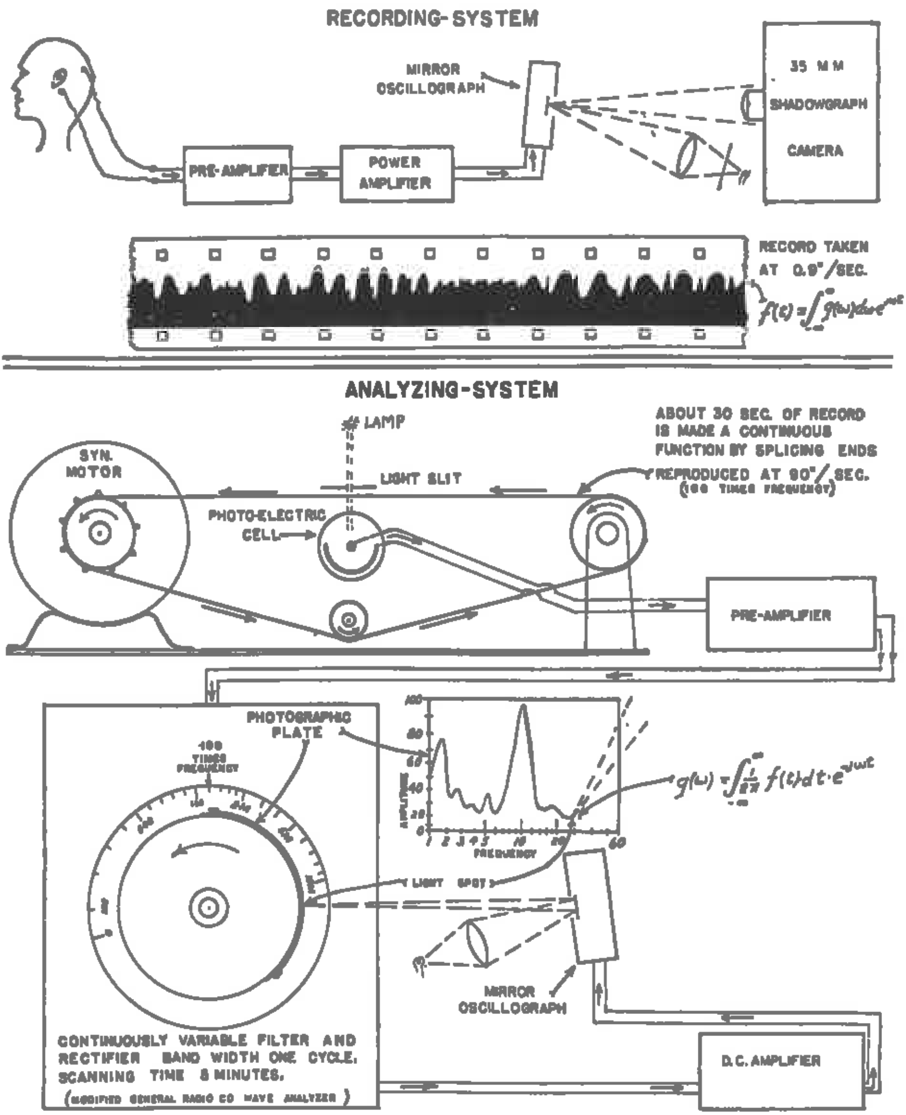
Fourier Analysis of EEG 1938-1944
Grass-Gibbs

The application of Fourier analysis to communication theory was introduced by Bell Labs. and by Guillemin at M.I.T. in the late 1920s and early 1930s. I was fortunate to study under Guillemin and was intrigued with Fourier and with the synthesis of filter networks. When later exposed to the nonrecurrent waveform of EEG, I couldn't wait to get Gibbs interested. This letter from Fred Gibbs in 1936 is evidence that he was interested and provided money and facilities. Also note the reference to a Rochelle salt crystal pen writer that Offner had helped develop. The inability of this latter device to stand the work demanded by EEG limited its usefulness.

Figure 55, from a paper published in 1938, shows the single channel analog Fourier system developed for Gibbs. Though it was accurate, probably more so in abiding by theory than the Fast Fourier Transform of digital systems, it relied on recording the EEG on photographic film and thus took time to develop and run through the analyzer. Nevertheless, the Gibbs were game and spent the next seven years analyzing thousands of EEG records in every conceivable respect; sleep, time sequence, all the epilepsies, mental patients of all kinds, murderers, anesthesia, etc. John Knott, Chuck Henry and many others came to study and help. At one time at least 30 persons were involved in processing EEG records to Fourier Transforms.

Since the Gibbs primary search was for a specific identification means for epilepsy and other brain disorders for each individual patient and since it appeared this could not be done, they abandoned the project in 1945 when they moved to University of Illinois to work with Gerard. The study did not get the attention it deserved by others for several reasons. It was war time, most all researchers were away and it probably was not understood by many. The analysis was not "on line", only one channel was displayed at a time but most of all, neurologists were looking for specific patient/malady diagnosis to avoid reading tons of EEG records. Since it couldn't do that, it was doomed, but it showed what could and couldn't be expected and the problem of specific waveform pattern recognition remains to be solved. However, it was the forerunner of serially produced FFTs used profusely today.

Gibbs was ingenious and developed many ways of trying to display the Transform including wood cutouts as shown in Figure 57. He made hundreds of these plywood sets to display the changes in the frequency spectrum with time, sleep, blood chemistry, drug uptake, anesthesia, etc. Bickford thirty years later called the display of sequence spectrums "Compressed Spectral Array" (CSA).



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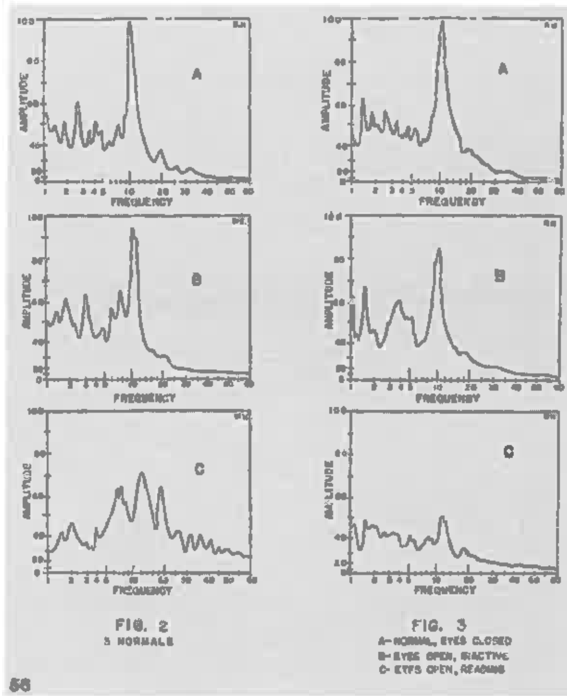
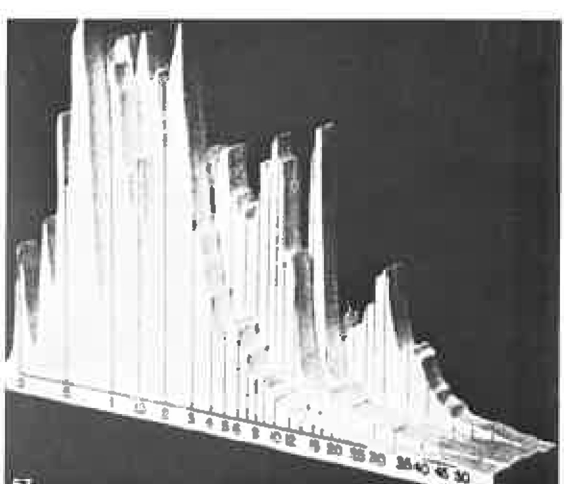
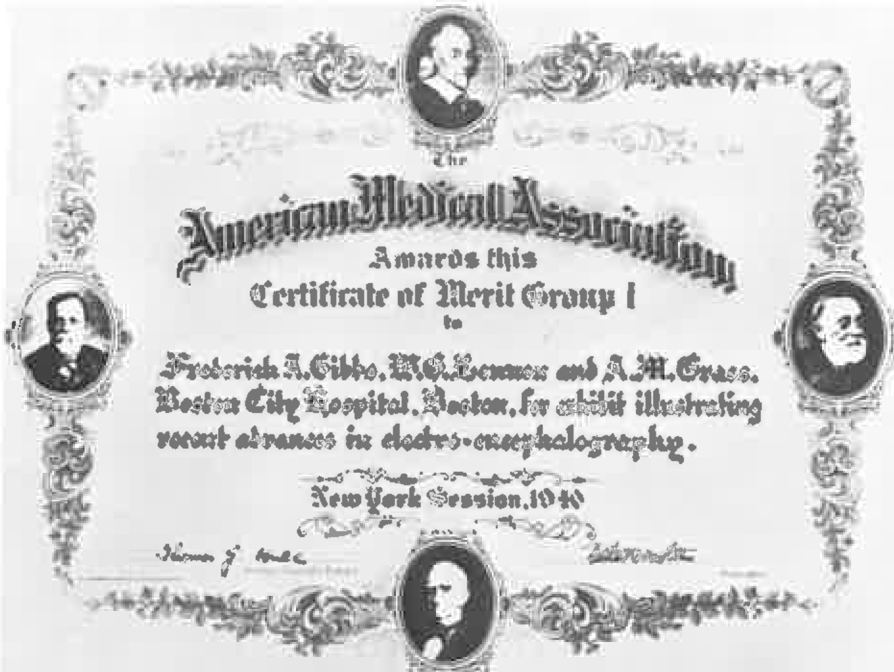
Schematic block diagram of the Grass-Gibbs EEG frequency analysis by Fourier Transform 1939. Albert M. Grass and Frederic A. Gibbs. A Fourier Transform of the Electroencephalogram. Journal of Neurophysiology, November 1938, I, 521-526.



EEG spectra of three normals. Gibbs 1939



Spectral Array with the third dimension of time. Gibbs 1941



The American Medical Association
Awards this
Certificate of Merit Group I
to
Frederick A. Gibbs, W.G. Lennox and A.M. Grass.
Boston City Hospital, Boston, for exhibit illustrating
recent advances in electro-encephalography.
New York Session, 1940

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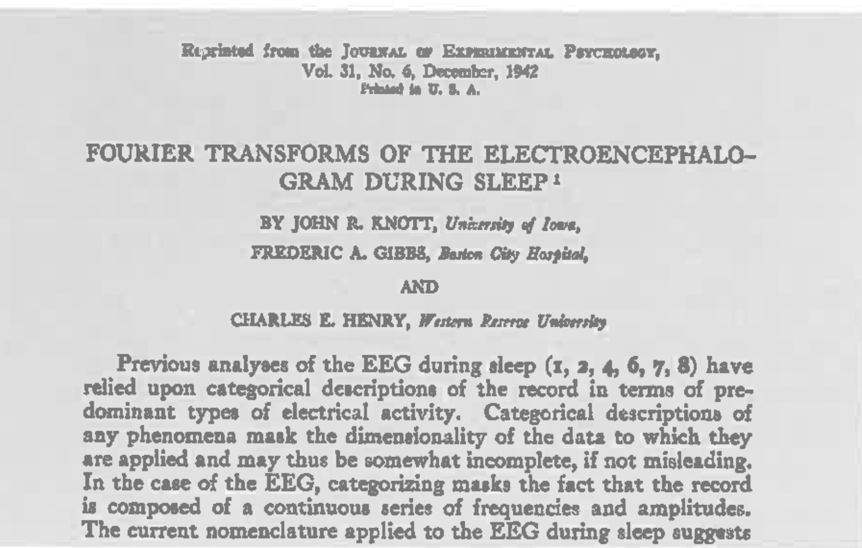
In 1940 the AMA again made an award to the team for their efforts.



Reprinted from the Journal of Experimental Psychology,
Vol. 31, No. 6, December, 1942
Printed in U. S. A.

FOURIER TRANSFORMS OF THE ELECTROENCEPHALOGRAM DURING SLEEP[1]

BY JOHN R. KNOTT, *University of Iowa,*
FREDERIC A. GIBBS, *Boston City Hospital,*
AND
CHARLES E. HENRY, *Western Reserve University*

Previous analyses of the EEG during sleep (1, 2, 4, 6, 7, 8) have relied upon categorical descriptions of the record in terms of predominant types of electrical activity. Categorical descriptions of any phenomena mask the dimensionality of the data to which they are applied and may thus be somewhat incomplete, if not misleading. In the case of the EEG, categorizing masks the fact that the record is composed of a continuous series of frequencies and amplitudes. The current nomenclature applied to the EEG during sleep suggests

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Instrumentation of Electrocorticography

This display "AD" from the EEG Journal in 1950 indicates the instrumentation of that period for electrocorticography. Cortical electrodes made of cotton wicks with a silver wire interface and kept wet with saline were designed by Erna Gibbs and the holder was made by Grass. Depth electrodes with 10 silver rings and holder to drive the electrode in were developed for Percival Bailey, John Green, Gibbs, and others. The first square wave electronic stimulator designed with timing circuits and developed for RADAR during World War II was built by Grass and used for the techniques developed by Penfield.


61

The Third International Congress of Electroencephalography and Clinical Neurophysiology, Cambridge, MA, September 1953

Figure 61 of the Grass Booth shows Models I (1935), II (1938) and III (1946) indicating development of EEGs over the previous 20 years. The photos on the walls are of non-U.S.A. EEG laboratories, mainly in South America, sent as proxies for those who could not come. Not all are posted but it represents the extent of the practice of EEG world-wide. Figure 62 shows two scientists who contributed much to neurophysiology and EEG, and who presented papers. Lord Adrian is untangling the microphone cable from Dr. Alexander Forbes.

Production models of Electroencephalographs from Europe were displayed at this Congress. We regret not having pictures of those that came, but the EEGs illustrated on the following pages are representative of that time and taken from advertisements.

Evoked Response, 1951
George Dawson

George Dawson from Cambridge, England was the first to successfully demonstrate instrumentation for recording repetitive physiologic responses that were smaller than the background noise. Dawson did this with vacuum tubes and analog technology which defined the basic requirements by segmenting the time axis into small increments and adding all the response activity for each segment of time in a storage capacitor that was synchronous with the stimuli. After a large number of responses, most of the nonsynchronous activity of the brain wave canceled and the activity of responses from stimuli added up. This ingenious system was enhanced as soon as solid state memories were available to store the time segmented response and later when digital computer technology created the present Evoked Response systems.

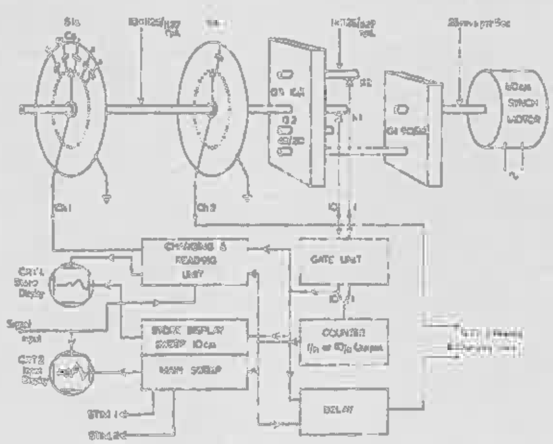


Fig. 3
Scheme of apparatus used for averaging. S1a and S1b are the two distributors. Cs1 to Cs63 the storage capacitors on one of them, and K1 and K2 are contacts closing 10 times a second and once a second respectively. G1, G2 and G3 are gear boxes giving the reductions shown. The input signal is observed on CRT 2 and the average waveform on CRT 1.

64

[*From the Proceedings of the Physiological Society*, 19 May 1951.]
Journal Physiology, Vol. 115.

A summation technique for detecting small signals in a large irregular background. By G. D. DAWSON. *Neurological Research Unit, Medical Research Council, National Hospital, Queen Square, London, W.C. 1*

The cerebral responses to nerve stimulation which can be picked up from the scalp in man are small in relation to spontaneous activity of scalp muscle and brain. They have been detected by superimposing a number of records; this emphasizes regular features, while the irregular background appears as a diffuse thickening of the whole trace (Dawson, 1947, 1950). In a majority of subjects,

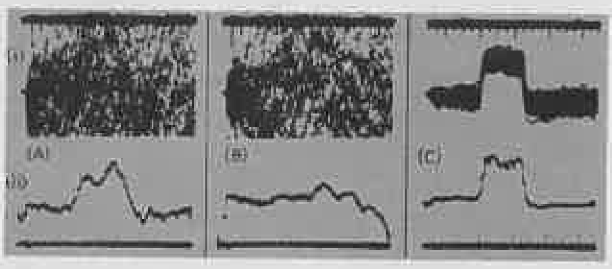


Fig. 1. An experiment to detect cerebral responses when the left ulnar nerve was stimulated at the wrist once per second. The upper line of traces shows sets of 55 records superimposed and the lower line the averages of these given by the machine. In A, from the contralateral scalp, there was one electrode on the midline and one over the right central sulcus. In B, from the ipsilateral scalp, the record was taken from the same midline electrode and one over the left central sulcus. In C is shown the result of making the electrode over the central sulcus positive to that on the midline by 5 μV. The largest spikes in the time scales show intervals of 20 msec., and the stimulus was applied 5 msec. after the start of each sweep.

however, the level of unwanted activity is too high for superimposition to show clearly the form and distribution of the responses. A much greater degree of discrimination may be obtained if instead of superimposing the records they are added to obtain the mean. Waves not regularly related to the stimuli are insignificant in the mean curve. To see how valuable this method was likely to be sets of records were measured by hand and averaged. When the results were plotted the responses became progressively clearer as the number of records added increased from 5 to 40.

The apparatus to be demonstrated automatically adds successive potential waveforms from the scalp during a series of stimuli and it displays the sum continuously. The additions are made in a bank of condensers to which the

[P.T.O.

Circa 1950 66

Circa 1950 67

Offner Electroencephalographs 1935-1960

It is with regret we do not have many photos of Dr. Frank Offner's early contributions to EEG Instrumentation. His work paralleled that of Grass. He worked for Dr. Ralph Gerard at the University of Illinois before forming his company to make EEGs. His early EEG designs used Rochelle salt inkwriters made in conjunction with the Brush Co. of Cleveland. While having higher frequency response they showed serious deterioration with temperature. When he changed this design, he did sell many EEGs as shown in Figure 66 and many more of the Type D shown in Figure 67. There also was a smaller version of the Type D (68).

Dr. Offner was the first to introduce transistors to EEGs in the late 1950s with the Type "T". Figure 68 illustrates this effort with one of the first "portable" EEGs. In the early 1960s he sold his company to Beckman and returned to academic life at Northwestern University. The "Average Reference" electrode which he developed with Dr. Douglas Goldman was one of his lasting contributions. These illustrations of Offner's EEGs are taken from journal advertisements.

EEGs of 1950 to 1960

By 1950, the 8 channel EEG was the established standard. In the mid 1950s, sixteen channel instruments were introduced, and became the instrument of choice by 1970. Multichannel instruments like these of Offner and Grass from the United States and EEGs from Europe (which follow) were made possible by two developments. First the narrow ink-writers using d'Arsonval galvanometers which were conceived by Grass in the 1930s. Second, the invention of the transistor by Shockley at Bell Laboratories in the mid 1950s. The first apparent advantages of the transistor as compared to the vacuum tube were the extremely high efficiency, lower operating voltages, and very small size. These three features led to miniaturization and low heat dissipation. Thousands of subsequent developments led to greater reliability and stability of all parameters needed for accurate measurements.

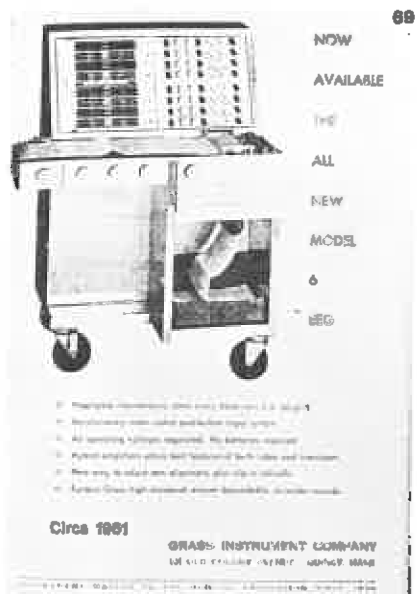
The early transistors were made from germanium which had large temperature effects. In a few years silicon became the material of choice and transistor design settled. Grass introduced the Model 6 EEG in 1961 which used the best of vacuum tubes and silicon solid state devices.

In the pages that immediately follow, this treatise on the early EEG design concludes with copies of advertisements of other manufacturers showing the configurations that had developed during the 1950s. Very few new, major, improved-performance of changes in the basic operational features of EEGs occurred during the 1960s and 1970s. This treatise will stop here and leave it to another time to evaluate application of digital techniques to the electroencephalograph per se design beginning in the late 1970s.

68

Circa 1957

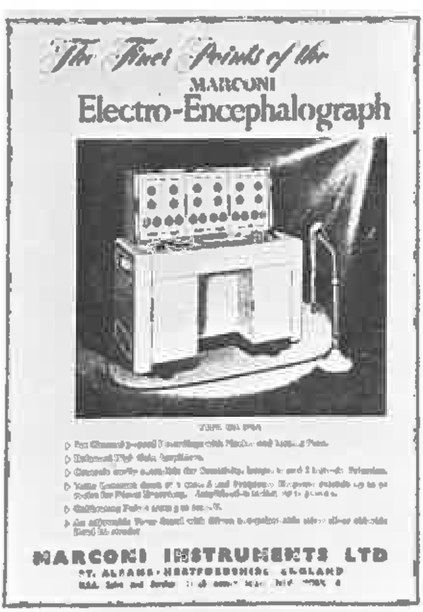
69



Circa 1961

Circa 1949 France 70

Circa 1950 U.S.A. 71



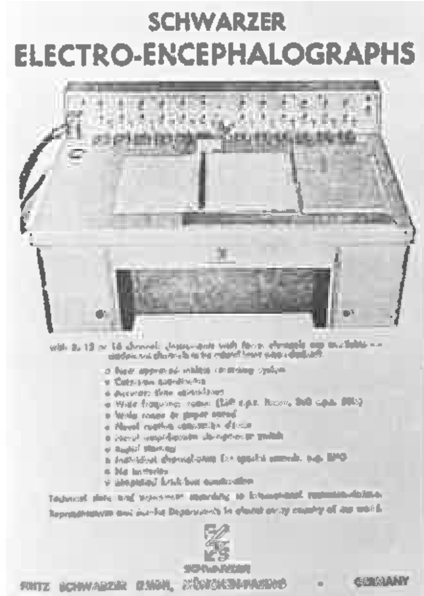
Circa 1950 England 72

E.P.L.
1949 U.S.A.
73

EDISWAN
1950 England
74

Circa 1957 France

75



Circa 1957 Germany

76

Circa 1961 Holland

77

CAT-Computer of Average Transients = Evoked Response System

During the first 10 years after Dawson (Figure 63), summation/averaging devices were built by investigators in their own laboratories. The CAT was the first system offered commercially in the U.S.A. "to separate the Evoked Response from random activity."

REFERENCES FOR FIGURES

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