Electroencephalography has served as one of the fundamental tools of clinical neurology for over a half-century. The spontaneous electrical rhythms of the mammalian brain were first demonstrated in the 1870s by Liverpool physiologist Richard Caton, and were subsequently investigated by Napoleon Cybulski, Adolf Beck, Fleischl von Marxow, and others. The development of the human electroencephalogram (EEG), however, can be traced to only one man: the German psychiatrist Hans Berger (1873–1941). Although Berger’s work has been the subject of anniversary reflections (Gloor 1969; Jung 1963), a more comprehensive view of this unusual man and his remarkable invention is only now beginning to emerge (Millett 2001). Understanding Berger's path to the EEG within the context of his own scientific era and life experiences highlights both the familiar and the foreign in Berger's story, and provides a historical prelude to the modern investigation of the brain and its functions. Indeed, a century after Berger’s first psychophysical experiments, the connection between cerebral blood flow and neural activity, a critical relationship for Berger’s psychophysical research, is fundamental to modern functional brain imaging.
Berger’s work on the human EEG was part of a 40-year program of psychophysical research, beginning in the late 1890s. By the time Berger recorded the first human EEG in the mid-1920s, his own life had become a strange dualism. The University of Jena had been Berger’s institutional home for nearly three decades, and Berger had served as Professor of Psychiatry and Director of the University Psychiatric Clinic since the end of World War I (Figure 1). Yet Berger became isolated in Jena as a result of his eccentric research program, the contentious circumstances of his professorship appointment, and his brooding, introverted personality. While he recorded his poetry, scientific aspirations, and spiritual reflections in his diaries and secretly pursued his scientific dreams in the laboratory, Berger’s rich, introspective private life was completely insulated from his austere public persona. Berger followed a strict, conservative, and routinized approach to his professional duties as a psychiatrist, completely separating his clinical obligations from his real passion for psychophysical research. Raphael Ginzberg, a young physician who worked at the Jena University Hospital from 1926–1932 and frequently served as a subject for Berger’s EEG experiments, later described this enigma of a man:

In the small medical world of Jena, nobody, least of all Berger’s associates, expected him to make a great scientific discovery. What could we expect from a chief who was tense, who hardly spoke to us, whose only topic of conversation...
was hospital affairs, who was always anxious to avoid trouble, who was seldom able to help us with complicated cases? He never overlooked a deviation from established routine, nor would he ever take any step that was not in accordance with this routine. His days resembled one another like two drops of water. Year after year he delivered the same lectures. He was the personification of static. (Ginzberg 1949)

It is perhaps difficult to imagine that this same man—“the personification of static”—was solely responsible for the invention of a technique that would revolutionize clinical neurology and psychological research, but there can be no doubt that the human EEG resulted from Berger’s strange and solitary journey.

Berger was born in 1873 to Paul Friedrich Berger, chief physician of the regional asylum in Coburg, located in the heart of Thuringen. His maternal grandfather was the famous poet Friedrich Rückert, whose verses provided a constant source of inspiration for Berger throughout his life. Although details of Berger’s childhood are sketchy, he appears to have been a generally happy and introspective child. As he neared graduation from the gymnasium at the age of 18, Berger planned to pursue a career in the natural sciences and aspired to become an astronomer. Thus, despite his father’s position, a career in medicine did not interest the younger Berger, who initially pursued mathematics and astronomy at the University of Berlin.

Life in Berlin turned out to be too much for the 19-year-old Berger, who was much more accustomed to the traditional life of Coburg, and he enlisted for a year of military service in Würzburg in 1892. During this period, Berger was involved in a bizarre incident that inspired his life-long search for a connection between mind and brain. One spring morning, while mounted on horseback and pulling heavy artillery for a military training exercise, Berger’s horse suddenly reared, throwing the young man to the ground on a narrow bank just in front of the wheel of an artillery gun. The horse-drawn battery stopped at the last second, and Berger escaped certain death with no more than a bad fright. That same evening, he received a telegram from his father, inquiring about his son’s well being. Berger later learned that his older sister in Coburg was overwhelmed by an ominous feeling on the morning of the accident and she had urged their father to contact young Hans, convinced that something terrible had happened to him. He had never before received a telegram from his family, and Berger struggled to understand this incredible coincidence based on principles of natural science. There seemed to be no escaping the conclusion that Berger’s intense feelings of terror had assumed a physical form and reached his sister several hundred miles away—in other words, Berger and his sister had communicated by mental telepathy. Berger never forgot this experience, and it marked the starting point of a life-long career in psychophysics (Berger 1940, pp. 5–6).

Berger resumed his university education after completing his military service with his efforts now concentrated on medicine, a traditional starting point for
many great physiologists and psychologists of the late 19th century. After studying medicine in Würzburg, Berlin, Munich, Kiel, and Jena during the 1890s, Berger passed his national examination in medicine in 1897 and immediately began work as an assistant to Otto Binswanger, the charismatic Professor of Psychiatry at Jena. His first projects under Binswanger were based on traditional clinical-pathological correlation and reflected Binswanger’s own interests in dementia paralytica—known to the 20th century as tertiary syphilis. During the late 1890s, however, Berger embarked on an unusual line of clinical research that would ultimately lead to his development of the human EEG. Although this work was certainly driven by Berger’s desire to understand the mysterious relationship between mind and matter, he found guidance in a surprisingly conventional scientific principle: conservation of energy.

**Conservation of Energy and the Study of Mind**

In order to understand the theoretical foundation that shaped Berger’s work, it is helpful to consider the impact of the principle of conservation on the understanding of the mind-brain relationship. There can be little doubt that the principle of conservation of energy was among the most important scientific principles to emerge from the 19th century. The most influential statement of the Energy Principle for many physicists, physiologists, and physicians was Hermann von Helmholtz’s 1848 lecture, “On the Conservation of Force.” Yet, Kuhn and others have shown that the principle of energy conservation was conceived numerous times during the mid-19th century, and led multiple lives until the fin de siècle (Elkana 1874; Kuhn 1959). The impact of the Energy Principle on studies of mind and brain may be seen in the writings of such diverse figures as the psychophysicist Gustav Fechner, the Viennese neuropsychiatrist Theodor Meynert, and experimental psychologists Alfred Lehmann, Hugo Munsterberg, and Oswald Külpe. Each of these men applied the principle of conservation of energy to the relationship between mind and brain somewhat differently: Munsterberg affirmed that conservation provided an inviolable principle in psychology but abstained from speculation on its physiological significance. In contrast, men like Meynert and Lehmann were more brazen in their application of this principle to the functions of the brain.

For example, in one of Meynert’s popular lectures, “On the Mechanism of the Brain,” he reasoned that when energy is produced in order to trigger some thought or movement in one part of the brain, an equal amount of energy must simultaneously disappear in another part of the brain (Meynert 1892a). Indeed, the speculative neuropsychiatrist argued that if the total sum of cerebral energy was not constantly partitioned and conserved in this manner, the human soul itself would violate the most fundamental law of nature. This energetic model of brain function was given a physiological interpretation in Meynert’s magnum opus, *Psychiatry*, where he suggested that the distribution of energy in the cere-
bral cortex is governed by subcortical vasomotor centers that regulate the flow of blood to different cortical areas (Meynert 1892b). For Meynert, cerebral physiology and energetics were inextricably linked, and he inferred that one function of vasomotor innervation was to permit different areas of the cerebral cortex to reciprocally inhibit each other such that the functions of the brain could conform to the principle of energy conservation in an orderly fashion.

Meynert and Lehmann proposed a psychophysiological relationship between the energy supply of the cerebral cortex on the one hand, and feelings of pleasure and pain on the other. According to Meynert, an abundant blood supply to the cerebral cortex produced a state of functional hyperemia, supporting a state of vigorous cortical metabolism and a corresponding sense of pleasure. A narrowing of cerebral vessels, on the other hand, resulted in cortical anemia, an undernutrition of cortical cells and a corresponding feeling of pain. Lehmann also argued that “Pleasure and pain are the psychical results of the transient relationship between the energy consumption required by the working system [of the brain] and the energy supplied by nutritional activity” (Lehmann 1892, p. 160). An important motivation for Berger’s early research was the challenge of providing empirical evidence to support this psychophysical relationship between cerebral blood flow, cortical metabolism, and emotional feelings of pleasure and pain.

There was one further aspect of Lehmann’s energetic model of the mind–brain interaction that drew Berger’s attention and rekindled his ideas about mental telepathy. Lehmann recognized that if one goal of psychophysical research was to determine the physical equivalent of feelings, emotions, and mental work, then it is essential to precisely measure all the components of cortical energy. The brain, like all organs, produces a store of chemical energy that it derives from various metabolic processes. Lehmann argued that this chemical energy is converted into three major forms of energy in the brain: heat, electricity, and what Lehmann called “P-energy,” the psychic energy associated with different mental states. On the basis of his own experimental work, measuring changes in peripheral blood flow during various mental states, Lehman argued that there is a direct relationship between energy transformation in the central nervous system and mental phenomena, such that “with the appearance of a certain quantum of P-energy an equivalent quantum of another form of energy is always consumed.” Here was finally a model of mind–brain interaction that Berger could endorse: Lehman’s theory of cerebral energetics was based on sound physical principles, theoretically complete in accounting for all types of cortical energy, and even recognized a form of “psychic energy” associated with feelings, emotions, and thoughts. A productive research program in cerebral energetics might even provide physical evidence to support rare instances of mental telepathy.

Lehmann’s theory of cerebral energetics clearly identified the boundary conditions for a psychophysical study of brain function—namely, the supply of metabolic energy to the brain and its transformation into heat, electricity, and mental phenomena. Over the next three decades, Berger adopted this model of brain
function and pursued each of these lines of investigation. He began by recording changes in blood flow to the brain, the most obvious indicator of the amount of energy supply to the brain. In the days before medical imaging, the human skull seemed like an impenetrable barrier to the study of cerebral blood flow. Here, Berger had two advantages over Lehmann, who relied on the changes in peripheral blood flow as a relative (negative) indicator of cerebral blood flow. First, Berger was familiar with the work of the Turin physiologist Angelo Mosso (1881), who had used the plethysmograph to measure changes in cerebral blood flow in a series of three patients with localized cranial defects. Second, Berger’s position in the Psychiatric Clinic brought him in contact with many patients who had undergone craniotomies in the course of their treatment. Thus, Berger was perfectly suited to follow Lehmann’s own suggestion that “were it possible in some manner to determine which changes in the blood flow, particularly the blood supply to the brain, occur during different psychical activities, then this would be the first towards a psychodynamic theory whose theoretical consequently are now utterly unforeseeable” (Lehmann 1899, p. 200).

The subject of Berger’s first psychophysical investigation was a 23-year-old factory worker with an 8 cm circular skull defect over the right parietal-temporal area from two surgical attempts to remove a lodged bullet. Although the young man suffered from a slowly progressive hemiplegia and intermittent seizures, he appeared cognitively intact and agreed to serve as a subject for Berger’s psychophysical study. Adapting Mosso’s technique, Berger filled a cap made of unrefined rubber (gutta-percha) with water, attached the edges of the cap to the skull defect, and connected the apparatus to a Marey tambour for recording the changes in intracranial volume on a rotating drum. With the help of an assistant, Berger simultaneously measured both the pulsations of intracranial blood flow and the blood flow to the arm while his subject was given a variety of sensory stimuli or asked to perform various mental tasks.

In order to analyze the cerebral blood supply during “voluntary concentration,” the subject performed simple problems of mental arithmetic, counted the spots drawn on the opposite wall, or awaited a tactile stimulus such as a light stroke across the ear. Changes in cerebral blood flow with “involuntary attention” were obtained by firing a pistol behind the unsuspecting subject—a particularly cruel test given the cause of this subject’s neurological deterioration. Stimuli such as the scent of pear or taste of sugar were used to analyze states of pleasure, and the subject was given a solution of quinine hydrochloride, was pricked by a needle, or was stimulated with a strong electrical current to produce a state of pain or discomfort.

Despite this peculiar set of testing conditions, Berger produced a great deal of graphical data that directly represented the pulsations of intracranial blood flow, and his analysis of this data supported a number of important conclusions. For example, by carefully comparing the changes in intracranial volume with simultaneous changes in arm volume, Berger concluded that pleasant sensations were
accompanied by an increase in local cerebral blood flow, while unpleasant sensations were accompanied by a decrease in flow. Furthermore, close analysis of the pattern of the pattern of volume changes suggested to Berger that it was the smaller, cortical vessels that were responsible for fluctuations in local blood flow. This careful analysis of graphical data was itself one of the most important aspects of Berger’s early study in cerebral blood flow, for just as Berger relied on volumetric changes in the arm in order to separate the effect of systemic effects from his analysis of cerebral blood flow, he would later learn to eliminate the artifacts generated by the electrical activity of the heart in his early EEG records by comparing simultaneous EEG and EKG tracings.

Yet Berger’s study of cerebral blood flow, which later appeared as On the Bodily Expressions of Psychical States (1904–1907), was disappointing as a foundation for his theory of cerebral energetics. Recording and analyzing the changes in intracranial volume was a tedious process, fraught with technical and theoretical pitfalls. Furthermore, the simple measurement of changes in cerebral blood flow failed to capture meaningful information about the most important process in Berger’s model of brain function, namely the transformation of energy in the cerebral cortex. In order to salvage his experimental work, Berger turned to recent developments in physiology. Max Verworn, Professor of Physiology at Jena, had recently developed a dynamic theory of tissue metabolism that offered a physiological language for translating Berger’s cerebral energetics. According to Verworn, normal tissue function rests on a balance between the opposing processes of assimilation, by which nutrients are taken up and transformed into protein, and processes of dissimilation, by which proteins are broken down to support the vital activities of living cells. These metabolic concepts—predecessors to the modern concepts of anabolic and catabolic metabolism—and Verworn’s concept of “biotonus” (the ratio of assimilation to dissimilation processes) allowed Berger to theoretically link psychological states directly to the energy transformations going on in cortical tissue without relying upon the fleeting changes in cerebral blood flow. Indeed, Berger hypothesized that when the cortical dissimilation of proteins exceeds a certain threshold, the rate of energy production exceeds the ability of cortical tissues to convert this energy into heat or electricity, and the remainder is converted into psychic energy for perception, feelings, emotion, and conscious thought.

This energy-based theory of mind–brain interaction was elaborated in Berger’s psychophysical papers and his diaries in the early 1900s. During these early years of research, Berger enjoyed institutional support from Binswanger, assistance from his colleagues at Jena, and research grants from the Carl Ziess Foundation. He was rewarded for his vigorous program of psychophysical research, teaching, and clinical work with promotions to assistant professorship in 1901 and associate professorship in 1906. In the years leading up to the outbreak of World War I, Berger expanded his research program at the peaceful, insulated University Clinic in Jena. He abandoned his prior efforts to measure the dynamics of energy supply to the
brain, and instead focused on measuring the conversion of cortical energy into thermal or electrical energy. Given precise measurements of the cortical energy converted into heat and electricity, one could theoretically calculate the energy converted into conscious perception, emotion, thought, and perhaps even mental telepathy. And this is exactly what Berger set out to do.

Berger’s earliest efforts to measure the electrical activity of the brain predate his study of cerebral blood flow (Berger 1929). In 1902, Berger attempted to replicate the earlier work of Caton and others, who had used a standard Lippmann capillary electrometer to record the electrical activity directly from the cortical surface of the dog brain. The capillary electrometer was the physiological workhorse of late 19th-century physiology, and consisted of a column of mercury suspended in a solution of dilute sulfuric acid. As the current passed through this column the curvature of the mercury meniscus would fluctuate, and a microscope lens optically magnified the bouncing meniscus for a photographic record. Berger’s first attempt met with only marginal success, as he was able to observe the electrical oscillations of the dog brain only once in a series of five experiments. He temporarily abandoned his efforts to record the electrical current of the brain in order to focus on the relatively simple measurement of cerebral blood flow. This study led Berger right back to the problem of recording the electrical activity of the brain, and at the conclusion of the cerebral blood flow experiments in 1907, Berger returned to this task. Technical difficulties proved intractable once more, however, and Berger turned his attention to the other measurable component of cerebral energy: heat.

Once again, Berger turned to the experimental work of Angelo Mosso for guidance. In *The Temperature of the Brain* (1894), the Italian physiologist simultaneously recorded cerebral and blood temperatures and argued that the fluctuation in the temperature of the brain was independent of blood temperature and was likely related to the metabolic activity of the brain itself. Attempting to improve upon Mosso’s measurements, Berger began a thermometric investigation of brain function in 1908, employing one chimpanzee and several psychiatric patients who were studied intraoperatively as part of the effort to localize intracranial lesions. This series of experiments and his interpretation of the results were published as *Investigations on the Temperature of the Brain* (1910). Using finely calibrated thermometers, Berger recorded slight increases in cerebral temperature as patients awakened from their narcosis or engaged in various mental tasks.

The last chapter of Berger’s monograph contains his psychophysical analysis of these data and the clearest articulation of his energy-based model of brain function. Here Berger argues that “the chemical energy of the brain . . . can be spent in different ways: it can be converted into only heat, or into heat and work, or finally, into heat, work, and other forms of energy.” Berger’s quantitative estimation of the “other forms of energy”—i.e., the energy of mental work or “psychic energy”—is theoretical in the extreme and reveals his growing obsession
with the qualification of psychic energy. Based on his own thermometric records, previous calculations of the weight, volume, and heat capacity of cortical tissue, and rough estimates of the heat and mechanical work produced by muscle cells, Berger estimated the maximum amount of energy that could possible be converted into mental work. First, Berger used estimated values of the specific weight and heat capacity of the brain and morphometric estimates of the volume of sensory and association cortices to calculate the heat required to raise the temperature of the cerebral cortex by one degree centigrade. Once he arrived at this value (348,435 cal), Berger used his own measurements of the rise in cerebral temperature during various psychological states—the excitatory stage of chloroform narcosis, awakening from anesthesia, and performing mental arithmetic—in order to calculate the energy required for the corresponding increases in temperature. These values were weighted and multiplied to give an estimate of 122 kg m of cortical energy released as heat during an eight-hour period of concentrated mental work. From Adolf Fick’s influential study of muscle physiology, Berger knew that the energy released in the form of heat was only one fraction of the total amount of energy released from living tissues, and he estimated that if about 40 percent of the available cortical energy was converted into heat, only 60 percent of the metabolic supply to the brain remained for conversion into psychic energy. This tenuous set of assumptions and calculations led Berger to the bizarre conclusion that the upper limit on the cortical energy available for mental work is approximately 30 million ergs per minute—an astronomical figure.

Even though the thermometric analysis of cerebral energy generated more quantitative psychophysical data the study of cerebral blood flow, Berger was unsatisfied. Although he could estimate the maximum energy available for mental activity, analyzing psychical energy using this thermodynamic approach still seemed like an impossible task without some grasp of the electricity produced by the brain. After purchasing a small Edelmann string galvanometer in 1910, Berger made one more attempt, but he was still unable to record the electrical currents produced by tactile, visual, or auditory stimulation in a number of dogs. It seemed like Berger’s decade-long psychophysical research program, based on a thermodynamic model of cortical function, had finally burned itself out.

1Thus, for an increase of 0.08°C per minute during the excitatory stage of narcosis or on awakening from anesthesia, Berger calculated a corresponding energy value of 7.6 kg m/min; during the first three minutes of mental arithmetic, an increase of 0.07°C corresponded to approximately half this amount of energy (3.474 kg m/min); and during the subsequent seven minutes, a much smaller increase (0.01°C) corresponded to an increase of only 0.213 kg m/min. (Berger expressed force in kg, the force that gravity would exert on a 1 kg mass; 1 kg equals 9.8 Newtons.)
From Cerebral Energetics to the EEG

The earliest of Berger's surviving diaries date from this pre-war period (1910–1911) and vividly reveal his preoccupation with cerebral energetics and psychic energy, his episodes of self-doubt and depression, and the many difficulties he encountered in acquiring and operating electrophysiological instruments. Here Berger reflects on his abortive 1910 effort to record the electrical activity of the dog brain with a mixture of exasperation and optimism:

November 30, 1910
Of nine experiments, one success and even this one rather doubtful, because in this case skin currents could not be excluded in the experiment. Once can therefore not say that I gave this thing up lightly. Eight years! Trying always, time and again.

Then, at the conclusion of these experiments just a few days later, he wrote:

December 3, 1910
C[ortical] system produces constant P.E. [psychical energy]. P.E. is the most important element in the cortical system—This P.E. production is individually differentiated—Consumption of all available energy as nerve-energy in epileptic attacks, which explains the comatose sleep after the attack. Idea of an antagonism of nerve-energy and P.E. production in the cortex (chemical energies of the cortex either transferred into P.E. or into nerve-energy in the epileptic attack!)—Available energy of the cortex always limited. . . .

No more financial worries, have paid for almost everything and still have 250 marks—I’ll get everything at the right time; wonderful help. I definitely plan to finish up the experiments on the cerebral cortex of dogs—Observations on man . . . .

Fraulein von B. (Jung 1963)

This was also a period of intense professional activities and personal fulfillment for Berger. In addition to his academic promotions, and experimental and clinical work, he continued teaching clinical neurology and psychophysiology. In marked contrast to his EEG research during the 1920s, Berger received considerable assistance from his staff and university colleagues, and he did not hesitate to present and publish his theoretical or experimental psychophysics. Baroness Ursula von Bülow, a technician in the Psychiatric Clinic whose name appears at the end of the above passage, began assisting Berger in his experimental work in 1910. Berger soon took a personal interest in von Bülow, and despite the difference in social standing between the two, they were married in 1911. The following year, the Bergers had a son, and two years later, a daughter.

During the 1910s, Berger's time and resources were largely devoted to familial, administrative, and clinical responsibilities in Jena. Binswanger promoted Berger to chief physician (Oberarzt) at the University Clinic in 1912, which left him
less time to pursue experimental work. The outbreak of war in 1914 interrupted Berger's scientific work and his family life. He left Jena to serve as an army neuropsychiatrist on the western front in Rethel. The modest responsibilities of this post, however, left Berger enough time to write a number of clinical papers, which appeared during the mid-1910s. He also studied the English language, read historical, literary, and philosophical works—particularly Kant and Spinoza—and strategically planned his post-war research activities. Although Berger did not have the opportunity to continue experimental work in cerebral physiology until after the war, he remained dedicated to the pursuit of cerebral energetics. As the following passage from Berger's 1915 diary reveals, he also began to think about the clinical applications for his psychophysical work:

Thinking about new paths in my scientific work. Go further along previous paths, but only those with some connection to [clinical] practice . . . i.e. Meaning of psychic origins for mental and other diseases (critical investigation!) . . . .
Physiological questions mark my path! Psychophysiology of mental diseases . . . .
Psychic energy and the body, but only from a practical viewpoint of establishing cortical measurements for psychiatry and neurology. (Jung 1963)

Upon Berger's return to Jena after the war, research once again competed with increasing familial obligations and clinical responsibilities: the Bergers soon had two more daughters, and in 1919, upon Binswanger’s resignation of his 37-year directorship of the Psychiatry and Neurology Clinic, Berger was promoted to full (ordinarius) Professor of Psychiatry and Director of the University Clinic in Jena. This appointment did not go smoothly, however, and the repercussions plagued Berger for many years. Several members of the medical faculty did not regard Berger’s research very highly, and Biedermann, the influential Professor of Physiology, questioned both the integrity and the originality of Berger's research (Jung 1992). The University search committee clearly preferred more clinically oriented external candidates, Wollenberg or Kleist, over Berger for the directorship of the University Clinic. Furthermore, Berger’s conservative political views did not ingratiate him with the socialist government in Weimar. In the end, Wollenberg was unwilling to leave his post at Marburg, Binswanger lobbied heavily for Berger's promotion, and Berger himself took advantage of his “plebeian” connections in Weimar.

Berger ultimately succeeded Binswanger as Professor of Psychiatry at Jena, but the victory was hollow and its price considerable. Binswanger, it turned out, had much more confidence in Berger’s research and administrative potential than his clinical skills: he pushed for Berger’s nomination as Director of the Psychiatric Clinic but entrusted his lucrative private practice to his second assistant Dr. Strohmayer, who succeeded Berger as chief physician at the University Hospital. Berger’s political manipulations also alienated many of his colleagues at Jena, who disavowed such tainted methods. As a result of the tension between Berger and his colleagues at Jena, as well as Berger’s own feelings of scientific inade-
quacy, he became an isolated figure at Jena, and he never received assistance from Biedermann or his associates in the Physiological Institute again. Berger's own troubles were paralleled by the decline of his native Germany, further contributing to his growing depression:

Germany’s defeat and the revolution of 1918–19 marked a critical period in Berger’s life. It seemed that his personal well-being was crumbling along with the Kaiser’s Germany. His achievements and irreproachable record as an obedient and loyal German professor seemed to have come to naught. Worse still, Binswanger, for unknown reasons, left Germany and went to Switzerland. The hospital lost its chief, and Berger his protector. (Ginzberg 1949)

This turbulent period was a time of bitter disappointment, and the emotional stress took its toll on Berger’s scientific vision and confidence.2 It was during this period that his external world—a world full of responsibilities to the University, the transitional German state, and his family—became dissociated from his internal world of spiritual and philosophical speculation.

Although Berger did not have the opportunity to continue experimental work in cerebral physiology for several years, he revisited the subject of dissimilation processes in the cerebral cortex in one of his first publications after the war, “On the transformation of energy in the human brain.” Just a few days after his appointment as Director of the Psychiatric Clinic in October, 1919, Berger delivered his inaugural lecture, “Brain and Soul,” to the General Medical Association of Thuringen. He took this opportunity to consider the philosophical implications of his energetic conception of brain function, contrasting his view of an energy-mediated interaction between mind and brain with the prevailing notion of a parallelism between physiological and mental events: “I openly declare that I do not hold the popular parallel principle as the solution [to the mind-brain problem], but instead I accept an interaction between mental and bodily processes and embrace an energetic perspective, against which all possible objections can be raised, like any other assumption.”

When he returned to the clinical laboratory in 1920, Berger resumed his efforts at recording the electrical activity of the brain. But success eluded him once more, and Berger took up yet another physiological technique: electrical stimulation of the brain. Direct electrical stimulation of the cerebral cortex was neither technically difficult nor controversial: Hitzig and Fritsch’s first report of the “excitable cortex” in 1870 was accepted and pursued by well-respected physiologists and clinicians such as David Ferrier, Victor Horsley, Fedor Krause,

2 Berger was, of course, not the only continental psychiatrist to be profoundly affected by the events of the Great War. The Swiss neurologist and psychiatrist Constantin von Monakow experienced a similar personal crisis beginning around 1914, which transformed his conceptual approach to the study of mind and brain, and was the subject of his later reflections and subsequent historical analysis. (See Harrington 1996.)
Harvey Cushing, Otfried Förster, and Charles Scott Sherrington. By the early 20th century, the cortical landscape had been parceled up into various motor areas, sensory areas, and “association” areas, and Berger naturally hypothesized that these areas would have different thresholds for the conversion of metabolic energy into psychic energy. By using weak electrical currents applied to the surface of the head in patients with skull defects, Berger hoped to induce a mild degree of dissimilation in different types of cortical tissue and observe a difference in psychological effect depending on whether sensory or motor areas were stimulated.

The first patient involved with this study was a 17-year-old college student by the name of Zedel who had undergone two craniostomies for the removal of a brain tumor, leaving him with a large cranial defect over the central sulcus and its adjacent motor and sensory gyri. Berger was completing his cortical stimulation experiments with Zedel in June of 1924, when he removed his Du-Bois-Reymond clay electrodes from the electrical stimulator and attached them to a small Edelmann string galvanometer, the same device that was routinely used for electrocardiogram recordings in the University Hospital. After several weeks of technical modifications—changing the position of the electrodes, tying different galvanometer threads, and adjusting the apparatus itself—there was the first hint of success. Berger later recalled that “only when the two clay electrodes were placed 4 cm apart in the vicinity of a scar running vertically from above downwards through the middle of the enlarged trephine opening, was it possible with large magnifications to obtain continuous oscillations of the galvanometer string” (Berger 1929). Further magnification of the miniscule cortical currents with a small galvanometer was a technical nightmare, however. When Berger attempted to increase the sensitivity of the galvanometer by shunting more current to the electromagnets, electrical noise or artifacts wrenched the platinum galvanometer string into direct contact with the magnet or shattered the expensive quartz string.

These first recordings of the human EEG are remarkably unimpressive: coarse shadows of minute oscillations in the galvanometer string captured on photographic paper (Figure 2). There was no hint of the large alpha waves, wave and spike complexes, or other characteristic waveforms that would be recognized among standard EEG records within a few years. When Berger failed to observe a change in the electrical activity of the brain while Zedel performed various mental tasks, he arranged for the purchase of a larger, more sensitive galvanometer. During this period, Berger looked forward to the third installation in his series of contributions to The Bodily Expressions of Psychical Processes:

Part III: Cortical currents (Circulation, Temperature, Electrical processes!) and the hope so beautifully expressed by Mosso that I always experience with the application of precise measuring instruments to the brain. . . . A method of operation that suits me and my whole—psychophysiological—attitude.
Later that year, Berger recorded his musings over this early success in his diary and dared to contemplate his future accomplishments: “Is it possible that I might fulfill the plan I have cherished for over 20 years and even still, to create a kind of brain mirror: the _Elektrenkephalogramm_!” It took several months for the large galvanometer to arrive, however, and the wait took its toll on Berger. During these months, Berger appears to have become increasingly withdrawn and preoccupied with poetry, philosophy and spiritual concerns. After WWII, Berger’s scientific quest for the quantification of psychic energy seems to have taken on a broader spiritual significance. The parallels between Berger’s Spinozistic monism and his thermodynamic approach to the interaction between mind and brain are striking. Spinoza had argued that that mind and body were simply different manifestations of a single divine reality. Berger seems to have arrived at an analogous metaphysical view, understanding the presence of God in the world in terms of energy and

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**FIGURE 2**

One of Berger’s earliest electroencephalograms. These EEG records were recorded in 1925–1926 with a small Edelmann string galvanometer, fitted with a 2600 Ohm platinum string that was just sensitive enough to capture the faint oscillations of cortical currents. Large 120-180 µsec waves and small 30-45 µsec waves, which Berger would later refer to as “alpha” and “beta” waves, can be barely discerned in these records.

Note: Reprinted from R. Jung and W. Berger, “Hans Bergers Entdeckung des Elektrenkephalogramms und seine ersten Befunde 1924–1931,” Archiv für Psychiatrie und Nervenkrankeheit 227:283, Fig. 2 (copyright 1979, Springer-Verlag).
its continuous transformation. Thus, the search for the human EEG had also become a spiritual quest for Berger. As his psychophysical research became increasingly isolated from his professional and familial duties, Berger’s spiritual reflection became an increasingly important means of self-encouragement.

Over the next five years, Berger’s faith in his electroencephalogram and in his own scientific abilities vacillated like the thread of his galvanometer. He was repeatedly disheartened when he discovered that each refinement in technique or instrumentation did not always translate into better EEG records. As a novice electrophysiologist, Berger learned slowly that the low resistance of needle electrodes was much more important than the non-polarizing feature of standard duBois-Reymond clay electrodes. The idiosyncrasies of the string galvanometer and the numerous sources of electrical interference—from the DC power supply of the clinic to the artifact of muscle currents—required constant surveillance. Indeed, each modification in recording electrodes and each new galvanometer introduced its own set of technical obstacles.

Furthermore, the challenges of Berger’s early studies of cerebral blood flow paled in comparison to the pitfalls of recording and analyzing the electrical activity of the brain. The electrical activity of the heart, the slightest movement of the extraocular or superficial muscles of the skull, the periodic changes in blood flow through the cerebral vasculature, and the pulsatile movements of the brain itself could all interfere with the recording of the brain’s electrical activity. With minimal training in electrophysiology, working alone in his pursuit of the human EEG, Berger was constantly operating the most delicate of physiological instruments at the outer limits of their sensitivity. Ginzberg, who worked closely with Berger during this period of intense work on the human EEG, describes a solitary, taciturn man who disclosed his EEG work to no one:

If [Berger] accepted any help, it was only technical help. In his published papers he often mentioned the name of Dr. Hilpert . . . Dr. Lemke, Dr. Witzleb, and Dr. Stehan, some of them old friends of mine. I am certain that their help was of a purely mechanical nature, as was the help of [Berger’s assistant] Hilpert. . . . Certainly at the time I was at the hospital no one, with the possible exception of Hilpert, had the remotest idea of electroencephalography . . . . There can be no doubt but that Berger was the sole creator of electroencephalography. He let nobody into the secret of his investigation. What he achieved, he achieved by his individual effort. (Ginzberg 1949)

Berger served as University Rector during 1927, and although he was unable to continue his work on the human EEG, he was still preoccupied with the topic of psychic energy: he initially hoped to give his Rector’s lecture on the subject of psychic energy, and he began planning a book-length treatment of the subject. When he returned to the laboratory in the fall of 1927, his spirits were high, and with a few technical improvements he consistently began to produce EEG tracings. He was soon able to record the human EEG from normal volunteers in
addition to his subjects with cranial defects. Ginzberg recalled that “As soon as it became obvious to him that electroencephalography was a success, he began to solicit the co-operation of everyone available for purposes of observation.” By mid-1928, Berger had adapted a new Siemens and Halske double-coil galvanometer, the most sensitive electrophysiological instrument available, to his EEG studies. With a variety of electrodes and condensers, he was finally generating high-quality EEGs that revealed distinct patterns of electrical activity—waveforms that changed with the psychological state of his subjects (Figure 3). Berger grew more confident than ever that his “brain mirror,” the human electroencephalogram, might actually reflect the mental activity of the brain after all!

By the spring of 1929, Berger had produced hundreds of EEGs from patients with skull defects and employees of the Psychiatric Clinic, as well as dozens of EEGs from his son Klaus and himself. Berger relied on many of the same types of mental tasks employed in his earlier studies of cerebral blood flow, but he also began recording the EEG in patients with epilepsy, dementia, brain tumors, and other neuropsychiatric disorders. He returned to the experimental psychology literature in an attempt to provide a psychological interpretation of these EEG patterns, and suggested that they might represent direct evidence for the “attention waves” reported by Wundt and other experimental psychologists. Despite this accelerated and productive pace of research, Berger was still troubled by “petty doubts on the significance” of the EEG. When he discovered that very little was known about the physiology of the cerebral cortex, and he decided “not

Two early high-quality EEG tracings that Berger recorded with the double-coil galvanometer in 1928–1929. The lower curve is recorded from “Dr G[inzberg]” and depicts the most robust EEG finding of the 1930s, 1940s, and 1960s: bursts of alpha waves appearing as the subject lies with his eyes closed in a state of mental and physical rest. In the lower tracing, Berger has attempted to correlate the trains of alpha waves with the “waves of attention” described by experimental psychologists such as Wundt, Lehmann, and others.

to go into hypothetical matters with the publication on the EEG, but only com-
municate purely concrete facts and findings!” In April of 1929, almost five years
after recording his first human EEG, Berger set aside his doubts about the human
EEG and submitted his first research report, “On the Human Electroencephalo-
gram” (Berger 1929).

**Conclusion**

Over the next decade, Berger focused his research efforts exclusively on this
“brain mirror,” publishing a series of 14 original scientific papers on his EEG
work. In these papers, Berger addressed the neurophysiological foundations of
the human EEG, the psychological significance of different EEG patterns, and
the clinical applications of EEG. Berger suggested that the complex EEG was composed of two fundamental waveforms: the larger 100 µsec alpha waves that were correlated with mental activity—the “physical concomitants of conscious phenomena”—and the smaller 35 µsec beta waves which were associated with the metabolic activities of cortical tissue. This analysis of the human EEG in terms of alpha and beta waves could be used to explain the results of Berger’s psychophysical experiments as well as the characteristic EEG patterns of the classical grand-mal seizures (Figure 4). Although the correlation between these two types of electrical waves and different types of cortical activity has been abandoned, Berger’s characterization of the EEG into alpha and beta components remains central to the clinical and research applications of EEG. In 1934, the more prominent “alpha waves” were given the eponymous name of “Berger waves” by Lord Adrian, the famous Cambridge physiologist who replicated many of Berger’s early EEG findings in 1934, bringing international recognition of the German psychiatrist (Figure 5).

The theoretical and philosophical aspects of Berger’s research program are striking when placed in historical context. At the end of the 19th century the great debate in neurology concerned the localization of brain functions. Indeed, since the 1870s clinicians and physiologists had argued whether particular functions of the brain were discretely localized or distributed throughout the entire cerebral cortex. On one hand, electrical stimulation of the cerebral cortex result-
ed in specific movements and cerebral lesions frequently produced discrete motor or sensory deficits. On the other hand, functional recovery from cerebral lesions was well documented in both the laboratory and the clinic, suggesting that some areas of the brain could take over the functions of damaged tissue and the brain functioned as a whole. Although questions of localization influenced most neurological research around the turn of the century, Berger’s thermodynamic approach to brain function transcended these contemporary debates on the structural architecture of cerebral function. Of course, Berger was no stranger to the localizationist-holist debate, and he articulated a compromise between these positions that emerged out of his EEG work and his background in psychophysiology (Millett 2001). This compromise made Berger an easy target of criticism among prominent German physiologists such as Jan Friedrich Tönnies (1933), who attacked Berger for having “never carried out his recordings with the question of localization in mind,” and instead conceiving “the bioelectrical effects of the cortex as a unity which he explains as a basic phenomenon of brain activity.”

Berger’s philosophical commitment to an interaction between mind and brain similarly set him apart from most of his contemporaries. In Britain, the influential neurologist John Hughlings Jackson and many of his followers insisted on a strict separation between the physiology of brain and the psychology of mind. During the 1860s and 1870s, Jackson developed an influential doctrine of psychophysical parallelism, which stated that that feelings, volition, and emotions are the psychological concomitants of underlying sensory-motor processes but cannot be conflated with the underlying physiology. This doctrine set the stage for later generations of British workers, including Ferrier and Horsley, who pioneered the mapping of motor and sensory functions over the cerebral surface, and Sherrington, who demonstrated that organized behavior could be understood as an integration of sensory-motor reflexes. Berger’s own belief in psychophysical interaction between mind and brain was more sympathetic to the older tradition of functionalism of German neuropsychiatry and psychology. After Berger became convinced that human thought was endowed with physical properties and could be transmitted from person to person, he joined men like Meynert, Flechsig, Lehmann, and others in their search for the neural mechanisms underlying mental or “psychic” phenomena. Here too, Berger occupied a moderate position, rejecting more radical functionalisms such as those advocated by Freud and Goldstein, men who, in Berger’s mind, had lost sight of the anatomical and physiological foundations of neurology. Berger believed that the key to interaction of neural processes and mental states lay in the elusive transformations of cortical energy, and his pursuit of the human EEG must be understood as a by-product of this psychophysical research program. It is particularly interesting to note that the central question of Berger’s early experimental work—namely, the relationship between cerebral blood flow, neural activity, and mental phenomena—has become a cornerstone of modern brain imaging. Indeed, techniques
such as positron emission tomography (PET) and function magnetic resonance imaging (fMRI) depict neural activity during various motor and cognitive tasks by detecting local changes in glucose concentration and blood flow, respectively. There can be little doubt that, just like EEG during the 1940s and 1950s, these techniques of modern brain imaging are revolutionizing clinical neuroscience before their physiological foundations have been completely understood.

Tragically, Berger would never enjoy the success of electroencephalography. Many British and American workers did not have access to the German journals where Berger published his papers on the human EEG in the early 1930s, and those workers who struggled through Berger’s reports (no small feat, due to Berger’s rambling and convoluted German prose) were convinced that the EEG was the result of some capricious electrical artifact. Indeed, Montreal neurologist Herbert Jaspers recalled that when he initially learned of Berger’s work in 1932, he and his colleagues “were highly skeptical of the possibility of recording anything of significance from the surface of the brain, in view of the enormous complexity of action potentials which must be coursing in all directions in the multitude of nerve cells and fibres of the brain” (Gloor 1969). The reception was even worse at home: Berger’s work cut across the grain of 1930s German neurophysiology, which had become politically, geographically, and conceptually focused on the problem of cortical localization at the Kaiser Wilhelm Institute for Brain Research in Berlin-Buch. Berger was considered a naïve amateur and an outsider who rejected the logic of cortical localization and refused the advantages of electronic amplification. After retiring as Professor of Psychiatry and Director of the Psychiatric Clinic at Jena in 1938, Berger’s health deteriorated as his congestive heart failure worsened and he was constantly plagued by an extremely painful furuncle. Confined to bed rest and unable to continue either his research or his clinical responsibilities, Berger sank deeper into depression, ultimately taking his own life in 1941. Yet, Berger’s EEG and his cherished project of understanding the relationship between neural events and mental phenomena continues to flourish (Gloor 1994).

References
Meynert, T. 1892b. Psychiatry: A clinical treatise on diseases of the fore-brain based upon a study of its structure, functions, and nutrition. New York: Putnam’s.