Historical Perspectives

Einthoven's String Galvanometer

The First Electrocardiograph

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Willem Einthoven (1860–1927), known as the creator of the electrocardiograph, won a Nobel Prize in 1924 for his contributions to the field of electrocardiography. He was dedicated to research and learning.

In developing the electrocardiograph, Einthoven built on the work of earlier physiologists who had studied the electrical mechanisms of the heart. Each earlier invention proved important by contributing concepts and knowledge that would shape Einthoven's device. Herein, we review the history of the electrocardiograph, with a focus on Willem Einthoven's quest to make the device a practical clinical instrument in the diagnosis of cardiac abnormalities. ***(Tex Heart Inst J 2008;35(2):174-8)***

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The electrocardiograph, among the most frequently used diagnostic devices today, was created by Willem Einthoven more than 100 years ago. His invention evolved from earlier observations and innovation, and from the discovery of muscle movement by electrical impulse through the development of the capillary electrometer. Herein, we review discoveries by the scientists who predated the invention of the electrocardiograph. We also highlight the life of Einthoven in his quest to make the electrocardiograph a practical tool for the diagnosis of cardiac abnormalities.

Electromotive Activity of the Heart: Early Measurement

In 1790, the Italian scientist Aloysio Luigi Galvani caused a dead frog's legs to move by means of electrical stimulation from a completed circuit that connected dissimilar metals. The discovery that nervous action could be induced by artificial electrical phenomena marked the beginning of the study of electrophysiology. Galvani described his work in a manuscript in 1791, *De Viribus Electricitatis in Motu Musculari*.[1-3]

For 3 decades thereafter, electrical activity was measured inaccurately by the study of contractions in frog legs. In 1820, the Danish scientist Hans Christian Oersted noted that changes in electrical current could deflect a needle. A resultant measuring device, the electric rheoscope, became known as the "galvanometer" in tribute to Galvani.[4]

The concept of "action potential" contributed to the creation of the electrocardiograph. Carlo Matteucci, a student of Leopold Nobili (who invented the thermopile), was a mathematician who was interested in physiology. In 1842, Matteucci introduced and described the term action potential after showing that the nerve of a suitably prepared frog limb—when placed over the muscle of a similarly prepared limb and stimulated—could contract the muscle below it.[5]

In 1868, Julius Bernstein accurately defined the concept of action potential that prevails today. His mentor, Emil du Bois-Reymond, had invented a rheotome. Bernstein improved this device so that it measured the time course of electrical activity in muscles. This differential rheotome (or "current-slicer") was one of Bernstein's several seminal contributions, which included the theory of bioelectricity of the cell.[6-9]

The 1st successful recording of electrical rhythm in the human heart was likely achieved by Alexander Muirhead in 1869. He used a Thomson siphon recorder (available at St. Bartholomew's Hospital in London) that had been designed to record transatlantic signals.[10,11]

Another important instrument that preceded the electrocardiograph was the capillary electrometer, which was created in 1873 by Gabriel Lippmann, a 1908 Nobel Prize laureate in Physics.[12] The capillary electrometer, as described by Barold,[9,13] consisted of a glass tube that contained mercury. One end of the glass tube was drawn

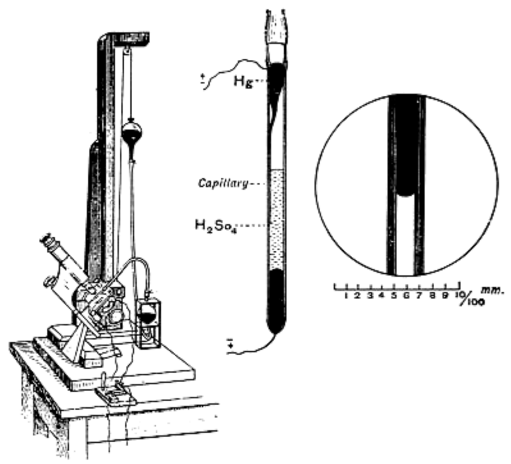

Fig. 1 *The capillary electrometer designed by Gabriel Lippmann.*

out into a fine capillary tube that was immersed vertically in a bath of diluted sulfuric acid (Fig. 1). Changes in electrical potentials produced movement of the mercury meniscus. The displacement was projected onto a screen with a moving photosensitized paper, which produced a permanent record.

In 1887, the medical doctor and physiologist Augustus D. Waller recorded the first human "electrogram" (as it was then called) in a clinical and physiological environment.[11] He would change this term to "cardiogram" a year later.[9] Waller showed that electrical activity of the heart could be recorded from the chest wall (and, later, from the esophagus) by use of Lippmann's capillary electrometer.[14] This idea was later adapted to the electrocardiograph. Waller noted 2 deflections that corresponded to ventricular depolarization and repolarization, and he named them V_1 and V_2, which are known today as the QRS complex and the T wave.[15] Waller was reluctant to appreciate the potential of his findings. As late as 1911, he said, "I do not imagine that electrocardiography is likely to find any very extensive use in the hospital.… It can at most be of rare and occasional use to afford a record of some rare anomaly of cardiac action."[16]

Willem Einthoven: His Early Years

Willem Einthoven (Fig. 2), a physiologist and medical doctor, foresaw what no one else did. Einthoven was born on 21 May 1860 in Semarang, Java, in the Dutch East Indies (present-day Indonesia). His Jewish ancestors had emigrated from Spain to the Netherlands during the Spanish Inquisition of the 15th century. His family's tradition of studying medicine began with his grandfather. Willem's father Jacob was an Army medical officer who later became Municipal Health Officer at Semarang. Willem was the oldest son and the 3rd of 6 children whom Jacob fathered with his 2nd wife, Louise de Vogel.[17]

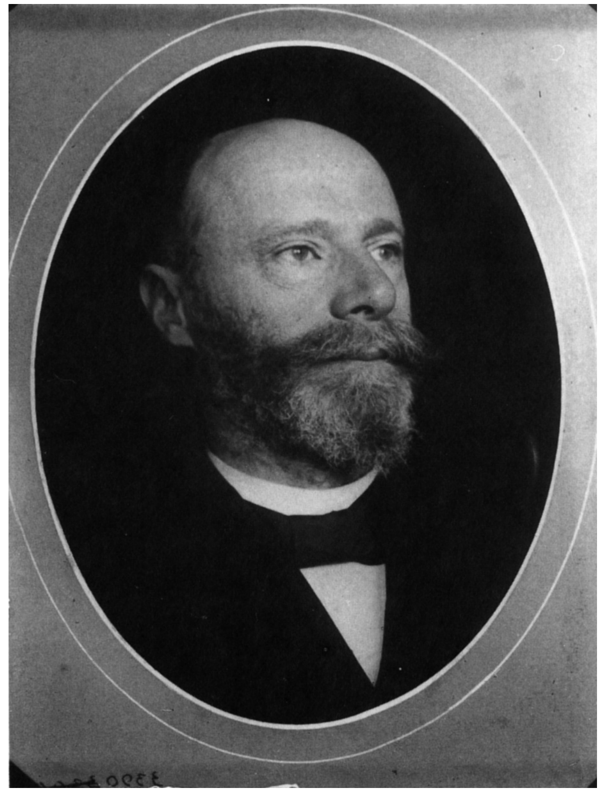

Fig. 2 *Willem Einthoven.*

When Willem was 6 years old, his father died of a stroke. At age 10, Willem moved with his family to Utrecht, where he attended high school and acquired early medical training.[18] His high school, Hogere Burger School, shortened its preparation of students for higher academic study by omitting Latin and Greek from the curriculum. Graduates of that school who entered a university were not permitted to submit a formal doctoral thesis. When Willem learned of that obstacle, he took a supplementary examination that enabled him to apply to a doctoral program and earn his degree. In 1879, at age 19, he completed high school and enrolled in the University of Utrecht as a medical student. In return for academic financial aid, he signed a contract with the Army to serve as a medical officer in the Dutch colonies upon the completion of his studies at Utrecht.[17]

In 1885, at age 25, Einthoven earned his MD and PhD degrees from the University of Utrecht.[19] That same year, the position of Professor of Physiology became available at Leiden University upon the death of the incumbent professor, Adrian Heynisus. Strong persuasion from a distinguished ophthalmologist and professor at the university, Frans Cornelius Donders, convinced the University's Counsel to appoint Einthoven as Professor of Physiology in February 1886. His faculty salary enabled him to repay the financial grant from the Army, which released him from his military obligations.[20] Einthoven later married his cousin, Frederique Jeanne Louise de Vogel.

The Ideal Device to Measure the Heart's Electrical Activity

From 1885 through 1889, Einthoven focused his research on respiratory physiology, particularly the action of the vagus nerve in the control of respiration.[9] In 1889, Einthoven attended the First International Congress of Physiology in Basel, Switzerland. There, he witnessed how A.D. Waller recorded a human electrocardiogram with the capillary electrometer. From 1890 through 1895, in order to understand the heart's electrical activity, Einthoven dedicated his full time to the use of the capillary electrometer, to which he made important improvements in function and resolution. Fye[21] states that Einthoven was able to register good electrocardiographic representations through complex mathematical and physical approaches, and that Einthoven considered each cardiac contraction to have 5 deflections, labeled P, Q, R, S, and T (Fig. 3).

Although the capillary electrometer helped to initiate the study of the heart's electrical activity, Einthoven was unable to boost the device's capabilities to acceptable diagnostic levels. He therefore began work with another instrument—the string galvanometer. An early article that Einthoven wrote about the string galvanometer's registration of the human electrocardiogram was published in a Festschrift book in 1902.[13,22]

When Einthoven began to devise his electrocardiograph, he was unaware that a similar instrument had been constructed in 1897 by the French engineer Clément Ader, for the purpose of communications. Ader's apparatus had an extremely low sensitivity that was inadequate for clinical electrocardiography.[9] Nonetheless, after Einthoven learned of this instrument, he cited Ader's work in a 1901 paper, "Un nouveau galvanometer,"[19] in order to credit all persons known to have contributed any idea associated with Einthoven's invention.

The string galvanometer comprised a thin, silver-coated quartz filament that passed between 2 electromagnets (Fig. 4). An electric current passed through

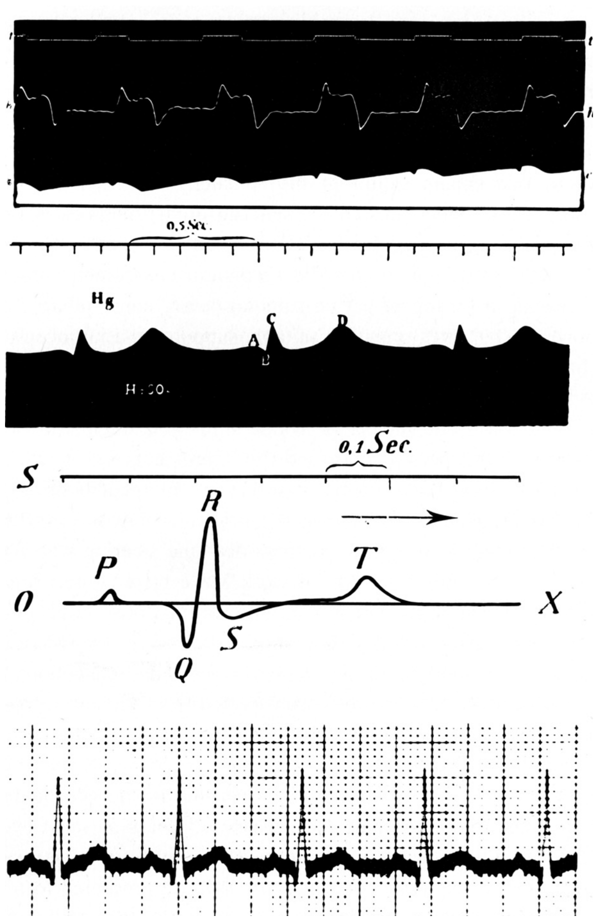

Fig. 3 *Waves obtained by A.D. Waller (top); waves obtained by Einthoven with his improved capillary electrometer (middle); electrocardiographic tracing by use of the string galvanometer (bottom).*

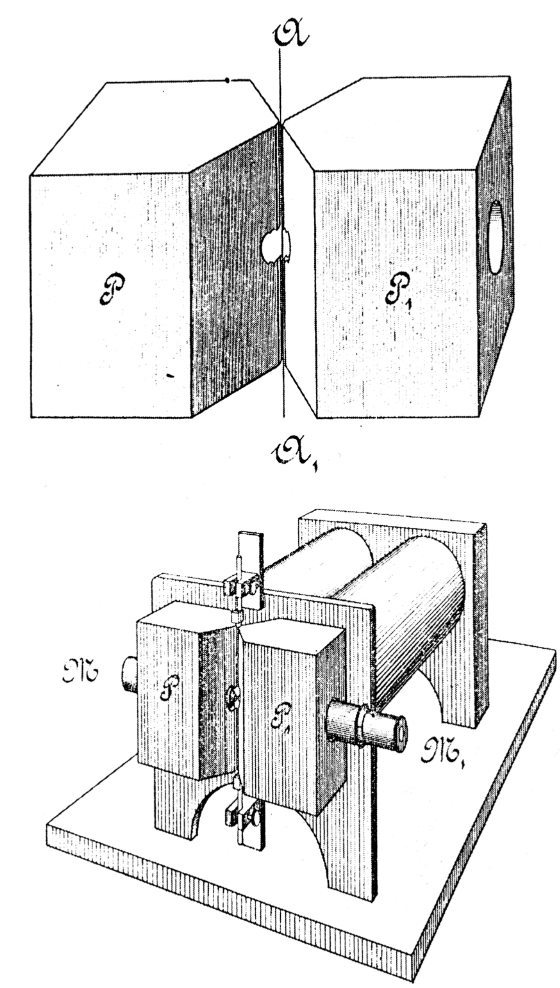

Fig. 4 *Einthoven's string galvanometer, from his 1906 paper "Le Télécardiogramme."*

the filament and produced a movement that projected a shadow, which was magnified and registered.[12] The string galvanometer provided readings of higher quality than its precursor, the capillary electrometer. This was due to the thinness and minimal mass of the string and to the ability of the operator to adjust tension to regulate sensitivity and response time.[23] According to Barold,[12] Einthoven achieved such amazing technical perfection that many modern electrocardiographs do not produce recordings of such high quality.

The string galvanometer caught the attention of other scientists who had been puzzled by the mechanics of the heart, and the instrument was used to study and classify many dysrhythmias. Einthoven also introduced the use of 3 leads to calculate the axis of the heart, which he depicted as a vector in an equilateral triangle.[12] This concept would lead to the creation of vectorcardiography.

Einthoven had a kind and friendly nature. In October 1924, while traveling in the United States, he won a Nobel Prize and $40,000 "for his discovery of the mechanism of the ECG." He looked for his old assistant, Van de Woerd, with whom he wished to share the monetary award. Unfortunately, Van de Woerd had died. Einthoven gave half of the money to Van de Woerd's 2 sisters, both of whom were living in poverty.[20]

During his later years, Einthoven dedicated his time to teaching and lecturing about electrocardiography. Einthoven had experienced arterial hypertension for many years, but he had probably never recorded his own electrocardiogram. He died on 29 September 1927 of abdominal cancer, at age 67.[17,20] He was buried in a churchyard at Oegstgeest near Leiden.

Further Development of the Electrocardiograph

Einthoven's creation was carried forward by many scientists. Thomas Lewis met with Einthoven, became interested in the string galvanometer, and purchased one to take to London for his own research. Lewis studied different patterns of dysrhythmias and grouped them into different categories, introduced the terms "pacemaker," "premature contractions," and "auricular fibrillation," and wrote books and articles about cardiac electrophysiology.[21] This body of work propagated the clinical advantages of the electrocardiograph throughout the medical community. In the United States, the physicians Horatio Williams and Walter James conducted early studies and stated that the electrocardiogram provided "an entirely new point of view of the normal and morbid action of the heart."[21]

For many years, the electrocardiograph, as scientists began calling the string galvanometer, was inconveniently large and immobile—it occupied 2 rooms and weighed approximately 600 pounds.[12] After World War I, companies began to produce models that could be rolled to a patient's bedside. The Cambridge Instrument Company built a device that weighed 50 pounds; by 1935, the Sanborn Company had reduced the weight to 25 pounds.[21] These developments made the electrocardiograph accessible to many practitioners. Today, the Holter monitoring system and the internal cardiac defibrillator exemplify the size to which the electrocardiograph has been reduced.

From reading Einthoven's early publications, physicians were able to identify different dysrhythmias, such as those known today as atrial flutter, premature ventricular contractions, and ventricular bigeminy.[24] Clinical applications of the electrocardiogram have since expanded—cardiologists can determine the severity of cardiac ischemia by analyzing the ST segment and its deviations, and thus decide upon the correct approach for reperfusion.[25] Electrocardiographic diagnosis also enables the recognition of certain genetic characteristics, such as those in Brugada syndrome and hypertrophic cardiomyopathy.[25]

Willem Einthoven's Legacy

Willem Einthoven dedicated his career to achieving an in-depth understanding of the mechanisms of electrophysiology. His insight and foresight enabled electrocardiography to emerge as a field of practical value. His persistence enabled accurate clinical use of the electrocardiograph to distinguish between various heart dysrhythmias. Einthoven's string galvanometer, in tandem with his conviction that electrocardiographic measurements could accurately identify different heart dysrhythmias, constitutes his legacy as the founder of modern electrocardiography.

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