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Willem Einthoven and the Birth of Clinical Electrocardiography a Hundred Years Ago

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Abstract. **The first electrocardiogram (ECG) from the intact human heart was recorded with a mercury capillary electrometer by Augustus Waller in May 1887 at St. Mary's Hospital, London. The tracings were poor and exhibited only 2 distorted deflections. Willem Einthoven (1860–1927) who was professor of physiology at the University of Leiden, The Netherlands, began his studies of the ECG with the mercury capillary electrometer, and improved its distortion mathematically so that he was finally able to register a good representation of the ECG before the beginning of the twentieth century. He later further improved ECG recordings with the introduction of a string galvanometer of his design. Einthoven published his first article about the string galvanometer in 1901, followed by a more detailed description in 1903 which included a report of ECGs taken with the new instrument. The year 2002 marks the centennial of Willem Einthoven's first recording of the ECG in a clinically applicable fashion with the string galvanometer. The clinical use of Einthoven's immobile equipment required transtelephonic transmission of the ECG from the physiology laboratory to the clinic at the Academic Hospital about a mile away as documented in the 1906 paper on the "télécardiogramme". This report contained a wealth of ECG patterns and arrhythmias. Einthoven developed a system of electrocardiographic standardization that continues to be used all over the world and introduced the triaxial bipolar system with 3 limb leads and thus established uniformity of the recording process. Einthoven also conceived the famous equilateral triangle with leads I, II, and III at its sides and the calculation of the electrical axis (in the frontal plane) depicted as a single vector with an arrow at the center of the triangle. Einthoven recognized the great potential importance of the ECG as a diagnostic and investigative tool and his achievements made him the founder of modern electrocardiography. He was awarded the Nobel Prize in 1924 (2 years after Waller's death) in physiology and medicine, "for the discovery of the mechanism of the electrocardiogram."**

Key Words. **Willem Einthoven, electrocardiography, history of electrocardiography, string galvanometer**

Introduction

The electrocardiogram (ECG) is the oldest and the most commonly used cardiology procedure [1–12]. It is noninvasive, simple to record and its cost is minimal. Possibly no other medical invention has had greater impact or is so universally used all over the world and despite competition from many new procedures, it has remained in continuous use for 100 years. The year 2002 marks the centennial of Willem Einthoven's first recording of the ECG in a clinically applicable fashion with a string galvanometer of his design. This achievement and his subsequent seminal work made him the father of electrocardiography [13,14].

Before Einthoven: Augustus Desiré Waller (1856–1922) [15–21]

Because of his interest in physiology of nerves and muscles, Augustus Waller from London postulated in 1887 there might be a way to record the electrical activity or voltage changes of the beating human heart from the surface of the body. In his experiments on animals and man, Waller found that electrical currents generated by the heart could be recorded with a mercury capillary electrometer when the electrodes were placed on the chest or the limbs [21]. The capillary electrometer was devised in 1873 by the French physicist Gabriel Lippmann (1845–1921) who was awarded the Nobel prize in 1908 for his work on color photography [22]. The capillary electrometer consists of a glass tube containing mercury with one end drawn out into a fine capillary (20 to 30 mμ) and immersed vertically in dilute sulfuric acid. Measurement is based on displacement of the mercury meniscus because mercury contracts and expands according to the potential difference between the mercury and acid which are connected to electrodes on two points on the body. "Permanent records are obtained by projecting a magnified image of the moving meniscus on sensitized paper moving uniformly at right angles to the direction in which the image is displaced." Waller indicated that the instrument reacted to as little as 1/40,000 volt. Waller's classic demonstration of the human ECG (called the electrogram at the time) from the intact human heart took place at St. Mary's Hospital, London, in May 1887 with surface electrodes strapped to the front and back of the chest. There were only 2 distorted deflections: ventricular depolarization and repolarization. The P wave was not discernible with the 1887 apparatus. (However, Einthoven later recorded

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atrial excitation with an improved Lippmann capillary electrometer). It is claimed that Einthoven also witnessed this historic event in 1887. Waller also used a number of other recording sites that included saline jars in which the extremities were immersed and in one instance placing one electrode on the left arm and a silver spoon in the mouth.

Initially, Waller failed to appreciate the diagnostic possibilities of the ECG. 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]." Soon afterwards, Waller, an attending cardiologist at the National Heart Hospital in London, took great interest in the further development of the ECG by Einthoven's technique and, in 1921 he published an account of the examination of 3000 ECGs [20]. Ironically at that time, Waller aptly stated that Einthoven's galvanometer was to the capillary electrometer as a high-power microscope is to a low-power microscope [7].

Although the capillary electrometer was quite sensitive, the records were poor, and distorted. They showed a slow response time, poor accuracy owing to the inertia of mercury, extreme sensitivity of the recordings to vibration and inability to record high frequency potentials. Nevertheless the capillary electrometer method played an important role during the formative years of electrocardiography and was an important forerunner of the more accurate and clinically applicable ECG developed by Einthoven who, himself, credited Waller with the first human ECG [16]. In his 1987 article on the occasion of the centennial of the first human ECG, Howard Burchell indicated that "All in all, the name Augustus Waller belongs in an electrocardiographic hall of fame [17]. Waller was a pioneer in human electrocardiography, a physiologic investigator and stimulating teacher. His range of interests was wide in the physiologic world and his contributions manifold [17]."

Willem Einthoven (1860–1927) [23–35]

Willem Einthoven (Leiden, The Netherlands) was the founder of modern electrocardiography and recognized the great potential importance of the ECG as a diagnostic and investigative tool. Einthoven, although a physician, was more of a physicist. He was awarded the Nobel Prize in 1924 (2 years after Waller's death) in physiology and medicine, "for the discovery of the mechanism of the electrocardiogram." The Netherlands issued a stamp in 1993 to commemorate Einthoven's Nobel prize.

Einthoven was born in the Dutch East Indies (now Indonesia), and received his medical degree from the University of Utrecht (The Netherlands) in 1885. He soon became professor of physiology at the University of Leiden. Early in his career Einthoven wrote a doctoral thesis on a complex aspect of ophthalmology and as a faculty member at the University of Leiden, he began doing research in respiratory physiology. He had been interested in the electrophysiology of the heart since 1890 and his focus then changed to the electrical activity of the heart.

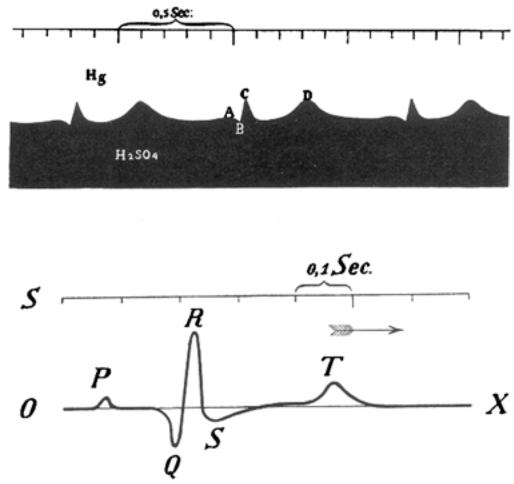

Fig. 1. *Improved recording of the ECG by Einthoven with the modified capillary electrometer. The lower tracing which is the reconstructed ECG corrected mathematically, bears a close resemblance to subsequent tracing obtained with the string galvanometer.*

In the early years, Einthoven used the Lippmann capillary electrometer like Waller, but was dissatisfied with it despite improving its distortion mathematically. Consequently he devoted a lot of effort to correct its problems. He was however, able to register a fairly good representation of the ECG which was subsequently further improved with his introduction of the string galvanometer. By calibrating and correcting the records from the capillary electrometer, Einthoven eventually predicted an ECG signal not much different from the "classic" one obtained with the string galvanometer [31] (Figure 1). Thus, the basic wave forms of the ECG were characterized by Einthoven before the beginning of the twentieth century and the advent of the string galvanometer. Based on examination of many ECG recordings with the improved capillary electrometer, Einthoven in 1900 concluded that the bioelectric signal of the diseased heart might differ from the normal [32]. This belief spurred Einthoven to develop an improved method of registering the ECG.

In 1895 Einthoven coined the term electrocardiogram (Elektrokardiogramm) but it appears that he attributed it to Waller as a token of respect for his colleague [2,16]. During these early years, Einthoven introduced the PQRST designation for the several electrocardiographic deflections as it is known today. The "P" may stand for a point in a Decartes scheme.

Decartes (1596–1650) was a French scientist who first stated the law of refraction and he labeled some of the points on the curves he drew as P and Q [36]. Later in 1903, Einthoven discovered and added the U wave. The reason for selecting these letters was never published.

Einthoven published a preliminary report of the string galvanometer in 1901 (Un nouveau galvanomètre") [33], and a more detailed description in 1903 which included a report of ECGs taken with his string galvanometer [14]. Although it is widely believed that Einthoven's first recording of the electrocardiogram with his string galvanometer was initially published in 1903 [14], Einthoven actually wrote an earlier article on the galvanometric registration of the human electrocardiogram in a Festschrift book dedicated to Professor Rosenstein which was published in 1902 [13]. A copy of this book is on display at the Boerhaave Museum in Leiden. The existence of this document was revealed by Snellen [26].

It is widely believed that Einthoven's galvanometer was substantially different from the one previously developed in 1897 by the Frenchman Clément Ader who was an electrical engineer. What is more important is the fact that Einthoven invented the electrocardiograph which was a major breakthrough in electrocardiography. According to Einthoven's description [3]: "…..the string galvanometer is essentially composed of a thin silver-coated quartz filament, (about 3 μm thick): which is attached like a string in a strong magnetic field. When an electric current is conducted through this quartz filament, the filament reveals a movement which can be observed and photographed by means of considerable magnification; this movement is similar to the movement of the capillary-electrometer. It is possible to regulate the sensitivity of the galvanometer very accurately within broad limits by tightening or loosening the string" (Figure 2). The extreme thinness of the string and its minimal mass provided a sensitivity and response time to enable high fidelity recordings of the electrocardiographic deflections. The difficulties Einthoven encountered in producing the delicate string can be found in his hand-written laboratory notes preserved in the Boerhaave Museum in Leiden [37]. Einthoven achieved such amazing technical perfection that many modern electrocardiographs do not attain equally reliable and undistorted recordings. The early work was followed by papers describing the advantages of the string galvanometer over the capillary electrometer. The string galvanometer was easier to use, free from damping and more sensitive. The original apparatus in Leiden was huge in size as it filled 2 rooms, weighed 600 pounds, included an enormous electromagnet and required 5 people to operate it. Overheating required a huge continuous-flow water jacket for cooling the electromagnet. Large buckets of saline were used as electrodes with the subject immersing his hands and feet in them. The clinical use of the immobile equipment required a telephonic connection from the physiology laboratory in Leiden to the clinic at the Academic Hospital about a mile away as described in his paper on the "télécardiogramme" [34]. Thus, a few years after his landmark paper, Einthoven described the clinical application of the ECG transmitted through telephone lines ("Le Télécardiogramme") [34]. In this context, it is amazing that Einthoven established transtelephonic transmission of the ECG almost 100 years ago. The 1906 report contained a wealth of ECG patterns and arrhythmias Einthoven identified the patterns of right and left ventricular hypertrophy, P mitrale, ventricular extrasystoles and bigeminy, complete heart block and other arrhythmias. The tracings of atrial fibrillation and atrial flutter were not recognized as such in the 1906 article. The classic paper "Weiteres uber das Elektrokardiogramme" published in 1908, firmly established the diagnostic possibilities of the electrocardiograph by presenting ECGs from patients with a wide variety of cardiac disease [35]. This terminology set the stage for the current abbreviation "EKG [6]." Not surprisingly, before 1910, the electrocardiograph was basically an instrument for physiologic research. However within 10 years of Einthoven's first clinical studies with the string galvanometer, the clinical application of electrocardiography began to expand dramatically, and clinical papers began to appear from around the world. Many arrhythmias were clarified. The prediction of Sir Thomas Lewis in the early 1910s that "the time is at hand, if it has not already come, when an examination of the heart is incomplete if this new method is neglected [38]," quickly became a reality.

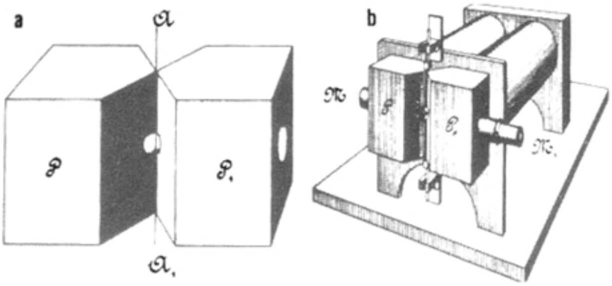

Fig. 2. *Principle of the string galvanometer depicted by drawings from Einthoven's 1906 paper [34]. The Poles P and P_1 in the electromagnet provide only a narrow space for movement of the string A-A_1 (thin wire of silver-coated quartz). The holes in the electromagnet are connected to the microscopes M and M_1 for illumination and observation.*

Einthoven developed a system of electrocardiographic standardization which continues to be used all over the world. Einthoven also introduced the triaxial bipolar system with 3 leads (standard leads I,

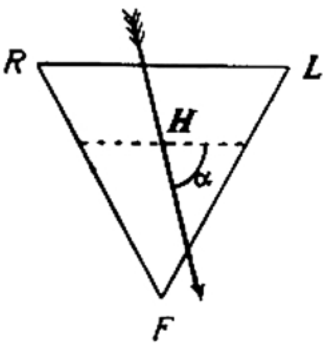

Fig. 3. *Method of Einthoven et al. [40] for calculating the electrical axis from the standard limb leads by using the equilateral triangle. R represents the right hand, L the left hand, and F the foot. The heart H is at the center. The arrow depicts the direction of the axis with the angle α between the mean electrical axis and the horizontal plane.*

II, and III) or "derivations" for recording the ECG and thus established uniformity of the recording process. Some of the early electrocardiographers advocated using only lead I. Although Einthoven's selection of leads was not optimal, leads I, II, and III are still being used, and are here to stay. In 1912 he formulated that lead II − lead I = lead III, a relationship which is now self-evident. Einthoven's views and understanding of biophysics were remarkably advanced as evidenced by his statement that "the curve must represent under all circumstances and in every moment, the algebraic sum of all the potential differences which at that moment are developed in the heart [39]." This statement should be considered in juxtaposition with Lewis' struggle with the concept of "levogram" and "dextrogram." Einthoven conceived the famous equilateral triangle with leads I, II, and III at its sides and the calculation of the electrical axis (in the frontal plane) depicted as a single vector with an arrow at the center of the triangle (Figure 3). The arrow representing a vector with magnitude and direction, was not called as such at the time, but described as "the manifest potential difference in the heart [40]." On this basis, Einthoven should perhaps also be considered the father of vectorcardiography which is really part of electrocardiography. Despite the controversy generated by these concepts, Einthoven's triangle remains used to this day for determining the mean frontal plane axis and axis deviation. Einthoven made no major contribution to electrocardiography after 1913, but he taught and lectured widely on the subject until his death. He never published a book based on his work.

The Three Giants of Electrocardiography

Only 3 men have dominated the field of electrocardiography like no others: Willem Einthoven, Sir Thomas Lewis from London, and Frank Wilson from Ann Arbor, Michigan. The time between 1908 and 1920 focused on the electrocardiographic study of arrhythmias and this period was dominated by Sir Thomas Lewis (1881–1945) who worked at University College Hospital in London [38,41–44]. He was Einthoven's successor and Frank Wilson's teacher. Lewis used the electrocardiograph to explore many disorders of the heart especially the mechanisms of arrhythmias (most of which he defined), and cardiac electrophysiology. He identified atrial fibrillation in 1909 at an early stage of his work, and even suggested a circus movement as its mechanism. Lewis probably did more than anyone else to establish the clinical value of electrocardiography. The magnitude of Lewis' contributions to electrocardiography is reflected by the statement made by Einthoven at the close of his Nobel lecture, " It is his conviction that the general interest in the ECG would certainly not be so high nowdays if we had to do without his work, and I doubt whether without his valuable contribution I should have the privilege of standing before you today [38]."

Following 1920, electrocardiography was influenced mainly by Frank Wilson (1890–1952) from Ann Arbor, Michigan [45–50]. Wilson made major contributions about the diagnostic usefulness of the ECG in bundle branch block (where he corrected previous misconceptions by Eithoven and Lewis), ventricular hypertrophy and myocardial infarction. He opened a new electrocardiographic vista and improved the accuracy of electrocardiographic diagnosis by adding standardized unipolar chest and limb leads to the 3 standard leads.

Conclusion

A hundred years after Einthoven's first ECG recording with the string galvanometer, the clinical applicability and importance of the ECG continue to grow. Computer interpretations of the ECG still remain inferior to physician interpretation especially with a higher rate of error in the analysis of rhythm. However, sophisticated signal processing algorithms derived from computers have recently introduced a new dimension in the usefulness of ECG recordings by analysis of RR intervals, late potentials, QT dispersion, T-wave alternans, etc., as prognostic markers in patients with structural heart disease. Many relatively recent advances such as the improved diagnosis of arrhythmias by the findings of invasive cardiac electrophysiology [51,52], the advent of complex pacemakers and implantable cardioverter-defibrillators, etc. have increased the complexity of electrocardiography creating a shortage of properly trained electrocardiographers. Fisch [2] has repeatedly emphasized this problem. In addition, Fisch [2] has emphasized that this issue dates back to the early days of electrocardiography as indicated by

Carl Wiggers in the preface of "Principles and Practice of Electrocardiography" in 1929. Wiggers, in the preface to his text stated that "unfortunately, the training of medical manpower in the use of such apparatus and the intelligent interpretation of the electrocardiogram has not kept pace with the increased demand. Few courses in electrocardiography are included in undergraduate and postgraduate curricula in medical schools, so that opportunity for systematic instruction is decidedly restricted [53]." Fisch is correct in stating that the issue of manpower addressed by Wiggers along time ago is still with us.

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