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Derivation of the correct waveform of the human electrocardiogram by Willem Einthoven, 1890–1895

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Abstract

In the period 1890 to 1895, Willem Einthoven greatly improved the quality of tracings that could be directly obtained with the capillary electrometer. He then introduced an ingenious correction for the poor frequency response of these instruments, using differential equations. This method allowed him to predict the correct form of the human electrocardiogram, as subsequently revealed by the new string galvanometer that he introduced in 1902. For Einthoven, who won the Nobel Prize for the development of the electrocardiogram in 1924, one of the most rewarding aspects of the high fidelity recording of the human electrocardiogram was its validation of his earlier theoretical predictions regarding the electrical activity of the heart. (Cardiol J 2010; 17, 1: 109–113)

Key words: capillary electrometer, string galvanometer, electrocardiogram

Introduction

As developed by Willem Einthoven (Fig. 1) of Leiden in 1902, high quality recording of the electrical activity of the heart by the string galvanometer was the beginning of modern electrocardiography (ECG) [1–5]. Tracings obtained with the highly sensitive quartz string device stand in sharp contrast to the markedly 'damped' recordings that were then available using the Lippmann capillary electrometer in humans, as first presented by Augustus D. Waller in 1887 [6]. This distinction is evident in the illustration used by Einthoven in his original report (Fig. 2), which contrasts the wide bandwidth string galvanometer recording on the bottom with the corresponding poor frequency response capillary electrometer recording on the top. In the middle of this illustration, we see a hand-drawn representation of predicted cardiac electrical activity, as derived by Einthoven from elegant mathematical transformation of the capillary electrometer recordings. This brief paper reviews these early transitions in ECG.

In the period 1890 to 1895, Einthoven greatly improved the quality of tracings that could be directly obtained with the capillary electrometer, and he then introduced an ingenious correction for their poor frequency response, using differential equations that allowed him to predict the correct form of the human ECG. The string galvanometer that followed shortly afterwards was a remarkable combination of a range of technological advances that evolved at the end of the nineteenth century [7–13]. But for Einthoven, a self-taught mathematician as well as a physician, one of the most rewarding features of the new galvanometer was its validation of his theoretical predictions regarding the electrical activity of the heart. Accordingly, these mathematically transformed and 'corrected' ECG curves form the link between the capillary electrometer and the string galvanometer. Their development is an important, but not widely known, episode in the

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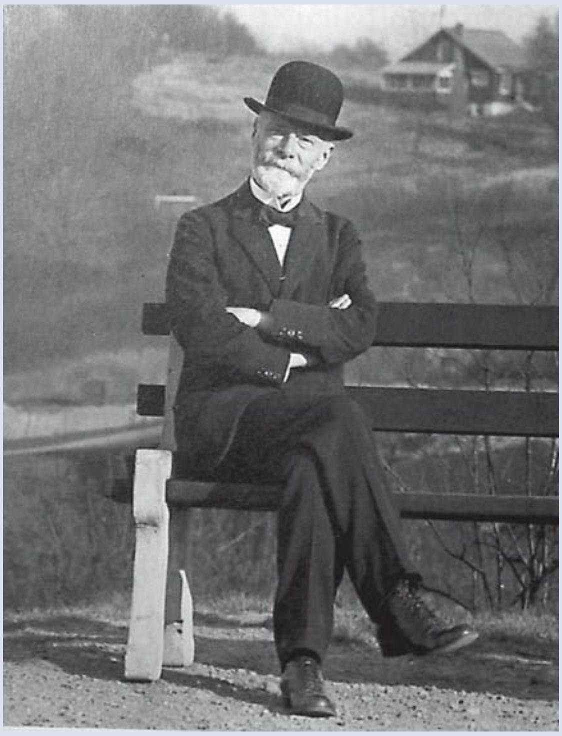

Figure 1. Willem Einthoven, in a photograph taken by Frank N. Wilson in Ann Arbor, shortly before Einthoven was awarded the Nobel Prize in 1924.

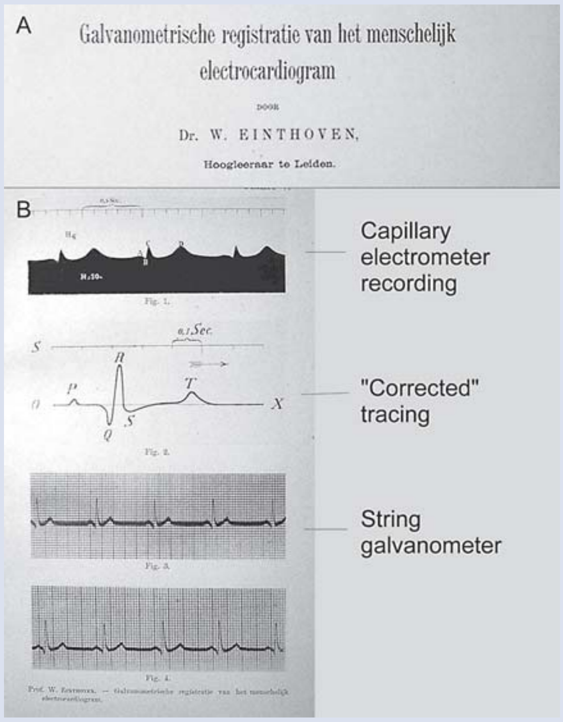

Figure 2. Title (**A**) and annotated illustration (**B**) from Einthoven's first paper on the electrocardiogram (ECG) recorded by string galvanometer, 1902. On the bottom is the ECG recorded by the new string galvanometer. On top is the corresponding recording obtained with a high quality capillary electrometer. In the middle is Einthoven's prediction of the true form of the ECG, as seen with the string galvanometer, but derived from mathematical transformation of the capillary electrometer waveform. From [11].

evolution of electrocardiography, and in the history of cardiology.

Einthoven ultimately was awarded the Nobel Prize for Medicine and Physiology in 1924 for the development of the string galvanometer method [14]. The ECG has since become one of the most widely used tools in medicine. The life and work of Einthoven (1860–1927) are detailed in the biographies by de Waart [15] and Hoogerwerf [16], although these are both in Dutch and have not been translated. Alternative biographical and source materials are available in the superb English language publications of Snellen [17–19]. The general history of electrocardiography is well documented by Burch and de Pasquale [20] and in technical, social, and clinical reviews by Burnett [7], Frank [8], and Fye [9]. A number of reviews of Einthoven's achievements have also appeared in conjunction with, and since, the centenary of the string galvanometer in 2002 [10–13].

Electrical activity of the heart before Einthoven

Prior to the development of the string galvanometer, the graphic detail of cardiac electrograms was limited by the sensitivity and frequency response of available equipment. At the time, the most useful device for animal electrophysiological study was the capillary electrometer [21, 22], which had been developed by Gabriel Lippmann (1845–1921) while studying in Heidelberg in the early 1870s. Lippmann later became professor of mathematical and experimental physics at the Sorbonne, and was awarded the Nobel Prize for Physics in 1908 for his work in color photography.

The capillary electrometer records the effect of small currents on the optically magnified movement of the meniscus formed at the interface of mercury and sulphuric acid within a thin tube with electrodes applied to either end. Change in current flow or in voltage (with constant resistance) raises or lowers the height of the mercury meniscus, forming a vertical axis of changing value that is photographically registered by projecting its shadow onto film moving along a horizontal axis, representing changing time.

However, while reasonably sensitive to small currents, the inertia of the heavy mercury in the capillary electrometer tube results in limited high frequency response that limits the detail within changing signals (see, for example, the capillary electrometer tracing at the top of Fig. 2). But even with limitations, the instrument was used productively to record cardiac electrical activity in animals by Marey [21], Burdon-Sanderson and Page [22], and Waller [6], among other experimental physiologists.

Augustus D. Waller (1856–1922) was the son of Augustus V. Waller, now remembered for his description of nerve degeneration (Wallerian degeneration). The younger Waller was appointed Lecturer in Physiology at St. Mary's Hospital in London at the age of 27 and later became Director of the Physiological Laboratory at the University of London. In his electrophysiological investigations, Waller expanded the application of the capillary electrometer from studying amphibians to the body surface recording of the mammalian heart, including that of his pet bulldog 'Jimmie'. In 1887, he published the first capillary electrometer recordings of the human heart, taken with saline-filled tub electrodes [6]. This paper can reasonably be considered the founding document of human ECG. This view was certainly held by Waller himself, along with his evident appreciation for the later achievements and contributions of Einthoven.

However, the original capillary electrometer waveforms recorded from humans by Waller were fairly crude, revealing little detail of the cardiac waveforms beyond the general direction of depolarization and repolarization. Greater fidelity was required for progress in understanding the electrical activity of the heart. Einthoven provided this progress in three stages: first, he improved the quality of the capillary electrometer. Eventually, he developed the string galvanometer. In between, he used mathematics to predict the 'correct' form of the human ECG from the low bandwidth data available from the capillary electrometer.

The capillary electrometer and the corrected form of the human electrocardiogram

At the First International Congress of Physiology in Basel, Switzerland, in 1889, Waller demonstrated his method for recording the human ECG by capillary electrometer to an enthusiastically appreciative European audience that included the only representative from the Netherlands, Willem Einthoven. This demonstration was reported to Dutch colleagues in detail by Einthoven on his return to Leiden [23], and it is evident from contemporary documents that Einthoven began similar electrophysiological studies in humans within a year of the Basel meeting. "I read [your papers] with much pleasure", Einthoven wrote to Waller from Leiden on 23 July, 1890 [24], "and had already the opportunity to deliver a lecture on your extremely interesting investigations and to demonstrate the electromotive changes connected with the beat of the human heart."

Waller's early writings focus strongly on the relationship of different lead amplitudes to the vector of normal depolarization, rather than on the diagnostic use of the tracings for the establishment of cardiac rhythm and waveform morphology. Interestingly, for nearly two decades after meeting Einthoven in 1889 and their beginning correspondence in 1890, Waller did little further original work on the electrical activity of the human heart, perhaps because he did not perceive the diagnostic clinical potential of the method [25].

During the period 1890 to 1895, Einthoven not only used the capillary electrometer extensively, but also made considerable improvements in its resolution. Technical advances in the instrument were afforded by more rapid transition in the bore of the capillary tube, by careful attention to cleanliness and drying of the tube, by advances in optical system magnification and focus, and by increased speed of the recording photographic plate transport mechanism. In contrast to the simple detection of ventricular depolarization and repolarization waves recorded by Waller, Einthoven was able to use the improved capillary electrometer to demonstrate atrial depolarization as well as biphasic ventricular depolarization and repolarization waves in his corrected tracings, which he labelled 'ABCD'.

But still, even in optimized form, the capillary electrometer method had important residual limitations for recording the human ECG. These limitations included its high moment of inertia and long periodic time, resulting in poor high frequency response of the recorded signal. In addition, considerable variability of recording was present between different instruments as a result of differences in capillary bore and shape, making direct comparisons difficult within and between patients when different electrometers were used.

Even before his innovative construction of the new string galvanometer, Einthoven's approach to resolving the interpretive difficulties of the capillary electrometer is a revealing insight into his scientific and mathematical talents. After his appointment to Leiden, Einthoven mastered differential and integral calculus as an aid to his physiological researches. In an extraordinary series of papers in the mid-1890s, he demonstrated that differential equations could be used to 'correct' the poor bandwidth tracings obtained from the capillary electrometer to approximate the 'true' form of an ECG that would be recorded by an instrument that was not limited by the frequency response [26–28]. The transformations were based on measurement of the frequency response characteristics for each capillary electrometer. The result, and success, of the mathematical correction is illustrated by comparing the top and middle graphs shown in Figure 2. The more detailed waveforms resulting from the mathematical transformations were labelled 'PQRST' in 1895 to distinguish them from the original 'ABCD' notation used for the improved capillary electrometer recordings [28].

With differential transformations individually tailored to each capillary instrument, manually corrected forms of the human electrocardiogram could be derived to represent the range of normal and abnormal findings and to compare findings between tracings taken with different electrometers. This provided a 'common standard' for early graphic recording of the electrical activity of the heart. Thus, even before the precision and fidelity that was subsequently introduced by the string galvanometer, the manual correction of electrometer tracings, albeit a highly time-consuming process, provided a basis for the evaluation and classification of large numbers of electrometer recordings that were gathered by Einthoven and his colleagues at the Physiological Laboratory and published in 1900 [29].

From the corrected electrometer tracing to the string galvanometer

Even with mathematical correction of individual ECGs taken with the capillary electrometer, significant residual problems limited Einthoven's work. Not only was individual mathematical correction time-consuming, but as a corollary, the tracings were not directly interpretable without adjustment. Further complicating their applicability, individual correction was required for each capillary tube. What ultimately was needed was a galvanometer with high sensitivity that produced an undistorted, directly readable graphic record of the electrical activity of the heart. Einthoven assembled his solution to these problems from an eclectic range of advances in industry that evolved from 1880 to the turn of the century [30, 31].

These advances included the development of accurate oscillographs for recording rapidly alternating voltages in the power industry, more accurate and sensitive galvanometers, the speeding-up of telegraphic transmission by undersea cable, carbon arc white light for streetlamp illumination, apochromatic projecting microscope lenses, and, of course, the engineering of quartz filaments. As observed by Burnett [7], the significance of the ECG designed by Einthoven was not just "the ingenuity behind its conception" but "the combination in one instrument of so many different and new ideas."

In a sense, Einthoven's publication of 1902 was as much a scientific validation of his mathematical correction of the capillary electrometer waveform, as it was an introduction of new diagnostic instrumentation. Einthoven was proud of his mathematical skills and basic grounding in physics, publishing many of his technical papers in the major pure science journals of the period [31]. Review of the plate in his initial paper [1] indicates how closely the 'corrected' tracings accurately predicted the 'true form' of the ECG that was revealed by the string galvanometer. As Einthoven observed in his Nobel Prize lecture, "there was a certain satisfaction... because this correspondence signified firstly that the earlier calculations were correct, and secondly that the new galvanometer fulfilled its purpose" [14].

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