IBEROAMERICAN JOURNAL OF MEDICINE
iberoamericanjm
Journal homepage: www.iberoamjmed.com

Review

From a laboratory to the wearables: a review on history and evolution of electrocardiogram

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ARTICLE INFO

Article history:
Received 05 August 2022
Received in revised form 02 September 2022
Accepted 06 September 2022

Keywords:
Electrocardiography
Electrocardiogram
Electrophysiology
Cardiology
History

ABSTRACT

The development of electrocardiography, one of the top scientific breakthroughs of the 20th century, occurred in the field of cardiology. The history of the ECG began long before its invention, with the advent of the study of electricity in the medical field. The idea of electrophysiology and Waller's initial recording of the 'electrogram' encouraged Willem Einthoven to develop new string galvanometers and turn this remarkable physiologic occurrence into a vital clinical recording tool. It has progressed from Einthoven's innovation to wearable technology. In the first part of the 20th century, a number of inventive people achieved a remarkable succession of discoveries and advancements that led to the development of the 12-lead ECG as we know it today. It went further than that. The evolution of science and technology over the years has allowed for continual development in terms of usefulness, ranging from five operators to one operator meant to record the ECG trace, and mobility, ranging from around 300 Kg to roughly around 1 Kg. Electrocardiographs in minimized form now exist thanks to the modern era of digitalization. We will go over the significant processes in the development of the ECG in this article.

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https://doi.org/10.53986/ibjm.2022.0038

Del laboratorio a la práctica: una revisión sobre la historia y evolución del electrocardiograma

INFO. ARTÍCULO

Historia del artículo:
Recibido 05 Agosto 2022
Recibido en forma revisada 02 Septiembre 2022
Aceptado 06 Septiuembre 2022

Palabras clave:
Electrocardiografía
Electrocardiograma
Electrofisiología
Cardiología
Historia

RESUMEN

El desarrollo de la electrocardiografía, uno de los principales avances científicos del siglo XX, se produjo en el campo de la cardiología. La historia del ECG comenzó mucho antes de su invención, con el advenimiento del estudio de la electricidad en el campo médico. La idea de la electrofisiología y el registro inicial del "electrograma" de Waller animó a Willem Einthoven a desarrollar nuevos galvanómetros de hilo y convertir este acontecimiento fisiológico notable en una herramienta de registro clínico vital. Ha progresado desde la innovación de Einthoven hasta la tecnología portátil. En la primera parte del siglo XX, varias personas ingeniosas lograron una notable sucesión de descubrimientos y avances que condujeron al desarrollo del ECG de 12 derivaciones tal como lo conocemos hoy. Fue más allá que eso. La evolución de la ciencia y la tecnología a lo largo de los años ha permitido un desarrollo continuo en términos de utilidad, que va desde cinco operadores a un operador destinado a registrar el trazo de ECG, y la movilidad, que va desde alrededor de 300 kg hasta aproximadamente 1 kg. Los electrocardiógrafos en forma minimizada ahora existen gracias a la era moderna de la digitalización. Repasaremos los procesos significativos en el desarrollo del ECG en este artículo.

HOW TO CITE THIS ARTICLE: Vincent R. From a laboratory to the wearables: a review on history and evolution of electrocardiogram. Iberoam J Med. 2022;4(4):248-255. doi: 10.53986/ibjm.2022.0038.

1. ETYMOLOGICAL ROOTS OF ELECTROCARDIOGRAM

Although the electrical nature of the heart was well recognised at the time, there were no tools available to investigate it. In reality, almost two centuries before Einthoven, the study of electricity in the medical area had already begun.

In the century that followed, more and more evidence of the electric nature of animals emerged. In 1769, Edward Bancroft proposed that the shock caused by the torpedoes was electrical rather than mechanical and compared it to the electric effect of Leiden's jar, a device for storing electrical charge that works on the same principles as a contemporary capacitor [1].

John Walsh proved a connection between electricity and living things in 1773 at Bancroft's suggestion, as documented in a letter to Benjamin Franklin [2]. This occurred almost concurrently with the Danish scholar Peter Christian Abildgaard's research in 1775. 'He succeeded in first rendering the fowl lifeless by an electric shock and then reviving them by a counter shock applied to the chest.' He accomplished ventricular fibrillation and defibrillation long before other physiologists described them [3].

'Following years as a result of study of torpedo fish, the ability of that fish to produce shock was appreciated as evidence for animal electricity. 'Later in years, Felice Fontana put out his ideas for how animal spirits aid with muscular movement and confine electricity. His final statement on the role of electricity in excitations of skeletal muscle by nerve followed by demonstration of Galvani [4].

Luigi Galvani, an Italian physician and physicist, was the first to discover that electrical current could be recorded from dissected skeletal muscles in 1786. He devised an instrument for measuring this animal's electricity, which was named after him and represents basically what electrocardiography is - the Galvanometer [5].

A few decades later, the astatic galvanometer was created, allowing Leopoldo Nobili in 1834 and followed by Carlo Matteucci in 1842 to measure and document the electrical activity of frog muscles [6, 7]. Rudolf von Koelliker and Heinrich Müller initially realized in 1856 that the frog's beating heart could generate electricity with negative variation [5].

Alexander Muirhead most likely made the first successful recording of electrical rhythm in the human heart in 1869. He made use of a Thomson siphon recorder that was intended to capture transatlantic signals and was accessible at St. Bartholomew's Hospital in London [8].

The first human "electrogram" was published in 1887 by British physiologist Augustus Desiré Waller of St Mary's Medical School in London (Figure 1). He used a Lipmann capillary electrometer with electrodes applied to the subject's back and chest. He demonstrated that ventricular contraction came before electrical activity. In his first report on a recording of cardiac electricity made on the body's surface, Waller used the term "cardiograph" [5, 9, 10].

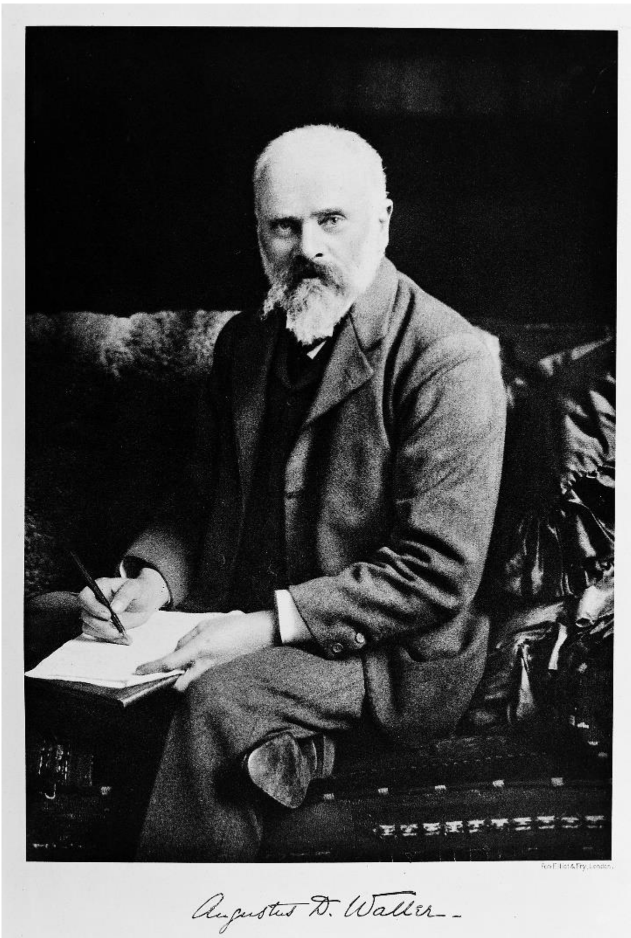


***Figure 1**: Augustus Desiré Waller [10].*

In 1891, with the use of an improved capillary electrometer, British physiologists William Bayliss and Edward Starling of University College London were able to show triphasic cardiac electrical activity in each heartbeat [8, 11].

2. BEGINNING OF CLINICAL ELECTROCARDIOGRAM

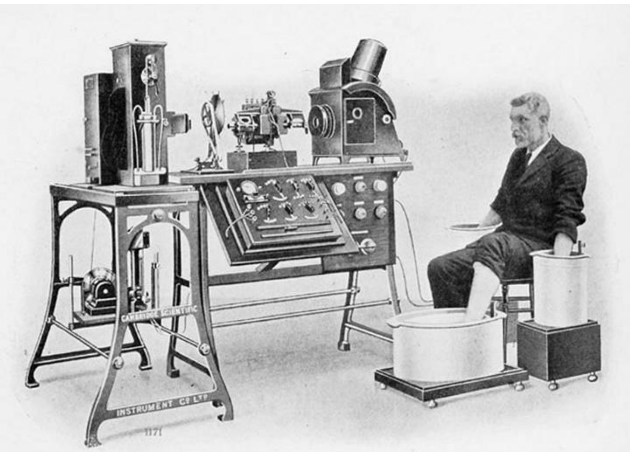
Willem Einthoven (1860–1927) was a Dutch doctor and physiologist (Figure 2) [12]. He was present at the International Congress of Physiology in London in 1887, when he saw Waller demonstrate the use of the capillary electrometer to record an "electrograph" of the heart [6, 11]. Einthoven established the term 'electrocardiogram' to designate these waveforms at the Dutch Medical Meeting in 1893 [11].

***Figure 2**: Willem Einthoven [12].*

Einthoven started experimenting with the capillary electrometer's potential for capturing minute electrical currents. He demonstrated five deflections that he labelled ABCDE in 1895. He created a mathematical adjustment to account for the capillary system's inertia, which produced the current curves that we see today. Following the mathematical tradition established by Descartes, he used the terminal part of the alphabet series (PQRST) to name these deflections [13].

Due to the drawbacks of capillary electrometers, Einthoven created a new string galvanometer that had extremely high sensitivity and was utilized in his electrocardiograph. The new string galvanometer was presented to the scientific community by Einthoven in 1901 [8, 14-16]. He established the foundations of telemedicine on March 22, 1905, when he successfully connected his laboratory to the Academic Hospital in Leiden located via telephone line, as suggested by Johannes Bosscha [17].

The pioneer of electrocardiography, Waller said in late 1911:"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" [18]. However, within 10 years of Einthoven's clinical studies with the string galvanometers transformed this curious physiologic phenomenon into an indispensable clinical recording device. The associations of T-wave inversion with angina and arteriosclerosis were discovered in 1910, along with several other arrhythmias such as bigeminy, complete heart block, P mitrale, right and left ventricular hypertrophy, atrial fibrillation and flutter, the U wave, and examples of various heart diseases [5, 11, 19-21]. With his new technique, he standardized the tracings and formulated the concept of “Einthoven’s triangle” by mathematically relating the 3 leads (Lead III = Lead II – Lead I) [22]. In 1924, the "Father of Electrocardiography" was awarded the Nobel Prize in Medicine.



PHOTOGRAPH OF A COMPLETE ELECTROCARDIOGRAPH, SHOWING THE MANNER IN WHICH THE ELECTRODES ARE ATTACHED TO THE PATIENT, IN THIS CASE THE HANDS AND ONE FOOT BEING IMMERSED IN JARS OF SALT SOLUTION

***Figure 3**: First table model Einthoven electrocardiogram manufactured by the Cambridge Instrument company of London in 1911. Showing the manner in which, the electrodes are attached to the patient, in this case the hands and one foot being immersed in jars of salt solution [16].*

3. EVOLUTION: FROM LABORATORY TO WEARABLES

Augustus D Waller used a Lipmann mercury capillary electrometer to record the electrical activity of the human heart in May 1887 at St. Mary's Hospital in London. The capillary electrometer was made out of a mercury-filled glass tube with one end pulled out into a fine capillary (20-30 µm) and submerged vertically in dilute sulphuric acid. Because mercury contracts and expands according to the potential difference between mercury and acid, which is attached to electrodes at two sites on the body, measurement was based on the displacement of the mercury meniscus. However, the tracings were weak, with just two distorted deflections.

Einthoven subsequently constructed a new string galvanometer in 1901, employing a fine quartz thread coated in silver instead of the wire coil anticipated by Deprez and d'Arsonval, which is attached like a string in a strong magnetic field. When an electric current is sent through this quartz filament, it exposes a movement that may be examined and photographed under high magnification; this movement is comparable to that of the capillary electrometer. By tightening or relaxing the string, the sensitivity of the galvanometer may be controlled extremely precisely within broad boundaries. The original device was immense, encompassing two rooms, weighing 300 Kg, having a large electromagnet within, and requiring five people to operate. Overheating required a huge continuous-flow water jacket for cooling the electromagnet. In earlier electrocardiograms, Waller employed 10 leads made up of varied combinations of five electrodes, one on each of the four extremities and the mouth, and five electrodes. By removing the electrodes on his right leg and the electrode on his lips, which he believed generated the lowest yield, he was able to decrease the number of electrodes to three. Einthoven's triangle, a crucial idea even today, was created using the three leads that were produced. The subject's hands and feet were submerged in large saline buckets that served as electrodes (Figure 3) [5, 14-16]. Improvements were made as the string galvanometer electrocardiograph was made accessible for clinical usage in order to make it more useful.

The electrocardiograph created by Einthoven was operational by 1903. In 1905 as recommended by his colleague Johannes Bosscha, Einthoven linked his device to the Academic Hospital in Leiden located 1500m away, through a telephone line to enable patient studies. This was a first for both teleelectrocardiography and telephonocardiography. One hundred years later, we are still waiting for these accomplishments to be fully implemented [17].

Sir Edward Schafer of the University of Edinburgh was the first to purchase a string galvanometer electrograph manufactured by The Cambridge Instrument Company for therapeutic use in 1908, while Dr. Alfred Cohn of Mount Sinai Hospital in New York introduced the first ECG machine to the United States in 1909 [5].

Thomas Lewis explored the excitatory processes of the heart and patterns of dysrhythmias, following in the footsteps of Einthoven and subsequently actually collaborating alongside him. In his book "Mechanism and Graphic registration of the heart," he summarized his discoveries and established a decisive transition of electrocardiography from bench to bedside [23, 24].

Because the current generated by the heart is minute, the string galvanometer had to be extremely sensitive. In the following years, vacuum tubes and followed by cathode-ray

***Figure 4**: Norman Jefferis Holter with his original 38-Kg electrocardiogram recording backpack device [26].*

tubes made it possible to replace the galvanometer and quickly adapted for the production of portable electrocardiographs which are highly sensitive. Because of its versatility, it opened many new avenues to research in recent years including spatial vectorcardiography, high-frequency electrocardiography and telemetry from outer space. As technology advances, direct-writing electrocardiographs gained popularity [5]. In 1928 Frank Sanborn's company turned Cambridge Instrument Company's table model ECG machine into their first portable version, weighing less than 12 Kg and powered by a 6-volt automotive battery [6, 11]. Taro Takemi, a Japanese physician, took it to another level in 1937 by delivering the first portable electrocardiograph machine [25]. These developments made the cardiograph accessible to many practitioners.

In 1957, American physician Norman Jefferis Holter invented the dynamic ECG (DCG), often known as the Holter ECG, in one of the early attempts to blend clinical monitoring and mobility. He created a backpack that weighed roughly 38 kg and had a device that could record the participant's heart activity (Figure 4) [26]. This portable gadget allows for the continuous monitoring of various electrical activity of the cardiovascular system for more than 24 hours, assisting in the study of arrhythmias and pinpointing the site of myocardial ischemia. Recognizing the potential benefits of such a monitoring device, Holter was able to eventually convert his idea into a valuable diagnostic tool by lowering the size and weight to 1 kg with increasing capital assistance from Del Mar Avionics, a well-known aircraft equipment manufacturer [27-29].

The advancement of science and technique over the years has allowed for a constant development in terms of usability, ranging from five operators to one operator being designed to record the ECG trace, and portability, from about 300Kg to around 1Kg. Contributions to development of ECG is summarized in Table 1.

However, not all technological advancements have led to clinical application, such as the one made in 1963 by Baule and McFee, who were the first to identify the magnetocardiogram - an electromagnetic field generated by the electrical activity of the heart [30]. Although a potentially beneficial technology, their method may detect the ECG without the need of skin electrode patches, but due to the high cost, it has never gained clinical acceptance

Commercial ECG machines have been employed more often since Einthoven, Lewis, and Wilson's work, and they continue to be among the most helpful clinical-instrumental instruments used in medical practice, even for occupational physicians. The digital age, silicon technology, and printed circuits have made it possible to miniaturize electronic medical devices. Wearable technology has been quickly gaining popularity in the medical field for a while now. The urge of customers to keep track of their own health was the major driver of this. The influence of wearables on cardiovascular care has become unavoidable because of continued research and development of new features that can evaluate and transmit real-time biometric data [31].

4. STANDARDIZATION ECG

During the first three decades of the 20th century, the three lead electrocardiogram usage expanded especially after improvements were made to make it more portable [32, 33]. Even though the three-lead ECG was a reliable way to evaluate arrhythmias, it was soon recognized that the heart included 'silent zones' where a myocardial infarction might not be detectable [34].

Table 1: Major contribution in history and evolution of electrocardiogram with timeline

Year	Contribution	Contributor
1769	Proposed shock caused by the torpedoes was electrical	Edward Bancroft
1773	Proved electrical activity in animals	John Walsh
1775	Proved electrical activity in animals & accomplishment of ventricular fibrillation and defibrillation	Peter Christian Abildgaard
1786	Discovered electric current from dissected skeletal muscles & Invention of Galvanometer	Luigi Galvani
1834	Measured and documented the electrical activity of frog muscles	Leopoldo Nobili
1842	Measured and documented the electrical activity of frog muscles	Carlo Matteuci
1856	First to realize the frog's heart could generate negative variation in electricity with each contraction.	Rudolf von Koelliker and Heinrich Müller
1869	First successful recording of electrical rhythm in the human heart	Alexander Muirhead
1887	Published first human 'electrogram'	Augustus Desiré Waller
1891	Discovered triphasic cardiac electrical activity in each heart beat	William Bayliss and Edward Starling
1893	Termed 'Electrocardiogram'	Willem Einthoven
1895	Identified five deflection in electrogram, named PQRST	Willem EInthoven
1901	New String Galvanometer	Willem Einthoven
1905	Foundations of Telemedicine	Willem Einthoven and Johannes Bosscha
1908	First purchase of string galvanometer for therapeutic use	Edward Schafer
1910	Electrocardiogram (ECG) patterns for several heart diseases	Willem Einthoven, Thomas Lewis
1915	Introduced the first ECG machine to the United States	Alfred Cohn
1928	First truly portable electrocardiograph	Cambridge instrument company
1928	The Sanborn's firm made first portable version	Frank Sanborn's company
1934	Concept of central terminal lead	Frank N Wilson
1937	Another portable version	Taro Takemi
1938	Recommended for standard positioning and wiring of V1 - V6 leads	American Heart Association and the Cardiac Society of Great Britain
1942	Introduction of augmented leads	Emanuel Goldberger
1954	Standardization of 12-lead ECG	American Heart Association
1957	Invented dynamic ECG	Norman Jeff Holter
1963	Discovery of magnetocardiogram	Baule and McFee

In 1934, the American physiologist Frank N. Wilson, a follower of Thomas Lewis, established the principles of contemporary electrophysiology by first standardizing its methodology. A central negative lead reflecting a 'ground' or reference terminal was made by connecting the three limb electrodes [35]. An electrode is connected to this ground through a galvanometer from the body surface to detect the potential difference and what is considered to be zero. These so-called 'unipolar' leads were distinct from 'bipolar' leads that measure the potential difference between two sites on the body surface. The unipolar lead was characterized as an exploring lead since it could have hypothetically been positioned anywhere on the body. In 1938, The American Heart Association and the Cardiac Society of Great Britain issued their recommendation for documenting these 'exploring lead' from six sites referred to as V1 through V6 across the chest [34].

Since the frontal plane was covered by the three-lead ECG in 60-degree increments, it seems plausible that certain areas were left unobserved. In 1942, Emanuel Goldberger built unipolar leads using Wilson's central terminal and linked them to additional positive unipolar leads on the left leg, left arm, and right arm. Despite the fact that this method provided more extensive coverage of the frontal plane, the signal from these unipolar leads was weak. To augment these signals, Goldberger proposed a way, yielding on what is now known as the augmented unipolar limb leads a-VL, a-VR, and a-VF. The a-VR has an odd appearance because this is the first time a positive electrode has been placed in the opposite direction of the electrical activation [36]. The 12-lead electrocardiogram as we know it today underwent a significant advancement by the invention of the unipolar leads [33].

The American Heart Association highlighted a recommendation for 12-lead ECG standardization in 1954 [34].

5. END NOTE

The history and evolution of the ECG began long before its invention. The concept of the electric nature of cardiac activity and the lack of a tool to study it led the scientific community to the invention of the electrocardiogram. All their contributions helped 'the Father of the Electrocardiogram', Willem Einthoven, to turn this curious physiological event into a crucial clinical recording tool that is still immensely useful in the modern era of digitalization in science and technology. From Einthoven's invention to the 12-lead ECG and Holter monitor that we have today, it took a significant amount of time and effort to advance. The importance of this vital tool was recognised by many practitioners even in its infancy and encouraged other scientists to contribute their part to the refinement of this crucial clinical device. Take a look at what we have today. A two-room-sized, gigantic laboratory recording device is minimized into wearable technology for daily life. The commercialization of such technology allows the general population to keep track of their health. It's just how science and technology work. We are always evolving, and we welcome participation from others.

6. CONFLICT OF INTERESTS

The authors have no conflict of interest to declare. The authors declared that this study has received no financial support.

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