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The origins of electrocardiography in Poland

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Abstract

The progress of science and technology in the 19th century enabled better understanding of the electrical activity that occurs during a heartbeat. However, it was only the construction and introduction of the galvanometer that cleared the way for appropriate experimental and clinical studies. Marey, Waller, Wenckebach, Einthoven, and Pardee are just examples of the world's pioneers of electrocardiography. Polish researchers, including Cybulski, Eiger, Rzętkowski, Surzycki, and Latkowski, also contributed to the development of this area of study. The following article is a review aiming to reconstruct the origins of electrocardiography in Poland, both as a measurement method used in experiments and as a diagnostic tool in clinical studies conducted in the years preceding the outbreak of World War I.

Key words: history of medicine, electrocardiography, cardiology, physiology.

Streszczenie

Badanie zjawisk elektrycznych zachodzących w organizmach żywych ma długą tradycję, lecz dopiero wiek dziewiętnasty wraz z postępami nauk ścisłych i techniki umożliwił lepsze poznanie ich natury. Już w pierwszej połowie tego stulecia zaobserwowano aktywność elektryczną w trakcie pracy mięśnia sercowego, lecz dopiero skonstruowanie i wprowadzenie galwanometru otworzyło drogę właściwym badaniom eksperymentalnym i klinicznym. Marey, Waller, Wenckebach, Einthoven czy Pardee to tylko niektóre z nazwisk pionierów światowej elektrokardiografii. Swój wkład w jej rozwój wnieśli także polscy badacze – Cybulski, Eiger, Rzętkowski, Surzycki, Latkowski. Poniższy artykuł nosi charakter pracy poglądowej, której celem jest zrekonstruowanie początków elektrokardiografii na ziemiach polskich i to zarówno jako metody pomiarowej w postępowaniu eksperymentalnym, jak i metody diagnostycznej w badaniu klinicznym. Jest to próba spojrzenia z perspektywy lekarzy, którzy w ostatnich latach przed wybuchem I wojny światowej rozpoczęli intensywne badania na polu elektrokardiografii.

Słowa kluczowe: historia medycyny, elektrokardiografia, kardiologia, fizjologia.

The origins of electrocardiography around the world

At the beginning of 1820, Hans Christian Ørsted, a Danish physicist, accidentally discovered the phenomenon that is now referred to as electromagnetism during one of his classes with students [1]. About two decades later, Carlo Matteucci, a professor of physics at the University of Pisa interested in neurophysiology, showed that every beat of a frog's heart generates electricity [2]. These were the first steps towards the study of electrocardiography.

In 1872, Gabriel Lippmann, a French physicist, invented the capillary electrometer, a simple device composed of a glass tube filled with mercury under sulfuric acid. Every change in electric potential caused changes in the location of the meniscus of mercury, the movement of which was observable under a microscope. Four years later, Étienne-Jules Marey, a French physiologist and a pioneer of chronophotography, used the Lippmann electrometer to record electrical activity in an exposed heart of a frog, preserving the results of his measurements on a photographic plate. This event may be considered as the true beginning of the path towards modern electrocardiography [3].

In the 1880s, Augustus D. Waller, a British physiologist, conducted systematic research on the distribution of positive and negative potentials in various areas of the human body as well as their changes in strict relation to heartbeat. He conducted his experiments on both animals and humans. Waller published the first human electrocardiogram in 1887 [4]. Willem Einthoven, who had the opportunity to see the technique demonstrated by Waller during a session of the International Congress of Physiology in 1889, was impressed by the achievement of the British scientist. In time, Einthoven would become a key figure in the development of electrocardiography [5-7].

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The term electrocardiogram was coined by Willem Einthoven during a meeting of the Dutch Medical Association in 1893, though some authors consider Waller to be the first to use it. Two years later, the Dutch scientist used an improved version of the electrometer and a correction formula enabling the proper calibration of initial recording results. In cooperation with George J. Burch, he distinguished 5 deflections labeled P, Q, R, S, and T [8].

In 1899, Karel Frederik Wenckebach, a Dutch scholar, published a work in which he analyzed irregular pulse characteristics with clear impairment of atrioventricular conduction leading to progressive lengthening and blockage of atrioventricular conduction in frogs. This phenomenon was later called the *Wenckebach block* (Mobitz type I) or the Wenckebach phenomenon (Wenckebach periodicity) [9].

Einthoven knew that capillary electrometer recordings requiring the use of a correction formula did not constitute a technique that could be practically applied in the future. Looking for a better solution, he turned his attention to galvanometers. However, it quickly turned out that their sensitivity was far from perfect. Between the years 1900-1901, Einthoven invented a new galvanometer using a fine quartz string coated in silver. His newly created string galvanometer was a milestone in the development of electrocardiography. As early as in 1902, Einthoven published the first electrocardiogram recorded with the use of this device. Significant improvement of recording and reading quality was achieved through intensive experiments and trials with the use of the string galvanometer. The device itself, from then on referred to as the *Einthoven galvanometer*, became known around the world.

In 1905, Einthoven transmitted an electrocardiogram created in hospital conditions to his laboratory over 1 km away via telephone cables [5]. A year later, he was able to publish a classification of normal and abnormal electrocardiograms recorded with a string galvanometer. This was the first time that left and right ventricular hypertrophy, left and right atrial hypertrophy, ventricular premature beats, ventricular bigeminy, atrial flutter and complete heart block were illustrated and described. It was also the first time that an image of the U wave was acquired. In 1912, Einthoven described an equilateral triangle formed by standard leads I, II, and III, which was later called *Einthoven's triangle* [10, 11]. In the same year, James Bryan Herrick, an American scientist, published his results from 1910, which proved that the use of Einthoven's electrocardiograph enabled the performance of in vivo diagnostics for myocardial infarction, which was the final confirmation of the method's usefulness in clinical diagnostics. In 1924, Einthoven was awarded the Nobel Prize in physiology and medicine for inventing the electrocardiograph [12]. Four years earlier, Harold Pardee, an American physician, published the first electrocardiogram of the course of myocardial infarction in a human and characterized the T wave [13].

First attempts at electrocardiography in Poland

Napoleon Nikodem Cybulski, an excellent physiologist, is considered to be the Polish pioneer of electrocardiography. Influenced by Einthoven's reports, he conducted heartbeat recordings on himself [14]. It should be noted that the publication of the results and conclusions of his studies coincided in time and place with a publication by Kazimierz Rzętkowski. Both texts appeared in 1910 in the periodical *Gazeta Lekarska*. The work by Rzętkowski was published in two parts, in the issues of April 16 (no. 16) and April 23 (no. 17), while the article by Cybulski, also in two parts, appeared in the issues of April 23 (no. 17) and April 30 (no. 18) [15-17].

The work by Rzętkowski was in fact a printed version of his lecture entitled "*O elektrokardiogramie*" ("*About the electrocardiogram*"), which was given by the author on March 1, 1910 during a session of the Warsaw Medical Association. Rzętkowski aimed to present a diagnostic method which was at that time new and relatively unknown. The abovementioned speech was largely a hands-on clinical summary. It was focused on the practical aspect of the discussed measurement technique as well as on the construction of an adequate and possibly interference-proof measurement system. The author made it clear that caution needs to be maintained when drawing any final conclusions due to technical and interpretational difficulties.

Rzętkowski started his deliberations with the findings of Waller, whom he considered the inventor of the method that was further improved and popularized by Einthoven. Briefly presenting the measurement principles of a string galvanometer and the application of the acquired results for heart function assessment, he emphasized the advantages of the device constructed by the Dutch scholar. Next, he provided a detailed technical description of the Einthoven galvanometer accompanied with a demonstrative illustration. Rzętkowski pointed out that the galvanometer itself is an element of a complex system called the

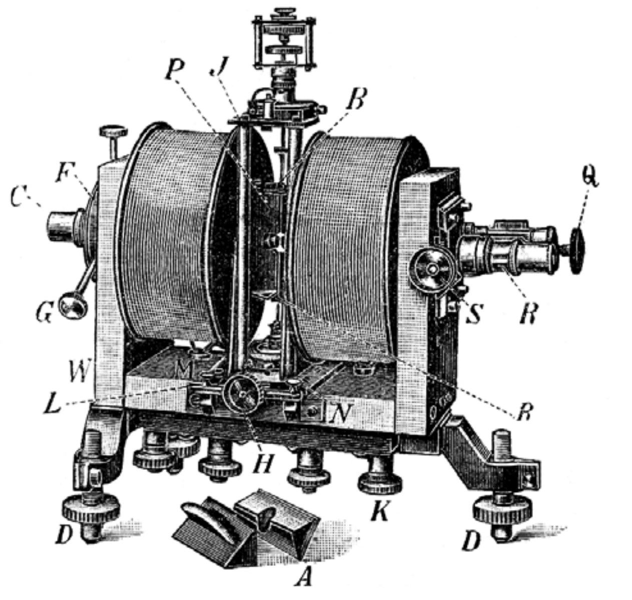

Fig. 1. Einthoven's galvanometer. Illustration from the article by K. Rzętkowski "O elektrokardiogramie" ("About the electrocardiogram")

Herzstation, which must be complete in order to perform effective electrocardiographic examination. He emphasized that the string galvanometer is a very sensitive device and, therefore, it is very susceptible to numerous interferences, including stray voltage or even slight mechanical vibrations. As Rzętkowski mentioned, he saw an electrographic system properly insulated from unfavorable external conditions at the unit headed by Professor Napoleon Nikodem Cybulski during the 1st Convention of Polish Internists, which took place in 1909 in Kraków.

The principles for the correct reading of electrocardiograms were presented further in the lecture, with reference to the characteristics of waves labeled as *P*, *Q*, *R*, *S*, and *T*. Rzętkowski pointed out that such a division was accepted by the majority of researchers, but there were certain disagreements in terms of the interpretation of their meaning. At the same time, he emphasized that the nature of the last wave (*T*) was a subject of an ongoing discussion, while the proper interpretation of the remaining waves was not entirely clear. Referring to the results achieved by Kraus, Nicolai, Hering, Samoylov, and Steszyńska, among others, he presented the benefits resulting from the use of electrocardiograms in the diagnostics of pathological heart lesions, drawing attention to the fact that many issues required further explanation. He referred to Einthoven's observations concerning the flattening of the T-wave and the appearance of a new U-wave on the cardiogram, which occurs in certain degenerative heart diseases. However, his research did not include his own experiments with electrocardiography.

The work of Cybulski, who devoted much attention to the electrical phenomena occurring in living organisms, was different in nature from the lecture given by Rzętkowski. When studying the mechanics of an isolated frog heart, the physiologist from Kraków focused primarily on the interpretation of cardiograms, hardly referring to any technical or practical issues in the use of the galvanometer. He considered electrocardiography mainly as an excellent method for studying physiological phenomena in both natural and experimental conditions.

Cybulski based his work on a principle formulated by Ludimar Hermann, a student of Du Bois Reymond. Hermann, contrary to the views of his mentor, claimed that no type of tissue, including muscles, has any constant electromotive forces, and that the surface of muscles is isopotential in the resting phase. Biochemical phenomena can only be observed during the active state of a muscle or tissue, and the active parts always exhibit negative potential. Cybulski, using the general principle formulated by Hermann and the observations conducted by Waller (who proved that the change in potential measured during a heartbeat is directly correlated with the changes in potential occurring in the entire human body), devoted his attention to the constant characteristics of potential changes and the correlation between these changes and the contractions of the myocardium, trying to systematize the studied phenomena.

He closely followed the cardiac cycle of a frog based on electrocardiogram interpretations. He also registered simultaneous and independent measurements of the atria and ventricles in the course of a single experiment. At that point, he demonstrated that short atrial action should be considered as first, while negative potential appears before the actual contraction. Next, during the atrial contraction, the line first reaches level "0"; for a short time at the end of the contraction, the line achieves a positive potential, and then it suddenly peaks at the opposite side immediately afterwards. According to Cybulski, such a reading indicated the moment at which the ventricle achieves "negativity". Only at that moment could he observe a contraction of an isolated heart. In this manner, Cybulski managed to demonstrate that the initiation of a contraction and the accompanying change in potential clearly precedes the actual contraction mechanics. He could, therefore, claim that electronegativity is not constant throughout the entire mechanical activity of the heart and that it changes during the active state – hence Cybulski's hypothesis that "the mechanical activity of a muscle is preceded and accompanied by certain internal disturbances in the protoplasm, which are closely correlated with the state of electrical potential, but do not at all interfere with the mechanical work performed by muscles or the heart" [16]. At the same time, he referred to an observation made by Helmholtz that electrical potential is measurable in the active muscle before the actual contraction. This phenomenon can be observed in the period of "latent irritation". Cybulski noticed significant similarities between Helmholtz's observations and his own work, which he summed up with the statement that electrical phenomena are most likely caused by changes occurring during metabolism, accompanying all anabolic and catabolic processes; the former he associated with increases of potential, and the latter with decreases. An equilibrium between anabolic and catabolic processes resulted in the balancing of potentials. It may be stated that it was in fact a biochemical concept for the regulation of the electrical processes occurring in a living organism.

During his research, including experiments on dogs and, later on, humans, Cybulski used a microphone to record heart tones. This enabled him to monitor and compare the deflections on electrocardiograms in real time. Thanks to this research method, he was able to establish that the R wave is actually a recording of a change in potential preceding a contraction. At the same time, he pointed out that the previous, widely accepted associations between the S wave and right ventricular contraction and between the R wave and left ventricular contraction were not confirmed by his observations and that maintaining these assumptions contradicts the nature of electrical phenomena. A clear deflection of the R and P waves with only a slight deflection of the T wave is, according to Cybulski, in line with the physiological image of heartbeat. The Q and S deflections should be, in principle, considered abnormal. Finally, he emphasized the importance of electrocardiography in diagnosing and monitoring patients and pointed to its virtually unlimited applications in basic sciences.

The year 1910 also brought about the publication of an overview of the experimental research conducted on animals by Cybulski and Marian Eiger, his assistant of the time and, later on, a professor of physiology at Vilnius University; the goal of the research was to prove or disprove the influence of anesthesia on electrocardiographic measurements [18, 19]. The researchers started with discussing the benefits resulting from the use of Einthoven's device and the characteristics of the ECG chart itself. Next, they pointed to a series of disputable issues associated with the then innovative diagnostic method. Finally, they described the results they obtained when subjecting laboratory animals to the influence of such anesthetic agents as ether or chloroform. They proved that anesthesia causes significant changes in the electrocardiographic curve. Changes in potential, from positive to negative, were visible during mechanical ventricular contractions; changes in heart rhythm (arrhythmias) were also present. When the effects of ether or chloroform wore off and the animals received clean air, the ECG curve returned to normal. These results were in line with experiments conducted on frog hearts (both in situ and isolated). Identical results were obtained in dogs. It was also observed that, after the administration of tropacocaine, the T wave on the chart changed its value from positive to negative.

Cybulski and Eiger emphasized that the results they presented should be considered as preliminary. They believed that comparing them with observations in humans is crucial for further research. Their report ends with the following statement: "One conclusion can undoubtedly be made on the basis of this research, namely that the electrocardiographic curve may serve as an objective criterion, as a test for the condition of the heart, both before and during anesthesia" [18]. Their findings were presented in October 1910 during the Convention of Polish Surgeons in Warsaw.

In the same year, on November 30, during a session of the Kraków Medical Association, Eiger gave a lecture entitled "Metoda elektrokardyograficzna, jej kliniczne znaczenie i zastosowanie" ("The electrocardiographic method, its clinical importance and application") [20]. The full text of this lecture appeared in the journal *Przegląd Lekarski* in 1911 [21]. Eiger, similarly to Rzętkowski before him, concentrated on the practical side of the use of electrocardiography, from describing the operating principles of the Einthoven galvanometer, through the ability to read and interpret electrocardiographic curves, to discussing the main theories – of Einthoven, Gotch, Kraus, and Nicolai – associated with the correct analysis of charts and the meaning of P, Q, R, S, and T waves. He described these issues more broadly than Rzętkowski had done one year before.

In the same year, Eiger published a larger study, which was actually the first part of a monograph in which he provided a detailed description of the characteristics of the ECG curve and conducted a critical analysis concerning the origin and characteristics of the waves [22-24]. Two years later, this text was published in German [25].

Eiger conducted a series of experiments on both isolated and non-isolated animal hearts, mainly of frogs and dogs. He used the results of experiments conducted on fish, oyster, and crayfish hearts with single atria and single ventricles as material for comparison. Apart from complete hearts, Eiger also conducted experiments on prepared hearts - atria without ventricles, beating venous sinuses in frogs after previous amputation of the atria and ventricles, or beating outlets of the venae cavae. By doing so, he acquired rich and diverse material, which allowed him to draw several important conclusions. In a summary of the obtained results he wrote: "The entire electrocardiographic curve, representing a single contraction of a frog heart, is mainly composed of the following components: a) a curve of beating cardiac vein inlets, b) a curve of beating venous sinus, c) an atrial curve, d) a ventricular curve, e) a curve of the beating bulb of the main artery" [22]. From then on, Eiger opposed the widely accepted view that waves Q, R, S, and T should be associated with the expansion of electrophysiological phenomena in ventricular structures alone. He demonstrated that waves Q, S, T, and P are visible in the ECG images of amputated and non-amputated atria of isolated and non-isolated frog hearts. In a beating bulb of the main artery and venous sinus, it was possible to register the characteristic R, S, and T waves. He observed the last two waves not only in animal hearts with two ventricles, but also in the hearts of lower animals with only one atrium and one ventricle. He claimed that these observations proved that the electrocardiographic curve of a ventricle and atrium should be divided into two separate parts. One part would record action currents before the occurrence of contractions and present the differentiation of potentials in the heart in the period preceding its mechanical activity. In the ECG curve, this is expressed by waves Q, R, S. The other part, characterized by the S T period and the T wave itself, should be associated with the biochemical processes taking place in the heart that are strictly correlated with its mechanical activity.

In a study published 3 years later, which was in fact a continuation and a supplement to the abovementioned text, Eiger analyzed the electrocardiographic curve as an algebraic sum of cardiac action currents. He conducted his research on animals, comparing the acquired results with human ECG recordings [26]. This work was later translated and published in German [27].

Eiger based the study on the results achieved by Napoleon Cybulski during his research on electrical phenomena in living organisms. He emphasized that all known electrical phenomena occurring in the heart are comparable to more general phenomena which had been previously discovered and described in the area of muscle electrophysiology. When referring to his study of 1911, he contested and criticized a series of works by, among others, Nicolai, Hering, and Hoffman, who, according to Eiger, misinterpreted and incorrectly quoted his previous findings. He once again revised the origin of the waves, reaching a conclusion that there is a different active state source for wave T than in the case of waves R and S. Moreover, he stated that R and S constitute the expression of the first, two-phase active state. A two-phase nature should also be ascribed to the T wave, which represents the second, reversed active state. Experiments confirmed that waves R and T, in terms of topography, have completely different sources in the ventricle of a spontaneously contracting heart. In conclusion, he wrote: "The electrocardiographic curve constitutes an expression of the algebraic sum of cardiac action currents generated by two active states starting at the opposite ends of a circuit formed by the base of the ventricle and flowing in two opposite directions from atrial walls" [26].

During the same period, Cybulski was cooperating with Józef Surzycki in order to establish the ECG characteristics of abnormal heart function caused by disease processes. During the meeting of the Krakow Medical Association in December 1911, Surzycki presented a report concerning the research he conducted together with Cybulski on the electrocardiographic image in the course of exudative endocarditis [28]. Several months later, in August 1912, the full text of the previous report appeared in *Przegląd Lekarski* [29]. The researchers began by establishing the characteristic features of the electrocardiographic image of this disease, in which waves P, R, and T clearly differed from the waves recorded in healthy individuals. Multiple examinations were conducted on a single patient, demonstrating that the consecutive electrocardiograms changed together with the patient's gradual recovery. Therefore, the relation between heart function and electrocardiographic readings was considered to be confirmed. However, the researchers were not able to compare the results they achieved in this manner with similar clinical cases, even though they claimed that they intensively searched for individuals suffering from the disease in question. Thus, they were forced to perform their experiments on animals.

The pathological factor that was the easiest to trigger during experiments on dogs was the introduction of fluid into the pericardial sac - saline solutions of different concentrations were used for this purpose. During the procedure, the animals were given morphine and curare. The study included 8 animals. The researchers discovered that, in all cases, both the introduction of fluid into the pericardial sac and its extraction resulted in immediate changes in ECG readings. When more fluid was introduced into the pericardial sac or removed from it, the changes visible in the readings became more pronounced. In two cases, with the introduction of over 100 cm^3 of fluid, a characteristic ECG image was achieved, in which the waves deflected in slowed rhythm but in opposite directions, just like in the normal state. Concurrently, the atrial P wave disappeared almost completely. The researchers hypothesized that the pressure from the pericardium might have caused disturbances in the functional mechanism of the atria and ventricles. As a result of this process, atrial function was almost completely inhibited, which was indicated by the fading P wave. The ventricles would contract in accordance with the course of the active state, but in a reversed sequence. However, the primary reason behind such behavior of the heart remained unknown for the researchers from Krakow.

Józef Latkowski also showed great interest in the opportunities offered by electrocardiography. During the meeting of the Kraków Medical Association of January 1912, he presented and analyzed a cardiogram of a patient with dextrocardia [29]. Using the results obtained by Cybulski, he confirmed that also in this case – of a normal but abnormally located heart – the occurrence of electrical activity took place before the actual mechanical action of the myocardium. However, the electrocardiographic image was completely reversed – this was clearly visible in the image of waves P, T, and R. According to Latkowski, this was associated with the reversed pathway of muscle activity. Latkowski emphasized that the literature of that time contained only two descriptions of full electrocardiograms of patients with dextrocardia, which were independently provided by Nicolai and Hocke. Therefore, the description by Latkowski was the third such publication in global medicine.

The interest in the new method was unabating, as confirmed by the exhibition which took place in February 1913 at the Kraków Medical Association, presenting electrocardiograms of healthy and diseased individuals and accompanied by a lecture given by Józef Latkowski [30]. During his speech, Latkowski referred to cases of patients undergoing ECG diagnostics, some of which had not yet been described in the literature, including the recording of a patient from the ward of Professor Lewkowicz, whose heart was fused with the chest and pericardium. Zubrzycki, when commenting on the lecture by Latkowski, wrote: "In this case, with electrodes going out of the left leg and left arm or the left arm and right leg, the curve shows only traces of cardiac contraction, while with the use of other configurations, excluding 'both legs', atrial and ventricular contractions are clearly visible on the curve. This change in ECG may signify higher resistance between the heart and the left arm, which almost completely prevents the flow of electrical current through this galvanometer path. This behavior of ECG also proves that the current generated in the heart is transmitted through blood vessels only to a small degree and mainly flows through other tissues" [31].

Final conclusions

The above analysis of the works of Polish physicians associated with the study of electrocardiography in the years directly preceding the outbreak of World War I appears to contain two general approaches which may be described as experimental (Cybulski, Eiger) and clinical (Rzętkowski, Latkowski, Surzycki).

The experimental approach was characterized by its focus on the problems associated with the correct understanding of the nature of the electrical phenomena occurring in the heart and their relationship with the mechanical activity of atria and ventricles, as well as the establishment of the sequence of bioelectrical processes at the basis of heart contractions. Another important goal was to establish the precise characteristics of ECG recordings and the nature of the P, Q, R, S, and T waves.

The clinical approach is mainly concerned with the acquisition of the full image of both normal and abnormal electrocardiographic recordings, including the recordings of rare diseases, and the use of the then new diagnostic tool as precisely as possible. Significant emphasis was put on the conditions in which ECG examinations were conducted, the proper protection of the measurement system from interference, and the necessity of comparing the results acquired through electrocardiographic examinations with the results provided by other methods of clinical diagnostics.

Both approaches complemented each other, creating the basis for the development of electrocardiography in Poland. The research by Cybulski and Eiger, characterized by its high methodological and factual standards, entered the international discourse and constituted a significant addition to the contemporary knowledge concerning the electrical phenomena occurring in living organisms [32].

Dislocure

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