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Research for the Working Theorem and Application of Electrocardiogram

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Abstract. Electrocardiograms (ECGs) are essential for diagnosing cardiac diseases, and recording the heart's electrical activity across cycles. Despite their critical role, there remains a gap in understanding the detailed principles and historical development of ECGs. This article introduces the historical development, basic principles, and application of ECG in the diagnosis of heart diseases. The working principle of ECG is studied, including the depolarization and repolarization process of myocardial cells, and how these physiological activities are manifested in ECG waveforms. The research involves analyzing the process of depolarization and repolarization in cardiomyocytes, illustrating how these principles manifest in ECG waveforms. The findings show that ECGs provide valuable insights into cardiac function, enabling the detection of arrhythmias and other conditions. This study concludes that ECGs are indispensable for cardiac diagnostics and highlights their continued significance in modern medicine. This study provides an in-depth exploration of ECG technology and its application in the diagnosis of heart disease, laying an important foundation for future research and practice.

Keywords: Electrocardiography; Physics; Medical science; Deep learning.

1. Introduction

An electrocardiogram (ECG or EKG) is a crucial tool in diagnosing cardiac diseases. ECG records the heart's electrical activity throughout repeated cardiac cycles.

The first step that human move towards the invention of ECG came in 1887. A.D. Waller, a British physiologist, utilized an invention of Gabriel Lippman, a French physicist who invented the color photographic plate and earned the Nobel prize for Physics in 1908, called the capillary electrometer, which could measure the voltage change of human heart pulses, first successfully captured and recorded a human heartbeat. In 1901, a physiologist called Willem Einthoven came up with a string galvanometer that rectified the inadequacies of the capillary electrometer. To increase the sensitivity of the galvanometer, it is necessary not only to increase the magnetic field strength but also to reduce the weight of the string. Therefore, he pulled a thin silver-plated quartz string (2.1um in diameter, which can be seen with a magnifying glass) suspended between the magnets on both sides. When there is a slight change in the electrocardiogram on the body surface, the string is going to oscillate, and when the oscillation is amplified 500 times, it will be recorded in the electrocardiogram. He then proposed an arrangement method called Einthoven’s Triangle (named later). Einthoven’s Triangle is an imaginary triangle consisting of three virtual leads called leads I, II, and III. To measure the potential difference across the myocardium, Einthoven attached electrodes to the right arm, left arm, and left leg [1]. It pinpointed the frontal plane axes of ECG leads and allowed people to make further determinations of the cardiac electric dipole axis, with the connecting of each electrode and making the estimation more accurate and precise. The electrocardiograph needle will trace the corresponding bias distance according to the measured voltage. Hence, the ECG is invented and widely used to diagnose diseases in people.

This passage mainly introduces how electrocardiography operates and aims to reveal its historical development, function, and significance in modern medicine.

2. Principles of ECG

2.1. Mineral Ions in the Human Body

The human body consists of many different minerals. Mineral salts are responsible for structural functions involving the skeleton and soft tissues and for regulatory functions including neuromuscular transmission, blood clotting, oxygen transport, and enzymatic activity. Macro-minerals like calcium ion ($Ca2+$), potassium ion ($K+$), or sodium ion ($Na+$) take a large amount of place in the human body. Calcium takes the largest part of the human body, making up 1.5 to 2% of the total body weight. Approximately 1,200 g of calcium are present in an adult human body. Magnesium, 60 to 65% is found in bone and 27% is located in muscles. Magnesium is second only to potassium and is essential both for the functions of many enzyme systems and for neuromuscular transmission [2]. These ions move across the cell membrane and form a current, which creates a potential difference inside and outside of the cell. The potential difference then creates a measurable voltage on the body surface.

2.2. The Cardiac Muscle and Its Function

The heart is contracting and relaxing all the time, and one type of muscle- cardiac muscle is doing this process. The cardiac muscle (or myocardium) makes up the thick middle layer of the heart. It is one of the three types of muscle in the body, along with skeletal and smooth muscle. The heartbeat forms by the sinus node (SA node) sends electrical signals along a pathway that causes the atria to contract and push blood into the ventricles. The signal then travels to the atrioventricular node (AV node). A group of specialized muscle cells called His bundle, a bundle of conducting muscle fibers in the heart leading from the atrioventricular node to the ventricles [3]. transmit electrical impulses from the AV junction down through the bundle branch to the apex of the heart.

The electrical signal then diffuses to the Purkinje fibers of the ventricular wall. The ventricle contracts and pushes blood out of the heart. The myocardium is surrounded by a thin outer layer called the epicardium (AKA visceral pericardium) and an inner endocardium. Coronary arteries supply the cardiac muscle, and cardiac veins drain the blood. The superior and inferior vena cava carry deoxygenated blood to the right atrium. Then blood is sent into the right ventricle. The right ventricle pumps blood through the pulmonary artery to the lungs for gas exchange. The pulmonary veins return oxygen-rich blood from the lungs to the left atrium. The blood is then pumped into the left ventricle. The left ventricle pumps blood out of the heart through the aorta. The four heart valves that direct blood flow in the heart and prevent blood from returning are the tricuspid, pulmonary, mitral (mitral), and aortic valves.

2.3. Cardiomyocytes

Cardiomyocytes are the individual cells that make up the cardiac muscle. The primary function of cardiomyocytes is to contract, which generates the pressure needed to pump blood through the circulatory system [4]. Then the cardiac muscle cell will do polarization, depolarization, and repolarization simultaneously.

First, polarization refers to when cardiomyocytes are at a resting potential (the imbalance of electrical charge that exists between the interior of electrically excitable nerve cells; the result of different ions' movement across various transporters and channels [5, 6]. The potential is negative on the inside and positive on the outside of the cardiomyocytes. Second, depolarization means after the cardiomyocytes received a stimulation, the degree of polarity inside and outside it decreased. Lastly, repolarization is the process of action potential generation and development, from the state of depolarization to the state that potential is negative on the inside and positive on the outside of the cardiomyocytes. In other words, repolarization is the return of the heart muscle to a normal state.

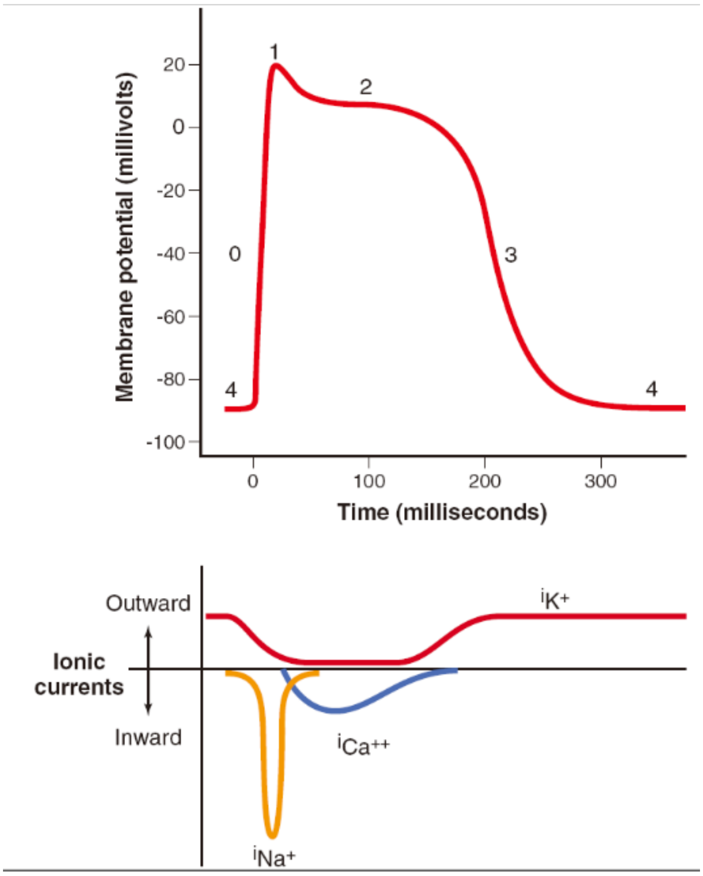

Figure 1. The membrane potential and ionic currents of myocardial cells [7]

According to Fig. 1, it shows the myocardial cell potential. At the period of curve 4, the cell is at the resting potential. Then at curve 0, the cell is at the stage of action potential, which indicates that the voltage of cardiomyocytes is experiencing a repeatable and regular pattern as Na+, Ca2+, and K+ across the cell membrane down the concentration and electrical gradient. Because of the stimulation, the cell causes depolarization. A large amount of positive sodium ions passes into the cell as the specialized Na+ channel opens, and the voltage is likely to surge immediately about 10mV of membrane potential. At the curve 1, early repolarization occurs. With the opened potassium channel, potassium ions are likely to escape from the cell, and calcium ions outside will enter the cell and stimulate the cardiac muscle to contract. After the contraction, we are at curve 2 named the plateau phase, and there are no voltage differences between the three lead systems. During this process, K+ escaped from the cell with continued inward flow of Na and Ca which lead the cell back to the state of resting potential called repolarization. This stage is going to end when the channels become inactive and the flow of Ca2+ and Na+ decreases. At this period, Na+ and Ca2+ transfer from the inner part of the cell to the outward part of the cell and the cell produces a diastolic state [8].

3. Electrocardiogram Analysis

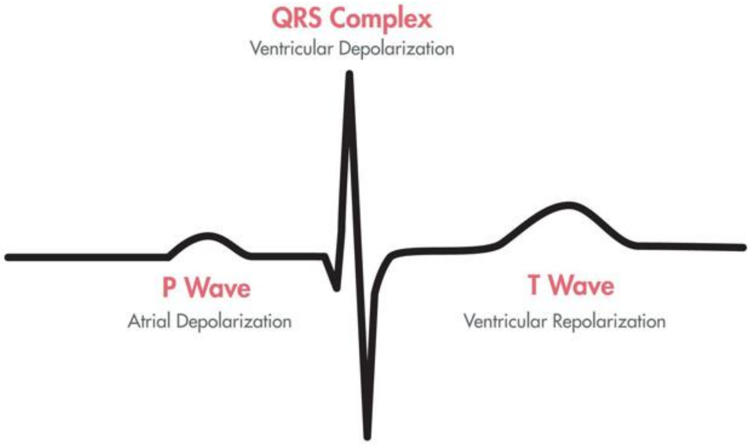

Figure 2. The general stages of ECG [9]

Fig. 2 illustrates the basic waveform composition of an electrocardiogram (ECG), including P waves, QRS complexes, and T waves, which reflect the electroactivity of the atria and ventricles during depolarization and repolarization, respectively. Each period of ECG consists of a P wave, QRS complex, and T wave. P wave indicates that the two atria are excited to undergo a depolarization process and the sum of the depolarization vectors of the left and right atria. QRS complex is the potential changes in the two ventricles during depolarization, which is the new changes in the contraction process of the left and right ventricles. QRS complex formed by the process of vector first travels from the left interventricular septum, then to the right ventricle, and finally to the left ventricle. Then the vector excites the left ventricle and finally the posterior wall of the left ventricle (the vector direction is to the right). A prolonged QRS may indicate hyperkalemia or bundle branch block [10]. T wave is the potential changes during repolarization of the left and right ventricles which is called the biventricular repolarization process. T-waves are formed by both the endocardium and the epicardium. The epicardial action potential has a short duration and ends up forming a T-wave peak. The endocardial action potential has a long duration and ends up forming a T-wave tail. T waves are not perfectly symmetrical, rising branches are slow, and falling branches are steep. This can be explained by the transmural difference between the inner and outer membranes, and the difference in the first half is smaller than that in the second half.

4. ECG Implementation

ECG is crucial in monitoring cardiac function and diagnosing different kinds of heart diseases. An irregular heartbeat or changes in ECG wave morphology could be caused by different arrhythmia, which is a result of an abnormal heart condition. Hence, ECG could be used to detect it. Also, depressive illness could be assessed by ECG recordings and ECG with QT prolongation showed no aggravation during cytoplasm treatment [11].

5. Conclusion

The passage assimilates a lot of research and outlines how the ECG is developed and how people studied and utilized the mechanisms of the human body to find out the pattern of heart pulse. Besides, the significance of each part of the wave is clearly illustrated and accounted for in the principles and some examples of the implementation of ECG. As a key cardiac diagnostic tool, ECG plays an irreplaceable role in identifying arrhythmias and other heart problems.

This study also has some limitations, such as the narration of the historical development of ECG relies on existing literature and does not explore the latest technological improvements in depth.

Based on the findings of this article, future research can consider exploring new developments in ECG technology, especially in combination with AI technology. Further research can explore how to optimize the processing and analysis of ECG signals. The significance of these findings for clinical practice lies in better utilizing ECG technology for early diagnosis and monitoring of heart disease. Overall, this study provides deep insights into ECG technology and its application in the diagnosis of heart disease, providing an important foundation for future research and practice.

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