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Research Article

An Introduction to Electrophysical Properties of the Human Heart

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Abstract

This article is a document which explains "An Introduction to the Electrophysical Properties of the Human Heart".

The electrical activity of the heart is a complex and delicate system that shapes not only biophysical processes but also Electrocardiography (ECG) applications, one of the basic diagnostic tools of modern medicine. In this study, the formation of the action potential of the heart muscle, the role of ion channels and the propagation of electrical impulses throughout the heart are discussed in detail; the organization of the signal starting from the sinoatrial node and spreading to the ventricular muscles is explained. In addition, the clinical reflections of electrophysiological processes and the interpretation of these processes via ECG provide an important tool in the early diagnosis of cardiovascular diseases. Knowledge of the electrical dynamics of the heart is of great importance not only for basic physiology but also for technological and clinical applications. This information improves diagnostic processes and enables more effective design of personalized medical devices [1-73].

Keywords: Advanced Biomechanics; Anatomy; Artificial Pacemaker; Biomechanical Analysis; Biomechanics; Bioengineering; Comparative Biomechanics; Electrophysical Properties; Electrophysical Properties Of The Human Heart; Energy Transfer; Fluid Mechanics; Heart; Heat Transfer; Health Science; Mathematics; Medical Engineering; Medical Technique; Medicine; Physiology; Thermodynamics

Introduction

Electrophysical Properties of the Heart

In vertebrates, the circulatory system, which consists of the heart, blood, and vascular systems, operates on three basic components. The heart acts as a pump thanks to its contraction feature and continuously circulates blood through a closed vascular network. This section covers the electrical properties that enable the heart to contract, and the mechanical aspects will be discussed in later sections. For detailed physiological explanations, you can refer to basic sources in the field of medical physiology and cardiology. The heart has muscle tissue that works with extraordinary efficiency. With an average of 6 watts of energy, it can pump approximately 7 liters of blood from each ventricle per minute. This corresponds to approximately one cubic meter of blood per day. The right and left ventricles of the heart work synchronously, separating the flow of oxygenated and deoxygenated blood through four chambers. The right ventricle sends blood to the lungs, while the left ventricle pumps blood to the rest of the body. This section will cover the basic electrophysiological principles that make this complex functionality of the heart possible [1-73].

Method, Findings And Discussion

Cardiac Action Potential: When cardiac muscle cells receive a stimulus, they depolarize and respond electrically. However, myocardial cells differ from skeletal muscle cells in several ways:

- Action potentials last longer and are followed by a long refractory period.
- There are special pacemaker cells in the heart that can generate spontaneous impulses.
- Cardiac muscle, unlike skeletal muscle, is not capable of tetanic contraction.

The action potential observed in nerve cells may last 2-3 milliseconds, whereas in cardiac muscle cells this process is extended to approximately 200-400 milliseconds. This allows myocardial cells to undergo long contraction phases and allows time for mechanical pumping. The absolute refractory period in the heart is the interval from depolarization to full repolarization, during which the cell cannot be re-excited. In the relative refractory phase that follows this period, re-depolarization can only be achieved with a higher threshold potential. The resting phase between ventricular contractions constitutes the diastolic phase, during which the heart refills. During the plateau phase, the electrical stimulus spreads throughout the myocardium, and this process directly triggers contraction. In the first phase of depolarization, fast sodium channels open and the membrane potential reaches approximately +40 mV. In the early repolarization phase that follows, sodium channels close while potassium channels begin to open. However, the simultaneous entry of calcium ions into the cell delays full repolarization, allowing the plateau phase to continue. The time-dependent permeability changes of ion channels determine the electrical properties of heart muscle cells. Specialized channels for Na+, Ca2+ and K+ ions are activated sequentially in the cell membrane and generate different phases of the action potential. The electrical stimulation of the heart begins in the sinoatrial node located in the right atrium. Specialized cells in this region can generate spontaneous action potentials at regular intervals. The stimulus emanating from the SA node spreads to the heart muscle cells and initiates contraction. There is no fixed resting potential in SA nodal cells. A slow and spontaneous depolarization process occurs starting at approximately -60 mV. This process initiates the action potential at around -50 mV, and Ca2+ ions play an important role in this phase. There is no plateau phase in SA nodal cells, and the action potential ends with rapid repolarization. This cycle is completed in approximately 100 milliseconds, and the resting rhythm of the heart is in the range of 70-80 beats per minute.

The resulting action potential is transferred to other parts of the heart through gap junctions. The depolarization sequence is as follows:

- The entire atrium is stimulated.
- The impulse passes to the atrioventricular node.
- The signal is divided into left and right branches via the AV bundle.
- The signal is transmitted to the ventricular muscles via Purkinje fibers.

The AV node can act as a rhythm generator that can take over from the SA node when necessary. It also provides regulation by filtering high-frequency signals from the SA node. Both nodes are regulated by the autonomic nervous system, particularly through Ca2+ permeability. This mechanism allows the heart rate to increase in situations such as excitement.

Electrical Polarization of the Heart

The electrical impulse in the heart starts from the SA node and spreads to the ventricular muscles. During this process, the electrical potential changes that occur in the cell membrane become perceptible from the external environment. Measurements are usually made by two electrodes, one representing the inside of the cell and the other the outside of the cell. The extracellular potential is measured directly from the outer surface of the muscle or nerve fiber. These measurements allow us to understand how the electrical changes in the cardiac cycle develop over time. In a resting cell, when the transmembrane potential is at its maximum negative value, the extracellular potential is zero. When depolarization begins, a positive potential rise is observed in the extracellular space, which causes the formation of an electrical dipole moment. This moment is directed from the negatively charged region to the positively charged region. In the full depolarization phase, although the membrane potential is reversed, the extracellular potential returns to zero. When the repolarization process begins, the direction of the dipole moment is reversed as the potential returns to the resting level. In the final phase, the cell reaches the resting potential again, and the extracellular potential is reset to zero. During each phase of the cardiac cycle, millions of cardiac muscle cells are excited, each producing its own unique dipole moment. The sum of these local dipoles is transformed into a vector that varies over time and represents the overall electrical activity of the heart. This combined vector reflects both the temporal and spatial distribution of electrical activity in the heart.

This combined dipole motion is directly related to the electrical events that occur in various parts of the heart. For example:

- P wave reflects electrical stimulation of the atrial muscles.
- The QRS complex represents depolarization of the ventricles.
- T wave shows the repolarization process in the ventricles.

Electric dipole moments resulting from the movement of ions in heart cells create electric potential differences in the surrounding areas. These differences are measured by electrodes placed at various points in the body and provide information about the electrical status of the heart. By measuring potential differences from various directions, the direction and intensity of the electrical dipole can be estimated. This approach forms the basis of the method developed by Willem Einthoven and called Electrocardiography (ECG).

Electrocardiography (ECG)

Before examining the electrical dipole movements in the heart, it is necessary to mention the triangle-based measurement system developed by Einthoven, which adapts to body physiology. In this system, potential differences obtained by electrodes placed at different extremities of the body are measured in three main directions:

- Direction I : between the right and left arms,
- Direction II: between the right arm and the left leg,
- Direction III: between left arm and left leg.

In this measuring system, potential differences are detected by electrodes connected between both ends. When the electrical charge movement occurs from negative to positive, a positive value is read on the measuring device. The same logic applies to II and III directions. Potential differences are expressed as follows:

$$\Delta V_I = \Phi_L - \Phi_R$$

$$\Delta V_{II} = \Phi_F - \Phi_R$$

$$\Delta V_{III} = \Phi_F - \Phi_L$$

The symbols Φ here represent the electrical potential at the relevant extremity. The relationship between these three directions is mathematically interconnected by Kirchhoff's laws:

$$\Delta V_I - \Delta V_{II} + \Delta V_{III} = 0$$

For example, let's say the right arm has a potential of -0.2 mV, the left arm has a potential of +0.3 mV, and the left leg has a potential of +1.0 mV. In this case:

- Direction I: +0.5 mV
- Direction II: +1.2 mV
- Direction III: +0.7 mV

These values are compatible with the linear structure of the system.

When the projection of a dipole in a certain direction is positive, the potential difference in that direction is also positive. The measured potential is proportional to the projection of the dipole vector in that direction. For example, a dipole with a 60° orientation gives a positive projection in all three directions of measurement, but the highest value is measured in direction II.

Each measurement direction reflects the potential changes corresponding to a phase in the heart. The time-dependent potential graphs obtained in this way are called Electrocardiograms (ECGs). Dipole moments formed in the same direction as the electrical axis of the heart create the waveforms in the ECG.

- The P wave represents the phase in which the atrium is electrically stimulated. It lasts approximately 0.1 seconds and has an average amplitude of 0.5 mV.
- Q point is the moment when the stimulus passes through the AV node and reaches the ventricular septum. The dipole formed here gives negative value in some directions.
- The PQ (or PR) interval is the time between stimulation of the atrium and the start of ventricular contraction; the average is 0.16 seconds.
- The QRS complex represents the main phase of electrical stimulation of the ventricles and has the highest amplitude.
- T wave reflects the repolarization process of the ventricles.
- Atrial repolarization cannot be observed directly on the ECG because it is masked by the QRS complex at this time. In general, it can be summarized as follows:

- P wave: Atrial depolarization
- QRS complex: Ventricular depolarization
- T wave: Ventricular repolarization

Goldberger and Wilson's Electrode System

The measurement method used in Einthoven's system is based on a bipolar arrangement that measures the potential difference between two ends. Alternatively, the method developed by Emanuel Goldberger uses unipolar measurements. In this system, the potential of a given electrode is measured with respect to a neutral reference point. This reference point is located at the center of the Einthoven triangle and is defined by equal-value resistances. The electrodes in the system are called aVR, aVL and aVF because they offer increased voltage measurements. Since the signals were weak in the measurements made without resistance at the beginning, the use of high resistance increased the clarity of the signal and the term "increased voltage" came into use in this context. Although Goldberger electrodes provide information similar to Einthoven's measurement directions, they allow for more precise evaluations and can capture the characteristic patterns seen especially in heart diseases more clearly. By combining these two systems, a vector orientation can be measured every 30 degrees. This circular arrangement is called the "Cabrera circle". The Einthoven orientations are placed at 60° intervals, while the Goldberger orientations are placed in the middle of these intervals. In this way, the electrical axis of the heart can be determined with much higher accuracy. For example, if the signal of one electrode is at maximum amplitude, the signal of the electrode perpendicular to it should theoretically be zero. With this system, the axis can be determined with a precision of approximately ±10°. When the electrical axis of the heart is evaluated, for example, the dipole moment formed in the direction of the R wave usually has an angle of approximately 60°. In this case, the electrode in direction II produces a maximum positive signal; the aVL electrode perpendicular to this axis shows a potential close to zero. At the same time, the aVR direction gives a negative projection, which is in agreement with the measured data.

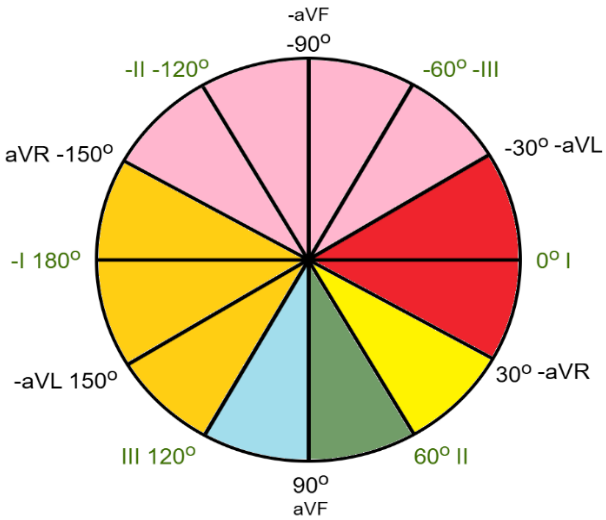

Figure 1: Cabrera circle Colors indicate the orientation of the cardiac axis. Yellow: standard indifferent, green: upright; blue: right; red: left. All other regions are extreme and are usually not observed.

- The orientation of the heart is categorized by different colors in the Cabrera circle:
- 30°, 60° (yellow zone): Standard (neutral) axis
- 60°, 90° (green zone): Vertical axis
- 90°,120° (blue area): Right deviated axis
- 30°, –30° (red zone): Axis deviated to the left

Values outside these orientations may indicate deviations in cardiac function or position. For example, a right-deviated axis may suggest conditions such as right ventricular hypertrophy or pulmonary embolism.

The Goldberger and Einthoven systems only cover measurements in the frontal plane. However, the electrical activity of the heart is three-dimensional. Therefore, the V1-V6 electrodes placed on the chest with the method developed by Norman Wilson also record projections in the horizontal plane. Thus, a three-dimensional analysis is obtained. A total of 12 derivations (3 Einthoven, 3 Goldberger, 6 Wilson) are used as standard in modern clinical practice. In fact, theoretically three independent derivations are sufficient to determine all vectorial components, but a larger number of measurement points allows for more detailed analysis. With these systems, the rhythmic activity of the heart, its position and potential pathological deviations can be evaluated with high accuracy.

Methods, Procedures and New Developments

- **Electrocardiography (ECG):** In the past, ECG measurements were only made with single-channel strip recorders. Since each derivation was recorded in order with this method, it was very difficult to compare signals coming from different directions simultaneously. Over time, this system gave way to multi-channel digital systems that could record all derivations simultaneously. The devices used today amplify the signals, convert them from analog to digital, and transfer them to computerized systems or digital screens. In this way, ECG can be monitored, analyzed, and recorded instantly. For long-term ECG monitoring, electrodes are attached to patients and the data is collected in a portable memory or sent wirelessly to the health center over the internet. This application is a modern approach that falls within the scope of telemedicine and offers remote monitoring. In classical measurements, electrodes must be attached to the skin with a conductive gel. These gels reduce the resistance difference that may occur between the skin and the electrode, ensuring a healthy signal. Alternatively, capacitive sensing methods have also been developed. This method can measure potential changes without direct electrical contact. Capacitive sensors, which are common in industry, were initially inadequate for detecting low amplitude signals such as ECG. However, this problem has been largely overcome with the development of new materials with high dielectric constants.

Capacitive sensors do not require contact, thus reducing the risk of skin irritation, allergies or infection. These sensors are easy to apply and user-friendly, and have become widely used in wearable technologies (such as smart watches) for individual health monitoring purposes. In such devices, one electrode is in constant contact with the skin. The other electrode is brought into contact with the finger to complete the circuit and take a measurement. In this system, the signal is recorded by a special sensor called EPIC (Electric Potential Integrated Circuit) and transferred to a digital device. Portable systems that work on the same principle can record ECGs from the Einthoven I direction based solely on thumb contact.

- **Magnetocardiography (MCG):** Electrical activity in the heart produces not only electric fields but also very weak magnetic fields. The intensity of these magnetic fields is usually around 100 Picoteslas (pT). In order to detect such low intensity signals, special sensors with high sensitivity are needed. With the developed systems, these fields are measured and a Magnetocardiogram (MCG), which is an ECG-like graph, is obtained.

There are two main types of sensors used in MCG measurement today:

- SQUID devices based on high-temperature superconductors – these sensors are powered by cooling with liquid nitrogen.

- Laser-pumped caesium cells – an alternative that works on the optical principle and is highly sensitive to magnetic fields.

The main advantage of MCG is that it can measure heart activity without contact. In addition, detailed magnetic maps can be created across the chest surface using multiple sensors. This allows for local analysis beyond the general data provided by the ECG. However, this method has some limitations. In order to distinguish weak signals from noise, multiple cardiac cycles must be overlapped and averaged. While this works well for individuals with normal heart rhythms, the time resolution may be insufficient for irregular heartbeats.

A promising area of use for MCG is the assessment of cardiac activity in unborn babies. Fetal ECG has been used in this area before, but it has not provided reliable results due to its low signal-to-noise ratio. MCG, on the other hand, may be effective in identifying problems such as prenatal arrhythmia by providing more stable signals.

- **Artificial Pacemaker:** Artificial pacemakers are electronic devices used to regulate the heart rhythm in cases where the heartbeat slows down or the rhythm is disrupted. These systems consist of three main components:

- Energy source (battery),

- The unit that creates electrical pulses,

One or more conductive wires with electrodes placed on them to communicate with the heart.

The battery and other electronic circuit elements are usually placed under the skin with a minor surgical intervention in the chest area, under the collarbone. The electrode wires that communicate with the heart muscle are delivered to the right ventricle of the heart via veins. This system constantly monitors the electrical signals coming from the heart and compares the current rhythm with the normal values previously defined in the device. If the heartbeat is too slow or irregular, the system steps in to produce appropriate stimuli and encourages the heart to beat regularly again. Most modern batteries are powered by lithium-ion technology and have an average lifespan of 8 to 10 years. When the battery life is over, the device is replaced with a minor surgical procedure. Today, many pacemakers are equipped with Bluetooth technology, so the heart rhythm can be monitored remotely and followed by the doctor via digital systems. Some models also have a defibrillator feature that delivers powerful electrical pulses when necessary. Wireless pacemakers represent a new and revolutionary phase of this technology. This device, which is a small capsule size containing all the components, can be placed directly into the heart with a catheter without the need for a surgical incision. During the procedure, the device is usually delivered to the right ventricle via the Inferior Vena Cava (Inferior Vena Cava) using leg veins and fixed to its wall. Once the electrical connections are established, the catheter is withdrawn and the device begins active operation. Wireless structures largely eliminate the risks of vascular damage and infection that may occur due to cables used in traditional systems. The device can operate without problems for approximately 12 years and can be removed and replaced with a new one using the same method when necessary. In both traditional and wireless systems, it is essential that all components in contact with the body are made of biocompatible materials. This prevents undesirable effects such as clotting on surfaces in contact with blood. [1-73].

Conclusion

The electrical activity of the heart is a complex and delicate system that shapes not only biophysical processes but also Electrocardiography (ECG) applications, one of the basic diagnostic tools of modern medicine. In this study, the formation of the action potential of the heart muscle, the role of ion channels and the propagation of electrical impulses throughout the heart are discussed in detail; the organization of the signal starting from the sinoatrial node and spreading to the ventricular muscles is explained. By evaluating the electrode systems developed by Einthoven, Goldberger and Wilson together, the three-dimensional electrical behavior of the heart can be analyzed with high accuracy. The vector projections provided by these systems have made cardiac axis orientation, rhythm disorders and structural heart diseases recognizable. In addition, the clinical reflections of electrophysiological processes and the interpretation of these processes via ECG provide an important tool in the early diagnosis of cardiovascular diseases. With the developing technology, ECG monitoring has become more accessible, portable and patient-friendly thanks to capacitive sensors and wireless systems. In addition, new techniques such as Magnetocardiography (MCG) that perform non-contact measurements are promising, especially in the evaluation of fetal heart health. On the other hand, wireless systems that have started to replace conventional wired pacemakers reduce invasiveness and increase long-term patient comfort. Information on the electrical dynamics of the heart is of great importance not only in terms of basic physiology but also in terms of technological and clinical applications. This information both improves diagnostic processes and enables more effective design of personalized medical devices. The study was carried out within the scope of a PhD course given by Dr. Emin Taner ELMAS. The name of this PhD course is “Medical Engineering and Advanced Biomechanics” and is given in the Department of Bioengineering and Sciences, Iğdır University. İsmail KUNDURACIOĞLU is a PhD student and one of the students taking this course. This article was prepared as a part of one of the assignments prepared using the summary translation of Reference [1]: Book-Chapter 7 (İsmail KUNDURACIOĞLU) within the scope of this PhD course [1-73].

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