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The Biophysical Foundations of Heart Function

Hanifabonu Norkuzi kizi Sabirova
Assistanat in "Kokand University in Andijan". Uzbekistan.
mahmudovahanifabonu@gmail.com

Abstract: The biophysical foundations of heart function study the main physiological and biophysical processes that regulate the heart's activity. These processes include the rhythmic contractions of the heart, its electrophysiological characteristics, the circulatory system, and the ion fluxes across cell membranes. Heart muscle contraction is primarily controlled by electrical impulses that originate from the sinoatrial node and are transmitted to the atrioventricular node. These impulses lead to ion exchanges in heart muscle cells, generating potential differences across membranes and resulting in heart muscle contractions. From a biophysical perspective, ensuring the effective functioning of the heart requires a balance between the electrical and mechanical processes. Moreover, to maintain the stability of the circulatory system, the heart's pumping function and regulation of blood pressure are crucial.

This topic aids in gaining a deeper understanding of the functional mechanisms of the heart and provides scientific foundations for preventing and treating cardiovascular diseases.

Keywords: hemodynamics; hydraulic model; Doppler effect; cardiopulmonary bypass; hemolysis.

Introduction:

The cardiovascular system is a vital system responsible for ensuring blood circulation within the body. It consists of the heart, arteries, veins, and capillaries. Its primary functions are to deliver oxygen and nutrients to tissues, remove metabolic waste, and maintain the body's internal balance.

1. Main Structure of the Cardiovascular System

- **Heart** – A muscular organ that performs the function of pumping blood. It is composed of the right and left sections, atria (chambers), and ventricles.
- **Arteries** – Blood vessels that carry oxygenated blood from the heart to the tissues.
- **Veins** – Blood vessels that return deoxygenated blood from the tissues to the heart.
- **Capillaries** – The smallest blood vessels that facilitate gas and nutrient exchange between cells.

2. Functional Model of the Cardiovascular System

The heart works like a pump, and blood circulates in two main loops:

- **Pulmonary Circulation** – Blood exits through the right ventricle to the lungs, where it becomes oxygenated, and returns to the left atrium.
- **Systemic Circulation** – Oxygenated blood spreads from the left ventricle via arteries to the entire body and returns to the heart through veins.

3. Models of the Cardiovascular System

The cardiovascular system is studied through various scientific models:

- **Hydraulic Model** – The movement of blood through vessels is analyzed based on fluid mechanics.
- **Electrical Model** – Explains the contraction of heart muscles through electrical impulses.
- **Computer Model** – Mathematical models of the heart and circulatory system are created to study the effects of diseases or surgical operations.

- **Physiological Model** – Analyzes biological mechanisms involved in blood pressure, heart rate, and circulation processes.

Methods for Determining Blood Flow Velocity

Blood flow velocity (hemodynamics) varies in different parts of the body, and various physical and medical methods are used to determine it. Below are the main methods and their scientific sources:

- **Doppler Ultrasound (Doppler Ultrasonography, DUS)**

  Principle: It works on the basis of the Doppler effect – red blood cells reflect ultrasound waves, allowing the determination of their movement velocity.

  Advantages: Non-invasive, real-time measurements, arterial and venous flow analysis is possible.

- **Thermodilution (Fick Principle)**

  Principle: A cold or colored fluid is injected into the blood, and the mixing rate is used to calculate flow velocity.

  Advantages: Accurately measures cardiac output fraction, widely used in clinical settings.

- **MRI and 4D Flow MRI (Magnetic Resonance Flow Tomography)**

  Principle: Blood flow direction and velocity are measured using magnetic resonance signals.

  Advantages: No contrast agents required, provides detailed circulation maps.

- **Plethysmography**

  Principle: Measures blood flow by detecting volume changes in hand or leg vessels.

  Advantages: Effective for assessing peripheral circulation.

- **Laser Doppler Flowmetry (LDF)**

  Principle: Laser beams reflect off erythrocytes, measuring their movement speed.

  Advantages: Used to determine microcirculation in the skin.

- **Electromagnetic Flowmetry**
  Principle: Blood movement generates an electric field that can be measured by sensitive sensors.
  Advantages: High accuracy, invasive (used directly in the vessel).
- **Radioisotope Indicator Method**
  Principle: A radioactive isotope is injected into the blood, and its distribution rate is observed using scanning equipment.
  Advantages: Requires special laboratory and equipment, but very accurate for measuring blood flow in the heart and brain.
- **Intravascular Ultrasound (IVUS)**
  Principle: An ultrasound catheter is inserted into the blood vessels to measure flow velocity and the internal structure of the vessel.
  Advantages: Provides detailed images of coronary arteries, useful in detecting heart vascular diseases.

Artificial Circulation Devices (Cardiopulmonary Bypass – CPB)

Artificial circulation devices temporarily perform the functions of the heart and lungs, ensuring oxygen supply and blood circulation during open-heart surgery.

1. Components of Artificial Circulation Devices

- **Pump** – Replaces heart contractions and pumps blood throughout the body.
- **Oxygenator** – Functions like the lungs, enriching blood with oxygen and removing carbon dioxide.
- **Heat Exchanger** – Regulates blood temperature to maintain hypothermia or normothermia.
- **Filters** – Remove microthrombi and air bubbles from the blood.
- **Reservoirs** – Used to temporarily store blood and balance pressure.

2. Types of Artificial Circulation Devices

- **Central Pump (CPB)** – Uses hydraulic or pneumatic drives for heart surgeries.
- **Roller Pump Devices** – Circulate blood at a specific speed.
- **Centrifugal Pump Devices** – Use centrifugal force to move blood and reduce thrombus risk.
- **ECMO (Extracorporeal Membrane Oxygenation)** – Used for prolonged support in cases of heart or lung failure.

3. Applications

- Open-heart surgeries (coronary artery bypass, heart valve replacement).
- Cardiogenic shock and severe heart failure.
- Lung support through ECMO (used in severe respiratory failure like COVID-19).

4. Drawbacks and Complications

- **Hemolysis** – Destruction of red blood cells due to mechanical movement.
- **Inflammatory Response** – The body reacts to foreign devices, activating the immune system.
- **Air Embolism** – Air bubbles may enter the circulatory system, potentially blocking vessels.

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