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Artificial Heart Design and Biomechanical Analysis

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Abstract

This article explains the "Artificial Heart Design and Biomechanical Analysis". The study has been realized within the scope of a Ph.D. lesson which is lectured by Asst. Prof. Dr. Emin Taner ELMAS. The name of this Ph.D. lesson is "Medical Engineering and Advanced Biomechanics" and taught at the Major Science Department of Bioengineering and Bio-Sciences at Iğdır University, Turkey. İsmail KUNDURACIOĞLU is a Ph.D. student and he is one of the students taking this course. This article has been prepared within the scope of this Ph.D. lecture, as a part of the final exam project of İsmail KUNDURACIOĞLU [1-56].

Keywords: Medical Technique, Medical Engineering, Biomechanics, Biomechanical Analysis, Bioengineering, Prosthesis, Heart Prosthesis, Artifical Heart

Introduction

The natural heart is a complex organ responsible for maintaining the blood circulation necessary for the vital functions of the human body [1]. However, in cases such as heart diseases, the heart's capacity to function may decrease or stop entirely. This situation has necessitated the development of artificial heart systems in the field of medicine. Artificial heart designs are created to mimic the physiological functions of the natural heart and improve patients' quality of life.

Technological advancements have led to revolutionary progress in artificial heart design. Innovative technologies such as biotechnology [2], robotics [3,4], and artificial intelligence [5,6] have enabled artificial heart systems to become more functional, efficient, and biocompatible. These new technologies make it possible to design artificial organs that are less invasive, more durable, and better suited to patients' daily lives. Additionally, advanced sensors and artificial intelligence algorithms allow artificial heart systems to continuously monitor the patient's condition and make necessary adjustments automatically. These innovations are driving significant evolution in both the design and functionality of artificial organs [7].

Artificial heart design involves a significant engineering and biomechanical challenge. When creating these designs, a wide range of factors must be considered, including biocompatible materials, mechanical durability, energy efficiency, and compatibility with the body [8]. Furthermore, the integration of biomechanical principles such as fluid mechanics, thermodynamics, and strength ensures the success of artificial hearts in both design and production [9]. This study aims to provide a detailed examination of artificial heart design and biomechanical analysis from the perspectives of medical techniques and biomechanics.

Method, Findings, and Discussion

The natural heart functions as a pump to support systemic and pulmonary circulation. Its primary role is to transport oxygen-rich blood to tissues and return blood carrying waste products like carbon dioxide to the lungs. These functions rely on the contraction and relaxation cycles of the heart muscle, the one-way flow ensured by heart valves, and the regulation of blood flow. The heart consists of four chambers (right atrium, left atrium, right ventricle, and left ventricle) and heart valves. In systemic circulation, the left ventricle pumps blood at high pressure, while the right ventricle is responsible for pulmonary circulation. The heart efficiently pumps blood through cardiac output and pressure differences. The average human heart pumps 4-6 liters of blood per minute. In the heart's operation, chemical energy (ATP) is converted into mechanical energy. The heart is optimized to operate with minimal energy loss, maintaining the body's energy balance. This information forms the basis for mimicking the natural heart's functions in artificial heart design [9].

General Structure of Artificial Heart Systems:

Artificial heart systems can be implanted into the human body or function as external devices. The biocompatible materials used in the design of these systems are critically important due to their compatibility with the human body, durability, and functionality. Commonly used biocompatible materials include titanium, silicone, polyurethane, and carbon-based composites [8].

- **Titanium:** Titanium is frequently used in artificial heart systems due to its high durability, lightweight nature, and biocompatibility with human tissue. Its resistance to corrosion also ensures reliability in long-term use [10,11].
- **Silicone:** Silicone is used in certain parts of artificial heart systems, particularly in moving components or membranes, due to its elastic structure and biological inertness. Its flexibility is essential for regulating blood flow [12,13].
- **Polyurethane:** Polyurethane is preferred in heart pump derivatives due to its flexibility and durability. Its chemical resistance and long-term performance make it an ideal material [14,15].
- **Carbon-Based Composites:** These materials, used in artificial heart valves and surfaces, have a low friction coefficient, allowing blood to be pumped without obstruction. They also reduce the risk of clotting, offering long-term biocompatibility [16,17].

The advantages of these materials include minimizing the risk of tissue rejection, enhancing the device's mechanical durability, and supporting biomechanical functionality. Material selection also considers factors such as cost, manufacturability, and long-term performance.

Design Process:

The first step involves a detailed examination of the natural heart's anatomical and physiological structure. The relationships between the heart's structure, vessels, valves, ventricles, and atria are analyzed. At this stage, biomechanical factors such as pressure differences, fluid dynamics, and energy usage are considered. This modeling of how the natural heart works provides the foundational data necessary for the artificial heart to function correctly. Details such as the blood pumping process, pressure differences within vessels, and energy consumption are critical factors shaping the artificial heart's design [18].

The next step is defining the design goals. Criteria such as the artificial heart's blood flow capacity, durability, energy efficiency, and longevity are clearly outlined. For example, determining how many liters of blood the artificial heart will pump per second, under what conditions it will operate most efficiently, and how its durability can be enhanced against potential failures are key considerations. Additionally, the size of the artificial heart is an important design criterion; it must be designed to fit the body's anatomy. Creating a heart design that is compatible with the human body, ideally sized, and functional is a direct factor in achieving success.

Material selection plays a critical role in artificial heart design. Biocompatible and non-toxic materials are preferred. Since the artificial heart will be integrated into the body, it must be made from materials compatible with biological tissues. These materials typically include biocompatible polymers, titanium alloys, or flexible yet durable materials like silicone. Furthermore, materials chosen for moving parts must be resistant to wear and fatigue over long-term use. Given that the artificial heart is a device that will continuously bear mechanical loads and operate, these factors must be carefully considered in material selection.

During the mechanical design phase, the heart's pumping mechanism is detailed. Diaphragm or piston-based systems can be used to facilitate blood movement. The primary goal is to accurately mimic the natural heart's contraction and relaxation movements, ensuring regular blood flow throughout the body. The artificial heart's mechanism must be designed to optimize blood flow and pressure changes similar to those in the natural heart. Additionally, the design of the heart's valves, pressure regulators, and other small components aims to prevent backflow and maintain proper pressure levels.

The final stage of the design process is prototype production and testing. Advanced manufacturing tools such as 3D printers and CNC machines are used to create physical prototypes of the design. The prototype is initially produced to test the design's accuracy and subjected to various laboratory tests. These tests evaluate the artificial heart's durability, energy efficiency, and biomechanical compatibility. The prototype also allows for necessary modifications to improve the design's performance. During testing, factors such as how the heart will perform under real conditions, blood flow regularity, pressure levels, and mechanical durability are measured [18].

Material Selection:

In artificial heart design, the materials used must consider critical factors such as ensuring biomechanical compatibility, enhancing durability, regulating blood flow, and providing biological compatibility. Material selection is crucial to ensure the long-term safe use of the artificial heart and its integration with the body. For the artificial heart to function successfully, the materials must be non-toxic when interacting with biological tissues, prevent clotting, and ensure biological compatibility [19].

The top priority is the material's biocompatibility. When the artificial heart is integrated into the body, the materials used should not interact with the immune system, create a risk of infection, or cause adverse effects such as clotting. Titanium and its alloys are known for their excellent biocompatibility and durability. This material is easily accepted by the body and is ideal for long-term use. Additionally, its low density and high tensile strength make it an excellent choice for artificial hearts. Polymers such as polyethylene (PE) and polypropylene (PP) are compatible with biological systems and meet flexibility requirements. Materials like silicone also offer significant advantages in terms of flexibility and biocompatibility. Durability and wear resistance are also of great importance in artificial heart design.

Since the heart will continuously perform mechanical movements, the material must be resistant to wear and mechanical stresses over time. Carbon fiber and composite materials stand out for their excellent mechanical strength and wear resistance. These materials can be used to enhance durability, especially in high-stress areas. Ceramics also exhibit high performance in terms of wear resistance and hardness and can be preferred for moving parts such as heart valves. Titanium alloys offer excellent wear resistance for long-term use and are resistant to metal fatigue. Flexibility is essential to naturally simulate contraction and relaxation movements. The artificial heart must adapt to the tension and stretching movements in blood vessels. Therefore, materials with high flexibility and resistance to mechanical stress should be selected. Silicone and similar elastomers are highly suitable in terms of flexibility, deformation capacity, and biocompatibility. These materials are ideal for parts requiring flexibility, such as heart valves and vascular surfaces. Materials like nitrile rubber and polyurethane, with their high elasticity, can also be used in heart valves and provide long-term durability [1].

Since the artificial heart will be in constant contact with blood, the materials must have properties that prevent clotting during blood interaction. Hydrophilic polymers exhibit anti-clotting properties when blood comes into contact with their surfaces. These materials help ensure smooth blood flow without adverse interactions on the artificial heart surfaces. Materials such as polyamide and polyethylene terephthalate can help direct blood flow smoothly while reducing the risk of clotting. Thermal properties are another important factor to consider in artificial heart design. The artificial heart must be energy-efficient and should not pose a risk of overheating. Otherwise, overheating materials could harm the body. Titanium and aluminum alloys are lightweight and have good thermal conductivity, allowing the risk of overheating to be controlled. Ceramic and composite materials can be used to provide thermal insulation and enhance system stability due to their low thermal expansion rates. Finally, the manufacturability of the materials used in artificial heart design must also be considered. In the production of artificial hearts, which requires high precision and engineering, materials directly affect the efficiency and cost of manufacturing processes. 3D printing materials enable the production of complex geometries with modern manufacturing techniques and can be preferred as biocompatible and durable materials.

Among the materials used in artificial heart design, titanium and its alloys, carbon fiber, composite materials, ceramics, silicone, elastomers, hydrophilic polymers, polyamide, polyethylene terephthalate, nitrile rubber, and polyurethane stand out. The selection of these materials should be based on a range of factors, including biocompatibility, durability, flexibility, biological compatibility, thermal management, and manufacturability. Each material offers an ideal solution to meet specific requirements, and the combination of these materials will ensure the long-term safe and efficient operation of the artificial heart.

Thermodynamics and Energy Balance:

In artificial heart design, thermodynamics focuses particularly on energy efficiency, heat management, and the thermal properties of materials during operation. Since the artificial heart continuously performs mechanical movements and pumps blood, energy conversions and heat generation play a significant role in its design. The efficient functioning of an artificial heart relies not only on biomechanics but also on thermodynamic principles. Thermodynamic analysis is a critical step to ensure the efficient use of energy, prevent heat accumulation, and enhance the long-term operability of the artificial heart system. As the artificial heart mechanism is a system based on energy production and transfer, minimizing energy losses is a key goal during the design phase. For example, energy loss during the pumping process occurs through heat generation and mechanical friction. Therefore, using materials with low friction coefficients increases energy efficiency and helps avoid thermal management issues. To ensure that the heat generated during the operation of the artificial heart does not affect the device's performance, materials that effectively dissipate heat must be selected [1].

The energy generated during the heart's pumping process is typically converted into mechanical energy, but losses occur within the system. These losses are mostly caused by factors such as friction, air resistance, and fluid viscosity. At this point, the thermal conductivity and heat distribution properties of the materials used in artificial heart design are of critical importance. Materials with high thermal conductivity help rapidly dissipate heat in a way that does not harm the body and maintain temperature balance. Additionally, energy efficiency must be considered throughout the artificial heart's operational lifespan. The heart should be designed to achieve maximum efficiency with minimal energy consumption while pumping blood. Therefore, the energy consumption of motors and other components performing mechanical movements must be optimized from a thermodynamic perspective. For this purpose, energy-saving motors and efficient energy conversion mechanisms can be used. From a heat management standpoint, thermodynamic analysis is crucial to ensure that the device's temperature levels are compatible with body temperature. Otherwise, as the artificial heart heats up, it could harm the body. Thus, materials providing thermal insulation may need to be used to control the heat generated within the artificial heart. Ceramics and composite materials, with their low thermal expansion rates and heat-resistant properties, can be effective in such applications [1].

In conclusion, thermodynamics plays a vital role in artificial heart design by reducing energy losses, ensuring efficient energy conversion, and optimizing heat management. To prevent heat accumulation, improve system performance, and ensure safety during long-term use, material and design choices must be made in accordance with thermodynamic principles.

Fluid Mechanics:

In artificial heart design, fluid mechanics is a critical factor to optimize blood movement and pumping efficiency within the artificial heart system. The artificial heart contributes to the circulatory system by pumping blood throughout the body. In this process, it is necessary to correctly analyze the principles of fluid mechanics such as blood flow, pressure distribution, friction and viscosity. An analysis from the perspective of fluid mechanics is very important to ensure the efficient operation of the artificial heart, to mimic the natural flow of blood and to increase the durability of the system.

First, the correct pumping mechanisms must be used to ensure blood flow in artificial heart design. Blood is a highly viscous and non-Newtonian fluid; that is, the rate of blood flow varies depending on the internal structure of the blood and its interaction with the vessel walls. Therefore, fluid mechanics must be optimized to mimic the natural flow of blood as much as possible in artificial heart design. Changes in blood velocity, pressure differences, and changes in fluid viscosity during the pumping process must be carefully examined. The pumping mechanism of the artificial heart usually creates pressure differences to move blood from one region to another. These pressure differences determine the speed and direction of the fluid. Pumps used in artificial heart design usually work with diaphragm or piston mechanisms. These mechanisms apply a force that increases the pressure and directs the blood through the vessels. However, during this process, friction and energy loss occur due to the effect of the viscosity of the blood. These losses can reduce the efficiency of the system and affect its long-term durability. Therefore, it is important for the materials used in pump systems to have a low coefficient of friction and to ensure smooth flow.

From a fluid mechanics perspective, another important issue is the interaction of blood with vessel walls and the risk of blood clotting. The flow of blood in the artificial heart system must be designed to ensure smooth circulation and minimize friction with the vessel walls. Friction can cause blood to accumulate in the vessels and increase the risk of clotting. Therefore, smooth and biocompatible materials should be used on the internal surfaces of the artificial heart to optimize blood flow. Additionally, hydrophilic coatings on the surface can help prevent blood clotting. During pumping, various fluid mechanics models are used to accurately model and optimize the fluid behaviour of blood. These models are employed to determine blood viscosity, flow velocity, and pressure differences. Utilizing these models in artificial heart design enhances pumping efficiency and ensures that blood moves naturally within the system. Finally, fluid mechanics analysis has a direct impact on the overall efficiency and safety of the artificial heart system. To mimic the natural flow of blood, ensure its smooth circulation, and reduce the risk of clotting, the design must adhere to fluid mechanics principles. These analyses are a critical step in ensuring the long-term safe use of the heart and optimizing its biological compatibility [1].

In general, fluid mechanics is an important factor in artificial heart design to ensure that blood is directed correctly during efficient pumping, to minimize friction losses and to eliminate the risk of clotting. Correct analysis of these factors will ensure that the artificial heart is long-lasting, efficient and biocompatible.

Conclusion

This article describes "Artificial Heart Design and Biomechanical Analysis". The study in question was carried out within the scope of a doctoral course given by Asst. Prof. Dr. Emin Taner ELMAS. The name of this doctoral course is "Medical Engineering and Advanced Biomechanics" and it is given in Iğdır University "Bioengineering and BioSciences Major Science Department". İsmail KUNDURACIOĞLU is a student of this doctoral course and this article is within the scope of his work carried out within the scope of his final exam project [1-56].

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