Artificial heartbeats for the treatment of heart failure

To all medical professionals who invest their time in the future of all of us.

RESUM

Partint de l'interès per les ciències de la salut, s'ha proposat analitzar un nou tractament cardiovascular. Encara que avui dia el mètode principalment utilitzat per a la cura de la insuficiència cardíaca sigui el trasplantament de cor, cal tenir en compte que la intel·ligència artificial i coneixements d'enginyeria i tecnologia han donat lloc a dispositius que són capaços de substituir les funcions de l'òrgan original.

Després de fer una recerca d'informació, s'ha procedit a fer un estudi del mecanisme artificial des del punt de vista de diferents disciplines científiques i consideracions ètiques. A continuació, s'han entrevistat un seguit de professionals que han permès complementar la informació prèviament cercada.

Finalment, s'ha comprovat que la investigació científica evoluciona i que, encara que la majoria de vegades no siguin utilitzats com a teràpia de destí, dispositius d'assistència ventricular i cors totalment artificials faciliten l'espera dels pacients pel futur trasplantament cardíac.

Paraules clau: *biònica, cor artificial, intel·ligència artificial, assistències ventriculars.*

ABSTRACT

Based on the interest in health science studies, it has been proposed to analyze a new cardiovascular treatment. Currently, even though the method mainly used for the treatment of heart failure is transplantation, it should be noted that artificial intelligence and knowledge of engineering along with technology have led to devices that are able to replace the functions of the original organ.

After some information research, a study of the artificial mechanism was carried out from the point of view of different scientific disciplines and ethical considerations. Then, a series of professionals were interviewed to complement the previously searched information.

Finally, it has been verified that scientific research is evolving and, in spite of being rarely used as a target therapy, fully artificial ventricular assist devices and hearts facilitate patients' wait for future heart transplantation.

Keywords: *bionics, total artificial heart (TAH), artificial intelligence, ventricular assist devices.*

APPRECIATION

I wanted to dedicate a special thanks to all those people who have contributed to the realization of this project because without their help it would not have been possible to carry out this research work.

First of all, I would like to express my gratitude to the tutor of this research work for advising and helping me whenever I have needed it. From day one she has been interested in my project and has shown great attention and concern. On the other hand, I would like to highlight the appreciation I feel for all the information I have received from professionals such as Steven Langford, from SynCardia Systems, and Dr. José González Costello from the Bellvitge Heart Failure and Heart Transplant Department. The fact that I have received such valuable data and magnificent explanations is a great honor for me. Finally, I would like to point out the unconditional collaboration of my family, who have always supported my decisions and been there when I have needed it.

INDEX

0. INTRODUCTION

As every year, the Education Department of Catalonia offers high school students the opportunity to experiment, document, and research on a topic of interest. This assignment is carried out between the end of the first year and the beginning of the second year of the baccalaureate and is supervised by a tutor, who advises the student. By carrying out this activity, students develop an interest in a topic that is relevant to them, work on the research and synthesis of information, stimulate the ability to explain themselves in front of an audience…

With the present research work, I am going to investigate an organ of the utmost importance for all of us and which is currently affected by many diseases. *How many times have we thought that having a damaged heart can lead to death in the short or long term? Or that a heart attack can mean the end of our lives?* Nowadays, different medical research institutions are designing and producing a future for these affected people. In other words, they are creating an artificial heart that is capable of replacing the human one and carrying out all functions to ensure the survival of these people.

The reason for choosing this subject is none other than my admiration for biology and medicine. As a matter of fact, I intend to study for a degree in medicine in the future to broaden my knowledge in this field of science and assist those people who need it the most. As I have always enjoyed this world of health science studies, being able to research such an important breakthrough is a great honour for me. While trying to decide which topic to address in my research work, my father surprised me with a collection of scientific journals. Browsing through them was when I saw an article that caught my attention and that later led me to this research work. When I was deciding where I wanted to focus this project on, I concluded that this subject not only brought great value to medicine, but also physics, chemistry, biology, ethics and technology, which are so related to it. This is the reason why I contacted one of the leading companies in this field, SynCardia, so that they could explain to me the technological processes and the physical and chemical factors that they had to take into account. On the other hand, and in terms of medicine and biology, I contacted a Bellvitge Hospital cardiologist who had operated on an artificial heart and who explained to me the process of insertion of this organ, the experience of some patients with this product… After researching a lot of information and discerning it (some of it is attached in the annexes), I acquired the basic knowledge that allowed me to create and submit this project.

On account of the fact that this mechanism has a high cost and that manipulating one of these products would be very expensive, I decided to do a compilation research work, where I will explain the most outstanding and relevant information. In the same sense, I am determined to analyze and describe the product's most outstanding features to better appreciate the difficult circumstances in which many patients find themselves. From my point of view, I consider it essential to understand the origins on which this product is based to then delve deeper into the subject. That is the reason why the first subject I am going to talk about is the bionic concept and where it comes from. Afterwards, during the densest part of this research, I intend to study the biological heart and examine the artificial organ in detail from the different fields of science to know as well as possible how they work. Finally, I will include the interviews with the different professionals related to this product, as I mentioned in the previous paragraph. This last point, in addition to providing great information value, allows readers to understand the opinion and intentions of the professionals related to this ambitious project.

1. BIONICS

Many times, we have heard of this word without having a clear idea of what it can mean. Large numbers of living beings have impressive qualities and abilities to adapt to the environment in which they develop and live. In terms of science, there is a section dedicated to the study and observation of the structure and functioning of living beings in order to create artificial mechanisms that can replace or simply copy them. Through the experimental method, scientists observe nature and devise possible hypotheses to improve certain mechanisms. Subsequently, and after conducting a series of experiments and designs, these professionals confirm or reject the initial hypotheses in order to guide and solve their problems.

It is important to highlight that this broad concept is applicable to a large number of different fields. From architecture to the design of everyday products, the majority of them are linked and influenced by bionics. In the same sense, detailing the whole history of bionics and all the areas that it encompasses would be like discussing all the advancements and improvements in life that have been made since the origins of human life.

1.1 Bionics applied to medicine

The main problem that arises in this therapeutic field is the scarcity of organs to be transplanted because, despite very active policies to promote organ donation, many patients have to wait long periods of time, with the aggravation that this can mean for their disease, and some others do not get the desired organ and die without having been transplanted.

When we think of bionics applied to medicine, most of us imagine a hand that works by itself. Despite being a great bionic product, this scientific discipline goes much further and covers many more areas. From bionic arms and legs to ears that make the lives of deaf people easier, this science aims to replace those atrophied organs with artificial ones that can perform all the functions of the biological organ. That is why we can state that through all these products, humanity tries to improve the quality of life of people. Nowadays, there is a large number of devices undergoing development, such as the retinal prostheses for blind people which can improve their vision. The bionics industry applied to medicine has been starring in four areas of the body: vision, the auditory system, orthopedics and, finally, cardiac and neurological functions. Most of the advances that have been made in the field of bionics have helped medicine make great improvements in the treatment of diseases and physical deficiencies.

Evidently, not only the process of implanting this new artificial organ is important, but the bionics applied to medicine must coexist with other scientific disciplines, such as physics, chemistry, biology... There are several features that need to be considered when designing these bionic products in order to ensure maximum effectiveness. The fact of inserting an artificial product into the human body makes it very difficult to design them. The materials used must be biocompatible in order to try to eliminate possible rejection by the body. Our immune system, which protects our bodies from invaders such as bacteria, viruses and other infectious agents, treats someone else's organs as intruders that must be destroyed. It is for this reason that before carrying out the operation, the immune system has to be eliminated to try to avoid rejection. However, it is sometimes unavoidable and, for this reason, the use of biocompatible materials is an essential element to consider. Resistant materials such as aluminum and carbon fibre are used to replace the skeleton, springs and synthetic fibres to replace tendons and imitate the behaviour of connective tissue, cables that are responsible for transmitting electrical signals in the same way nerves would do it, a polymer gel that replaces muscles and responds to electric currents, self-powered hydraulic cameras to replace ventricles and lungs, microphones and video cameras to substitute the ear and the retina of the eye that transform data captured into electrical impulses which are sent to the auditory and optic nerve… Thanks to three-dimensional printers and stem cell research to create tissues, in the future, organs will be designed and obtained from the patient's cells. This fact will suppose a great advantage, as the possible immunological reactions that the body may have against the new implanted organ will be almost non-existent. On the other hand, the fact that these products replace the originals is a limiting factor in terms of size and shape of this new artificial organ. To cite one example, we could put the case of a bionic hand designed without any fingers. This deficiency could be detrimental to the patient and, therefore, the medical designer would be making a serious mistake.

The fact that surgeons can implant and replace damaged organs is a great advantage not only for people with any disease, but also for those who have had an accident and even, in the future, for those who want to change or improve some parts of their body. However, this last point could run into certain moral and ethical dilemmas that would call into question its medical function.

2. BIOLOGICAL CARDIOVASCULAR SYSTEM

The cardiovascular system is formed by the blood vessels and the heart, which allow the blood to circulate and transport nutrients, oxygen, carbon dioxide, hormones, and blood cells to and from the cells in the body to provide nourishment and assist in disease prevention, stabilize temperature and pH, and maintain homeostasis. Human cardiovascular system is closed, which means that blood never exits the network of blood vessels. In contrast, oxygen and nutrients diffuse through the blood vessel layers and enter interstitial fluid, which transports oxygen and nutrients to target cells, and carbon dioxide and wastes in the opposite direction.

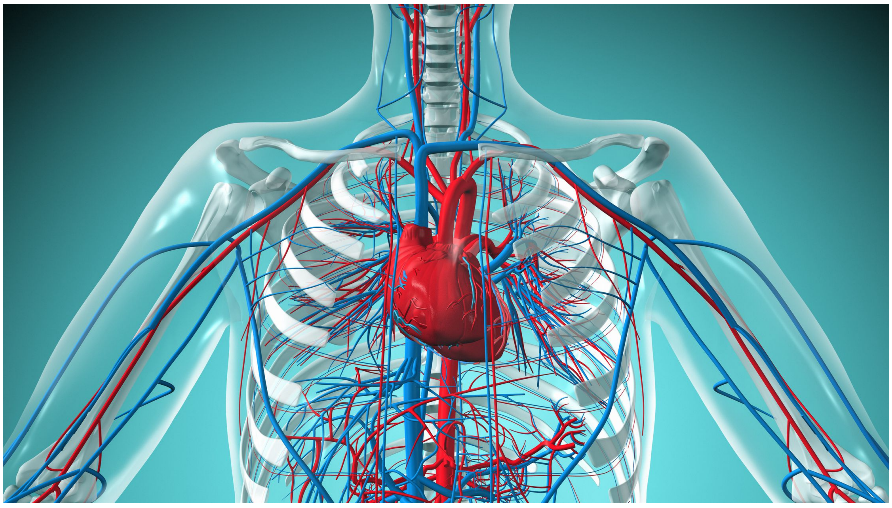


Figure 1. Cardiovascular System
https://www.thoughtco.com/cardiovascular-system-373577

2.1 Heart

The heart is the main organ of the circulatory system, and its importance is such that it is one of the first organs to form and begin to perform its function. This muscular organ is located to the left of the midline of the thoracic cavity and is around the size of a closed hand. The weight of the heart varies according to the person's age, size, and weight. Thus, it is estimated that the heart weighs 0.45 percent of body weight in males and 0.40 percent in women, implying that the weight of the heart in an adult of average height is between 250-350 grams in men and 200-300 grams in women. This organ is in charge of pumping approximately seven liters of blood every day through the arteries, arterioles and capillaries where nutrients, dissolved gases, electrolytes and waste products are exchanged between the blood and surrounding tissues.

The heart has traditionally been considered one of the most essential organs in the body, even though they are all equally vital depending on the role they serve. Without the correct working of the majority of them, complications can occur in the body, some of which are more significant than others, making life difficult for the individuals affected. Small dysfunctions or abnormalities present in the heart can cause drastic changes or effects in the human body. As a result, it is critical to highlight the most important functions that this organ performs as the main component of the circulatory system:

- Pump oxygenated blood to the rest of the body.
- Transport hormones and other vital substances to various areas of the body.
- Receive deoxygenated blood and deliver metabolic waste products from the body to the lungs to be oxygenated.
- Maintain blood pressure.

2.1.1 Localization and shape

The position of this organ in the body is due to the genes that produce proteins responsible for converting an immobile cell into a mobile one. These proteins are essential during embryonic development, as in this phase the heart and other organs appear in the midline of the body to later be placed in the corresponding localization in the body. Malfunction of these proteins would result in the involution or death of the embryo. Although these genes are deactivated once the process is concluded, they can be reactivated during adulthood, leading to serious heart diseases or the development of cancer. The merit of this series of discoveries is attributed to a group of researchers from the Neurobiology Unit of the Institute of Neuroscience of Alicante (CSIC-UMH).

2.1.2 Pericardium

The pericardium is the membrane that surrounds and protects the heart, preventing it from shifting the position in the mediastinum while permitting the heart to contract properly. The pericardium is divided into two parts, the fibrous pericardium and the serous pericardium. The former section consists of a sac of fibrous connective tissue, which is non-elastic. The major role of this is to protect the heart and attach it to the mediastinum by preventing excessive stretching during diastole. Unlike the fibrous pericardium, the latter is a thin membrane which is divided into two layers, the visceral and the parietal, which are separated by a thin membrane called the pericardial cavity, which stores the pericardial fluid and is crucial for minimizing friction between the visceral and parietal layers during heart movements.

2.1.3 Heart wall

The heart wall is made up of three layers: the inner endocardium, middle myocardium and the outer epicardium. These are surrounded by the pericardium and are important when studying the disease conditions affecting the heart.

The endocardium is a thin layer which protects the covers of the heart as well as the heart valves, reducing friction as the blood passes through the heart chambers. On the other hand, the myocardium is a thick and muscular middle layer of the heart which is in charge of the contraction and relaxation required to pump blood through the vessels. Lastly, the epicardium is an outer layer of the heart which is enclosed in a double-layered pleural sac called the pericardium, that reduces the friction as the heart beats. The epicardium is the visceral pericardium, while the outer layer of the sac is the parietal pericardium.

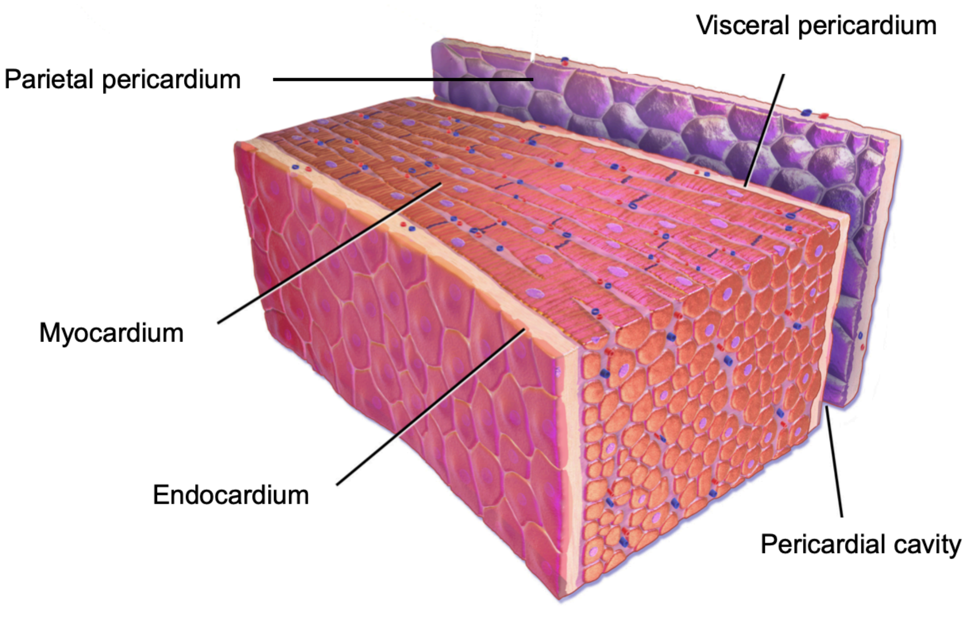


Figure 2. Heart wall
https://commons.wikimedia.org/wiki/File:Blausen_0470_HeartWall.png

2.1.4 Chambers

The human heart is divided into four chambers: upper left and right atria, which receive blood from the veins, and lower left and right ventricles, which receive blood from the atria and pump it out of the heart into arteries. The right atrium and ventricle are commonly referred to as the right heart, whereas its left counterparts are referred to as the left heart.

The right atrium is a narrow, thin-walled chamber which is separated from the left atrium by the interatrial septum, identified as a marked depression in the right atrium, the fossa ovalis. It receives deoxygenated blood from three vessels: the superior and inferior vena cava, as well as the coronary sinus. Internally, the rough pectinate muscles and crista bundle of His serve as a boundary within the atrium. In terms of circulation, blood flows from the right atrium to the right ventricle through the right atrioventricular orifice, which has the tricuspid valve, so named because it contains three cusps.

A thin-walled rectangular cavity that lies behind the right atrium and forms most of the base of the heart constitutes the left atrium. It gets oxygenated blood from the lungs via the left and right pulmonary veins and pumps it to the left ventricle through the mitral valve. In this same sense, its main function is to serve as a retention chamber for blood returning from the lungs.

The right ventricle consists of an elongated, thick-walled cavity that forms the front of the heart and which contains muscular elevations, called trabeculae carneae. Its top front surface constitutes a large portion of the heart's sternocostal surface, whereas the under surface is flattened, constituting part of the heart's diaphragmatic area, that rests on the diaphragm. An additional piece of information is that blood flows from the right ventricle through the pulmonary lunate valve to the pulmonary artery trunk, which is divided into the right pulmonary artery and the left pulmonary artery.

Finally, the left ventricle is a cavity which constitutes the apex of the heart, almost its entire face and left edge, and the diaphragmatic face. Its wall is thick and presents trabeculae carneae and chordae tendineae, which fix the valve cusps to the papillary muscles. Further, the left ventricle has thicker walls than the right because it needs to pump blood to most of the body, while the right ventricle fills only the lungs.

In this same sense, blood flows from the left ventricle through the aortic semilunar valve into the aorta artery.

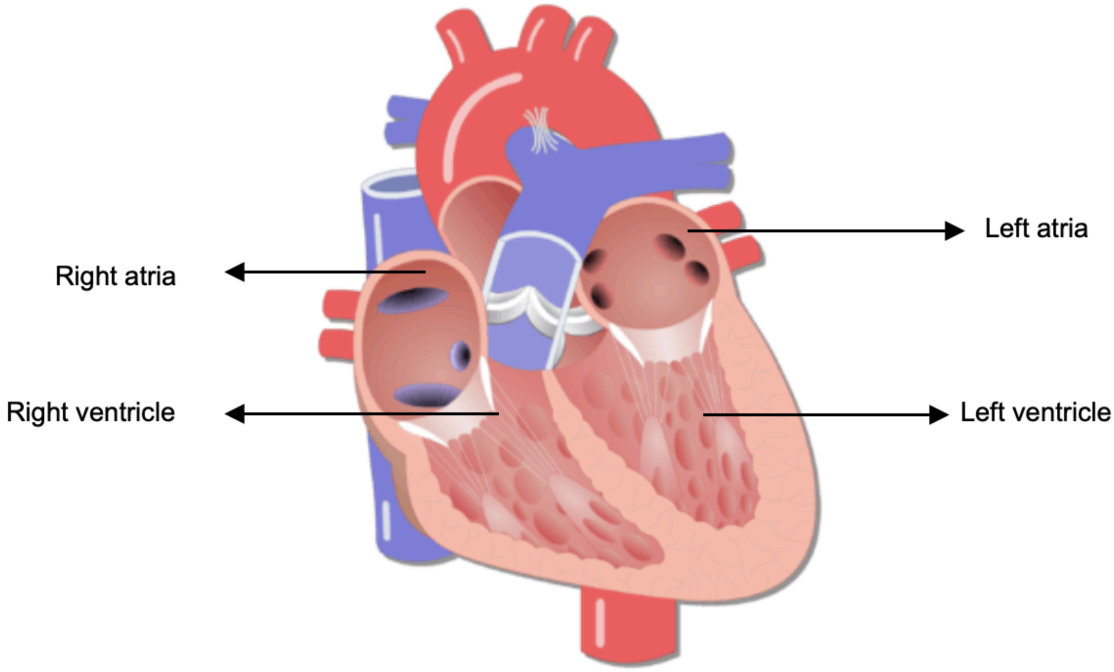


Figure 3. Heart chambers
https://www.getbodysmart.com/heart-anatomy/heart-chambers

2.1.5 Valves

A heart valve is a one-way valve that generally permits blood to pass through the heart in just one direction and, as well as the chambers, is surrounded by the endocardium. The valves contain flaps, called leaflets or cusps, which open to enable blood flow and then close together to shut and prevent backflow.

The two atrioventricular valves, the mitral and tricuspid valves, are located between the upper and lower chambers. In other words, they are located between the atria and ventricles and prevent backflow from the ventricles into the atria during systole. They are attached to the walls of the ventricles by chordae tendineae, which prevent the valves from inverting. The chordae tendineae are connected to papillary muscles, which create tension in order to better maintain the valve in place. The subvalvular apparatus is composed of the papillary muscles and the chordae tendineae and prevents the valves from prolapsing into the atria as they close. However, the subvalvular apparatus does not influence the opening and closing of the valves, which are solely determined by the pressure gradient across the valve.

On the one hand, the mitral valve, often known as the bicuspid valve because it has two leaflets or cusps, is located on the heart's left side and permits blood to pass from the left atrium into the left ventricle. The tricuspid valve, on the other hand, has three leaflets or cusps and is located on the right side of the heart. It is positioned between the right atrium and the right ventricle and prevents blood from backflowing between these two.

The aortic and pulmonary valves, which constitute the semilunar valves, are located at the aortic and pulmonary trunk bases, respectively. These permit blood to be forced into the arteries and prevent backflow from the arteries into the ventricles. These valves do not contain chordae tendineae and are more akin to vein valves than atrioventricular valves. On the one hand, the aortic valve has three cusps and is located between the left ventricle and the aorta. On the other hand, the pulmonary valve, which has also three cusps, is placed between the right ventricle and the pulmonary artery.

When we talk about valves, it is important to highlight the heart sounds heard during a heartbeat. The movement of the heart muscle and the large blood vessels around it causes these sounds. When the ventricles contract, the tricuspid and bicuspid valves close owing to blood backflow, resulting in the first heart sound. The second sound is produced when the aortic and pulmonary valves close quickly due to the movement of blood inside blood vessels and the two ventricles.

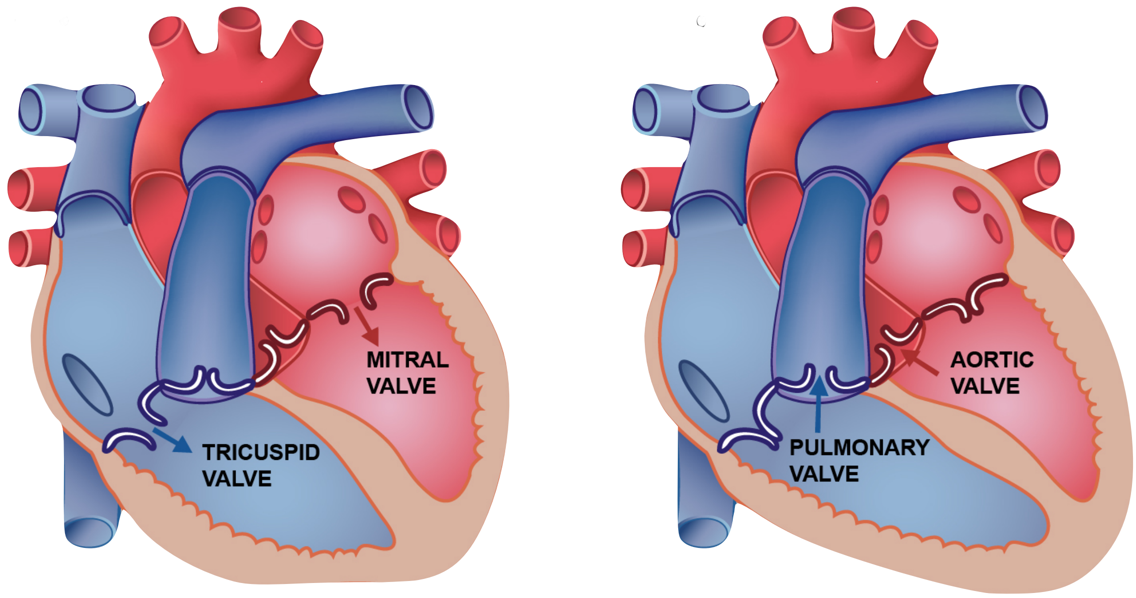


Figure 4. Heart valves
https://www.texasheart.org/heart-health/heart-information-center/topics/valve-repair-or-replacement/

2.2 Blood vessels

Because of their ubiquitous and widespread presence in every organ, blood arteries may be one of the most important tissues studied. It is essential to note that blood vessels are classified into three types: arteries, veins and capillaries. The main function of the arteries is to transport the blood contained in the cavities of the heart to the different organs of the body. On the other hand, and unlike the first case, the veins carry blood from the organs to the heart. Finally, the blood capillaries allow the exchange of substances between the blood and the different cells of the body.

The walls of arteries and veins are composed of three layers: the tunica intima, the tunica media, and the tunica adventitia. The tunica intima is made up of endothelial cells on a basement membrane and a collagen and elastic fibre-rich subendothelial layer. Smooth muscle cells, elastic fibres and collagen form the tunica media, while collagen and elastic fibres constitute the tunica adventitia.

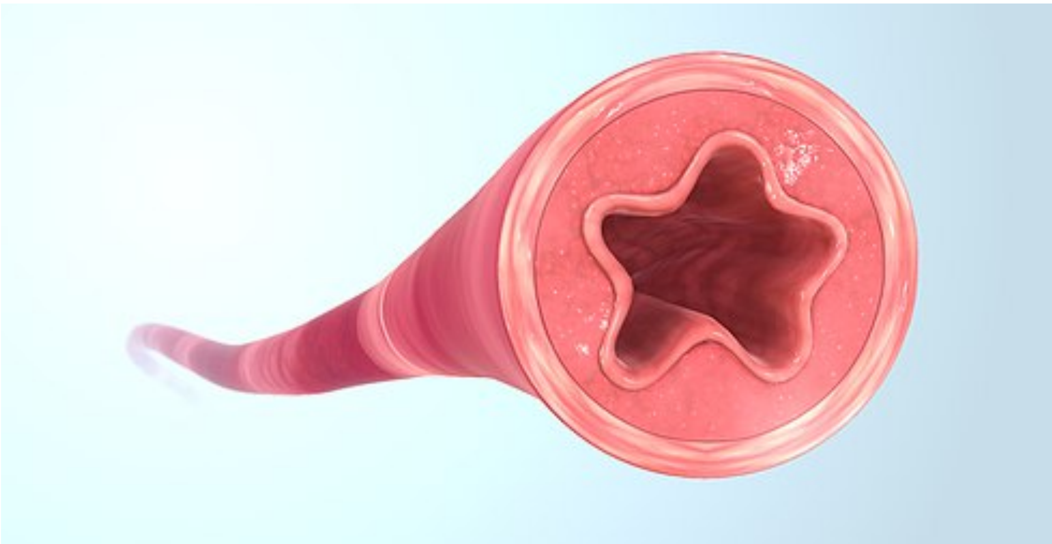


Figure 5. Three tunicas
https://en.wikipedia.org/wiki/Blood_vessel

2.3 Cardiac cycle

The period which includes the set of mechanical, resounding, electrical and pressure events associated with the blood flow that travels thanks to the contraction and relaxation of ventricles and atria, the closure and opening of the cardiac valves and the depolarization and repolarization of the myocardium. It is a continuous process divided into two stages: the systole period of contraction, in which the blood is pumped into circulation, and the diastole or relaxation phase, in which the chambers are filled with blood through the veins. Therefore, coordination between myocardial contraction and relaxations is essential to achieve proper blood pumping through the body.

The duration of the cardiac cycle increases as the heart rate decreases, while it decreases as the heart rate rises. One cardiac cycle lasts 0.8 seconds at a normal heart rate of 75 beats per minute. At rest, systole takes up one-third of the cardiac cycle, while diastole occupies the other two-thirds. Nevertheless, once the heart rate increases, the duration of diastole reduces significantly more than the duration of systole.

2.3.1 Atrial systole

Each cardiac cycle begins with an action potential in the sinus node that results in electrical depolarization and contraction of the atria. This contraction causes an increase in pressure inside these cavities, which results in the expulsion of the blood they contain into the ventricles through the atrioventricular valves. The atria do not need to contract much because 80 percent of the blood goes passively to the ventricles. Atrial systole, also known as auricular systole due to the contraction of the heart's two auricles, lasts around 0.1 seconds.

2.3.2 Ventricular systole

At the end of the atrial systole, the electrical impulse reaches the ventricles and causes depolarization first and then ventricular contraction. The pressure inside the ventricles increases due to the large volume of blood they contain, leading to the closure of the atrioventricular valves. As the ventricular pressure is higher than the atrial pressure, blood tends to go towards the latter. However, the closing of the atrioventricular valves prevents this movement from taking place and results in the first heart sound, which lasts for 0.04 seconds. During the period of time between the closure of the atrioventricular valves and the opening of the aortic and pulmonary valves, ventricular pressure increases rapidly without a change in ventricular volume, hence the contraction is isovolumetric. Then, sigmoid valves open, blood flows from the ventricles to the aorta and pulmonary trunk, and the ventricular pressure decreases as it increases in these vessels. Ventricular and blood vessel pressure ends up equalizing and a considerable volume of blood remains into the ventricles at the end of the ejection, which is called the residual, telesystolic or final systolic volume. On the other hand, the volume of blood expelled is the systolic or beat volume. No heart sounds occur during the ejection phase because the opening of healthy valves is silent.

2.3.3 Ventricular diastole

After the partial exit of the blood and thanks to the repolarization of the ventricles, the ejection velocity of the blood progressively decreases and ventricles relax, leading to a decrease in the pressure inside these cavities and an increase in pressure in the blood vessels. This results in the closure of the sigmoid valves so that the blood does not return to the ventricular cavities and in the second heart sound. Although ventricular pressures decrease during this phase, volumes do not change because all valves are closed. Then, the ventricular pressure decreases considerately, the atrioventricular valves open and the ventricular filling takes place since blood flows from the atria to the ventricles following a pressure gradient.

2.4 Blood circulation

The cardiovascular or circulatory system can be divided into two secondary systems: the systemic circuit and the pulmonary one. The first of these attempts to transport blood to all cells in the body for them to get the oxygen and nutrients it contains, as well as to collect waste substances. The second circuit, on the other hand, seeks to transport to the lungs blood that has already circulated throughout the body and has little oxygen.

2.4.1 Systemic circuit

The systemic circulation begins in the left ventricle, which expels the blood it contains through the aorta artery with each beat. Then, this blood reaches all the cells in the body and provides them with the oxygen and nutrition they require, while cells release waste substances into it. Finally, the oxygen-poor blood is then returned to the heart via veins that converge and form bigger ones until it reaches the superior and inferior vena cava, which flow into the right atrium.

2.4.2 Pulmonary circuit

During systole, the right ventricle contracts and pushes blood into the pulmonary artery, which exclusively transports blood to the lungs and not throughout the body. This artery divides into several branches, finally becoming small blood vessels known as pulmonary capillaries. These have a thin wall and enable oxygen to enter inside them and, subsequently, enter red blood cells, which are in charge of delivering oxygen and removing accumulated carbon dioxide. Blood passes from the pulmonary capillaries into the veins, which eventually become the four pulmonary veins and discharge into the left atrium.

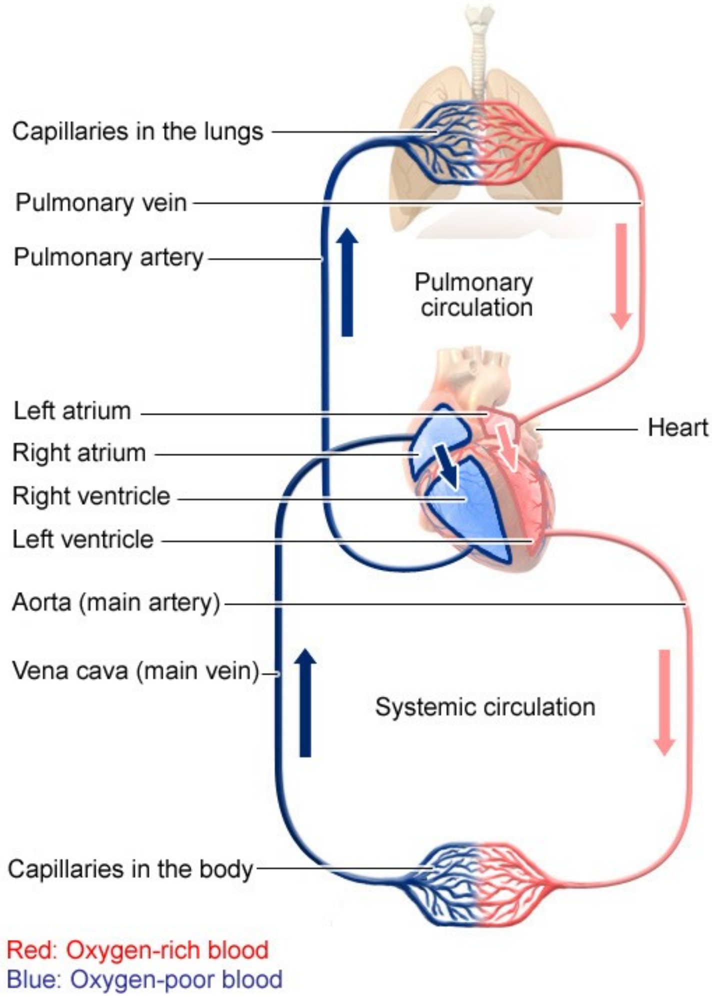


Figure 6. Blood circulaion
https://www.informedhealth.org/how-does-the-blood-circulatory-system-work.html

2.5 Heart transplantation

The present research work explains that the insertion of an artificial device such as the TAH serves as a bridge for a future heart transplant. The goal of heart transplantation is to implant a heart from another person, usually a brain-dead donor, to replace the patient's damaged heart.

2.5.1 Why is it done?

Heart transplantation is a type of organ transplant surgery performed on patients with a state of heart failure or severe ischemic heart disease, in whom the other therapeutic alternatives have been exhausted. In children, heart failure is caused by a congenital heart defect or cardiomyopathy, whereas in adults this disease can be caused by the following conditions:

- Weakening of the heart muscle (cardiomyopathy)
- Coronary artery diseases
- Heart valves diseases
- Heart problems at birth (congenital heart defect)
- Abnormal and dangerous heart rhythms not controlled with other treatments (ventricular arrhythmias)
- Failure of a previous heart transplant

However, not all people can undergo heart transplantation. People may not be good candidates for a heart transplant if:

- They are elderly people, which could hinder the recovery process after transplant surgery
- They have another illness that could shorten their life, regardless of whether they receive a heart transplant, such as a serious kidney, liver, or lung disease
- They have an active infection
- They have a personal and recent medical history of cancer
- They do not want or cannot make the lifestyle changes necessary to keep their new heart healthy, such as not drinking alcohol or not smoking.

2.5.2 Surgical technique

A heart transplant usually begins with the search for a heart of a recently deceased or brain-dead donor compatible with the patient. The patient to be transplanted is notified by the area and admitted to evaluate the operation and receive pre-operative medication. At the same time, the donor's heart is removed and inspected by surgeons to determine if it is suitable for transplantation. Once the donor's heart has passed the routine inspection, the patient is taken to the operating room and given general anesthesia. Two procedures can be followed for transplants, orthotopic or heterotopic, depending on the patient's conditions.

Orthotopic transplantation	It begins when the surgeon makes an incision along the sternum to expose the mediastinum. The pericardium opens, the large valves are dissected, and the patient undergoes a cardiovascular bypass. The diseased heart is removed by cutting the valves and a portion of the atrium. The pulmonary vein is not sectioned, and a good circular portion of the atrium is left to contain the pulmonary vein to the right of the site. The donor's heart is carefully fitted into the remaining space of the atrium and valves. The new heart is restarted, the patient is disconnected from the cardiopulmonary bypass.
Heterotopic transplantation	The patient's heart is not removed before the donated organ is implanted. The new heart is placed in such a way that the chambers and valves of both hearts can be connected in such a way that it acts effectively as a "double heart." The procedure can provide the patient's original heart with a chance to recover, and if the donor's heart fails, the donor's heart must be removed, allowing the original heart to begin functioning again.

Finally, patients are taken to the Intensive care unit (ICU) for recovery. When they wake up, they can be transferred to a rehabilitation unit. The duration of the process depends on the general health of the patients and the way the new heart behaves. Once discharged, patients must return to the hospital for regular check-ups and rehabilitation sessions.

2.5.3 Risks

The main risks that people must contemplate when transplanting a heart are:

Rejection of the donor heart	One of the most significant risks after a heart transplant is that the body will reject the donor heart. The immune system may consider the donor's heart a foreign object and try to reject it, which can damage the heart. Each heart transplant recipient receives medications to prevent rejection (immunosuppressants).
Primary graft failure	With this condition, which is the most common cause of death in the first few months after transplantation, the donor's heart does not work.
Problems with the arteries	After transplantation, the walls of the heart arteries may thicken and harden, which can lead to cardiac allograft vasculopathy. This can make it difficult for blood to flow through the heart and can cause a heart attack, heart failure, cardiac arrhythmias or sudden death.
Side effects of medications	The immunosuppressants that patients will need to take for the rest of their lifes can cause serious kidney damage and other problems.
Cancer	Immunosuppressants can also increase the risk of developing cancer. Taking these drugs can increase the risk of skin and lip growths and non-Hodgkin lymphoma, among others.
Infection	Immunosuppressants decrease people's ability to fight infection. Many people who receive heart transplants have an infection that requires them to be hospitalized for the first year after the transplant.

3. ARTIFICIAL HEART

As the term suggests, an artificial heart is a non-biological organ that replaces the original one. In other words, it is an artificial device that replicates the functions of a healthy biological heart.

3.1 History

As previously mentioned, talking about the history of bionics would be equivalent to exposing human life since its inception. However, history referring to the artificial heart is a less dense concept and, therefore, easier to detail. But, why is it important to explain the process of development and improvement of the artificial heart? The response lies in the fact that the scientific method is based on studying hypotheses and discarding the false ones. Throughout time, researchers and scientists have observed and analyzed all the possible ways of designing an artificial heart that is suitable and functions in the best possible way. At the same time, they have taken into account the previously studied and discarded options, in order to formulate new hypotheses and try to move forward in this field of science. For this reason, studying and having knowledge about the history of this product allows us to improve and do not encounter unnecessary and previously overcome obstacles.

The origins may be traced back to 1947, when Dr. Willem Johan Kolff began investigating the development of an artificial heart. During the 1950s, he collaborated with Dr. Tetsuzo Akutsu on a series of prior studies that enabled him to execute artificial heart implantation in animals.

Paul Winchell, a ventriloquist, received the first patent for an artificial heart in 1963. Years later, at the University of Utah, Winchell signed his patent rights to Dr. Kolff. This last investigator left the Cleveland Clinic in 1967 to establish the University of Utah's Division of Artificial Organs. In addition to that, Kolff worked on his concept alongside surgeon Clifford Kwan-Gett and engineer Thomas Kessler.

Dr. Denton Cooley, of the Texas Heart Institute, was the first cardiac surgeon to implant an artificial heart in a human patient in 1969. Dr. Domingo Liotta's mechanical heart kept the patient alive for 64 hours, but he died 32 hours after a donor heart transplant.

Over the years, more than 200 doctors, engineers, students, and faculty members worked together to create, test, and enhance Kolff's artificial heart. Kolff designated project managers to assist oversee his various initiatives, and each project was named after its manager. Robert Jarvik, a postgraduate student, was in charge of the artificial heart project, which was subsequently dubbed Jarvik 5 TAH. *(Figure 7).* This mechanism was implanted in numerous calves throughout the 1970s, which perished after a few days.

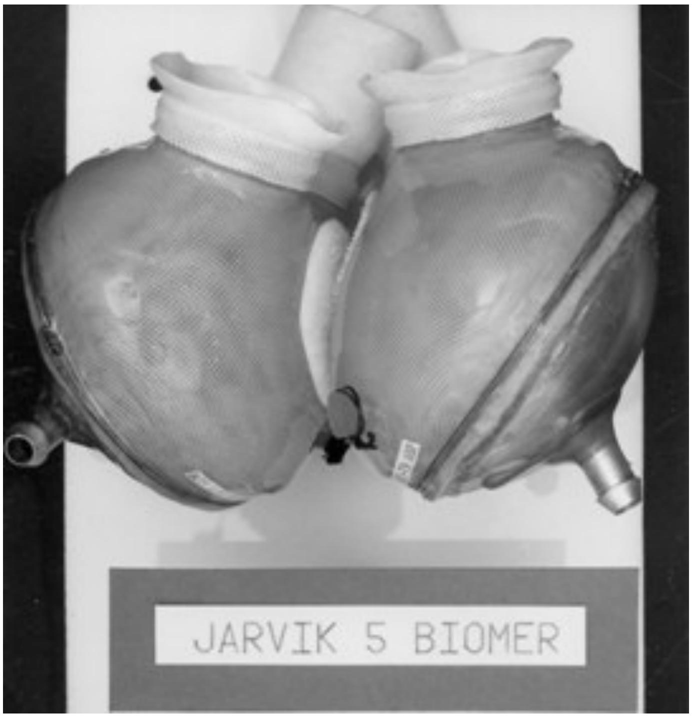


Figure 7. Jarvik 5 TAH
https://syncardia.com/artificial-heart-timeline/

William DeVries applied to the FDA in 1981 for authorization to implant Jarvik 7 in a human. Kolff inserted the artificial heart Jarvik 7 in Barney Clark, a Seattle dentist suffering from acute congestive heart failure, on December 2, 1982. After spending 112 days tied to an external air compressor, a 180 kg piece of equipment, this individual died. In 1984, William J. Schroeder became the Jarvik 7's second human recipient and survived for 620 days before dying of a lung infection. This was the longest someone had lived with an artificial heart at the time. At the same time, the Abiomed company was founded to develop another artificial heart which could help people.

Dr. Jack Copeland, of University Medical Center in Tucson, Arizona, implanted the Phoenix artificial heart prototype in a patient who had rejected a transplanted heart in 1985. Michael Creighton survived with a Phoenix heart for 11 hours before dying 60 hours later following a second donor heart transplant. The same doctor became the first surgeon to use Jarvik 7 as a bridge for human heart transplantation. His patient, Michael Drummond, lived nine days with the Jarvik 7 before receiving a donor heart *(Figure 8).*

Figure 8. Richard Smith and Jack Copeland with Michael Drummond
https://syncardia.com/artificial-heart-timeline/

In 2001, SynCardia Systems, Inc was founded by cardiologist Dr. Marvin J. Slepian, biomedical engineer Richard G. Smith, MSEE, EEC, and cardiothoracic surgeon Dr. Jack Copeland.

Robert Tools received the AbioCor implantable Replacement Heart from AbioMed of Danvers, Massachusetts on July 2, 2001. It was the first artificial heart transplant that was completely self-contained. The operation was carried out at the University of Louisville's Jewish Hospital, in Louisville, Kentucky. On September 6, 2006, the AbioCor device became the first completely implanted artificial heart to be certified under the 'humane devices' category.

After extensive research and development, the SynCardia company made a product capable of prolonging the lives of patients suffering from cardiovascular diseases. The Clínica Universidad de Navarra in Pamplona was the first medical team in Spain to use one of these devices in 2017 *(Figure 9).*

Figure 9. Óscar, the first patient to receive the SynCardia Total Artificial Heart in Spain, and the medical team at Clínica Universidad de Navarra
https://www.businesswire.com/news/home/20170111005087/en/Cl%C3%ADnica-Universidad-de-Navarra-Implants-Spain's-First-SynCardia-Total-Artificial-Heart

3.2 Artificial heart in terms of physics

When studying the physics associated with this product, it is noteworthy the relevance of the mechanics and electricity that interact to promote the proper functioning of this device.

An essential factor to consider when studying this product from a physics standpoint is pressure. This physical magnitude is defined as the action of a force that presses or pushes a body to which it is applied. In other words, is the force applied perpendicular to an object's surface per unit area over which that force is spread. Its international unit is the pascal (Pa), and additional units used include the millimeter of mercury (mmHg), bar (bar) and atmosphere (atm).

On the one hand, there are totally artificial hearts that do not have a battery or motor in their interior. These are electrically fed thanks to an external device which regulates the rate and pressures that pump the blood of the artificial heart. This device releases air through two tubes linked to the artificial heart and then compels to pump the blood retained in the ventricles of the artificial heart implanted through the rest of the body. In order to carry out this process, a motor runs a piston that then compresses the air and pushes it through the tubes to feed the artificial heart. In this case, the power supplier is always transported wherever the patient goes, since without it the person would have a heart that could not contract and the individual would die.

On the other hand, we find artificial hearts that have a battery in their interior, and for that reason, they are called stand-alone replacement hearts. This battery is charged via a transcutaneous energy transmission system (TET), which means there are no wires or tubes that pierce the skin, reducing the risk of infection.

3.3 Artificial heart in terms of chemistry

All the mechanisms in this medical device are manufactured with biomaterials, which are synthetic or organic materials used to create machines capable of replacing a part of a living system or operating in direct contact with living tissues in a safe and efficient manner. It is crucial to distinguish between the terms biomaterial and biocompatible, because the latter refers to compatible biomaterials that replace a specific part of the body. In other words, a biomaterial that is biocompatible in one application may be incompatible in another. Biomaterials of medical interest must fulfil specific requirements before they can be used for therapeutic applications. One of the essential factors is that materials must not damage the cells of the body. In addition to that, biodegradability, mechanical stability, simplicity of manufacture, and affordability are important considerations to evaluate.

Biocompatibility, the interaction of diverse materials with biological tissues to minimize harmful immunological reactions, is a crucial factor in biomedical engineering. It should be mentioned that aluminum, carbon fiber, titanium, silicone, PTFE and PET-P are the most often used materials in the bionics business. However, it is important to classify these materials in order to acquire maximum knowledge.

According to the origin, biomaterials can be classified into:

Natural	Autogenous: obtained from the same individual who will receive the graft
	Allograft: from another individual
	Xeno-graft: from a different species than human
Synthetic	Metals: good mechanical properties and used in orthopedic prostheses, dental implants…
	Polymers: close to living tissues properties and widely used in implants and tissue engineering.
	Ceramics: chemically inert and statable, and used in bone prostheses, heart valves…
	Compounds: used in all fields of bioengineering, since they have varied properties depending on the elements they constitute.

On the other hand, they can also be organized according to the biological role:

Toxic	Substances that may cause harm to an individual in contact with their body.
Bioactives	They actively participate in tissue repair and are used for dental implants and orthopedic prostheses. Some examples are high-density hydroxyapatite, titanium compounds, bioactive glasses, and some glass ceramics.
Bio-inerts	There is no interaction with the body, they can remain for long periods in a highly corrosive environment of body fluids. They are used for permanent implants, maxillofacial and cranial surgery. Some examples are titanium, chrome-cobalt, ceramic materials based on alumina, zirconia and magnesium oxide…
Biodegradable	Materials which can be decomposed by the action of living organisms into water, carbon dioxide and biomass.
Non biodegradable	They are usually synthetic materials which cannot be decomposed by the biological process.
Bio-resorbable	They are reabsorbed and provide the necessary elements for tissue repair.

In the case of the artificial heart, ventricles are replaced with self-feeding hydraulic chambers, and valves are often made of titanium or stainless steel and covered with PET-P. An external pneumatic pump is in charge of sending air pulses to the chambers in order to produce the required pressure and pump blood throughout the body.

3.4 Artificial heart in terms of medicine

Currently, cardiovascular disease accounts for 31% of deaths worldwide. Although in many cases they are treated with a heart transplant, finding the right donor with the right features is quite a challenge. In one year, only 4000 hearts are available to be transplanted globally, which is a clear drawback. In this same way, the design and creation of artificial hearts is a breakthrough as far as medicine is concerned, as it proposes an effective method to prolong the lives of many people. An artificial heart is commonly used to bridge the time to heart transplantation and, on extreme occasions, to replace the heart in case a donor is not found.

3.4.1 SynCardia TAH surgical technique

When describing this bionic advance from the field of medicine, it is relevant to highlight the surgical process that this device requires. The operation begins with the application of general anesthesia to the patient and, subsequently, a standard median sternotomy takes place, which consists of a vertical inline incision made along the sternum *(Figure 10).*

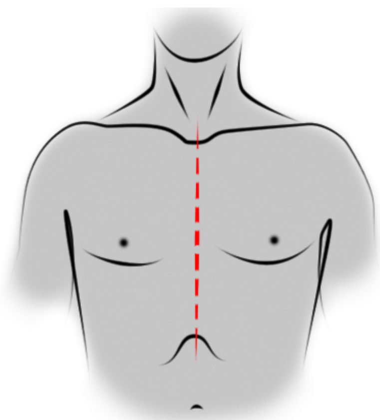


Figure 10. Median sternotomy
https://en.wikipedia.org/wiki/Median_sternotomy

In the second place, the pericardium is opened in order to analyse the requirement for a TAH by means of a trans-oesophageal echocardiogram. In this step, the doctor makes use of a transducer to send ultrasonic sound waves. These sound waves reach the heart tissues and resound within the organ. The transducer captures the reflected waves and sends them to a computer, which then converts them into images of the heart walls and valves. Thereupon, two small incisions are made along the left middle clavicular line in order to place the two transmission cannulas, which are tunnelled with the help of a 36 Fr thoracic tube. With the aim that ventricles stand properly, an attempt takes place to insert the transmission line at an angle to the left pleural space. The aortic and pulmonary outflow grafts are sprayed with a layer of CoSeal Surgical Sealant to prevent patients from haemorrhage. Afterward, the ventricles and grafts are soaked with rifampicin and then the complete heparinization takes place.

A mediastinal dissection is performed to facilitate future transplantation. The distal ascending aorta is then cannulated and the bi-caval cannulation is performed through the right atrium to leave the superior vena cava and the inferior vena cava intact. Tapes are then placed around them while carbon dioxide floods the surgical field. The patient is introduced to cardiopulmonary bypass after achieving an appropriate coagulation time. This is possible as the patient's temperature rises to 34 degrees Celsius.

The aorta is then cross-clamped, and a cardiectomy is performed by incising the right ventricle first along the right atrioventricular groove and then circumferentially around the base of the right ventricle, taking care to leave the tricuspid annulus intact *(Figure 11).* The remaining ventricular muscle should be thin and around a centimetre broad. The tricuspid valve is removed, leaving around 1 to 2 mm of tricuspid leaflet connected to the annulus. This is frequently used as a supplementary buttress for future anastomosis. The left ventricle is then cut just above the mitral annulus, keeping the mitral annulus intact. The mitral valve is resected to the same level as the aortic valve. The aorta and pulmonary artery are then transected just above the aortic and pulmonic valves, ensuring that the aorta and pulmonary artery remain for the transplant. The coronary sinus is then identified and oversewn. The atrial septum should be carefully examined for an atrial septal defect and closed if present.

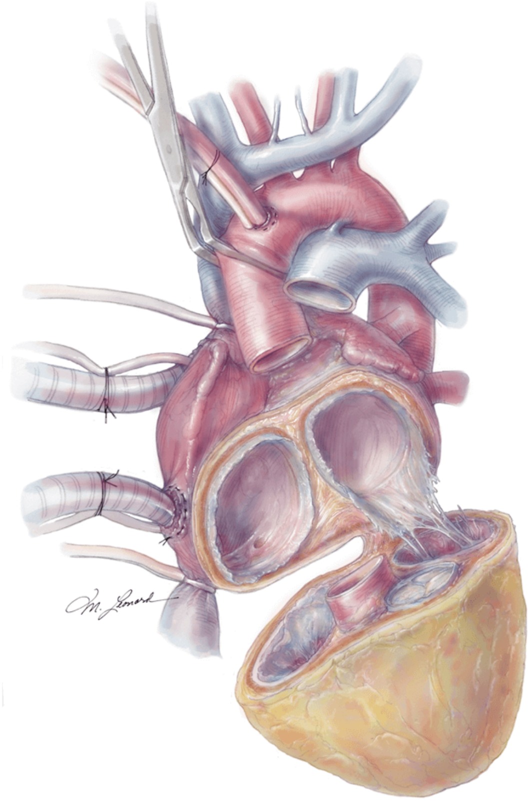


Figure 11. Cardiectomy for total artificial heart implantation
https://www.annalscts.com/article/view/16695/html

The quick connections are then prepared by circumferentially cutting the cuff, leaving a small rim around 5 mm wide. The fast connections are then anastomosed to the respective atrioventricular valve annulus in a running way using 3-0 proline. The surgeon can stabilize the quick connection within the ventricle by using a U suture. A Lone Star retractor may also facilitate implantation by stabilizing and elevating the heart. When sewing in the fast connect, care is taken to ensure that the suture only passes through the cuff and includes the annulus on the atrial side. Stitches for reinforcement are then added as needed. The left ventricle rapid connection anastomosis is done first, then the right ventricle one *(Figures 12 and 13).* To support the anastomosis when the patient's muscle is friable, a strip of felt bandage coated with a thin GORE-TEX membrane might be applied. To correctly estimate the length of the aortic and pulmonary grafts, the ventricles are implanted but not linked. Since it overrides the aortic graft, the pulmonary one is longer than the aortic graft. Sizing must be done carefully to avoid kinking or stretching both grafts.

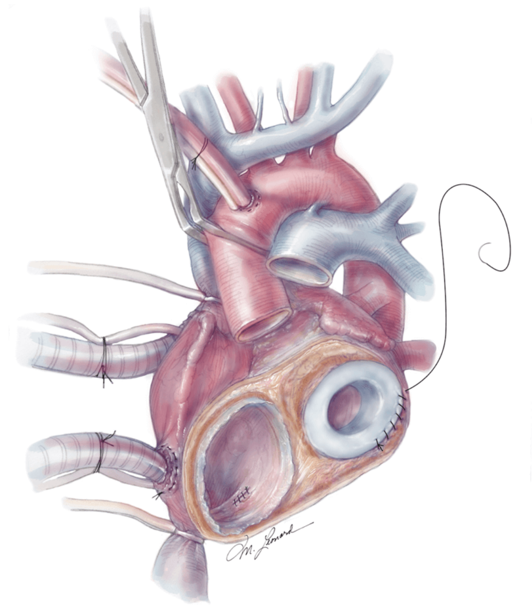


Figure 12. Left quick connect anastomoses
https://www.annalscts.com/article/view/16695/html

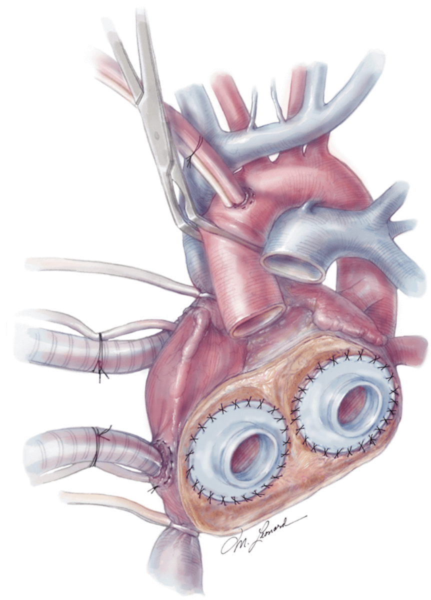


Figure 13. Left and right quick connect anastomoses
https://www.annalscts.com/article/view/16695/html

Thereafter, the aortic and pulmonary graft anastomoses are accomplished *(Figure 14).* The leak tests are then performed on the ventricles and outflow graft anastomoses using diluted methylene blue. Manual compression of the pulmonary veins with the surgeon's hands is conducted while evaluating the left ventricle. A vascular clamp is also placed on the pulmonary artery distal to the anastomosis to check for leakage. Sutures for reinforcement are then used if necessary. Then, a 0.1 mm GORE-TEX membrane is placed at the level of the left pulmonary veins. Two hefty ties wrap around the ventricle knobs before they are put into the pericardium. After that, the left ventricle is inserted first *(Figure 15).* The ventricle is inserted after three blunt needle drivers are positioned at the 10 o'clock and 2 o'clock locations along the fast connect. The aortic quick connect is then attached in almost the same way. The left ventricle is allowed to fill with blood before the aortic connection is completed, and irrigation is inserted into the ventricle to expel as much air as possible. After that, the right ventricle is inserted and positioned *(Figure 16).* Snares are subsequently released, and blood is pumped into the right ventricle as the pulmonic linkage is established. Then, the Total Artificial Heart is connected to the C2 driver, and the aortic cross clamp is removed. During this phase, aggressive de-airing from a root vent in the ascending aorta is required, and trans-oesophageal echocardiography is employed to detect air in the aorta. Then, the TAH is started with single manual beats to de-air. After proper de-airing takes place, the artificial organ is adjusted to 60 beats per minute. Normal post-bypass parameters are as the following ones: rate 120-135, left pressure 180-200, right pressure 80-100, and vacuum 10-15.

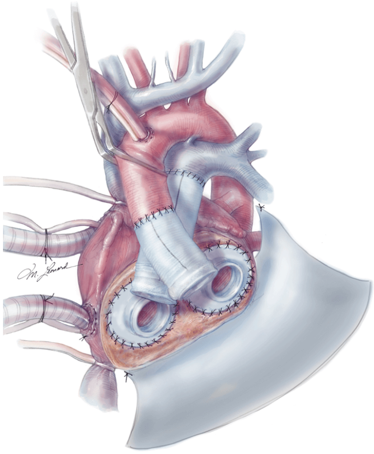


Figure 14. All anastomoses completed https://www.annalscts.com/article/view/16695/html

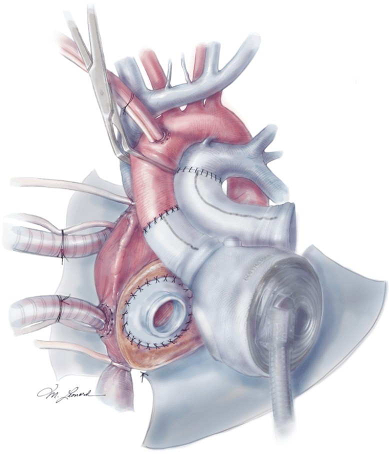


Figure 15. Left ventricle insertion https://www.annalscts.com/article/view/16695/html

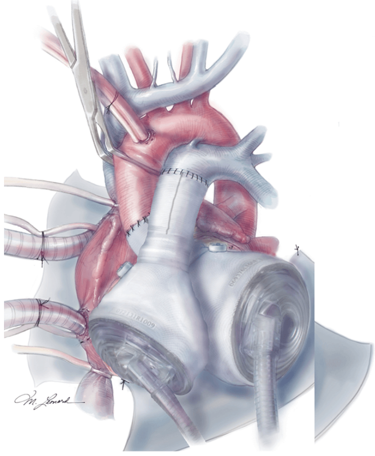


Figure 16. Total artificial heart implanted https://www.annalscts.com/article/view/16695/html

The pulmonary veins should be carefully examined, and velocities should be checked with trans-oesophageal echocardiography to ensure an unobstructed return to the left atrium. The Inferior vena cava is also examined to rule out ventricular compression. These structures should be assessed not only at device start-up, but also during device closure. Coagulation is a problem in these patients because of their severely decompensated status, and the chest is commonly kept open for one day. Several manoeuvres are performed at the moment of final closure to guarantee ease of re-entry at the time of transplant. A GORE-TEX membrane is applied along the right ventricle and atrium to the right pulmonary veins. Silastic “blue” bands are wrapped around the aorta and pulmonary anastomoses, as well as the inferior vena cava and, in certain cases, the superior vena cava. On re-entry, these bands aid in the identification and isolation of these structures. To enable the redo sternotomy, the sternum is closed with sternal wires and a thin silastic membrane is placed between the wires and the sternum.

The aperture of the left pleural space permits the device to be turned downwards and laterally towards the left pleura if the anteroposterior diameter of the chest is limited.

At this point in the procedure, the surgeon must be aware of the left pleural veins, which can be injured and obstruct blood flow. Nevertheless, if the mediastinal space is large enough, saline implants or tissue expanders are inserted to maintain the mediastinal space, as pericardium contraction is common.

3.5 Artificial heart in terms of ethics

Artificial organs are a relatively new type of life-saving technology that relies on techniques such as 3-D printing and stem cell implementation, both of which are becoming increasingly widespread in the medical field as automation progresses. Scientists have recently invested a large amount of research and resources in the development of these artificial organs, owing to the large disparity between people in need of organs and those who are actually receiving them. While artificial organs may appear to be the perfect solution, there are some major ethical implications that arise as a result of greater deployment.

When discussing the TAH, the high cost of these high-tech organs is a major concern. An artificial heart implant costs around 95,000 euros, not including the 14,000 euros in yearly check-ups. This economic requirement is out of reach for the vast majority of people suffering from cardiovascular diseases. Given that these organs would only be available to those who could buy them, it may be considered not virtuous to enable them to become widely available, as others who cannot afford these conditions will be at a significant disadvantage. Furthermore, since one can not manage its health when it is on the approach of death, it is unfair to make these organs available to people who can pay the expensive costs. Since it is only available to a select few, this product is an illusion for several patients and a reality for very few. However, the development of a mechanism capable of saving or prolonging the lives of certain patients supposes a significant benefit and advancement in the field of science and medicine.

It is also crucial to note the many religious or personal beliefs that can lead one to believe that utilizing an artificial heart means to offer a person a second life, in other words, avoid natural death. Justice is paramount, as a person with cardiovascular difficulties may be given a second chance at life, whereas a person with terminal cancer does not. It goes without saying that in a world where science has been broken into distinct sectors, it is not surprising that they all progress at a different speed. What today appears to be a normal cold was formerly one of the major causes of mortality globally, along with cardiovascular issues. However, the current common cold is a far more treatable and well-known disease than cardiovascular illness, resulting in a new injustice.

4. ARTIFICIAL INTELLIGENCE

Are there intelligent machines capable of carrying out typical human life activities? The answer to this question is found in artificial intelligence (AI), a branch of computer science which examines the development of algorithms which enable a machine to make intelligent decisions or behave as if it had human intelligence. In other words, it is a device which perceives its environment and performs actions that maximize its chances of success in a goal or task. Although the definition of this discipline may seem more or less simple, over the last century, mathematicians, engineers and philosophers have taken part, voluntarily or unintentionally, in a debate over it.

Currently, AI systems are part of the routine in disciplines such as economics, medicine, engineering, and military, as well as a broad range of software applications, strategy games such as computer chess and other videogames. As a matter of fact, experts predict that AI will completely transform every current sector and industry. However, what makes it so fascinating? Unlike humans, AI-based technologies can evaluate large quantities of information without needing to rest. Furthermore, the likelihood of a mistake is significantly smaller than that of a human executing the same task. In general, AI-based technologies are used to help people in benefiting from the considerable advances that these machines provide, as well as to experience greater efficiency in nearly every area of life. However, the rapid expansion of AI requires us to be alert in order to prevent and analyse possible direct or indirect problems.

Artificial intelligence is already being used in medicine, from the diagnosis of diseases to their treatment. This discipline is useful during image analysis, since AI has proved itself to interpret retinography, echocardiograms, CT, and radiography considerably better than the human eye. However, AI not only analyses or assists in decision-making, but also acts on information received. AI robots are currently being utilized in precision surgery procedures, such as cardiac ablations, which involve making small incisions in the heart muscle tissue to regulate arrhythmias. It is hoped that in the near future, all these potential capabilities for improvement in diagnosis and treatment will be increased as artificial intelligence-based programs can count on the technological support of quantum computers and their enormous computing power. Given the definition of this scientific discipline, it is not surprising that the technology used in the artificial heart is based on and related to artificial intelligence. The biological functions of the human heart, such as pumping blood, are replaced by the artificial organ, resulting in a machine capable of acting as if it had intelligence and autonomy.

5. CURRENT MODELS OF ARTIFICIAL HEARTS

5.1 SynCardia Total Artificial Heart

Headquartered in Tucson, Arizona, SynCardia was founded in 2001 by renowned cardiothoracic surgeon Jack G. Copeland, biomedical engineer Richard G., and interventional cardiologist Marvin J. Slepian. Versa Capital Management, a Philadelphia-based private equity investment firm, acquired SynCardia in September 2016. Its cooperation with Versa has given financial and operational resources to support the company's continued growth and success in the United States and throughout the world. This support has also allowed us to continue developing innovative medical devices and to look for new indications to benefit more patients. SynCardia improves outcomes for critically ill adults and adolescents whose best chance of life is complete heart replacement by collaborating with, educating, and supporting healthcare professionals at more than 140 transplant hospitals and heart failure programs in more than 20 countries. SynCardia provides a new heart without the wait for patients at risk of dying or becoming too ill to transplant due to end-stage biventricular failure when a donor heart is not available or is not an option.

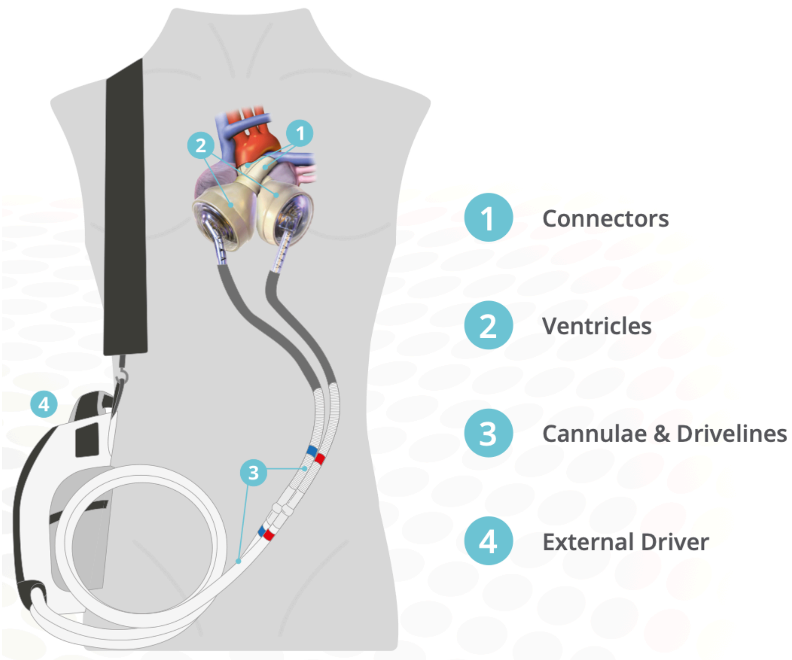


Figure 17. SynCardia TAH parts
http://syncardia.com/wp-content/uploads/2018/08/Mktg-854_Rev_002.pdf

The current product offered by the company is described as a pneumatically driven pulsatile system which is used for orthotopic replacement of the biologic ventricles and four valves. The device in question can be divided into four components, each one with its indispensable function. Following the order shown in the previous image *(Figure 17),* the connectors are the cables that allow all the electrical activity required for the proper functioning of the artificial heart. In the second place, the two independent and artificial ventricles are manufactured in two different sizes, 70 cc and 50 cc. The following table compares the principal characteristics of the two models:

Characeristic	**50 cc TAH-t**	**70 cc TAH-t**
Maximum stroke volume	50 cc	70 cc
Valve diameter (aortic/mitral)	23 mm / 25 mm	25 mm / 27 mm
Maximum cardiac output	7.5 l/min	10.5 l/min
Weight	200 g	240 g
Displacement volume	250 ± 25 ml	400 ± 20 ml
Beat rate	125 ± 15 bpm	125 ± 15 bpm
Right drive pressure	80 - 100 mmHg	80 – 100 mmHg
Left drive pressure	180 - 210 mmHg	180 – 210 mmHg
Right vacuum pressure	0 – (-10) mmHg	0 – (-13) mmHg
Left vacuum pressure	0 – (-13) mmHg	0 – (-13) mmHg

In relation to the cannula of each artificial ventricle, it serves as a conduit for air from the driver to the ventricles. Each cannula, which is partially covered with velour fabric to promote tissue ingrowth, is tunneled through the chest wall and connected to drivelines that link to the external pneumatic driver. Finally, the external driver stands out since it produces pulses of air which travel through the drivelines and cannula to inflate the diaphragms to fully eject the blood. This power source is available in two different versions: the Companion 2 Hospital Driver and the Freedom

Portable Driver. The former one is basically used during patient recovery in the hospital, whereas the latter one, which weights 6 kg, offers an increased mobility and freedom to the patient. The two lithium-ion batteries of the latter model provide power to the motor, which makes an internal pneumatic piston work. This mechanism compresses the air and pushes it through the tubes to feed the artificial heart.

5.2 Aeson, Carmat Total Artificial Heart

Development of the CARMAT TAH began in 1993 in Paris by a medical team directed by Alain Carpentier in association with an engineering team from Matra Defense, a subsidiary of Airbus Group. In 2008, CARMAT SAS was founded to expedite the development and manufacture of the prosthesis, with funding from venture capital, the French Innovation Agency, and an Initial Public Offering in 2010.

The Carmat TAH, known as Aeson, consists of three distinguished parts *(Figure 18)*:

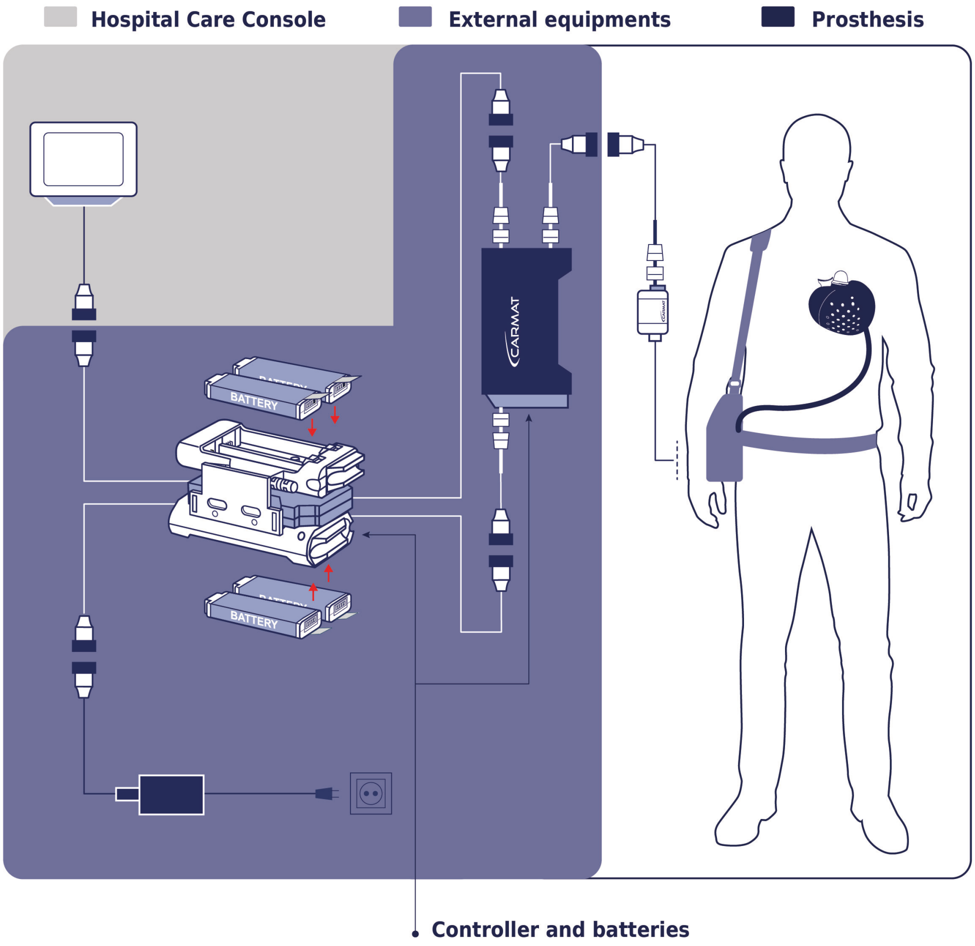


Figure 18. Parts of Aeson TAH
https://www.carmatsa.com/en/our_product/

First and foremost, the implanted prosthesis consists of a series of mechanisms which cooperate to replicate the essential function of the biological heart, which is blood pumping *(Figure 19)*. These devices are:

- One motor pump group composed of two micro pumps, which push actuator fluid to the membranes and cause systole and diastole.
- Two ventricles, separated by a membrane, one for blood and the other one for actuator fluid. This membrane's blood-contacting layer comprises biocompatible materials.
- Embedded electronics, microprocessors, and integrated sensors providing autoregulated reactions to the physiological demands of the patient.
- A flexible external bag, which contains the actuator fluid.
- Four biological valves, which provide unidirectional pulsatile blood flow at the input and exit.
- Two output conduits, which allow the prosthesis to be connected to the pulmonary artery and aorta.
- A percutaneous driveline, which connects the prosthesis to the external components.

Figure 19. Parts of the implanted prosthesis
https://www.carmatsa.com/en/medias/#bloc13121

On the other hand, the external equipment stands out for its function of providing the autonomy and liberty needed to live an ordinary lifestyle. This apparatus weighs 4 kg and has a controller, as well as two battery pockets, which provide approximately 4 hours of autonomy.

Finally, there is the hospital care console, which is used by the medical team in order to operate the prosthesis during implantation and tracking how the mechanism is functioning.

Regarding the functioning of this TAH, it should be mentioned that Aeson is a medical device developed to replace the ventricles of the native heart in patients suffering from severe or acute heart failure. In the first place, the machine is electrohydraulically operated similarly to the human heart. Once attached, the Aeson doubles the activity of a regular heart by giving mechanical circulatory assistance and restoring normal blood flow throughout the body.

Aeson is currently only commercially available in Europe and can be implanted in patients with end-stage biventricular heart failure who are not candidates for maximum medical treatment or LVAD. This product acts as a bridge for a subsequent heart transplant, which means that patients with an Aeson heart must have a heart transplant within 180 days after the artificial device's installation.

The internal electrohydraulic action of the Aeson membranes, unlike the SynCardia product, removes the need for an external actuator and produces no audible noise. Sensors, electronics, and microprocessors that control the system are integrated inside the prosthesis. It is also worth noting that the resultant blood flow ranges from 2 to 9 l/min, depending on the patient's demands.

6. OPERATION OF A SYNCARDIA TOTAL ARTIFICIAL HEART AT BELLVITGE HOSPITAL

Bellvitge University Hospital is a Catalan Institute of Health publicly-owned hospital with outstanding medical, teaching, and research activity. It is specialized in very complex medical treatment and provides all medical and surgical specialities except for pediatrics and obstetrics.

Figure 20. SynCardia TAH operation in Bellvitge Hospital
https://bellvitgehospital.cat/es/actualidad/noticia/bellvitge-implanta-su-primer-corazon-artificial-total

On May 27, 2019, the mechanical circulatory support program of Bellvitge University Hospital implanted the second artificial heart in Spain. A heart transplant or mechanical biventricular support were not options for the patient, a 30-year-old man with pulmonary hypertension and failure of the two ventricles of the heart. Faced with this circumstance, and considering the severity of his illness, he was offered the temporary implantation of a complete SynCardia artificial heart. The team of surgeons and cardiac medicine professionals led by Dr. José González Costello, an expert in mechanical ventricular assistance, extracted the damaged heart to proceed with the implementation of the artificial model while monitoring all patient parameters and data in this operation. The doctors removed both ventricles from the patient's heart during the complex surgery, leaving the atria, aorta, and pulmonary artery intact. They then implanted the artificial heart connections and placed the new device, which consisted of two artificial ventricles that replaced the previously excised biological ones. The implanted device was linked to an external portable console through two tubes, which generated the impulses transmitted via an air system.

The following days after the surgery, the patient was unable to return home because he had a renal failure that did not completely recover. The patient had a transplant of another person's biological heart after spending four months in hospital with the artificial heart. Unfortunately, the young man died of another disease after only a month with his new heart.

7. INTERVIEW WITH A SYNCARDIA MEMBER, STEVEN LANGFORD

Figure 21. Steven Langford
https://www.zdnet.com/article/artificial-heart-goes-portable/

Concerning the SynCardia Artificial Heart, could you please explain to me the most notable facts?

- *The overarching concept of the artificial heart is to provide a way for people who are at high risk of dying from heart disease, a pathway to improving their health and to get well for receiving a heart transplant. Many times, a person who needs a heart transplant will die from the effects of the poor cardiac output from a diseased heart. A matching heart may not be immediately available. The kidney, liver, lungs and digestive systems all suffer and begin to deteriorate and begin to malfunction. These vital organs are still healthy if they receive the proper cardiac output. By restoring the blood flow to these vital organs, the health of these organs can be restored, and the person can be a better candidate for a human heart transplant. Many patients have waited years before getting the correct match for a human transplant, and by that time they are essentially healthy individuals who do very* *well with the heart transplant. There is no doubt that this is a high-risk procedure and a transplant is a high-risk procedure, however, there is no alternative and without the artificial heart and a subsequent transplant, there is no hope of survival. There is a great satisfaction to see the people and the families that go through this process be restored to their health and to go on with a normal and fulfilling life with their loved ones.*

As for medicine, it is clear that this type of heart has greatly facilitated the process of transplanting this organ. However, could you explain to me the process that doctors must follow when using this product?

- *The underlying problem is that the person is suffering from the effects of low cardiac output due to heart disease. The process involves the removal of the dying natural heart, and we replace it with the artificial heart. The natural heart pumps blood to the lungs from the right ventricle and to the body from the left ventricle. The upper chambers of a natural heart are the atria. These chambers are the collection reservoirs for the blood returning to the natural heart. When using the artificial heart, the upper atrial chambers remain as the collection chambers of the blood returning to the heart. The ventricles that do the pumping of the blood are removed and replaced with plastic ventricles. The plastic ventricles are each about the size of a tennis ball, and inside each ventricle is a balloon-like membrane that can be inflated. When the balloon-like structure (called a diaphragm) is inflated, the blood that has entered the ventricle is pushed out of the ventricle to the lungs (right ventricle) and to the body (left ventricle). The direction of the blood flow is controlled by tilting disk valves that allow unidirectional blood flow. The pumping action is very similar to the normal pumping action of a natural heart. So, the answer is that the diseased ventricles are surgically removed, and the artificial heart is connected to where the heart was. Connector tubes are sewn to the native tissue and the artificial ventricles are snapped onto these connectors. Because the ventricles are made of biocompatible plastic, polyurethane, there is no rejection involved.*

If we talk about improving people's lives, this product is a great example. But, how can it help them in terms of their daily life? From your point of view, what it is like or will be like living with an artificial heart?

- *These patients are suffering from biventricular failure. Many of them are on life support systems to keep them alive before the implant of the artificial heart. Many are considered "cardiac cripples" and most cannot even get out of bed. Within a day or two most people can stand and walk a few steps and within a week they are walking 100 meters! By week three, most are able to go to a portable driver system, and they prepare to go home while they wait for a heart transplant. Typically, they take some medication to manage their blood pressure and to be mildly anticoagulated (blood thinners to reduce the risk of blood clots). The artificial heart allows the person to return to near normal health status. Their big constraint is that they are always attached to the backpack that supplies the pulses of air that make their artificial heart pump blood. Most patients are at home for only a few months while they recover, get stronger and wait for the matching donor heart. All normal activities are resumed, except they cannot go swimming! Other than swimming, there are very few restrictions to the patients' activities. Many people have returned to work after going back home. The big adjustment is that the patient is always attached to the Freedom Driver system. They must always be aware of the power to their backpack that holds the Freedom Driver. They plug their Driver into the home power when sleeping and during the day they have 2-3 hours of time while unplugged, then they need to switch in fresh batteries. The patient generally has six batteries. They get very accustomed to managing their power and looking for plugs at restaurants and shopping centres!*

Obviously, we don't just need to consider the medical field when we talk about this artificial organ. Both chemistry and physics play a major role in the manufacture and operation of this product. How do these two fields of science intervene?

- *This is an excellent observation. There is an enormous amount of technology to be considered with the artificial heart. First of all, the plastic must be biocompatible and not react to the blood and not cause a clotting action with the blood. This is a huge part of the chemistry of technology. Next, the material must be extremely durable. The performance cannot change or wear out over time. There are so* *many chemicals in human blood, and many materials will degrade when implanted in the body. Next, we must assure that each heart is constructed exactly according to the specifications. Each batch of plastic must be tested with several tests to assure that it meets the specification. During construction and assembly, each step is done very carefully and then inspected by two or three other people to make certain it is perfect. The pathway the blood takes in the heart is important by providing the direction to the flow through the valves that will cause the circulation within the ventricle to wash over all surfaces inside the ventricle to prevent clots from forming. Yes, there is an extreme amount of technology in chemistry, physics and engineering.*

Like everything, this project has some shortcomings. Always having to carry a bag which supplies the energy needed for this artificial organ so that it works properly is a big disadvantage. Is an attempt being made to find a solution to this problem so that this product is not only useful during transplants but also to forever replace the heart organ that some people have atrophied?

- *Yes, it is a disadvantage, but it is only temporary until the person gets a heart transplant. People adapt quickly, and it becomes a part of their normal routine. The important thing to remember is that there is no other way that these people can live. Their lives are different while on the artificial heart, but they feel as well as you and I, and the inconvenience is typically for under a year until they get their heart transplant. We have one patient who was not eligible to get a transplant, and he lived in his apartment with his wife for 6 years and 9 months. He passed away this past July. His grateful wife sent me a very nice email thanking us for such a technology that allowed them almost seven years of enjoyable life together while on the artificial heart. We and a few other research companies are looking for advances in technology that will offer a permanent technology. So far, most solutions are about a 5-year solution. The heart consumes a great amount of energy. We continue to research to improve this. Currently, the best solution is a heart transplant, and there are more people waiting for a transplant than there are donor hearts available.*

Does Syncardia plan to design and manufacture another artificial organ?

- *We do have another heart design underdevelopment. The design and testing are huge projects that demand many resources in engineering, physics, chemistry, durability, and physical compatibility. These are no trivial problems and are very expensive to research and develop. Fortunately, we have learned so much from the pneumatic artificial heart that is the only heart in the world that has been able to be commercially available and have the health ministry approval around the world.*

8. INTERVIEW WITH A BELLVITGE CARDIOLOGIST, DR. GONZÁLEZ COSTELLO

Dr. José González Costello, president of the Heart Failure Association of the Spanish Society of Cardiology (SEC) and professional in Cardiology Intensive Care in the Heart Disease Area at Hospital Bellvitge.

Figure 22. Dr. José González Costello
https://cardiologiabellvitge.cat/index.php/component/search/?searchword=josé%20gonzález%20costello&searchphrase=all&Itemid=935

Firstly, could you briefly explain to me what your job position consists of, that is, what is your day-to-day life as a doctor in the heart failure and heart transplant unit?

- *I am a cardiologist, cardiology specialist, and I have been engaged in advanced heart failure and heart transplantation since 2008. I had previously worked in the cardiology and coronary unit, but was always quite focused on the topic of heart failure. I was educated in circulatory mechanical support at Columbia University, in the United States of America, for a year, and then I came back here. My day-to-day life is to see patients with advanced heart failure both in the cardiology plant and in the coronary unit or intensive care unit. These are patients with unusual heart* *failure who have evolved or who have not responded to the usual treatment, and we think they need additional therapy. One of these therapies that we can offer them is mechanical circulatory support or heart transplantation, but most patients with medical treatment or with synchronous pacemaker treatment can avoid requiring the other two devices mentioned above. In addition, I see these patients in outpatient clinics and I also deal specifically with patients with cardiac sarcoidosis.*

Do you think that cardiovascular diseases are one of the leading causes of death in Spain?

- *It is a fact. Specifically speaking of heart failure, it has a risk of mortality which is higher than that of most cancers. So, this gives you an idea of the high mortality that heart failure has in particular, and this should be taken into account when thinking about this type of disease. For example, heart failure is one of the leading causes of hospital admission globally.*

If we focus on the field of the Total Artificial Heart, could you explain to me what process professionals follow when determining which patient is best suited to be a recipient?

- *The TAH is a device that completely replaces the heart. This one has two atria, two ventricles and four valves. It is a support which is pneumatic, that ejects the blood and makes the patient have pulsatility, and is a device used before transplantation. It is a type of mechanical support that we use very little in cardiology. So that you have an idea, only two have been put in total in Spain. Why? Because we have other pre-transplant alternatives that are cheaper and less complex than TAH, which is very expensive, and the surgery required is very complex; subsequent transplantation also requires complex surgery and the management of these patients is also very complex. We put one and it was a complex experience. What we use the most is a continuous flow left ventricular assistance. We put between six and eight a year, which is the highest rate of implants in all of Spain. This is a very old device dating back to the eighties, and it is a device that works and is used, although it is only required if both sides of the heart fail. In most cases, if it is only this side that fails, and we have a correct right ventricle, we can put the left* *ventricular assistance devices in continuous flow. The implantation of these devices is much simpler, they have much longer durability, they give fewer complications, and they can even be used either as a bridge for a heart transplant or as a targeted therapy. This means that we use this machine in patients who are not candidates for a heart transplant as a definitive treatment. This type of device is much more useful and, above all, more practical and reliable. When both ventricles fail, we either go directly to the transplant or use ventricular short-duration assist that can support both ventricles. Initially, everyone who had the TAH had to stay hospitalized, but now some consoles allow the patient to go home. In Spain, where we have fairly high availability of organs, we can use this short-term support strategy prior to transplantation.*

Can you describe to me the process involved in the implementation of these types of mechanisms?

- *In a simple way, it is basically removing the two ventricles and part of the two atria and sewing the two atria into the atria of the artificial heart. Next, sewing the grafts from the aorta and pulmonary artery that come out of the artificial heart into the biological arteries in question. So basically, what you have is a total replacement of the heart, but it becomes a machine with a pulsating pump where air is injected and the artificial heart pumps blood through a membrane. Above all, the risk of this type of intervention is, first, that the thoracic cavity may contain this TAH, as a minimum chest volume is needed and, subsequently, the risk of bleeding and haemolysis. Obviously, when you completely replace some part, you depend on this device and, if it fails at any time, then you are lost.*

As for the damaged biological heart, does it have any practical utility after extraction?

- *None.*

Have you ever been involved in the implementation of a Total Artificial SynCardia heart? And if so, could you tell me about your experience in that regard?

- *I participated in one. The recipient was a young heart transplant candidate who had severe biventricular dysfunction and pulmonary hypertension. We put this device on before the transplant. The surgery went well, even though he bled after* *the surgery. Having a TAH that contains plastic and mechanical valves requires anticoagulation and antiplatelet. This treatment means that, especially right after surgery, there is a risk of bleeding. He bled, needed reintervention, and then the thing stabilized. This patient was relatively well, he was not discharged at any time because he had a kidney failure that did not recover completely, and this made him unable to go home with the device. The TAH was transplanted four months after the implant, the surgery went well, the transplant went well but after a month, unfortunately, the patient died of another disease. And this is the experience we have with this device, with SynCardia.*

In reference to the postoperative period, which type of treatment should be applied to patients?

- *Basically, anticoagulant and antiplatelet treatment, treatment if the patient is hypertensive,... Apart from that, few treatments are added because the device works basically alone. You have to program the heart rate at which you want it to beat, that it is usually high, as the ventricles are rather small and a high heart rate is needed. Apart from that, the follow-up is quite conventional, as in any patient with heart disease. Control of blood pressure, sugar, cholesterol and especially the issue of anticoagulation, which is the most important so that there is no thrombosis and that there may be an embolism or, conversely, some bleeding problem if the anticoagulation is excessive.*

I have recently been able to see that another company, Carmat, has also proposed a new type of TAH, do you have any information on this issue?

- *The Carmat is a fully biological device that eliminates the issue of mechanical valves and is supposedly an artificial heart that has much greater biocompatibility compared to SynCardia. The Carmat has been on the market for some time, but it is still in the process of assessing its feasibility. Some published articles have recently come out, again it has been used as a bridge for transplantation, and it seems the results are not bad at all. The first patients had results that were not good and then, the device had to be redesigned. We know it has been redesigned and with this new design we would have it available if we wanted to put a Carmat. We have not put any yet, but we have this availability, and it would be a matter of* *trying it and see how it goes. This is a device that seems very interesting, in the sense that it is functionally very similar to that of SynCardia, as the patient can go home after the operation, but the idea is that it is more biologically compatible. However, there are less than 30 implants of Carmat in the world, and this is a very small number.*

What do you think are the main advantages and disadvantages of the TAH?

- *I think total heart replacement is a complex, feasible thing, but doing it in many patients is something that if we have heart transplantation where we only have to treat the rejection, obviously transplantation is still the treatment of choice in these patients who need a heart replacement. Given this therapy where we have thousands of cases done with survivals of more than thirty years, the TAH still has a long way to go to have this durability and these clinical results. Obviously, if you see a patient with a heart transplant on the street it's the same as you or me, but for those who go with SynCardia, first, we'll hear some noises, because it has four valves that are running all the time and then because the person carries the machine, can't bathe or shower, has the cables coming out of it,… I think that it is useful as a temporary thing and, in fact, the continuous-flow left ventricular assistance devices are much simpler systems and sometimes, the simplest is the most useful. The Carmat or the SynCardia are very complex devices, and sometimes such complexity makes them not applicable to the usual clinical practice and only in very selected cases.*

How do you think heart transplant technology will evolve in the future? Is it possible that one day a completely reliable and autonomous artificial heart will be designed?

- *I think technology should evolve. I don't think TAH is the future, I think these are devices that will become obsolete over time. The future is surely in tissue engineering. If we can generate tissues, hearts that are much more compatible from the point of view of hemocompatibility and immunocompatibility, this would be the ideal world. Imagine that from a pig, which has a heart very similar to ours, we could generate a heart that is designed for a person we know needs a heart transplant and that could be hemocompatible. Even if we can generate a heart artificially with bioengineering, I think this should be the future, as this removes the* *wires, the tubes coming out of the body that can become infected, mechanical devices that can have a problem with its operation. If we have biological tissues, they solve these problems for us, which is ideal.*

Finally, do you think that the technology used in this mechanism would be applicable to other organs and diseases?

- *I think it is unlikely with other organs, as there is only one pump, the heart, that beats and expels the blood that reaches it. On the other hand, a lung, a liver, a kidney, a pancreas, have nothing to do. So I don't see this technology as applicable in the world of medicine, maybe in the field of engineering or some other discipline. As for other diseases, this is applicable in heart failure, which is when the heart does not function as it should. When it stops working completely, obviously, we have tools that can help us get the patient out of death and then come up with other alternatives. Obviously, this artificial heart technology consists of hydraulic pumps, a technology that is not particularly new, but has been known for a long time. Maybe the Carmat is a little different, as it tries to adapt to the ability to exercise, it does have certain things that are a little more worked out, but there is still a long way to go for the Carmat, for example, to be applicable to a significant percentage of patients with heart failure.*

9. VENTRICULAR ASSIST DEVICES

On many occasions, as Dr. González Costello commented to me, patients with cardiovascular abnormalities have mostly the left ventricle affected. In the same vein, the doctor explained to me that in most of these cases, professionals use ventricular assist devices, such as LVADs when the affected ventricle is the left one, RVADs for the right ventricle, and BiVADs to assist both ventricles. The type of VAD implanted is determined by the underlying cardiac disease and the pulmonary arterial resistance, which influences the right ventricle's workload.

Long-term implanted VAD devices are intended to keep the patient alive and ensure a good quality of life while awaiting a heart transplant (bridge to transplant). Other devices can be used permanently because the characteristics of the patient do not make it suitable for a heart transplantation (destination therapy) and, in some occasions, they are used only to support the heart while it recovers from some other disease (bridge to recovery). In any of these cases, some risks must be taken into account. In the first place, we find blood clots, which can slow or block normal blood flow through the heart and lead to stroke or heart attack, or cause the VAD to stop working. In addition to that, there may be bleeding, device malfunctions and infection due to the control unit for the VAD which is located outside the body and connected through a port in the skin.

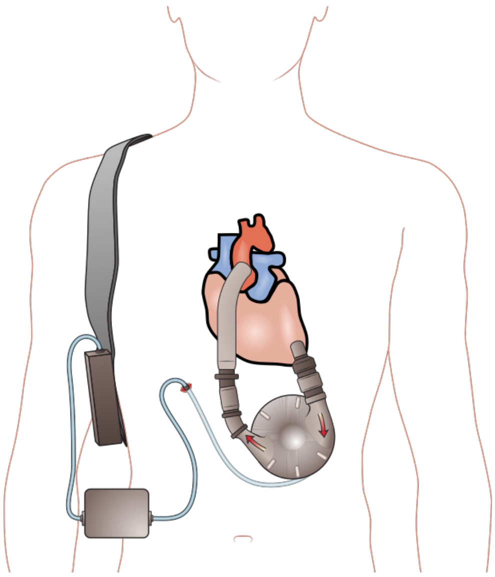
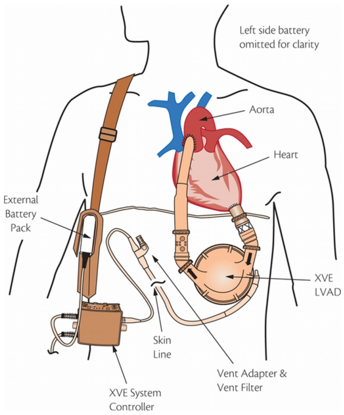
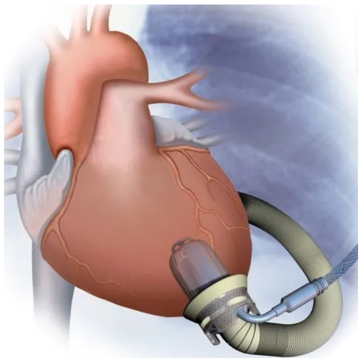
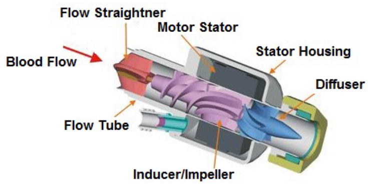


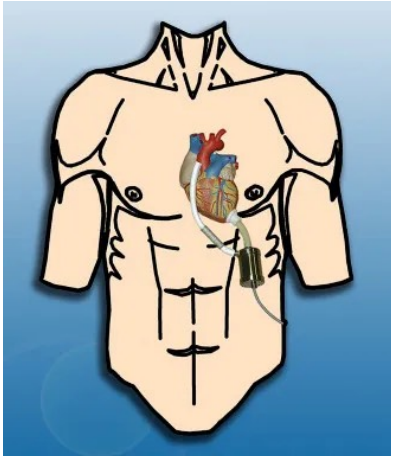
Figure 23. LVAD
https://es.wikipedia.org/wiki/Dispositivo_de_asistencia_ventricular#Lista_de_dispositivos_VAD_implantables

Device	Manufacturer	Type	Figure
Novacor	World Heart	Pulsatile	 Figure 24 https://novacor.com/products/r-test-4/
HeartMate II	Thoratec	Axial continuous flow with ball bearings	 Figure 25 https://www.dicardiology.com/content/thoratec-recalls-heartmate-ii-lvad-due-outflow-graft-kinks

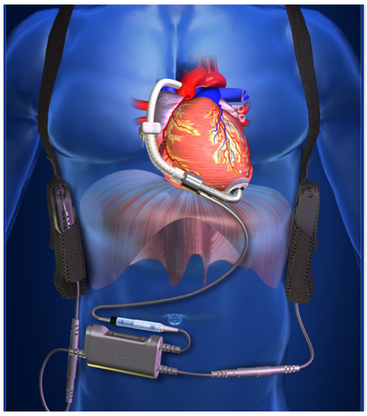
Device	Manufacturer	Type	Figure
HeartMateXVE	Thoratec	Pulsatile	 Figure 26 https://www.heart.org/en/news/2018/06/13/the-past-present-and-future-of-the-device-keeping-alive-carew-thousands-of-hf-patients
HeartMate III	Thoratec	Axial continuous flow, magnetically suspended	 Figure 27 http://www.siacardio.com/consejos/cirugia-cardiovascular/editoriales-cirugia-cardiovascular/momentum-3-resultado-a-2-anos-en-pacientes-tratados-con-heartmate-3/

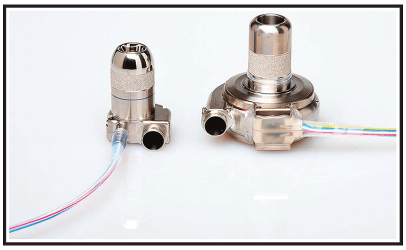
Device	Manufacturer	Type	Figure
Incor	Berlin Heart	Axial continuous flow, magnetically suspended	 Figure 28 https://www.researchgate.net/figure/Berlin-Heart-Incor-Source-Berlin-Heart-wwwberlinheartcom-accessed-December-31_fig8_280717404
Excor Pediatric	Berlin Heart	Pulsatile, outer membrane designed for children	 Figure 29 https://www.berlinheart.com/medical-professionals/excorr-pediatric/

Device	Manufacturer	Type	Figure
Jarvik 2000	Jarvik Heart	Axil continuous flow with ceramic bearings	 Figure 30 https://www.jarvikheart.com/products/
MicroMed DeBakey VAD	MicroMed	Axil continuous flow with ceramic bearings	 Figure 31 https://www.researchgate.net/figure/The-MicroMed-deBakey-VAD_fig7_281618245
VentrAssist	Ventracor	Continuous flow wih centrifugal rotor, hydrodynamically suspended	 Figure 32 https://collection.maas.museum/object/383167

Device	Manufacturer	Type	Figure
MiTiHeart LVAD	MiTiHeart Corporation	Continuous flow wih centrifugal rotor, magnetically suspended	 Figure 33 https://mitiheart.com/?page_id=127
HVAD	HeartWare (now Medtronic)	A third generation miniature device with a hydro-magnetically suspended centrifugal rotor that can be placed on the pericardium.	 Figure 34 https://www.researchgate.net/figure/Illustration-of-the-HeartWare-HVAD-system-Courtesy-of-HeartWare-International-Inc_fig10_319419464

Device	Manufacturer	Type	Figure
DuraHeart	Terumo Heart	Centrifuge, magnetic levitation	 Figure 35 https://www.terumo.com/pressrelease/detail/20101208/381/index.html
Thoratec PVAD (Paracorporeal Ventricular Assist Device)	Thoratec	Pulsatile	 Figure 36 https://www.researchgate.net/figure/Thoractec-Ventricular-Assist-device-A-and-Berlin-Heart-Excor-B-shown-in-the-range-of_fig1_242334009

Device	Manufacturer	Type	Figure
IVAD (Implantable Ventricular Assist Device)	Thoratec	Pulsatile	 Figure 37 https://www.researchgate.net/figure/The-Thoratec-IVAD-titanium-alloy-pump-and-driveline-Courtesy-of-Thoratec-Corporation_fig4_295250573
HeartAssist5	ReliantHeart	Conttinuous flow driven by an axial flow rotor	 Figure 38 https://ww1.prweb.com/prfiles/2013/11/05/11315432/ReliantHeart%20HeartAssist5.png

Device	Manufacturer	Type	Figure
MVAD	HeartWare	Development-stage miniature ventricular assist device, approximately one-third the size of HeartWare's HVAD pump	 Figure 39 https://www.researchgate.net/figure/Size-comparison-of-the-MVAD-PumpVThe-HeartWare-HVAD-Pump-right-weighs-160-g-compared_fig1_330109872
FiVAD	Leviticus Cardio	Versatile wireless system for LVAD.	 Figure 40 https://www.trendlines.com/fda-designates-leviticus-cardios-fivad-as-a-breakthrough-device/

10. CONCLUSION

After this long but rewarding learning journey, I have been able to study in great depth a subject of research which is practically unknown to most people. In the same sense, my major aim, to inform myself on the most important aspects of the artificial heart, has been accomplished with great interest and self-satisfaction. Thanks to a large amount of information searched and chosen on the web, the knowledge gained from professionals working in this field of science and the books and journals consulted, I have been able to carry out a great research project, which you are about to finish reading.

As it has always been stated, I believe that following healthy habits, such as a nutritious diet and sports sessions, decreases the chances of suffering from most existing illnesses. However, it is important to note that health encompasses the combination of systems present in the human body and that talking about this topic is not as simple as it may seem.

From birth, and although each organ has its main and equally important functions, the heart is responsible for pumping and supplying blood to all organs, tissues… Despite this, more and more people are affected by cardiovascular problems, some of these mild and others more serious. In this same sense, having an artificial product that can replace the natural and original organ in case of deficiency is a great breakthrough for science. The opportunities for this product to increase patients' life expectancy or make it easier to wait for a transplant are clear advantages when it comes to the artificial heart. However, it is important to note that we do not yet have a mechanism that allows patients to be self-sufficient, as they always depend on sources of electricity supply. For this reason, the title refers to the path we are building to achieve a bionic or artificial chorus that works autonomously, an artificial organ that can completely replace the original one.

Conducting the research work has allowed me to enjoy an insight into the world of medical engineering and cardiology while contacting professionals who provided me with the information I needed. On the other hand, it is important to mention that the topic treated in this research work is directly related to the professional career I would like to pursue. In this sense, it has been a motivating experience which has taught me to develop my scientific knowledge and to acquire new skills that I did not know I had. Having conducted this research project has convinced me more that my future is linked to the world of medicine, a world of help and humanitarian work.

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12. ABBREVIATIONS

1. AI: Artificial Intelligence
2. BiVAD: Biventricular Assist Device
3. CSIC-UMH: Neurobiology Unit of the Institute of Neuroscience of Alicante
4. CT: Computed tomography
5. EEC: Electronic Engine Control
6. FDA: U.S. Food and Drug Administration
7. LVAD: Left Ventricular Assist Device
8. MSEE: Materials Science and Electrical Engineering
9. PET-P: Polyethylene Terephthalate
10. pH: Potential of Hydrogen or Power of Hydrogen
11. PTFE: Polytetrafluoroethylene
12. RVAD: Right Ventricular Assist Device
13. TAH: Total Artificial Heart
14. TET: Transcutaneous Energy Transmission system
15. VAD: Ventricular Assist Device
16. 3D: Three Dimensional

ANNEXES

Annex I

ara

SOCIETAT | 18/06/2019

Bellvitge implanta per primera vegada un cor artificial total

El pacient, que no podia optar pel trasplantament, està en situació estable

Cèlia Codina

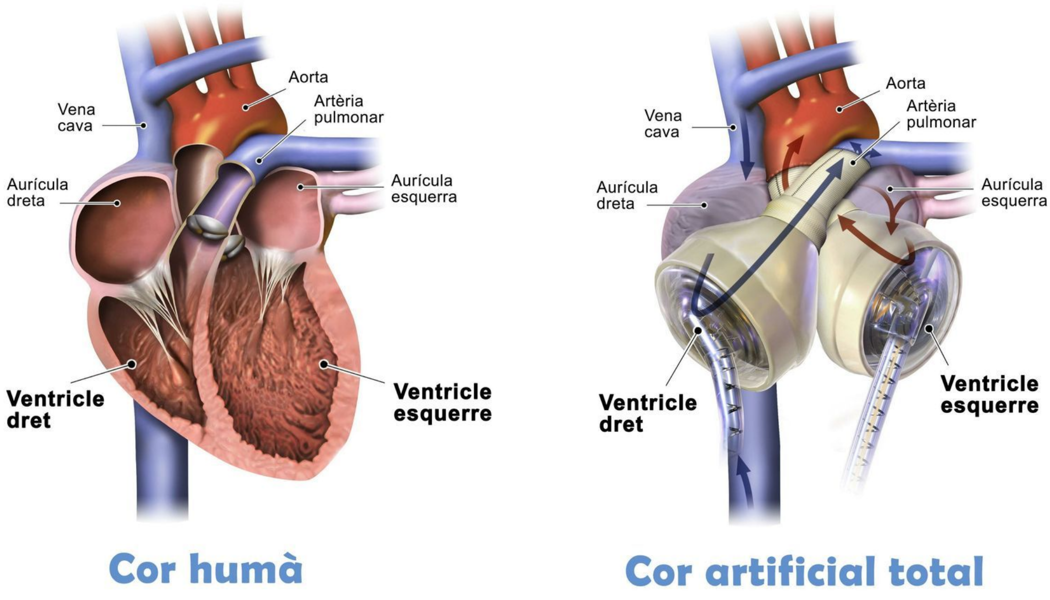
Imatge de la implantació d'un cor artificial total a l'Hospital de Bellvitge ACN

BARCELONA L'Hospital Universitari de Bellvitge ha implantat un cor artificial total per primera vegada. Es tracta d'una tècnica complexa i d'una intervenció excepcional que només s'havia realitzat amb èxit una vegada a Espanya. L'operació s'ha fet en un pacient amb fallada dels dos ventricles del cor i hipertensió pulmonar, una condició que no permet optar pel trasplantament.

L'objectiu de la intervenció és que el dispositiu artificial substitueixi la funció dels dos ventricles, i permeti normalitzar la tensió arterial pulmonar del pacient, de manera que, d'aquí uns mesos, pugui sotmetre's a un trasplantament cardíac definitiu. La implantació d'aquest cor artificial ha permès, doncs, millorar un pronòstic que, si no s'optés per aquesta tècnica, seria "nefast", en paraules del cirurgià del centre hospitalari Daniel Ortiz. Actualment el pacient, operat el 27 de maig passat, està ingressat a l'Hospital de Bellvitge en situació estable.

L'Hospital de Bellvitge va ser el 2007 el primer d'Espanya a col·locar un cor artificial a un pacient ingressat que no podia rebre trasplantament. En aquest cas, es tractava d'una intervenció que només substituïa la funció d'un dels dos ventricles. Des d'aleshores, el centre ha fet 24 assistències com aquesta, la xifra més alta registrada a tot l'Estat. En 10 d'aquests casos, el pacient ha rebut posteriorment un trasplantament de cor amb èxit i, en 10 casos més, l'afectat fa vida al seu domicili amb el dispositiu implantat a l'espera de poder rebre l'òrgan del donant. En els dos pacients restants, ha sigut una implantació que s'ha plantejat com a definitiva.

No va ser fins al 2011 que es va aconseguir col·locar un cor artificial d'aquestes característiques (en què només se substituïa un dels ventricles) a un pacient que va poder fer vida normal a casa després de la intervenció. El malalt patia una insuficiència cardíaca avançada des que el 1999 va tenir un infart que l'obligava a ingressar repetidament a l'hospital. Els metges van optar per aquesta solució ventricular mecànica perquè acabava de superar un càncer, situació que contraindica l'operació. Es tractava del primer dispositiu de llarga durada, amb una vida de fins a tres anys.



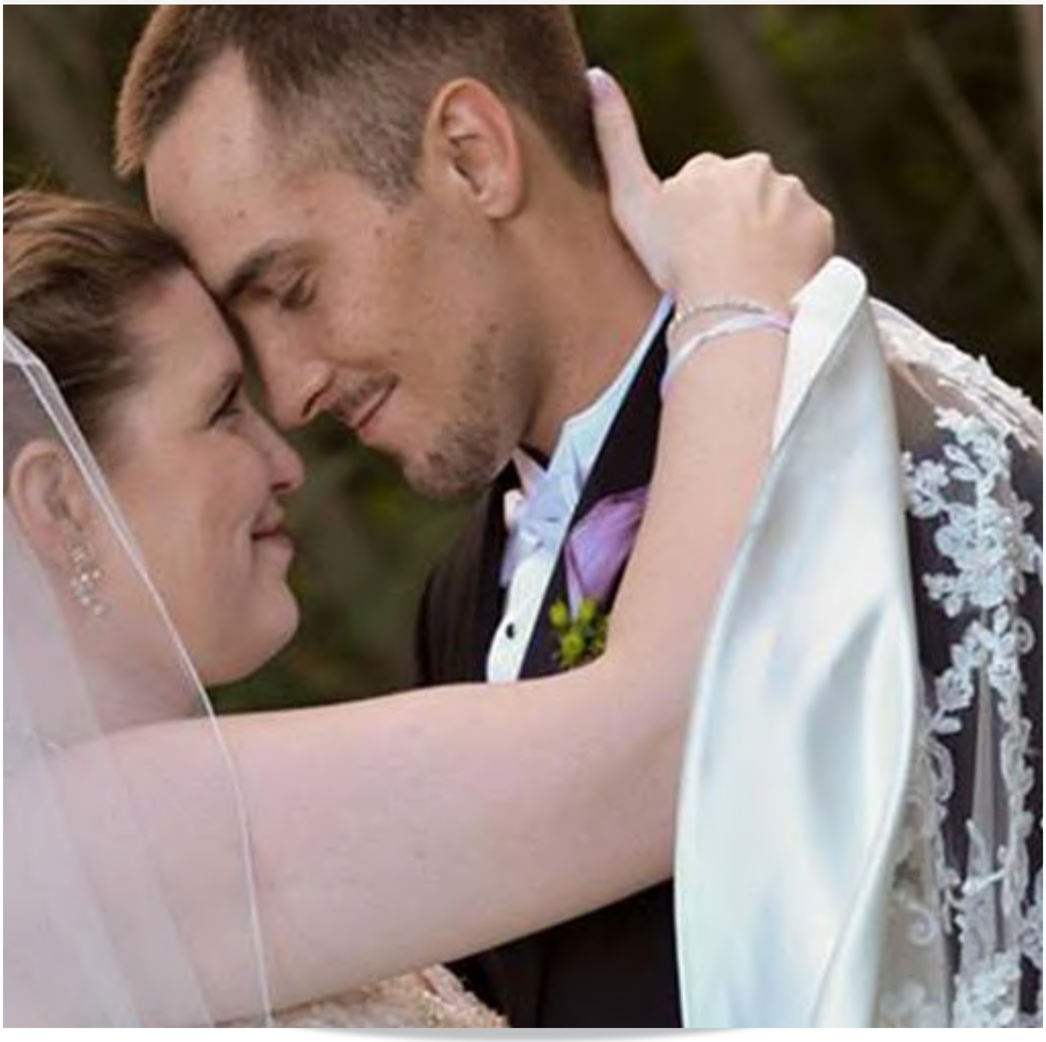
Bellvitge implanta per primera vegada un cor artificial total ARA

La implantació d'un cor artificial total com la que s'ha fet per primer cop ara és una operació d'alta complexitat. Consisteix en retirar els dos ventricles del cor del pacient per adjuntar-hi el nou dispositiu, que funciona a través d'un sistema d'aire i buits que activa el mecanisme de bombament de la sang. L'activitat del cor artificial és controlada a través d'una petita consola externa connectada al dispositiu a través de dos tubs. El pacient ha de portar aquest aparell sempre a sobre, i procurar que no s'acabin les dues bateries que inclou.

El temps d'espera per als trasplantaments s'està allargant, i es calcula que un 20% dels receptors necessitaran un cor artificial. Les innovacions en aquest terreny suposen una nova esperança per a aquells que esperen un trasplantament o que no el poden rebre de manera immediata per qüestions de salut. Per cost i complexitat, però, no tots els pacients són aptes per a aquestes intervencions.

Annex II

SynCardia



DANIELLE, 22

Danielle, 22, was born with Marfan syndrome, a genetic disorder that affects connective tissue. When her aorta became enlarged — a common complication of the disease — Danielle underwent surgery to receive an aortic graft and a pacemaker. While she felt fine after the surgery, her energy levels never returned to normal. An active member of the dance team in high school, Danielle felt fatigued and took several long naps each day.

Danielle's doctor sent her to the hospital immediately. Tests for pneumonia revealed that a massive infection of her heart had led to endocarditis, inflammation of the inside lining of the heart chambers and valves.

"I was told the infection was like ping pong balls all over my heart, the pacemaker wires and the valves," said Danielle. The infection had also spread to her kidneys, spleen and lung.

After a heavy regimen of antibiotics, surgeons hoped to repair the damage to her heart, but while lying sedated in the operating room awaiting surgery, Danielle's heart stopped. Luckily, surgeons were able to quickly transfer her to a bypass machine, saving her vital organs from further damage.

Doctors gave Danielle's parents three options: do nothing, repair what they could before her organs gave out, or implant the SynCardia temporary Total Artificial Heart (TAH) to keep her alive until a donor heart became available. Knowing that their daughter could have a long and happy life ahead of her, her parents chose the TAH.

Danielle post-transplant with her husband, Chris, and their son, Aiden.

RECOVERY AND TRANSPLANT

When Danielle woke up after the implant surgery, she was shocked to find herself without a heart, but quickly appreciated the difference the SynCardia TAH made. “Physically, I could tell that my body was working better,” she said. “I was awake most of the day, which was a new thing for me.”

During her recovery, Danielle pushed herself to walk a little farther each day until she could traverse the entire hospital floor. Three weeks later, she learned that a donor heart had been found and she received her heart transplant. She was discharged from the hospital two weeks later.

Danielle went on to earn her associate’s degree in early childhood development, graduating with honors. Today, she continues her career as an infant teacher. In her spare time, she and her mother volunteer for Donate Life to encourage organ donation.

Thanks to the SynCardia TAH, Danielle was able to marry her longtime partner, Chris, who stood by her side throughout the transplant process, and proposed on the day of her discharge from the hospital. Soon after, they celebrated their marriage with more than 300 friends and family members.

“I would have missed all of that,” said Danielle. “Now look at what I get to look forward to because the SynCardia artificial heart was available to me. I’m so blessed with everything that’s coming. I try not to take one moment for granted.”

Annex III

INNOVATION

This AI Can Help Emergency Responders Diagnose a Heart Attack

A Danish company developed an AI that takes into account unspoken cues to diagnose heart attacks faster than ever before.

By Shelby Rogers
Jan 16, 2018

Pixabay

For every minute that someone has a heart attack, their chances of survival decreases approximately 10 percent with each minute that passes. Most heart attacks aren't properly diagnosed until first responders are on the scene, which leaves emergency operators to estimate the severity of the situation while on the phone. However, one impressive AI could be a key in diagnosing heart attacks by using clues that most human operators wouldn't pick up.

The Corti Signal is an AI developed by the company of the same name that uses real-time speech analysis with advanced machine learning to help read the context clues of critical conversations. It's been so successful that Copenhagen EMS uses it to detect cardiac arrest faster and with better accuracy.

"Conversations are noisy, implicit, and hard to understand, but they contain a goldmine of information," the company's website noted. "We have developed a multitude of deep neural networks that listen directly to a sound stream and extract the most important features. The better the quality of these features, the better our prediction and reasoning frameworks are."

The partnership between Corti and the Danish city started in 2016. For over a year, dispatchers have been able to have an assistant in triaging a patient. The AI not only listens to the caller's conversation, but it also picks up on nonverbal cues like breathing patterns. That data is synthesized by Corti against millions of earlier emergency calls for patterns.

Over **1.5 million** heart attacks and strokes happen each year in the United States alone. Cardiovascular emergencies account for one in every three deaths in the U.S. as well. Those numbers get just as difficult overseas and elsewhere around the world. However, thanks to Corti, dispatchers in Copenhagen have help in lowering those numbers.

"This is an innovation with the potential to change the way Emergency Medical Services handle emergency calls," said Freddy Lippert, the CEO of EMS Copenhagen.

With each dispatch, Corti's understanding of the emergency situations increase. Corti chief executive Andreas Cleve detailed one such story in Fast Company. A woman called for an emergency dispatch after she believed a man broke his back. However, Corti heard the patient's breathing and analyzed the rattling noises to determine that his heart had stopped and that the man had fallen because he'd gone into cardiac arrest. However, Corti was still in the learning phase of development and was unable to assist that particular dispatcher in the situation. The man did not survive, according to reports.

However, Cleve said now Corti is learning and growing, and the team is closer to getting the AI to partner with more dispatch teams around the world.

"I would always, especially when it comes to my health, prefer human contact. But augmented by a supportive system that might be using AI - that, to me, is sort of an end-game scenario."

Annex IV

SALUD

El Hospital Germans Trias implanta el primer microordenador intracardiaco de España

- Su tecnología sin batería permite la monitorización diaria y en remoto de la presión de la aurícula izquierda del corazón
- Para monitorizar la insuficiencia cardíaca
- El juez suspende el tratamiento con ozonoterapia a un paciente covid en la UCI en Vila Real

El Hospital de Can Ruti durante la implantación del microordenador cardíaco (HGTiP)

FEDE CEDÓ
BADALONA
27/08/2021 19:40 | Actualizado a 27/08/2021 20:02

Gracias al acceso a los datos clínicos del paciente en tiempo real, los profesionales sanitarios pueden proporcionar un mejor tratamiento farmacológico, estabilizar a los pacientes con antelación y reducir los posibles reingresos hospitalarios. La monitorización y atención médica a distancia representan un gran avance para los pacientes con insuficiencia cardíaca, que tienen un mayor riesgo con la Covid-19.

Un equipo de cardiólogos del Hospital Germans Trias ha implantado con éxito un nuevo dispositivo de monitorización remota del corazón. Este sensor, llamado VLAP, permite que los cardiólogos puedan hacer un seguimiento diario y a distancia de la actividad del corazón de los pacientes con insuficiencia cardíaca y, a través de la información telemétrica, detectar a tiempo real los cambios en la presión del flujo sanguíneo en la aurícula izquierda del corazón que indican un empeoramiento de la función del mismo. El dispositivo proporciona acceso a los datos de presión del corazón las 24 horas del día.

"Los pacientes que reciben este implante pueden monitorizar su enfermedad desde la comodidad de su domicilio. Este hecho es especialmente relevante en el contexto de pandemia que vivimos, en el que hemos visto clara la necesidad de potenciar la telemedicina", explica Antoni Bayés, director clínico de Cardiología de Germans Trias. Y añade: "Gracias a que tenemos acceso a los datos clínicos del paciente en tiempo real, podemos proporcionar un mejor tratamiento farmacológico, estabilizar a los pacientes con antelación, reducir los posibles reingresos hospitalarios y, en definitiva, mejor su calidad de vida".

V-LAP es un microordenador digital y sin batería que se carga a distancia desde el exterior del cuerpo del paciente y que le puede acompañar durante toda su vida. El sensor telemétrico ha sido validado en el estudio que lleva el mismo nombre, V-LAP, un ensayo clínico en el que también participan investigadores de Alemania, Italia, Israel y el Reino Unido.

Una intervencion pionera en el estado

El equipo de Hemodinámica de Germans Trias, liderado por el médico Omar AbdulJawad, realizó la primera intervención para implantar el sensor el 21 de julio. La intervención fue pionera en España y la paciente, de 80 años, fue dada de alta a los pocos días. En septiembre hay programadas dos intervenciones más.

La insuficiencia cardíaca, una enfermedad de alta prevalencia
En Cataluña hay unas 180.000 personas con insuficiencia cardíaca. Se trata de una enfermedad de alta prevalencia que, debido al aumento de la esperanza de vida y los mejores resultados obtenidos en el tratamiento de otras cardiopatías, como el infarto de miocardio, está adquiriendo cifras epidémicas en Europa, donde se calcula que hay unos 10 millones de personas afectadas. La insuficiencia cardíaca ocurre cuando el corazón no bombea suficiente sangre al resto del cuerpo. Esto provoca síntomas como falta de aliento, tos seca, sudoración en los tobillos y las piernas, aumento de peso, fatiga y ritmos cardíacos irregulares, que suponen una pérdida de la calidad de vida de los pacientes.