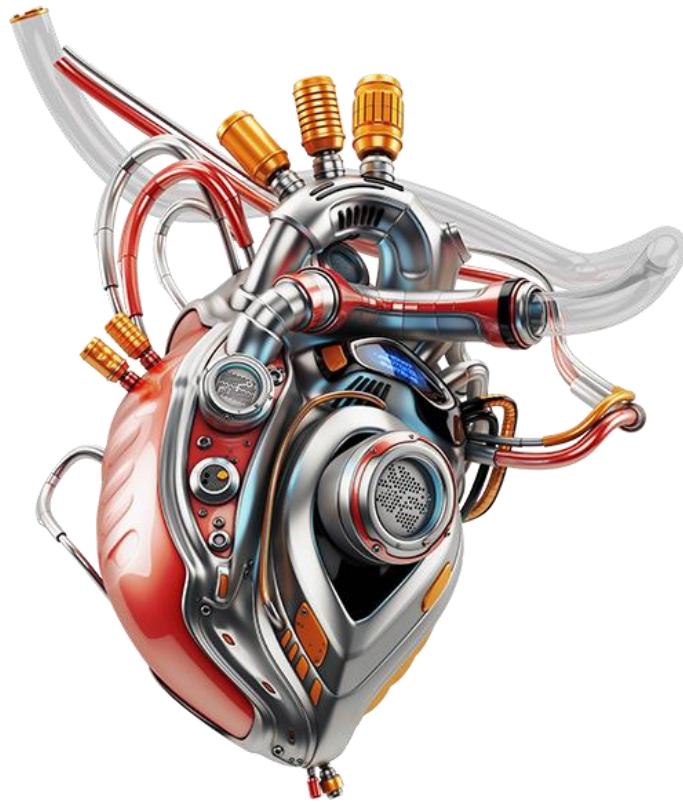


The Route to a Bionic Human Heart

How far are we and how far can we go?

A literature review



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Abstract

Cardiovascular diseases and specifically heart failure is the number one cause of death around the world. An end-stage dysfunctional heart has one treatment left: replacing the failing heart with a healthy donor. The vital function of the heart makes the corresponding pathophysiology quite extensive, including coronary artery diseases, heart failure, arrhythmia's and valve diseases. The discipline of biomimicry is asked for advice about a successful artificial human heart. Every element could theoretically have biomimetic potential alternatives. A total artificial heart is a mechanical device that is powered by an external battery pack and mimics the function of a natural heart by pumping blood through the body. The bionic future of replacing human hearts involves the use of artificial hearts or heart assist devices that can either completely replace or augment the function of a failing human heart. This comes together with an ethical debate about the limitations of technology in healthcare. Nevertheless, the device of BiVACOR is a promising bionic heart containing a spinning disc, which is magnetically levitated within a cavity to create a continuous blood flow to both the lungs and to the body simultaneously. However, mimicking a multifunctional tissue is still very challenging and will need more research and development. While a bionic heart cannot fully replicate all the functions of a healthy human heart, it can offer a promising treatment option for patients with severe heart disease, helping to improve their quality of life and overall cardiovascular function until a real donor heart becomes available.

Keywords: human heart, cardiovascular diseases / failure, heart transplantation, biomimetics, bionics

Layman's Summary (ENG)

Diseases targeting the heart or vascular system of the human body are very common. Specifically, heart failure and heart attacks are the leading causes of death around the world. A human heart that is at the end of treatments becomes eligible for a real heart transplantation. This implies the replacing of the failing heart with a healthy donor that just passed away. These surgeries are not happening regularly and cost a lot of time and money. Due to the key function of the heart in the body are the possible diseases and other complains quite extensive. For example coronary artery diseases (when the blood vessels of the heart itself are being affected). Also, arrhythmia's and valve diseases are common. The discipline of biomimicry/biomimetics is asked for advice about a successful artificial human heart, also called a bionic heart. Every element of the heart could theoretically have a biomimetic alternative. A total artificial heart is a mechanical device that is powered by an external battery pack that the patient must carry with at all the times and mimics the function of a natural heart by pumping blood through the body. This raises an ethical debate about the limitations of technology in healthcare. Nevertheless, very promising is the device of BiVACOR, an Australian company that is developing a bionic heart. However, it appears that mimicking a multifunctional and complex tissue is still very challenging and will need more research and development. While a bionic heart cannot fully replicate all the functions of a healthy human heart, it can offer a promising treatment option for patients with severe heart disease, helping to improve their quality of life and overall cardiovascular function until a real donor heart becomes available. Because a natural heart still remains the best option for transplantation.

Lekensamenvatting (NL)

Ziektes die gericht zijn op het hart of op het vasculaire systeem van het menselijk lichaam komen zeer vaak voor. Met name hartfalen en hartaanvallen zijn wereldwijd de belangrijkste doodsoorzaken. Een ziek menselijk hart dat niet meer verder behandeld kan worden komt in aanmerking voor een harttransplantatie. Dit houdt in dat het falende hart wordt vervangen door een gezonde donor die net is overleden. Deze operaties vinden niet regelmatig plaats en kosten veel tijd en geld. Door de sleutelfunctie van het hart in het lichaam zijn de mogelijke ziektes en andere klachten behoorlijk uitgebreid. Bijvoorbeeld als de kransslagaders (de bloedvaten van het hart zelf) zijn aangetast. Ook hartritmestoornissen en klepaandoeningen komen veel voor. De discipline biomimicry/biomimetica werd om advies gevraagd voor de ontwikkeling van een succesvol kunstmatig menselijk hart, ook wel een bionisch hart genoemd. Elk element van het hart zou in theorie een biomimetisch alternatief kunnen hebben. Een volledig kunsthart is een mechanisch apparaat dat wordt aangedreven door een externe batterij die de patiënt altijd bij zich moet dragen en die de functie van een natuurlijk hart nabootst door bloed door het lichaam te pompen. Tegelijkertijd roept dit een ethisch debat op over de grenzen van technologie in de gezondheidszorg. Toch is het apparaat van BiVACOR, een Australisch bedrijf dat een bionisch hart ontwikkelt, veelbelovend. Het blijkt echter dat het nabootsen van een multifunctioneel en complex weefsel nog zeer uitdagend is en dit zal meer onderzoek en ontwikkeling nodig hebben. Hoewel een bionisch hart niet alle functies van een gezond mens volledig kan repliceren, kan het een veelbelovende behandelingsoptie bieden voor patiënten met een ernstige hartaandoening. Hierdoor kan hun kwaliteit van leven en algehele cardiovasculaire functie worden verbeterd totdat er een echt donorhart beschikbaar komt. Want een natuurlijk hart blijft nog steeds de beste optie voor transplantatie.

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Introduction

Cardiovascular diseases and specifically heart failure is the number one cause of death in men and women no matter the demographic. (World Health Organization (WHO), 2021) When it comes to heart failure, there is currently only one gold standard of treatment: replacing the failing heart with a healthy donor. And while there are globally nearly 6.000 heart transplants done annually, there are about a million requests for donor hearts each year of which are 600.000 from the United States alone. The main limitation to heart transplantation is having a suitable donor heart because every patient is unique. So that also means the donor heart has to be healthy and not affected by the way of death of the donor, which is not happening frequently. (O'Rourke et al., 2015) In order to save the lives of patients dying from heart failure, innovations in artificial heart technology to replace real heart transplantations are urgently needed. (Laslett et al., 2012) If the heart of a patient with severe cardiovascular diseases could be taken out and be replaced with a machine, modern medicine would do it all the time. How close are we to permanent artificial hearts? Can we create a machine that can accurately mimics the function of a beating human heart? It would be one of the biggest accomplishments in modern medicine and will rid us of the number one cause of death in the world.

Human heart anatomy and physiology

Functionally, the heart is just a pump. Every cell in the body needs nutrition and oxygen and has to clear waste products via the blood stream driven by the heart. So, by some metrics the heart is a very simple device, but incredibly complex by others. Together with the blood vessels and blood cells this vital organ forms the vascular system, the first organ system to develop in vertebrate embryos in order to meet the needs of the rapidly developing tissues. (Lewis Wolpert et al., 2019) The heart arises from the complex morphogenesis of a mesodermal (the middle germ layer) tube. This tube consists of two layers of cells: the inner endocardium and the outer myocardium. This primitive tube already starts to pump blood at the moment of developing. At the same time, the tube elongates and turns into two chambers, creating a first atrium and ventricle. After looping of the tube along with further dividing in two atria and two ventricles divided by septa and the developing of a third layer on the outside called the epicardium, the four-chambered mammalian heart has its final structure around day 50 after fertilization. (Figure 1) Outside the epicardium, there are two thin layers of connecting tissue forming a membrane around the heart. This so called pericardium is forming the exterior of the heart. The liquid in between the epicardium and the pericardium enables the heart to pump with almost no friction. (J.A.M. Baar & C.A. Bastiaanssen, 2006)

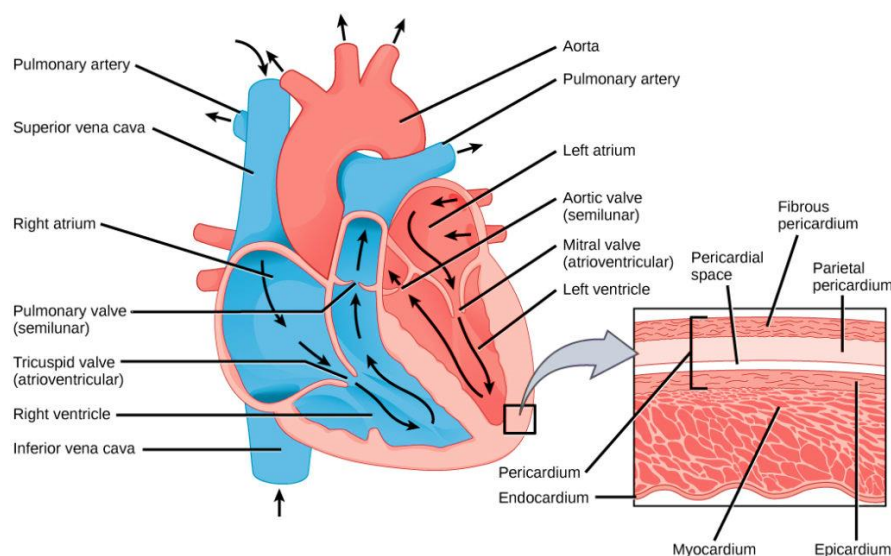


Figure 1: The human heart anatomy. (Lumen, 2023)

The human heart is around the size of a fist and is located in the protective thoracic cavity. The left and right side of the heart are divided with a septum. Every side is divided in an upper part (atrium) and a lower part (ventricle) with valves, called the tricuspid valves in the right side and the mitral valves in the left side. (Neil A. Campbell et al., 2018) Thanks to these valves, there is a one-way flow of blood through this pumping organ. The atria are the parts where the veins are connected that deliver the blood inflow. The blood outflow is going through the arteries, starting in the ventricles. The right ventricle pumps the blood to the lungs for gas exchange. After the rejuvenation in the lungs, the blood enters the left atrium and subsequently passes the left ventricle. Again, to prevent blood flowing back, there are valves between the ventricles and the arteries that leave the heart. In the right side they are called pulmonic valves, in the left side they are called aortic valves. With tendon cords (Figure 2), the papillary muscles, the valves stay in their place and close after letting the blood of a single contraction pass. (J.A.M. Baar & C.A. Bastiaanssen, 2006)

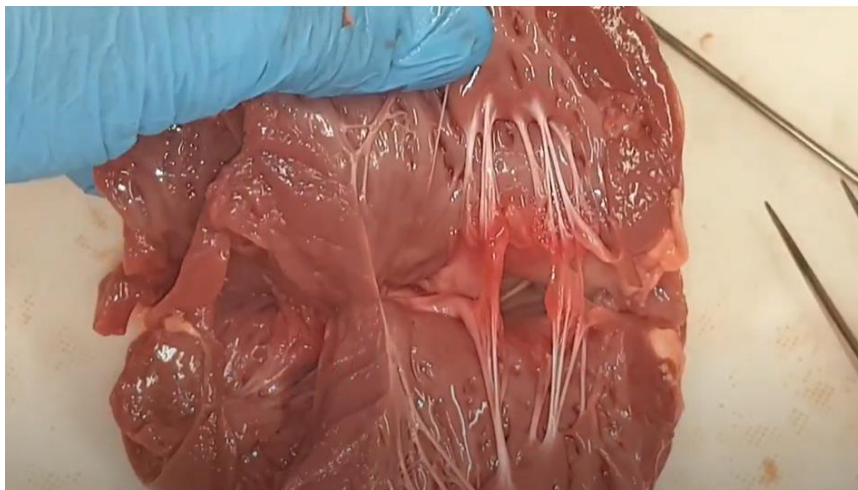


Figure 2: Ventral-dorsal cross-section of the heart of a sheep, showing the muscularity and the papillary muscles (white) attached to the inner side of the myocardium and to the valves. (Menno Bas, 2020)

The left ventricle is the most muscled part of the heart and pumps the blood to the rest of the body. The cells of cardiac muscle are called cardiomyocytes, which are highly resistant to fatigue. (Frangogiannis, 2015) This is the reason the heart does not get tired during the continuous beating process. Cardiomyocytes have around ten times more mitochondria than other muscle cells. The metabolism in the cardiomyocytes uses glucose as a fuel but can also run on free fatty acids and lactate, insuring the endurance of the heart. (Leri et al., 2015) The heart itself is nourished by the coronary arteries, which also serve as a flowing cooling mechanism to prevent the heart from overheating. They are connected originated at the base of the aorta and merge into the coronary veins which drain the “used” blood to the right atrium. (Neil A. Campbell et al., 2018)

The different layers of muscle keep the blood moving in a repeating autonomous process of repeating heartbeats. Especially the tunica media (myocardium, Figure 1) is making this possible by staying elastic for over a lifetime. The level of exercise or emotional excitement will influence the frequency of the heartbeats. Cardiomyocytes are innervated by the nervus vagus and are autonomous controlled. (Leri et al., 2015) Specialized cardiac muscle cells in the walls of the heart send signals that cause a contraction. This group of cells, called the cardiac conduction system, exist of the sinoatrial (SA) node, atrioventricular (AV) node, bundle of His, bundle branches and Purkinje fibers. (Figure 3)

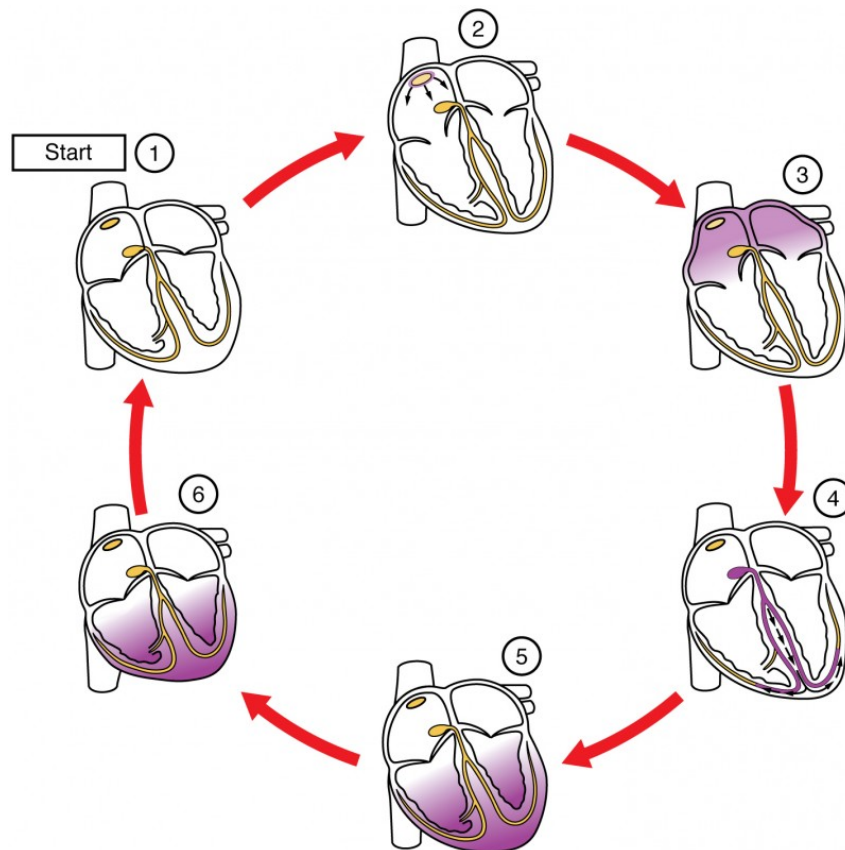


Figure 3: The cardiac conduction system (in yellow illustrated). The SA node starts the sequence by causing the atrial muscles to contract (in purple gradient illustrated), likewise called the anatomical pacemaker. From there, the signal travels to the AV node, through the bundle of His down the bundle branches and through the Purkinje fibers causing the ventricular muscles to contract. As a result, when the atria contract the ventricles are relaxed and vice versa. (Anatomy and Physiology, 2023)

This signal creates an electrical current that can be measured with electrodes stuck to the skin on the chest. The sequences can be visualized on a graph called an electrocardiogram (ECG). This is a great medical tool to see how well the cardiac conduction system works. Any changes to the ECG indicate changes in the heart physiology, possibly for example an infarction or developed hypertrophy that can cause reduced heart function. (Na et al., 2022)

Human adult heart pathology, what can go chronically wrong?

The vital function of the heart makes the corresponding pathophysiology quite extensive. Heart pathology can be developed during life or be congenital. Several factors can indicate problems with the heart, for example chest pain and difficulties with breathing. (World Health Organization (WHO), 2021) The main categories in heart pathology are discussed in the next paragraphs.

Coronary artery diseases

Diseases targeting the blood vessels that supply the heart itself are called coronary artery diseases or ischaemic heart diseases. The main cause is the forming of plaque attached to the inner layer of the walls of coronary blood vessels, leading to atherosclerosis. (Frangogiannis, 2015) Plaque is a combination of the build-up of fats, calcium, cholesterol (a waxy substance within the blood) and dying cells or cell debris. (Figure 4) The plaque can stay attached (likely to cause stable angina) or the plaque can slowly fall apart and detach into the local bloodstream (likely to cause unstable angina). Both situations will cause poor blood flow to the heart tissue or will eventually block the blood supply of the heart tissue. This leads to acute myocardial infarction, causing a heart attack.

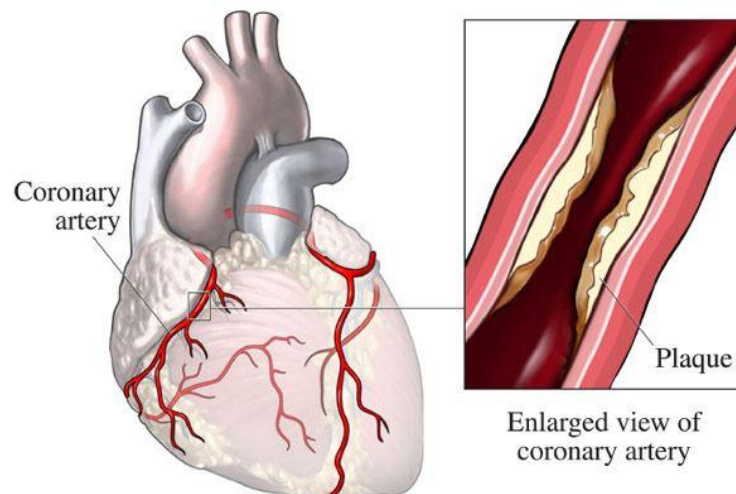


Figure 4: Coronary arteries with plaque formation. (Nucleus Medical Media, 2019)

Subsequently after a heart attack, the myocardial tissue will die via necrosis due to a lack of oxygen and other supplying, which will threaten the life of the sufferer. (Lu et al., 2015) Deviating from the norm will likely cause heart failure. Left side heart failure leads to accumulation of blood in the lungs and will eventually trigger right sided heart failure as well, when there is blood congestion in other tissues like the liver. Congestive heart failure includes both sides and will endanger the safety of the heart and thus the life of the sufferer. Heart attacks come in a spectrum of severeness.

Heart failure

Heart failure has many different causes. One of them has to do with the blood pressure. (Vera J. Goh et al., 2017) Blood is applying force on the walls of the vessels, making up the blood pressure. Due to many causes (for example not getting enough physical activity) the blood pressure can slowly become elevated over time, leading to a situation outside the normal values, called hypertension. This can cause vasculitis and cardiomyopathy of the heart. The abnormality of the heart can be dilated, hypertrophic or restrictive. The stress on the cardiomyocytes causes changes in the heart. Based on the law of Laplace that relates to blood pressure and the thickness of the wall of the heart, it will adapt to create a bigger volume (eccentric hypertrophy) or a thicker wall (concentric hypertrophy). However, these are just temporary adaptations of the heart to keep the blood flow going.

Arrhythmia

The pumping sequence of the heart creates a pulsing circulation through the arteries in the body. This gives a valuable medical parameter to show how a patient is doing. Difference in systolic pressure or diastolic pressure can indicate decreased cardiac function. (Neil A. Campbell et al., 2018) A systolic problem occurs when the heart is contracting and ejecting the blood without enough force. While a diastolic problem has to do with the moments that the heart is filled with blood prior to contraction; usually is a hypertrophy of the heart muscle causing a reduced preload.

The electric signals of the cardiac conduction system can go less and more frequent (tachycardia). When the impulses go too slow, bradyarrhythmia's are caused. (Na et al., 2022) It also can develop into an uncoordinated frequency of heartbeats. There is a wide range of different arrhythmia's and associated severeness's. The worst are ventricular arrhythmia's, where the cardiac conductive system after the AV-node is affected, because this is place where the blood is pumped with the biggest force. Most common arrhythmia, however, is fibrillation of the atria's.

Valve diseases

Diseases concerning the different valves in the heart can lead to heart failure. Infection, birth defects or age-related changes are the main factors that influence the development valve diseases. (Coffey et al., 2016) When as a result the valves do not open fully anymore, it is called valvular stenosis. Valvular regurgitation means that the valves do not close fully.

The tricuspid and pulmonary valves in the right side of the heart experience a lower pressure than the aortic and mitral valves in the left more muscular side of the heart. The valves are supposed to be specialized for the function at their specific location.

Biomimetics

Perhaps the discipline of biomimicry can help in the challenge of creating a successful artificial human heart. The author already elaborated on this in previous work. (Menno Bas, 2022) The philosophical field of biomimicry tries to apply the same design principles nature has come up with after 3.8 billion years of evolution since the first life developed on this planet. During the process of natural selection, only the best designs will stay. As reported by Dayna Baumeister and Janine Benyus, the two driving forces behind the biomimicry research field, innovative biomimetic solutions can be created for all the challenges humans are facing by integrating biology into design. (Baumeister & Benyus, 2011) Copying nature is more than just good design, it is innovation. When nature is used as a model, mentor and measure, the bio-inspired innovations are defined as more efficient and more sustainable in terms of climate impact than the custom mechanical solutions. (Dicks, 2016) "Life creates conditions conducive to life", a quote from Benyus, further explains the theory behind biomimicry. Nature does not maximize, like humans tend to do, but optimize in such a way that many future generations can still live the same life. Organisms, including the human body, have figured out over hundreds of millions of years what the best strategy is for living the most efficient way in their own context. During the still ongoing evolution of life, in every context only the most optimized designs are able to thrive. (Baumeister & Benyus, 2011)

Recreating multifunctional tissues

Although the potential innovative properties of biomimicry, there are some reasons to be sceptical. (Menno Bas, 2022) The solutions of nature are designed in a context and cover multiple functions. Optimizing a certain characteristic for the context it is functioning in can be to the detriment of the optimization of another characteristic with a different function. (Fisch, 2017) For example, muscles can create a contraction and, in that way, achieve movement. However, muscle tissue stores amino acids and glycogen and is well supplied with blood vessels so that it can produce heat when the body has a need for that. (Coffey et al., 2016) The design of the muscle tissue is optimized for a complex context and is multifunctional. To thrive as an organism the balance of all the different adaptations during evolution is optimized instead of every single adaptation on its own. For the biomimetic approach, it is important to not just copy how nature looks but be inspired by nature and mimic the functioning. (Baumeister & Benyus, 2011) Using this information, it would be interesting to discover the possible solutions nature has for the challenge of creating a successful artificial human heart. There is a synergy of the different elements of the heart. Like a soccer team that consists of individual players that can only function as a team, so they have to work together. (Haag et al., 2022)

Myocardium, the main element of the heart, forms through the process of cardiomyogenesis. (Leri et al., 2015) In the field of tissue-engineering, it is possible to derive cardiomyocytes from human induced pluripotent stem (hiPS) cells. (Ronaldson-Bouchard et al., 2019) These cultured cardiomyocytes can be used as basis for artificial heart muscle tissue. However, scaling is the problem, since it needs scaffolding to have the right properties. To date, it must be scaffolded with an abiotic construct, making a symbiotic mechanosensitive product. It is challenging to create the right 3D topology that is physiologically correct. Nevertheless, 3D bioprinting techniques are attracting much attention for modelling and creating these complex structures. (Wang et al., 2021)

After a heart attack or other damage, when the heart is still able to beat, the damaged part will develop scar tissue. This scar tissue has not the right properties at all to function as cardiac muscle. The goal with cardiomyogenesis is let the body replace the scar tissue with new cardiomyocytes when you offer them on the right spot. Moreover, zebrafish and some salamanders are able to regenerate a part of the heart after damage. (Sanz-Morejón & Mercader, 2020) This could be a huge inspiration to create something similar with humans. This way, a buffer would be created for the human heart to have accidents and still continue like usual.

The diseases and difficulties mentioned above will be treated when there is hope to cure. When medical treatment does not do the job anymore, the patient prefers transplantation. This leads to the following question:

To what extent can a bionic heart replace a dysfunctional human heart?

The state of the art in artificial heart elements

Self-assembly is something nature is very good at. Combining tissues with different properties and aspects form a kind of synergy, which makes the combined tissues and design strategies of more value than the sum of their separate values. (Haag et al., 2022) First, the next paragraphs go deeper into the individual cures and biomimetic elements for the affected heart.

Biomimetic potential: supplying the heart itself

Medications to lower blood cholesterol or blood thinners such as aspirin are only useful in early stage patients of atherosclerotic cardiovascular diseases. To prevent problems when the plaque build-up is getting worse, instead of targeting the risk factors, scientists developed a drug coded carbon nanotube that reduces and even reverses the plaque build-up itself. (Flores et al., 2020) It is already shown in mice arteries that such a nanotube does the job without causing harmful side effects. Unlike conventional drugs, nanotubes of three to three nanometres in diameter can target very specific cells and regions without having the side effect of damaging healthy cells. They are boned with special dye so they can be tracked. Then the tubes are loaded with a molecule (SHP1i) that has the ability to make the plaque substance being recognized by the immune system as foreign so that macrophages will target the dead cell debris in the plaque deposit and destroy the clogging. (Sha et al., 2022)

Another more conventional method for handling clogged corona arteries is percutaneous coronary intervention, also referred to as angioplasty. (Hoole & Bambrough, 2020) First, doctors insert a thin tube called a catheter into an artery on the wrist or leg. This tube has a deflated balloon at the end. Using X-rays as a guide, doctors direct the balloon catheter to the blocked coronary artery. Then they gently inflate the balloon which widens the artery and restores the blood flow. Finally, doctors implant a stent (using the balloon), which looks like a piece of scaffolding. This will keep the artery open.

Biomimetic potential: cardiac muscle

During a complete blockage of the blood flow to a certain part of the cardiac muscle, the cardiomyocytes of that area die, and the heart becomes seriously damaged. Even if a person survives a heart attack, the part of the heart is permanently damaged. (Lu et al., 2015) To support the damaged heart, researchers are trying to grow stem cells to form a regenerative heart patch. Healing the heart after a heart attack is challenging, it needs to keep expanding and contracting, not giving the damaged part a chance to heal. When a heart keeps beating with a damaged part will form scar tissue that keeps growing thicker and eventually keeps the heart from moving properly. Viscoelastic adhesive epicardial patches are developed to support the heart and ensure that it keeps pumping blood. (Lin et al., 2019) Using a computer model of the heart before and after a heart attack, the size and thickness of the hydrogel patches (same kind of material that contact lenses are made of) can be optimized so that it keeps expanding and contracting with the heart.

In 2019, British researchers have created a living patch of muscle cells that actually moves independently. (Jabbour et al., 2020) It supports the heart (tested on mice) and even helps the heart regenerate healthy tissue. When the researchers succeed to make it electrically and mechanically becomes a part of the heart, it is like the heart stood still for a while to recover. Stem cells have been used as a possible heart repair mechanism before, but they were injected directly into the heart, which did not give the opportunity to actually repair any tissue before the heart cleared them out. The advantage of introducing them in a patch is that they have a cellular scaffold (made of fibrin for example) that keeps them in place. (Pennisi, 2019) Reparative heart patches out of stem cells have time limitations but work long enough for the heart to reverse the damage of the heart attack. A significant percentage of people dying from heart failure does not die due to the sudden damage, but as a consequence of the bad pump function of the heart that never had the time to recover.

Biomimetic potential: heart control

As already mentioned, electrical activity within the heart controls the heart rate. When there are problems with the rhythm of the heart, especially when the heart rate is too slow, a pacemaker could maybe help. (Na et al., 2022) This small medical device comes in several different types and is placed under the skin below the collar bone. It is used to treat symptoms related to slow heart rate. A pacemaker is composed of two parts: a pulse generator and a wire. (Figure 5) The wire is passed through a vein and contacts the heart muscle. The pulse generator constantly monitors the heart rate. When it detects deviations past a certain level it sends an impulse down the wire to the heart, which causes it to beat. With a small surgery the pacemaker is implanted in the patient. The wire is passed through the vein to the right side of the heart using X-ray guidance. The pacemaker contains a battery with a lifespan of 7 to 8 years, after which it needs to be replaced. It would be interesting to let the pacemaker function through kinetic heart energy. (Bigdeli et al., 2010)

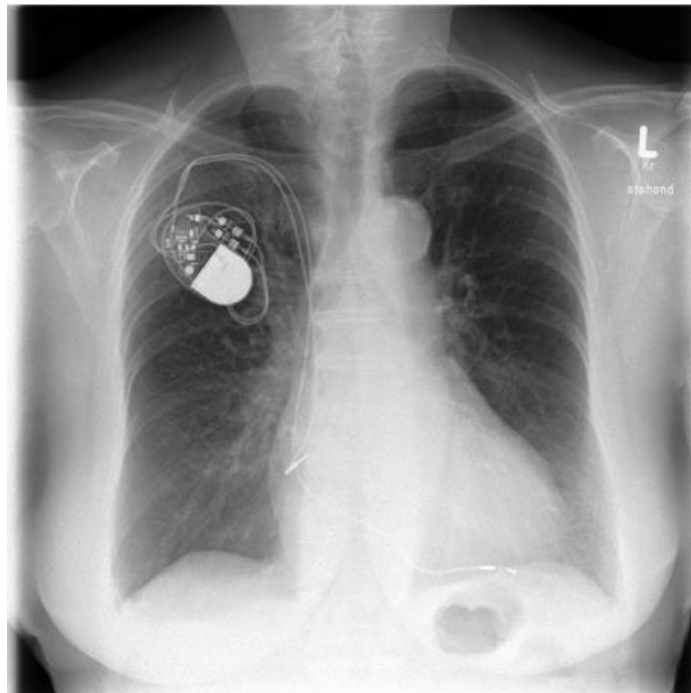


Figure 5: X-ray picture of the chest of a patient after pacemaker implantation. (Bigdeli et al., 2010)

Biomimetic potential: heart valves

Misfunctioning heart valves can be replaced by prosthetic heart valves, which are bioprosthetic or mechanical. Biological valves that are used usually comes from a pig. They have a limited life span (about 10 years), but there is no need for anticoagulation. This makes bioprosthetic valves best suitable for older patients. Mechanical valves are made of metal and have a life span of over 20 years, however because of the metal the patient need to use anticoagulation to lower the risk of blood clotting. Mechanical valves come in several different varieties, of which the so called St Jude's valves look the truest to real valves containing two discs that tilt with the blood flow. (Emery et al., 2005)

The state of the art in heart transplantation

It is over 55 years ago since the very first human-to-human heart transplantation, after a long period of experimenting. (Hunt & Haddad, 2008) At that time, there was even a lack of proper donor management. Developments in the heart transplantation research field are accelerated over the years. Donor and recipient are carefully matched, focussing on the chance of a bad immune response.

Immune tolerance after transplantation is the ultimate goal and scientists are understanding this better and better. Yet a readily available non-natural donor heart would be preferable.

Scientists have looked at the heart function and tried to mimic it. The really first artificial heart was designed by two pioneering scientists and heart surgeons, named Domingo Liotta and Michael DeBakey, and first clinically used in 1969 which lasted only for 64 hours due to the valves that broke up the blood what subsequently was causing the kidneys to fail. However, it showed that this type medically engineering was possible. The heart had bladders with one way valves, that filled and emptied with compressed air that drove the blood forward. Based on this technology there is currently a device called SynCardia, which is the world's first approved device, with much better membranes, valves, material and manufacturing techniques. (Hulman et al., 2019) Next to this, in Europe, the Carmat device has been approved as well. This device uses two electro-hydraulic pumps with integrated pressure sensors. Although, the Carmat heart is bigger than a natural heart which makes the implementation in the body more complex. (Petukhov et al., 2015) There are no other approved artificial hearts in the world right now.

However, they are currently approved only as bridge to transplant devices, so as temporary hearts that work to keep patients alive until a real donor heart becomes available. (Latrémouille et al., 2015) The longest an artificial heart has ever lasted in a patient is roughly four years. When a heart is beating 70 times a minute, that is over 100.000 times in a day and almost 40 million times in a year. The real limitation is long-term durability. In contrast to natural hearts, artificial hearts wear out and are not suitable yet for permanent replacement. Synthetical material that has to flex over and over again will eventually degrade over time. (Hunt & Haddad, 2008)

BiVACOR, a start-up from Australia, has come up with a device that hardly resembles a human heart at all. The artificial heart that they are creating in the last two decades has a spinning disc, which is magnetically levitated within a cavity to create a continuous blood flow to both the lungs and to the body simultaneously. (Figure 6) It is effectively an impeller that is inside the artificial heart. (BiVACOR, 2015) This approach is not inspired by the natural world but tries to rise above nature. Because of the perfectly controlled levitation of the (only) moving part and lack of flexing materials, mechanical wear is eliminated, and it could in theory work forever. Wide clearance gaps prevent the damage on blood cells and blood clotting. Although, the centrifugal spinning is an unknown physical force for the blood cells and is possibly not blood-friendly. The two sides of the spinning disc have a different relief to create different pressures to the lungs and to the body, just like the difference in power between the left and right side of a natural heart. However, human trials are needed to find out whether BiVACOR patients will have a pulse. Because this device propels blood without a pulse, there will likely be a lack of a pulse in the complete blood stream when implemented in a human body. It is unknown what the consequences will be for the rest of the body. For this reason, BiVACOR is already introducing pulsatility by experimenting with spinning the disc back and forth instead of constantly rotating. This artificial beat rate could even be changed, so for example when the patient is exercising the required higher beat rate could be met and while sleeping the pulse rate can be slowed down. (Emmanuel et al., 2022) In the end, these changes in heart rate need to go automatic based on blood pressure changes that occur when a patient moves from one type of physical activity to another.

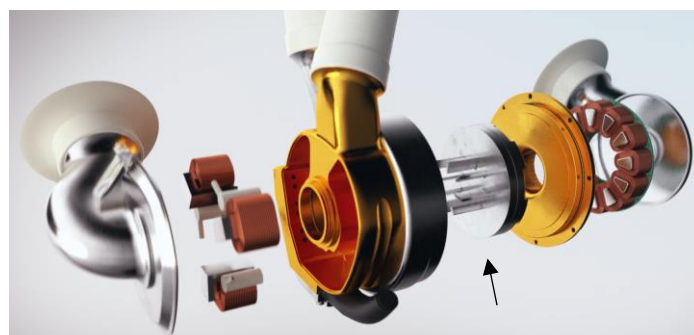


Figure 6: The different parts of the BiVACOR artificial heart shown apart. The spinning disc is indicated with the black arrow. (BiVACOR, 2015)

Complications

As promising as these relative new technologies are, one big remaining downside is the briefcase-sized power pack that have to stay permanently connected to the hearts through the patient's skin. (Petukhov et al., 2015) Advancements like extending battery life and replacing cable drive lines with wireless charging technology would have to be realized before an artificial heart patient's freedom is truly equal to a healthy transplant recipient. For now, this is still a complication for the patient.

Next to that, in The Netherlands at the end of December 2022, a very special heart transplantation was conducted in the academic hospital in Groningen. (Janneke Kruse, 2022) A patient received a transplant heart and liver at the same time, being the first of the country. The patient had lived for 35 years with the congenital heart disease called Fontan palliation, which means the ventricles of the heart are fused and smaller. This causes a slowed down blood flow, difficulties with catching up with the body's demand and blood congestion in the liver, inducing fibrosis and eventually the development of hepatic cirrhosis. (Reardon et al., 2018) Also the kidneys are vulnerable to develop blood congestion issues. This case illustrates the complexity of heart diseases and their operations.

Every technology goes through a sigmoidal adoption curve; first a minority is doing it and then suddenly it saturates and goes vertical. And now in the last decade the technology is there to make devices that potentially could last a decade or more. Still, humanity is in the low phase because there are 5.000 pumps implanted every year, but 400.000 people are dying of heart failure. (Emmanuel et al., 2022) There is a whole bunch of technical forces that are converging on having an artificial heart that lasts a long time and that does not have a wire through the skin. Then, maybe heart failure will not be the number one cause of death in the world anymore.

The bionic future of replacing human hearts

A total artificial heart is a mechanical device that is powered by an external battery pack and mimics the function of a natural heart by pumping blood through the body. The bionic future of replacing human hearts involves the use of artificial hearts or heart assist devices that can either completely replace or augment the function of a failing human heart. This technology has advanced significantly in recent years, and while there are still some limitations and risks associated with these devices, they offer the potential to greatly improve the lives of people with end-stage heart failure. (Petukhov et al., 2015) The bionic future of human hearts needs to manage a complete mimicking of the functioning of the biological heart. However, as mentioned before, mimicking a multifunctional tissue is still very challenging and will need more research and development.

Conclusion

A bionic heart is a mechanical device that is designed to replace the function of a damaged or dysfunctional human heart. The extent to which a bionic heart can replace a dysfunctional human heart depends on the specific design and functionality of the device, as well as the patient's individual medical needs.

In some cases, a bionic heart could in theory fully replace the function of a human heart, allowing the patient to live without a natural heart. In other cases, bionic heart elements may be used to assist a failing human heart, helping it to pump blood more effectively and improving the patient's overall cardiovascular function. One of the key advantages of a bionic heart over a human heart is that it does not experience fatigue or wear and tear in the same way that a natural heart does, meaning it can potentially function more reliably and over a longer period of time. However, as with any medical technology, there are potential risks and ethical limitations to consider, including the potential for complications or side effects over time.

Overall, while a bionic heart cannot fully replicate all the functions of a healthy human heart, it can offer a promising treatment option for patients with severe heart disease, helping to improve their quality of life and overall cardiovascular function until a real donor heart becomes available.

Discussion

Heart transplantation gives the patient a new second life. Post-transplant life should be comparable to a normal situation. However, long-term data in humans is very limited. The question how often a bionic heart need maintenance or replacement arises. For example, an artificial knee or hip have a lifetime of about 20 years with almost no maintenance. (J.A.M. Baar & C.A. Bastiaanssen, 2006) Related to life expectancy, data about the timeline of a bionic heart will indicate the age at which it becomes relevant to go on board on this bionic track.

Medications, immunosuppressants, are actually what makes heart transplantation possible. These are medications that actually lower your immune system that tries to protect the body from the foreign object. (Hunt & Haddad, 2008) Without immunosuppressants, rejection of the new heart will likely occur. However, because the immune system is lowered it puts the patient at risk for infections, especially during the first year after transplantation.

However, the medical world keeps improving. The Organ Care System for example, or “Heart in a Box”, allows for reassessment of the function of the heart after it has incurred the process of essentially stopping and dying. With this relative new method, it is actually possible to transport the heart much further distances than using cold storage. (Hulman et al., 2019)

Besides, when decided on continuing the development of a total artificial heart, the natural human heart should be used as the biological model. (AskNature & MIT, 2020) The bio-inspired approach can lead to a biohybrid design where a poorly functioning heart is supported, or to a heart transplantation with a bionic heart including the expertise of soft robotics. On top of that, a bionic heart that works on its own without a body allows faster testing and development of artificial heart elements.

A developing heart

Currently, there is no artificial heart that can grow with a person throughout their life. One of the challenges in developing an artificial heart that can grow with a person is designing a device that can accommodate changes in the size and shape of the heart over time. Additionally, the materials used in an artificial heart must be biocompatible and able to function over a long period of time without breaking down or causing harm to the patient. However, researchers are working on developing a variety of new technologies that could potentially be used to create an artificial heart that grows with a person. (Petukhov et al., 2015) For example, 3D printing technology could allow for the creation of a customizable artificial heart that could be adjusted to match a patient's changing cardiac anatomy. Additionally, new materials and fabrication techniques could enable the creation of more durable and biocompatible artificial heart components. While the development of an artificial heart that grows with a person is a challenging and complex task, continued advancements in medical technology may one day make it possible. (Wang et al., 2021)

Technology beats physiology?

The biggest downside for the patient of an artificial heart are the permanent power packs outside the body. Maybe there is a bio-inspired solution for this outside in the natural world. And there is also the question whether a bionic heart influences the risk factors for cardiovascular diseases and how.

Technology can beat physiology in certain situations, particularly when it comes to addressing physical limitations and improving the overall function of the human body. However, it is important to note that technology is not always superior to physiology, and there may be situations where relying on natural physiological processes is the best approach. Medical treatments rely on the body's natural immune response to fight foreign substances. The development of a bionic heart could offer a promising treatment option for individuals with severe heart disease, particularly for those who are not eligible for heart transplantation. Although, it is important to evaluate the long-term outcomes of bionic heart treatment, including the potential for complications or side effects over time.

The BiVACOR artificial heart sounds very promising, this all points towards new research opportunities. For example, it is conceivable that the rotating disc creates a centrifugal force making the local blood flow highly turbulent. When Reynold's numbers (physical dimensionless parameter that indicates laminar and turbulent flow) are high enough, blood cells will probably get damaged since it is a force they are not adapted to. (Gallen et al., 2021) It would be interesting to set up an experiment with blood transfusion packs inside and outside a body with a BiVACOR heart in action. When there is a difference in the half-life of erythrocytes in the different packs, the BiVACOR heart is likely to have a wearing interaction with the blood that is passing under a certain pressure. Damaging blood can be dangerous since it causes blood coagulation factors to be released, inducing blood clotting. Most of the experiments in this field are conducted in animal models. At least, BiVACOR is working on their first human implant. (Emmanuel et al., 2022)

Ethics

The development of a total artificial heart raises a number of ethical arguments, both for and against its use. (1) Addressing organ shortages, a total artificial heart could potentially help to address the shortage of donor hearts available for transplantation, which can save many lives of patients that have to wait too long for the right donor heart being available. (2) Improved patient outcomes for individuals with severe heart disease who are not suitable for heart transplantation, a total artificial heart could offer an alternative treatment option and potentially improve health outcomes. (3) New technologies usually lead to new insights for other technical developments and applications. There is no such thing as useless research.

However, there are ethical arguments against the development of a total artificial heart as well, for example about the risks and complications. (1) The use of a total artificial heart carries risks, such as infections, blood clots, and mechanical failures. This could potentially harm patients. (2) Developing and implementing a total artificial heart is expensive, which could limit access for patients who cannot afford the treatment. The surgery needs a lot of time, people, management and money. (3) Implications for organ donation could rise as well. If a total artificial heart becomes widely available, it could potentially reduce the number of individuals who donate their organs, since the need for donor hearts would be reduced. For now, a real transplant heart is still the best option for the patient, so this would be an unwanted development. It is important to consider these ethical arguments to determine whether the benefits of a total artificial heart outweigh the risks and potential downsides.

Tension is rising?

In a world where the biggest concern of humanity is undisputed the consequences of biodiversity loss and climate change due to human overpopulation and non-sustainable handling of the planet, it feels weird to go all out to extend the life of dying people as far as we can. From an evolutionary point of view, people suffering from heart failure that can only successfully continue their lives after heart transplantation would not make it through the process of natural selection. The question whether we want to revolutionize healthcare in such a way that we could save any patient suffering from a cardiovascular disease by just replacing their hearts with a bionic one, is hard to answer. There would be no difference between strength and fitness of different people, which is very important in the natural process of evolution. Humanity can create its own bypass from evolution towards the future, but the consequence would be that we slowly lose our nature versus nurture balance. Humans are very social and emphatic beings. If possible, we want everyone we care about to be immortal, or at least live as long as possible.

Healthcare is a fundamental human right and is essential for ensuring a high quality of life for both individuals and communities. Addressing overpopulation requires a complex approach, including measures to improve access to education, promote family planning and reproductive rights, and reduce poverty and inequality. Overpopulation is a complex issue that is not only a result of access to healthcare, so the other factors that contribute to population growth should be examined as well before making conclusion about the (bio)technical healthcare revolution.

While bionic advancements have the potential to significantly improve healthcare, there are also some arguments against their use and further development. (1) Some may argue that relying too heavily on technology could lead to a loss of personal touch and empathy in healthcare. Technology can also fail or be subject to human error, which can lead to negative health outcomes. However, maybe when biomimetics is used that the gap between nature and technology feels smaller and more comfortable. (2) As mentioned before, technological advancements like an artificial heart are expensive to develop and this cost may be passed on to patients through higher healthcare costs. (3) Building on that, new technologies may not be accessible to all patients, particularly those in low-income areas. This can create inequality in healthcare access.

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