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Board 147/Innovative Advances: Triboelectric Nanogenerators Powering Pacemakers: A High School Student Review

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Review of Triboelectric Nanogenerators for Powering Pacemakers

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Abstract

Triboelectric nanogenerators were introduced in 2012 by Professor Zong Lin Wang. Since then, TENG has been tested in Smart Homes, clothing, and multiple aspects of daily life. Recently, TENGs have been incorporated into medical devices to develop a new generation of implantable pacemakers, ICDs, nerve stimulators and so on. TENG powered pacemakers have been of great interest due to their biomedical properties for greatly benefiting the life and health of both humans and animals. The battery life of these traditional implantable often only last a few years. They have to be surgically replaced after that via invasive procedures, which pose great risks to the patients and a significant cost to the healthcare system. Not only is this unsustainable due to the cost, it is also detrimental to the environment. This review article will give the history and downsides of current battery-powered pacemakers before explaining TENG powered pacemakers in detail and focusing on the recent progress of TENG powered pacemaker research and clinical studies. Various types of TENG powered pacemakers (respiration or inertia) and their clinical trials in animals like Inertia driven TENG(I-TENG) will be discussed. The instructions and models on how to build a TENG powered pacemaker are also included. Finally, this review summarizes some challenges that TENG-powered pacemakers must overcome to improve use and function such as more efficient energy conversion and utilization, as well as research perspectives.

Introduction

Battery powered medical devices were one of the best examples of innovative healthcare. Not only did they enable patients to have better mobility, but they also helped health professionals to have access to statistics and program these devices remotely via Bluetooth. These devices also help reach the goals of healthcare by improving the quality of life of patients and preventing diseases. These popular battery powered devices range from being wearable to even implantable. According to Leticia Salazar at Penn Carey Law School, America is one of the biggest consumers of these devices. In fact, 32 million Americans have implanted medical devices [1]. Although these devices help save lives, not all of them are the best option for the future. As of now, most of these battery powered devices are still being made with non-rechargeable batteries that are bulky and contain security flaws that could be hacked. Some of these devices include pacemakers and implantable cardioverter-defibrillators (ICDs), both of which are implantable battery powered devices. Pacemakers are used to help hearts beat normally in both rhythm and rate. Similarly, ICDs are used to correct dangerous heart rhythms. However, to do this these devices require electrical signals which are supplied by large non-rechargeable lithium batteries. Due to the non-rechargeable batteries, the procedure must be done

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every 5-7 years which can be costly and increase the health risks due to the additional surgeries. This battery powered implantable often have risks like surgery risks, infection, implant failure, and implant reactions which can include bruising and pain [2]. For battery replacement surgeries, the risks include infection, blood clots, damage to blood vessels, and more. Not only are battery powered implantable costly and dangerous, but they also pose a risk to our climate. According to the National Institute of Health, more than 110,000 ICDs are implanted per year in the US [3], while Yale Medicine reports that at most, 3 million Americans live with implanted pacemakers [4]. With this many cases, all of which require a non-rechargeable lithium battery each time, it is not environmentally conscious. This excessive but required use of batteries may cause mountains of batteries to pile up. So, what are the other options we have instead of using batteries?

Many people have tried to create a new way to power these implantables. Some are using radiation, heat, or even solar energy. However, not all of these are successful. One innovative, promising area of study that offers a new, better alternative to batteries is the triboelectric nanogenerator (TENG), invented in 2012 by Professor Zhong Lin Wang and his team. Due to its self-charging abilities and the ability to turn mechanical energy into electrical energy, it has been heavily researched for its use in healthcare and how to incorporate it into a biomedical setting. In recent years, it has been integrated into medical devices for therapy or even, in some cases, to prevent and treat heart disease. Other ideas are to incorporate it into pacemakers or similar implantables. Although these TENG-powered pacemakers and implantables have yet to hit the market, much research has already been done on the subject. It is already clear that these TENG-powered pacemakers will change the future of pacemakers, but before that happens, there are still trials and challenges that researchers must overcome to make a successful pacemaker.

A reason for its popularity in research is the multiple ways it can extract energy. These methods of extracting energy include respiration and inertial force, both of which and their benefits will be discussed below. All in all, the future of TENG-powered pacemakers seems successful. While these pacemakers are still in trials or development, the results seem conclusive that they will be able to be used in the future in place of regular pacemakers. The history of battery powered pacemakers, the downsides of these devices, and the newfound solution of TENG powered pacemakers and its progress will be discussed in the following main body.

History of Pacemakers

In the past years as battery powered devices, both pacemakers and ICDs have experienced changes in powering and types of batteries. The history of both is complicated and has involved various transfers and changes to the batteries and types. Electricity and the heart have had a long history of being studied since 460 BC by Hippocrates [5]. The first external pacemaker was developed in 1928 by Mark Lidwell through needle insertion into the heart's ventricle and intermittent electrical stimulation. In 1932, Albert Hyman created the world's first artificial pacemaker powered by a hand cranked motor [5]. These external pacemakers faced a multitude of technical problems and opposition. The first Implantable Pacemaker was first developed and implanted in a human in October 1958 by Ake Senning and Rune Elmqvist [6]. This handmade pacemaker had nickel-cadmium batteries and was covered by epoxy resin. It had a diameter of 55mm and a thickness of 16mm. This model was used before a transition to a zinc mercury battery for better longevity. Although this pacemaker was meant to be a short-term solution for Arne Larsson, to prolong his life, it inadvertently turned into a long term one. However, with the pacemaker units often failing quickly, with the first failing after eight hours and the second one failing after little more than a week, Larsson faced multiple pacemaker and lead replacement surgeries till his death in December 2001. At the University of Buffalo, the first model of a long-term implantable pacemaker was accidentally developed by Wilson Greatbatch. This two cubic inch implant proved as a long-term solution to cardiac problems like irregular heartbeat. This was first implanted in a canine in May 1958 to test Greatbatch's theory on it being able to drive a heart before being patented by Greatbatch in 1959. In 1960, William Chardack implanted the device into a seventy-seven-year-old human male who lived for an additional two years before a death of natural causes. In 1961, the "Bow Tie Team" of Dr. William Chardack, Wilson Greatbatch, and Dr. Andrew Gage, implanted the pacemaker into fifteen other patients. Later, Greatbatch invented the lithium battery that was corrosion-free and long-life as a better battery option to power the pacemaker. Pacemakers have transitioned from a nickel-cadmium battery that was rechargeable to a zinc mercury battery that lasted more than two years to the current battery used: a lithium iodide battery.

The history of ICDs started in 1966 when the development of the first ICD started. This implantable device was first called the Automatic Implantable Defibrillator (AID) and developed to treat ventricular fibrillation and more cardiac arrhythmias before the name modification to Automatic Implantable Cardiac Defibrillator (AICD). The first prototype was created in 1974 by Dr. Michel Mirowski, and in 1975 it was proven successful at resuscitation by canine tests [7]. In 1980, the first human implantation occurred when Dr. Mirowski and his team implanted the ICD in the patient's abdomen [8]. The first prototypes of ICD were bulky (280 g) and large (8 × 11.5 cm, 170 cm3) [8]. The first-generation devices used "silver vanadium pentoxide batteries". ICDs now use "lithium-silver vanadium manganese oxide batteries" causing an increase of battery life. Other models use two connected batteries to improve patient safety with a lesser charging time. However, this creates bulkiness due to the extra batteries. ICDs have had a transition from "silver vanadium pentoxide batteries" to "lithium-silver vanadium manganese oxide batteries" [8]. The transition of newer and better batteries has solved many problems once associated with the old batteries like battery life, cost, and environmental/toxicity problems with metals like nickel and cadmium, both of which are present in nickel-cadmium batteries [9]. However, some problems persist like bulkiness and the required surgeries for upkeep.

The downsides of lithium powered implantable pacemakers

Both pacemakers and ICDs are some of the most popular battery-powered implantables on the market. Their purpose and use have innovated healthcare for the better and saved millions of lives. But both devices are still nowhere near perfection. Due to the climate impact of these battery-charged devices, required surgeries of upkeep, and health risks, both options are unsustainable and not the most desirable option for the earth, patients, and healthcare systems.

Climate health is a very urgent issue. The effects of climate change are seen now in the forms of rising sea levels and severe wildfires around the world. Climate change is caused by a multitude of issues, one of which is increased carbon dioxide emissions. Both ICDs and pacemakers require lithium-based batteries. The production of lithium batteries is one of the causes for increased carbon dioxide emissions. Lithium batteries require mined lithium. Most of this metal is found underground in reservoirs and rock mines. The extraction and processing process is energy consuming and is powered by the burning of fossil fuels emitting CO2. In hard rock mining, 15 tonnes of carbon dioxide are emitted into the air for every tonne of lithium mined [10]. Manufacturing a battery requires a temperature of 800 to 1,000 degrees Celsius for material synthesis, which is also only able to happen cost-effectively by the burning of fossil fuels. Pacemakers require upkeep for battery depletion, often happening around the seven-year mark. This means that these batteries are often thrown out. Although some pacemaker batteries are getting recycled and the materials are being reused, most of them in the past have been thrown out [11]. This proves to be an environmental hazard due to its lithium batteries which are classified as hazardous waste. The pollution of lithium batteries is also a worrying problem with its effects on ecosystems and water sources due to lithium's toxicity. Another impact of lithium batteries is if not disposed of properly, they are likely to catch on fire, especially if exposed to heat or moisture which is commonly found in garbage trucks and household waste facilities. Due to the unsustainability and environmental impacts of lithium powered pacemakers and ICDs, there is a great need for other options.

Another dilemma related to the use of lithium powered implantable pacemakers and ICDs is upkeep. Both ICDs and pacemakers usually last 5-7 years before battery drainage. Due to both devices' batteries being an important part of the circuit, the whole device, other than the leads, must be replaced along with the battery. Rarer and riskier replacement surgeries include the replacement of the devices' leads, often including an overnight stay at the hospital. Both replacement surgeries are both costly and risky. These risks include heavy bleeding, infection, allergic reaction to anesthesia, and a risk of needing surgery to replace the pacemaker's leads. The cost of the battery replacement ranges from $5,000 to $20,000 USD. The cost of these replacement surgeries can put a heavy financial strain on both patients and healthcare systems. With the inevitable need of multiple battery replacement surgeries as prevention, patients require an economically better option. With studies showing that the longevity of batteries in battery powered pacemakers can affect therapy costs in the long term for both manufacturer and hospitals [12], a long-term battery solution is also needed. With the overwhelming number of batteries and pacemakers needed to keep patients alive plus upkeep, scientists have started to research and discover new methods to power pacemakers that can solve healthcare costs and risks while also being a long-term battery powered option, one of which is TENG powered pacemakers.

A new solution

With the prevalent and existing issues with battery powered pacemakers, scientists have found a solution in the form of triboelectric nanogenerator powered pacemakers. This was able to happen with the invention of the triboelectric nanogenerator (TENG) by Professor Zhong Lin Wang and his group in 2012. However, the use of TENGs to power pacemakers and other implantables has been a more recent event. These TENGs have many advantages when compared to the regular pacemaker. With the lack of batteries, TENG powered pacemakers have a lower environmental impact, helping the health of the earth. The pacemakers also have longer service life, which could help reduce the cost and upkeep as well as risks evident in these surgeries [13]. Other than that, the lack of batteries due to the TENG generating energy from rubbing or physical contact is the most evident one [14]. Other advantages include more accuracy and efficiency, giving the healthcare practitioner and patient a clearer picture of the possible issues, making healthcare decisions more accurate.

There have been three main types of TENG powered pacemakers, inertia-based pacemakers, respiration-based pacemakers, and pacemakers that use magnetic resonant coupling. Most are battery free and pose a possible future replacement for the battery powered pacemakers. Other than that, there are also TENG powered CEDs (Cardio-electronic devices), for treating heart disease. These TENGs would be made of two pieces of film which could access electrons. These soft films would fit well to skin or organs due to its flexibility. There are multiple ways and models it can be placed but textile and elastic models are used as of now. If it is used in blood, it should be tested before adding it on. All implantable nanogenerators hold the risk of rejection like the risk of rejection of other implantables due it being a foreign object within the body. However, the piezoelectric and triboelectric nanogenerator has been tested and it seems to be biocompatible. When it was tested there was no infection or changes to the tissues and no function changes in the heart or overall structure. Currently a lot of CEDs were not meant for implantation inside the human body, so there should be more options to be explored. Energy harvesting is still low when compared to the transmission of the energy(wireless). The frequency of breathing and body motion with physical motion creates a small amount of energy. However, if just used by breathing and high frequency it creates a higher amount of energy. Electrical stimulation on the vagus nerve has been researched and turns out it can improve heart function [15]. There are many ways Nanogenerator (NGs) can help in the health and well being of humans therefore more options of CEDs NGs should be explored in the future.

The symbiotic pacemaker is the pacemaker that uses inertia-based energy, powered through an implanted TENG. This pacemaker harvests energy through cardiac motion and stores it in the capacitor of the power management unit until use. For this pacemaker, an inertia based triboelectric nanogenerator (I-TENG) was used and was composed of two layers, a structure, and a shell with two layers with a sponge as the spacer [16]. It had the ability to reach 65.2 V. open circuit voltage but also was able to become low enough to have no adverse effects. In trials, this I-TENG powered pacemaker was able to successfully achieve cardiac pacing on a large-scale animal, a pig, and corrected a sinus arrhythmia and prevented future deterioration. Pacing therapy was able to be successfully done on a 35 kg male porcine [16]. This I-TENG powered pacemaker was able to boast excellent mechanical durability and cytocompatibility. Another I-TENG powered pacemaker was a self-rechargeable pacemaker. Similarly, it uses gravity and energy created from the motion of the body, helping make use of energy that is usually wasted. However, unlike the symbiotic pacemaker, the self-recharging pacemaker includes self-charging batteries developed by the team. The pacemaker works through its fascinating design. It uses layered materials of copper and gold in the nanogenerator [17]. Cooper and the polymer base receive the upward force as the body moves up and the gold receives the downward force when the body moves. The device uses inertia to its advantage, allowing the units to touch multiple times everyday, creating energy. The device is then coated with a biocompatible polymer covering which prevents cross contamination in the body and then a 0.5-1.5 titanium packaging before being coated with silicon both helping with biocompatibility along with stabilization [17]. This pacemaker was tested on a large animal's back on the muscle layer. The voltage increased when the tester was active and consumed and saturated to make up for the tester when it was not active. When the stimulation was halted, the pacing was turned off and normal condition was observed. There was a mild inflammatory response to the TENG and the medical device, but no infection was observed, and the tester expressed the same behavior as before. Masson's trichrome stain was used to test biocompatibility. Pacemaker was able to successfully sense a heart rate change from 120 to 80 bpm and took action to pace the ventricle when the heart rate dropped under 90 bpm [17]. This pacemaker helped open speculation over the lower financial burden and lesser health risks it offered compared to the traditional pacemaker.

The second type of TENG powered pacemakers is the respiration-based pacemakers. Although many implantable TENGs use energy from muscle movement, respiration has long been considered a possible source for energy generation. These pacemakers are powered by TENGs that can be driven by breathing (12-16 times per minute) [18]. This pacemaker utilizes the best biomechanical energy source overall, respiration. Respiration has enough energy in watts to support small electronics. Respiration driven pacemakers use the involuntary movement of breathing allowing the pacemaker to always have an input of energy and an output of mechanical energy despite time and what the body is doing. Involuntary movement is a better option for powering pacemakers when compared to voluntary muscle movement as it does not require the patient to exercise to get power. Not only that but involuntary movement creates stable energy. Another involuntary movement is the beating heart, but respiration is a better way to power the TENG than the heart beating as respiration is more accessible and creates more energy. The TENG used is simple, light, durable, and has a large power generating process. There has not been much respiration-based pacemaker research for TENGs yet, but the research so far seems promising. Respiration based in vivo powered TENG has worked on a pacemaker prototype that was used to regulate heart rate. The energy from respiration was stored in a capacitor and drives the pacemaker prototype. With seventy percent of TENGs based on respiration were designed for nose/mouth or chest, these areas give versatility for how the TENG could be used, whether for implantables electrostimulation, IMDs, and electric energy generation.

The final pacemaker is a battery free pacemaker that uses a TENG powered by magnetic resonant coupling. This pacemaker included digital communication with the implant which was visible for many other prototype pacemakers. This pacemaker used platinum covered copper which usually lasts 1.5 years and was a full subdermal implantation. Energy was harvested by a wave rectifier. This pacemaker was safe in MRI and CT imaging scans and had no functional nor mechanical degradation. Although it was not a full pacemaker, it was a research pacemaker prototype that was tested on small animals. Heart failure can be induced by using the pacemaker [19]. The results were promising. Adult rats older than 6 weeks were used as testing animals. The obtrudes were sutured on the surface of the left and right ventricle. It was very functional as it still works when extremely twisted. 13 devices were implanted into 13 animals and only one died during the procedure, giving it a 7.7% mortality rate [19]. The weight of the animals decreased 3 days after the surgery but stabilized 6 days after and became normal. Although all three of these pacemakers created had promising results, lifetime service is an unrealistic goal of the TENGs as it may not be possible with the current prototypes along with the wear and tear of the materials as well as weakness of the material over time. There are still big steps needed to create the best pacemaker for patients, healthcare systems and professionals.

Figure 1 - Each I-TENG in the inertia-based pacemaker [20]

Building a TENG powered pacemaker

While TENG are being built in labs for research, this review article also includes steps on how to build an i-TENG, symbiotic pacemaker, implantable TENG (i-TENG) used as the power source for the pacemaker, and the battery free pacemaker discussed earlier, along with explanations on why certain materials and techniques are used. The high-performance inertia driven TENG that uses body motion and gravity that is the size of a coin battery and developed in South Korea will be the one first shown as Figure 1. Nanogenerators utilize the friction of rubbed surfaces to generate energy. The first step in building a TENG is to attain materials to layer together to create these friction sources. The Korean i-TENG utilized copper, gold, and then two triboelectric polymer-based materials: amine-functionalized poly with vinyl alcohol (PVA-NH2) and perfluoro alkoxy (PFA) [21]. The copper and the polymer base receive the upward force as the body moves up and the gold receives the downward force when the body moves as shown in Figure 2.

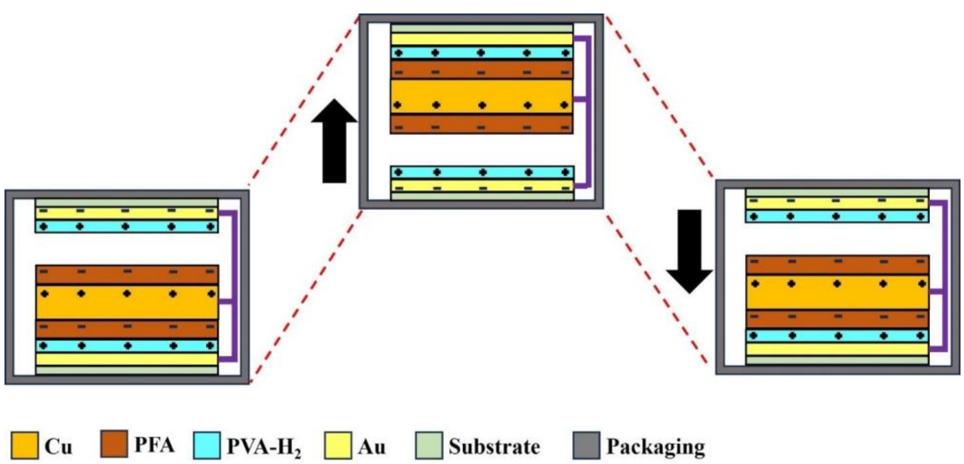

Figure 2 - How the i-TENG layers work as it is placed in motion [20]

The reason for TENGs being used instead of MEMs for this case is for pacemakers that will utilize energy, MEMs only rely on motions which limits the scope of where it can be placed [20]. Other than that, TENGs are low cost and lighter. The i-TENG first gets charged from stimuli friction and then these chargers go into the nanogenerator enabling a generation of current, enough to power a small device. Then an electrostatic charge induction mechanism happens, and both work to power the device.

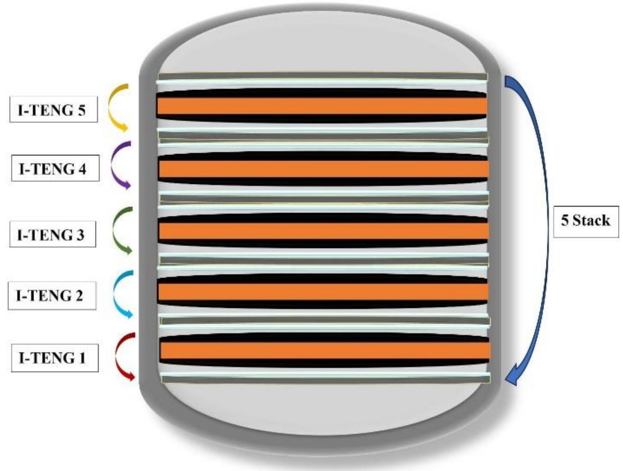

Figure 3 – The final compositions of the i-TENGs used in the pacemaker [17]

The final i-TENG used to power the cardiac pacemaker ended up being five TENGs being placed on top of each other as shown in Figure 3. These five TENGs were placed on top of each other after tests proved that they produced a substantial amount of additional peak voltage when compared to using one TENG. The peak voltage increased from 36 to 136 V [20]. The final connections between the heart to the i-TENG are shown in Figure 4.

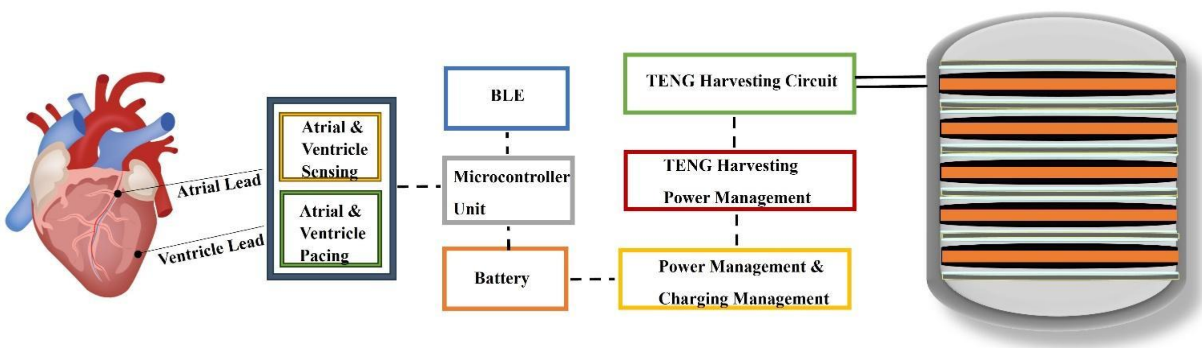

Figure 4 – The connections between the heart and the i-TENG [17]

The i-TENG development first included tests of the nanogenerator itself showing that it can generate sufficient energy from mechanical motion in the z-axis and not be influenced by the x and y axis motion, allowing for more accurate energy and data. It also proved competitive to other high energy generators with the volume power density of energy conversion of 4.9

μW/cm3 at a load resistance of ~10 MΩ [20]. Once proved sufficient in harvesting energy outside of the body, the TENG moved onto animal tests which used insertion of the I-TENG on different places of the animals for energy generation [20]. Data was collected via Bluetooth and proved true in generating enough energy to charge a lithium-ion battery in a biological environment. The second phase then started where the researchers put the I-TENG onto a pacemaker and started preclinical trials on animals. The I-TENG was able to charge the battery of the pacemaker with PMIC (power management integrated circuit). The I-TENG also continued to charge when the animal was asleep. The preclinical trials were successful but there was still work to be done before these pacemakers are approved for trials.

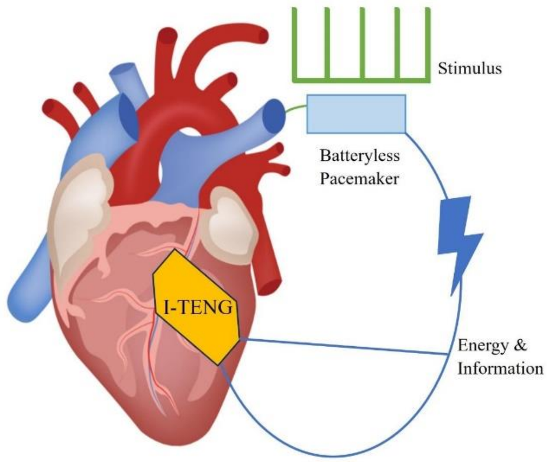

Figure 5 – The symbiotic pacemaker system [16]

The second pacemaker with instructions is the symbiotic pacemaker [16]. While this one also utilized an implantable triboelectric nanogenerator it was made in three separate units, the pacemaker unit, the TENG unit, and power management unit as shown in Figure 5. All will be illustrated.

Figure 6 – Structure and composition of the inertia driven TENG of the symbiotic pacemaker [16]

The first step in building a TENG is to attain materials to layer together to create these friction sources, same as the i-TENG. This TENG included two triboelectric layers, with support and a two-encapsulation layer shell [16]. The triboelectric layer utilized nanostructured polytetrafluoroethylene (PTFE) as a thin film for the first layer. Then an elastic sponge was used as a spacer. It was three dimensional and consisted of ethylene-vinyl acetate copolymer (EVA). Highly resistant titanium in the form of a memory alloy ribbon was used as the keel. Then the entire TENG was encapsulated by polydimethylsiloxane (PDMS) and Teflon film, boosting stability and protecting it from possible liquid damage. This is all shown in Figure 6 where all of the materials are utilized to showcase the structure of the TENG. The power management unit utilized a bridge rectifier, capacitor, and a reed switch and it is illustrated below in Figure 7. The electrical energy generated was stored within the capacitor. The capacitor was able to be charged from 0 to 4V in sixty-three minutes with each cardiac cycle's harvesting energy as 0.495 μJ, more than the pacing threshold energy of humans and pigs.

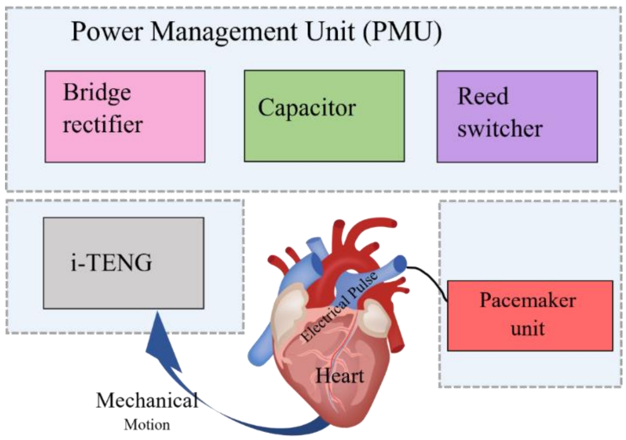

Figure 7 – Power Management Unit's integration in the symbiotic pacemaker system [16]

For this triboelectric nanogenerator, a corona discharge system was utilized to maximize surface charge density and to also maximize overall output of the TENG [16]. This symbiotic pacemaker was ultimately tested in a pig where it exhibited the signs that an ECG would also produce. The pacemaker ended up generating electrical pulses of 0.5ms. The test was a success as the pacemaker was able to correct a sinus arrhythmia and prevent future heart deterioration induced by sinus node hypothermia on a male adult Yorkshire porcine. While this was a success, there are still many challenges left before clinical applications. There needs to be a smaller, high-energy density, and biosafe TENG that is able to effectively be fixed to tissue and a better power management unit that is more efficient compared to the current one.

The third pacemaker is the in vivo powered pacemaker. This pacemaker is powered via respiration and was successful at regulating the heart rate of a living rat. For this in vivo powered pacemaker, and in vivo TENG was also utilized. This was quite different compared to other TENGs as it required a sensitive TENG to utilize respiration and also narrow, irregular TENG. However, similar to the other TENGs it utilized soft and biocompatible material as packaging to make sure that the TENG would not be affected in case when in the in vivo environment. This pacemaker utilized energy generated from periodic breathing of a rat to power this prototype pacemaker. With respiration being an involuntary action, this allowed the rat to not have many changes in lifestyle while also powering its pacemaker for almost a lifetime without the need of lithium batteries.

To create this in vivo TENG, several structures had to be put together before it was packaged. A PDMS film made by PDMS elastomer and crosslinker being spin coated on a Si wafer [21]. After it was ready, it was peeled off the mold it was sitting on and put on a Kapton Substrate before being deposited with gold. With the thinness and flexibility of the layer of PDMS and Kapton, the layers were able to deform in response to the in vivo motion caused by the rat breathing. Then aluminium foil was added into the design as the electrode and contact layer before a PET spacer was inserted in between the contact layers, allowing the closure of the PDMS film. This guaranteed the protection of the inner structure from the outer environment. Wires were added to the back of aluminum foil electrodes via silver paste. As a second form of protection from the biofluid in the in vivo condition the device was surrounded by a polymer layer to isolate it from conditions. In the diagram, a thin PDMS layer was used for encapsulation due to its leak proofness, flexibility, small inflammatory reaction after implantation, and biocompatibility. This is shown below in Figure 8. The size of the TENG was 1.2 cm by 1.2 cm with a contact area of about 0.8 cm by 0.8 cm [21]. A circuit diagram is also included to help with building of this prototype pacemaker in Figure 9.

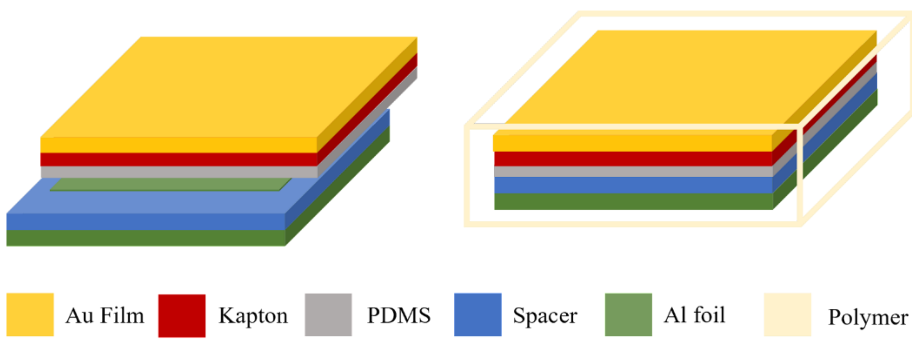

Figure 8 – The diagram of in vivo respiration powered pacemaker [21]

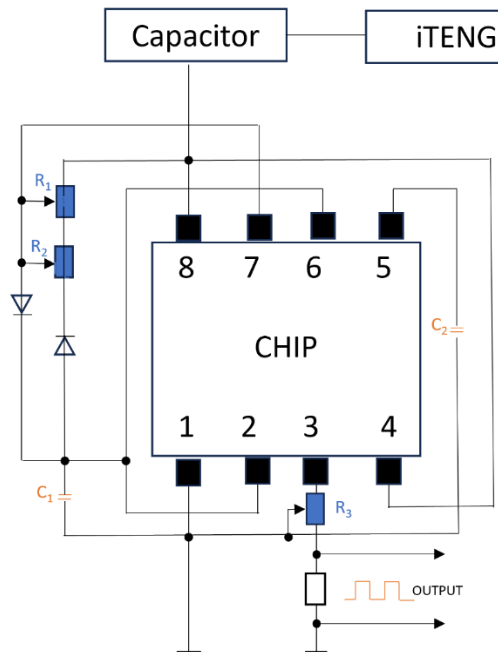

Figure 9 – The prototype pacemaker's circuit diagram [21]

While this is an experimental model for a mouse, it can surely be adapted into a human sized model. A bigger TENG could be redesigned for more electrical output and was shown in the article to have potential for implantation [21]. Other than that, with the research done with this model, it is a viable solution for humans if adjusted to.

The fourth and last TENG powered pacemaker used that is included in this review is a TENG powered by magnetic resonant coupling. It is a small animal model pacemaker and utilized rats for experimentation. The TENG powered pacemaker allowed digital communication helping activation of electrical and optical stimulation from many sites. Energy harvesting was enabled by the circular platform in the diagram. These devices were layered and used polyimide flex circuit substrate and an existing layout so it would be easy to spread the design around the scientific community. This layout is shown below in Figure 10. The electrode, the bottom and top, consisted of platinum coated copper and a coating of parylene C acted as an encapsulation layer supporting it for up to 1.5 years [19].

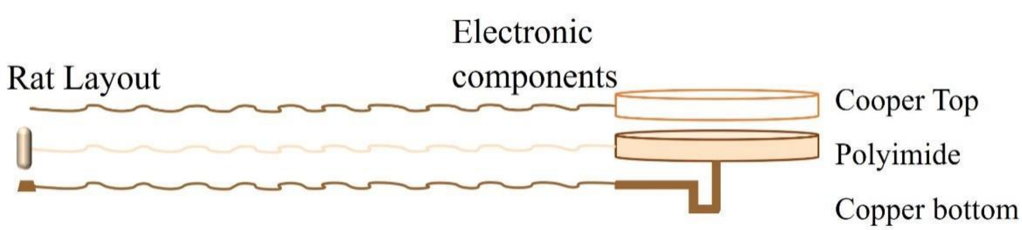

Figure 10 – Overall design of the TENG that showcases the layered components [19]

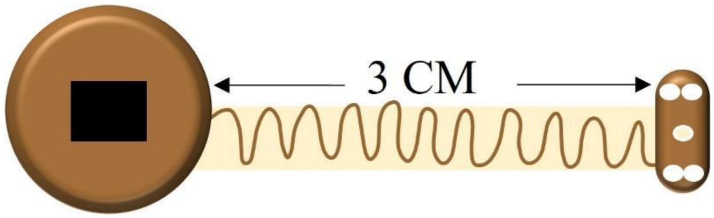

Figure 11 – Design of the device showcasing the length [19]

The length of the device's layers was 3 cm as shown above in Figure 11. This small design allowed for sub dermal implantation in rats allowing for experimentation. This pacemaker utilized a single wave rectifier for power harvesting and gave enough power to the microcontroller, helping control stimulus in both electrical and optical [19]. While this was a small animal model, it, similar to the respiration based in vivo pacemaker, can be adjusted and adapted to a human model as steps to the human sized battery-less TENG powered pacemakers of the future.

Steps forward

Despite the monumental progress TENG powered pacemakers have had, there are still things to improve on. While some of these are needed for all, others differ from pacemaker to pacemaker, but all are required to be solved to have the best pacemaker for each patient. For the symbiotic pacemaker, it needs a small i-TENG with high energy density and a better energy efficient power unit [16]. Other than that, this i-TENG must also be able to be efficiently fixed onto tissue with bio-tissue. Since it would also be in the body, biosafety must also be considered for it to be successful in the long term. This can be solved with better materials science, fabrication, and electronic techniques.

To make the best respiration powered pacemaker possible, the TENG needs more efficient energy conversion and utilization [18]. It also has challenges with stability and accuracy over time due to it being easily affected by environmental factors such as humidity and temperature [18]. Better packing research on how to isolate the respiration TENG without sacrificing its ability and performance need to be considered and done. Durability is also needed for this TENG especially since it may be exposed to the elements. The respiration powered pacemakers also have problems with other motions interfering with the TENGs, for example TENGs picking up other motions like arm movement. However, this is a common problem for many TENGs, which can be solved with both short term and long-term research and experimentation on where to anchor the TENG for the best energy taking and less interference. The last problem of the respiration powered TENG is lack of productive utilization of modules. Preferably, the TENG should be an all-in-one system, but current TENGs lack this and still require multiple modules to work. To make and engineer such a TENG would be a great feat. This itself is not just limited to TENGs applicable to pacemakers but also other implantable energy harvesting devices. This requires research from multiple sectors of science and engineering from material sciences to biomedical, mechanical, and electrical engineering.

For the magnetic resonant coupling pacemaker, being a prototype tested on animals, there were not any improvements needed for human use other than starting human trials. Overarching issues with TENG powered pacemakers include from complicated designs to build and engineer to too much wear and tear of the materials as well as degradation of the material over time. There needs to be progress in the design, engineering, and materials for the practically useful TENGs. Smaller TENGs and better energy storage in capacitors means that better developed electrical parts need to be created. For some TENGs there needs to be better sticking together of the cells to the NGs to make it work [15]. More layers, better materials, hydrophobic films, and hermetic structures are needed to be sustainable as well as prevent noise signal interference. They also need to be water resistant, comfortable for the patient, biocompatible and no cytotoxicity to prevent rejection [15]. NGs sutured into the heart can potentially cause damage to the heart, therefore we need better ways to fix the NG into the heart like using textiles instead. For biodegradable NGs, research is required to decrease the degradation rate for longer life. In addition, a better and smaller sensor is necessary for manufacturing an overall better device [22]. Overall, there needs numerous long and short-term research and testing to solve these problems mentioned above.

Conclusion

This article provides an overview on the history, downsides, new solutions, diagrams, and steps needed for future TENG powered pacemakers. Since 1926, pacemakers have been a saving grace for millions of people throughout the world. However, their downsides: their cost, bulkiness, risks from the additional surgeries needed for upkeep, and the eco-unfriendliness due to the constant need for batteries, makes it not the best option for the Earth nor healthcare systems and patients. Due to all these downsides, alternatives have been investigated and researched. One of them is the battery-free TENG powered pacemaker. They would solve the downsides of the traditional pacemaker and ICD and give a multitude of advantages like better energy utilization and smaller sensors. While there is hope for a future of Triboelectric Nanogenerator powered pacemakers, much progress needs to be made before it can occur. For battery-less pacemakers, much research is also needed to make it into a viable and affordable as well as healthy option for patients. More research is also needed for the best anchoring and way to utilize the TENG to its full potential. Engineers and healthcare professionals should also work together to find more viable designs and project ideas for TENG implantables. Research of biodegrading materials is needed to prevent biodegradable TENG powered pacemakers from degrading too fast. While the future for triboelectric nanogenerator powered pacemakers is huge due to its lack of the downsides of the traditional lithium powered implantable, all of it comes down to more research. For now, battery powered pacemakers and ICDs will still stay as a medical asset of the present and the future. Although it is not the most environmentally free nor cheaper option for the planet and people, TENG powered pacemakers offer a promising alternative for the near future.

Perspective of High school Student:

I am Joanna Li, a high school student at Fox Chapel High School in Pittsburgh, PA. I have had a great interest in science since my childhood. My father specialized in microbiology and now works in providing anesthesia for surgical patients. My mother specializes in organic chemistry. Triggered by their jobs and the piles of textbooks on their shelves, I have a desire for more scientific knowledge about biology, chemistry, engineering, and medical science. In high school, I joined the Science Fair Club and Technology Student Association to pursue more research and science. From the time I did an in-school project on the health of the ancient Roman Empire compared to the United States to my current research on triboelectric nanogenerator-powered pacemakers, I learned a lot about cardiac health and loved it. Other than that, during the lectures of the I Look Like a Cardiologist program, I learned that heart disease is a worrying problem in America, especially due to its high and deadly occurrences. I also learned about the roles of a cardiac electrophysiologist, a pacemaker doctor. After learning about their role, my interest in pacemakers increased, and I set out to do my research on this interesting topic. The research that I found showed a worrying trend of climate health problems due to the batteries in pacemakers. As an environmentally conscious person, this was unfortunate, so I set out to research the alternatives to this problem that will become worse as our population ages and climate change effects are more felt. One of the multiple alternatives were triboelectric-powered pacemakers. I reached out to Professor Haifeng Wang for this topic. He suggested that the best and most efficient way to research a topic was to read extensively and thoroughly about it and write a scientific review. It was hard to understand some concepts when I started reading those scientific articles, but thanks to Professor Haifeng Wang, Google, and YouTube, I was able to digest them and put them into writing. In addition, I believe my review also allows my peer high school students to take a look at this newfound topic and the broader topic of triboelectric nanogenerators to see how we can expand this research and technology for it to become safe during clinical trials and established as a new alternative to battery-powered pacemakers, helping planet health and the health of other patients, as this alternative can help reduce health risks and surgeries associated with the traditional pacemaker. Other than that, this is a fascinating topic that can be taught in a high school health sciences class as a topic within heart disease and could be connected to a high school course project or as research course work. It can also be taught as a topic in an engineering class because of the versatility of engineering innovations. This nanogenerator review connects to my high school engagements by allowing me to be knowledgeable in the topic of nanogenerators, allowing me to join and spread this in conversation, helping more people learn about this amazing idea. Other than that, it could be used in the future as a topic in biotechnology research competitions or even scientific writing contests, whether the overall topic is about biotechnology inventions that are helping lessen the impact on climate health or cardiac health inventions. I have already participated in numerous competitions and with my newfound knowledge, I can apply this into my writing and research. Although I learned much about TENG-powered pacemakers themselves, the most important lesson I learned while researching and writing this review paper was that engineering designs can always be thought of on another level. This was shown through the versatility of triboelectric nanogenerators, which I also researched. They were used for clothing, pacemakers, and even floors.

References:

[1] L. Salazar. (2021). *Addressing the Medical Device Safety Crisis*. Available: https://www.theregreview.org/2021/10/27/salazar-addressing-medical-device-safety-crisis/

[2] M. C. Staff. (2023). *Pacemaker*. Available: https://www.mayoclinic.org/tests-procedures/pacemaker/about/pac-20384689

[3] A. R. GREEN *et al.*, "Decision-Making Experiences of Patients with Implantable Cardioverter Defibrillators," *Pacing and Clinical Electrophysiology,* vol. 39, no. 10, pp. 1061-1069, 2016.

[4] M. Schoenfeld. *Cardiac Pacemaker*. Available: https://www.yalemedicine.org/conditions/cardiac-pacemaker

[5] O. Aquilina, "A brief history of cardiac pacing," (in eng), *Images Paediatr Cardiol,* vol. 8, no. 2, pp. 17-81, Apr 2006.
[6] V. S. Mallela, V. Ilankumaran, and N. S. Rao, "Trends in cardiac pacemaker batteries," (in eng), *Indian Pacing Electrophysiol J,* vol. 4, no. 4, pp. 201-12, Oct 1 2004.
[7] T. Kenny, "The History of ICDs," in *The Nuts and Bolts of ICD Therapy*, 2006, pp. 12-15.
[8] G. H. van Welsenes *et al.*, "Improvements in 25 Years of Implantable Cardioverter Defibrillator Therapy," *Netherlands Heart Journal,* vol. 19, no. 1, pp. 24-30, 2011/01/01 2011.
[9] D. Leff. (2023). *Nickel Cadmium Batteries: The Status of State Requirements*. Available: https://www.cga.ct.gov/PS95/rpt/olr/htm/95-R-0091.htm#:~:text=Both%20nickel%20and%20cadmium%20are
[10] Y. S.-H. I. Crawford, and D. Keith. (Feb. 16, 2022). *How much CO2 is emitted by manufacturing batteries?* Available: https://meche.mit.edu/news-media/how-much-co2-emitted-manufacturing-batteries
[11] B. T. Runge MW, Davis S, Weatherwax K, Goldman E, Eagle KA, Crawford TC. , "Pacemaker recycling: A notion whose time has come," *World J Cardiol,* vol. 9(4), pp. 296-303, 2017.
[12] M. Landolina *et al.*, "The economic impact of battery longevity in implantable cardioverter-defibrillators for cardiac resynchronization therapy: the hospital and healthcare system perspectives," *EP Europace,* vol. 19, no. 8, pp. 1349-1356, 2016.
[13] Y. Quan, X. Wu, S. Zhu, X. Zeng, Z. Zeng, and Q. Zheng, "Triboelectric nanogenerators for clinical diagnosis and therapy: A report of recent progress," *Medicine in Novel Technology and Devices,* vol. 16, p. 100195, 2022/12/01/ 2022.
[14] H.-J. Yoon and S.-W. Kim, "Nanogenerators to Power Implantable Medical Systems," *Joule,* vol. 4, no. 7, pp. 1398-1407, 2020.
[15] L. Zhao, S. Y. Wong, J. Y. Sim, J. Zhou, X. Li, and C. Wang, "Triboelectric nanogenerators and piezoelectric nanogenerators for preventing and treating heart diseases," *BMEMat,* vol. 1, no. 2, p. e12020, 2023.
[16] H. Ouyang *et al.*, "Symbiotic cardiac pacemaker," *Nature Communications,* vol. 10, no. 1, p. 1821, 2019/04/23 2019.
[17] H. Ryu *et al.*, "Self-rechargeable cardiac pacemaker system with triboelectric nanogenerators," *Nature Communications,* vol. 12, no. 1, p. 4374, 2021/07/16 2021.
[18] J. Li, Y. Long, F. Yang, and X. Wang, "Respiration-driven triboelectric nanogenerators for biomedical applications," *EcoMat,* vol. 2, no. 3, p. e12045, 2020.
[19] P. Gutruf *et al.*, "Wireless, battery-free, fully implantable multimodal and multisite pacemakers for applications in small animal models," *Nature Communications,* vol. 10, no. 1, p. 5742, 2019/12/17 2019.
[20] L. Critchley. *Using TENGs to Build a Implantable Self-Charging Pacemaker*. Available: https://www.electropages.com/blog/2021/08/tengs-self-charging-pacemaker
[21] Q. Zheng *et al.*, "In Vivo Powering of Pacemaker by Breathing-Driven Implanted Triboelectric Nanogenerator," *Advanced Materials,* vol. 26, no. 33, pp. 5851-5856, 2014.
[22] C. Moerke, A. Wolff, H. Ince, J. Ortak, and A. Öner, "New strategies for energy supply of cardiac implantable devices," *Herzschrittmachertherapie + Elektrophysiologie,* vol. 33, no. 2, pp. 224-231, 2022/06/01 2022.