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Advancement in self-powered implantable medical systems

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ABSTRACT

Many different elements of patient monitoring and treatment can be supported by implantable devices, which have proven to be extremely reliable and efficient in the medical profession. Medical professionals can use the data they collect to better diagnose and treat patients as a result. The devices' power sources, on the other hand, are battery-based, which introduces a slew of issues. As part of this review, we explore the use of harvesters in implanted devices and evaluate various materials and procedures and look at how new and improved circuits can enable the harvesters to sustain medical devices.

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1. INTRODUCTION

Implantable devices are becoming more efficient and physically larger as technology advances in the biomedical field. The depletion, for implantable devices could lead to surgical complications or leakage into the human body. If you're looking for a means to cut down on the size of your battery or even get rid of it altogether, you may want to look at biocompatible harvesters. Biocompatible materials, such as piezoelectric and triboelectric nanogenerators, biofuel cells, and environmental sources, can be used to implement harvesting processes. Biocompatible harvesters can be implemented in a variety of ways, some of which use less power than others, depending on the device and the site of implantation.

Today, implantable biomedical devices serve an essential role in many parts of medicine, including diagnosis and treatment. In conjunction with high resolution biosensors and efficient circuit designs and biocompatible materials, these devices can monitor a variety of diseases [1]–[4]. Subcutaneous devices such as defibrillators, pacemakers, medication pumps, cochlear implants, and stimulators are examples of biomedical implanted devices. Implantable devices can have a significant influence on people who have irregular heartbeats (arrhythmias) and require constant monitoring and analysis. Patients with arrhythmia can lead normal lives with the help of a pacemaker. In addition to biomedical equipment, non-implantable devices like watches and rings that assist in the monitoring aspect can be of considerable assistance [5]–[7].

Despite the fact that implantable medical devices can be extremely reliable and only have small problems, powering them is a huge issue. Battery power is essential to the operation of most implantable medical devices, which mostly consist of electronic circuits. Batteries, however, eventually run out of juice, necessitating a surgical procedure to replace them. The primary goal of practically every implantable medical device is to minimize the amount of space it occupies while also minimizing the amount of discomfort it causes the patient. The batteries' limited power storage capacity makes this goal feasible with current technology, but it is made harder by the necessity to identify ways to harvest electricity from the human body or its interior environs [1], [3], [7].

Power consumption for a typical implantable medical gadget is minimal. The power required by a device is determined by it is function and voltage specifications, which can be as low as 2-3 volts [5]. One of the most essential considerations is how much energy the device consumes and how much energy it generates; both of these factors must be taken into account when designing a new product to maximize its longevity. In order to make the most appropriate modifications, it is necessary to know how much power a particular device requires [8], [9].

2. IMPLANTABLE MEDICAL SYSTEMS

2.1. Piezoelectric

The lead zirconate titanate (PZT) energy harvesting is based on the idea that mechanical energy can be converted into electrical energy. As a result of applying an external load on piezoelectric material, the dipoles of polar surfaces will be charged with piezoelectric capacity as shown in Figure 1. The properties of the PZT substance determine the PZT conversion efficiency. 1980 saw the development of the first in vivo implanted PZT for energy harvesting [5]. The most popular piezoelectric materials are PZT and polyvinyl fluoride (PVDF) [5].

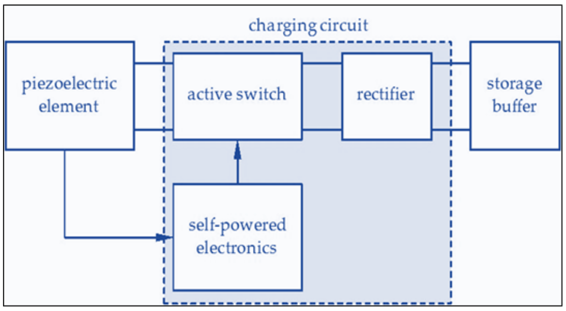

Figure 1. Configuration of piezoelectric energy harvester

Small amounts of vibrational energy were harvested by Wang and Song [10] using a ZnO-nanowired piezoelectric nanogenerator. The ZnO nanowires piezoelectric nanogenerator (PENG) energy harvester was found to have a power density of roughly 10 pW/m^2. To power nanodevices, this approach can transfer vibrational energy into electricity. A single ZnO nanowire implanted by Li *et al*. [11] demonstrated an implanted PENG. In order to harvest energy from the beating and breathing of a living rat, this apparatus was connected to the animal's diaphragm and heart [12] with their PZT set. Dagdeviren and colleagues extracted energy from living organs like the heart and lungs in an animal model with a harvester of 0.18 W/cm^{-2}.

It was shown that by altering the expansion and contraction mechanisms of the aorta, Wan and Bowen [13] could obtain an in vitro yield power of up to 40 nW with an ultrathin PVDF piezoelectric membrane. Two metal wires were used in the PZT energy harvester by Hwang *et al.* [14] to directly stimulate a rat's heart through the ultrathin PZT layer. More than twice as much peak energy as is required to cause an action potential in the heart to occur during a single working cycle of the system (about one-hundredth as much). PZT energy harvesters have been constructed in 2017 by Jeong *et al.* [15] on the basis of lead-free thin films sutured to pig hearts and driven by the pig's heartbeat to produce 5 V. The PZT micromodel developed by Han's team was a thin PVDF film that could capture kinetic energy from a mouse's hind leg and generate an output voltage of 0.79 V [16]. The research in [16] with an average peak voltage of 3.22 V, the microchip composite that Xu *et al.* [17] created in 2020 can be attached to a pacemaker electrode and collect energy from the dynamic motion of a heartbeat.

2.2. Triboelectric

Based on the triboelectrification and electrostatic induction coupling features, the triboelectric nanogenerator (TENG) was developed. The triboelectrification effect causes the two friction layers to be charged with triboelectric effects when they come into contact [1], [5], [18]. Polydimethylsiloxane (PDMS) as shown in Figures 2(a) to (f) skin of rats.

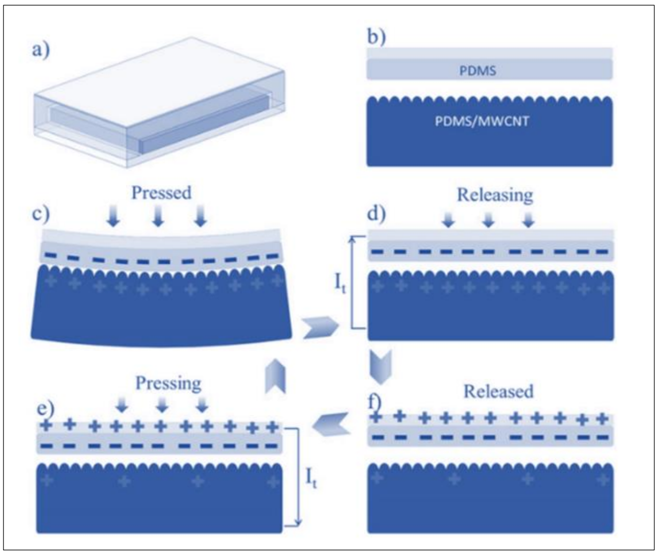

Figure 2. Design and working principle of the nanogenerator; (a) schematic view of the nanogenerator prototype, (b) three layers of the nanogenerator prototype, (c) electrons are transferred from PDMS/MWCNT to PDMS when they contact with each other, (d) electrons transfer between electrodes at separating state, (e) vertical forces are applied on the generator again, and (f) PDMS and PDMS/MWCNT at full-separated state

An estimated power density of 8.44 mW/m^2 was obtained from the vibrating breathing energy, which might be used to power a pacemaker model [19]. For the first time, Jiang *et al.* [20] in 2018 implanted bioabsorbable TENGs in rats, and the assessed power density was 21.6 mW/m^2. TENG biological degradation in vivo can really be photothermally changed to the photocatalytic activity of the gold nanorods, according to further research. The in vivo harvest electrical power's maximum output voltage was 2 V. It was also discovered that applying an in vivo output voltage to fibroblast cells could speed up wound healing by as much as threefold [21]. For peripheral nerve stimulation, Lee *et al.* [22] used a water/air integrated TENG to control a rat's leg muscles and obtain a peak power value of 2.93 W.

To stimulate the vagus nerve in rats, Yao *et al.* [23] designed a totally implanted TENG that was applied to the stomach surface and generated an electric pulse during gastrointestinal action with a maximum output of 40 W. In vitro, Wang *et al.* [24] created a 500 W peak-power TENG stacked diode amplifier powered by hand thumping for the activation of rat leg muscle. In 2020, Wu *et al.* [25] produced a skin-like liquid solitary electrode based on TENG that is sustainable and flexible, performing various bodily movements like folding, spinning, crumpling, and stretching, with a maximum peak power density of 4.61 W/m^2.

2.3. Biochemical

It was originally used in 1974 for medical implanted devices to generate power using biochemical renewable energy techniques [1], [5]. Biocatalysts are used in the production of electricity by biofuel cells [26]. Cells use biological reactions to convert biochemical energy into electric energy, and there are unlimited amounts of microwatts of electricity in living creatures [27]. At an electric output efficiency of 38.7 W/cm^2, mesoporous carbons and carbon nanotube biofuel cells were shown to be more efficient than each other in the 2009 study conducted by Zhou *et al.* [28]. When Miyake *et al.* [29] presented a bio-anode needle for accessing biofuel in a rabbit's artery in 2011, they stated that it could provide 26.5 mW of power. Cuts in the abdomen of Blaberus discoidalis allowed from an implanted biofuel cell that generated an output power density of 55 W/cm^2 [30]. Cockroach enzymatic biofuel cells were studied by Shoji *et al.* [31] were able to generate 333 nW of power and power both a light-emitting diode and a wireless temperature sensor.

2.4. Environmental

Using low-grade power sources including ultrasonic transducers, electromagnetic generators, and solar panels, bio-environmental energy harvesting drives implantable medical devices [1], [32]. The use of ultrasonic transducers as energy harvesters for implantable medical devices has been studied in several ways. Using a piezoelectric oscillator installed beneath a goat's skin, Kawanabe *et al.* [33] measured a transmission output power of 2.1 W from the described model. Using a system developed by Towe *et al.* [34], researchers may evaluate and monitor biological processes. With the use of this technology, an ultrasonic beam applied to the skin was transformed into a high-frequency current. With an implanted piezoelectric with $BaTiO_3$, Alam *et al.* in 2019 [35] built a PENG for stimulating paretic muscles in rats with active, endogenous ultrasonic acoustic energy. The stimulated maximum power was 5.95 mW. Using piezoelectric materials, Kim *et al.* [36] developed an ultrasonically implantable model microlight for cancer therapy with a power density range of 0.048-6.5 mW/cm^2. Motion in this model is converted to spinning activity, which is utilized to wind a spring to generate mechanical energy by using the kinetic renewable resources generated by movement in the human body. The spring permits the electromagnetic generator to create electrical pulses once it has accumulated a specific amount of mechanical energy [1], [31].

Heartbeat power was converted into electricity and applied to the right ventricular wall of a dog by Goto and his colleagues using an automated quartz watch [37]. A pulse generator circuit that timed the dog's heart for 30 minutes was powered by the transmit power of 80 millijoules (mJ). Using a heart transplant, Zurbuchen *et al.* [38] created an automated wristwatch that converted mechanical cardiac energy to electrical energy. The proposed model is capable of generating 16.7 nW. An automatic wristwatch with a power output of 50 W was developed by Zurbuchen's team to be implanted into the hearts of living pigs [39]. Light energy harvesting has also been utilized to power implanted devices in the work of Haeberlin *et al.* [40], who created an electromagnetic generator with biocompatible cardiac turbines that could be placed into the heart of a pig via catheter.

In order to convert solar energy into electrical energy, photovoltaic cells are surgically inserted. The photovoltaic effect is also commonly exploited in semiconductors to generate voltages and currents [5]. For the biopsied energy harvesting system, Laube *et al.* [41] placed two solar cells and an LED inside a rabbit's eye, producing 1.5 mW of power output.

It was found that a photovoltaic cell may be put in the transcutaneous location of a pig to gather optical energy and run an electronic peacemaker for two weeks in darkness [42], [43]. For the first time, Song *et al.* [43] demonstrated solar cell arrays in the transcutaneous site of a hairless mouse. An implanted chip with 256-pixel artificial sub-retina was produced in 2018 by Wu *et al.* [44] mounted in the next ocular pole with a maximum output conversion current of 16.7 A.

3. RESULTS AND DISCUSSION

The incorporation of cutting-edge technical concepts into already existing power harvesters can serve as a point of departure for future research. By integrating various energy harvesters with contemporary nanotechnology, which can overcome long-term hurdles, new solutions for the diagnosis, treatment, and prevention of illness can be produced [45]-[50]. Table 1 highlights the ultimate power outputs achieved in the research that were discussed. When comparing the harvested energy from the emerging systems, one last conclusion emerges from Table 1: the biochemical energy harvester provides the most power and power density, whereas the environmental energy harvesters create the maximum current and energy. The highest voltage is generated by energy harvesters that are based on piezoelectricity.

Table 1. The ultimate power outputs achieved in the research in reviewed works

Implantable medical systems	The ultimate power outputs	Reference
Piezoelectric implantable medical sensors	0.18 μW/cm^2	[12]
	0.1 mJ	[14]
	5 V	[15]
Triboelectric nanogenerator implantable medical sensors	2 V	[21]
	2.93 W	[22]
	416 μW/cm^2	[25]
Biochemical implantable medical sensors	1 mW	[28]
	402 mW/m^2	[29]
Environmental implantable medical sensors	5.95 mW	[34]
	80 mJ	[36]
	16.7 μA	[43]

The currently available approaches for energy harvesting from implants show a lot of potential. However, it is essential to conduct an in-depth analysis of each method due to the potential challenges and drawbacks that could hamper the commercialization of these techniques and their application in implanted devices. It is feasible to combine the benefits of many techniques, and it is also conceivable to compensate for the shortcomings of one strategy by capitalizing on the advantages offered by another strategy. It is possible that in the future, the harvesting systems that are currently in use may be adequate for future applications. This would make it possible to do away with batteries entirely and make improvements to components that consume less energy.

Although every form of energy harvesting has its drawbacks, the most effective way to overcome these challenges is to use a hybrid form of the technology. Hybrid energy harvesters are able to compensate for any constraints that are imposed by the absence of a single energy source. This is possible because hybrid energy harvesters may extract electricity from many sources. A hybrid device is guaranteed to get electricity whenever one or more of its associated energy sources is operational.

4. CONCLUSION

Even while the battery storage capacity of implantable devices has increased, and the average implantation device’s circuits now require less power, it is still a huge challenge to find ways to harvest electricity and return it to the battery packs. However, despite their convenience, implantable medical technology has one major drawback: the batteries need to be replaced at regular intervals, which requires potentially expensive surgical operations. The harvesting strategy for the implantable device may be a viable option for reducing the need for surgery, either to completely eliminate the usage of batteries or to delay the requirement for surgical intervention. This could be done in one of two ways: either to completely eliminate the need for surgical intervention. In this article, a variety of different techniques for harvesting have been shown; these techniques were selected according to their applicability in terms of their power output, advantages, and disadvantages, along with the depiction of their testing on animals and humans.

Among the many difficulties associated with implantable devices, one of the most significant is reducing the degree to which the wearer is conscious of the existence of the device. Because they contribute to an increase in the total bulk of implantable devices, it has been suggested that the size of batteries be cut down or eliminated entirely. If you are seeking for a technique to gather power from implantable devices, this may be a more viable option than using a battery that includes potentially dangerous materials that could seep into the body of the patient. When it comes to power harvesting, these tactics hold a lot of promise; however, not all of them will work in the real world, particularly when it comes to safety and the potential to be sustainable over the long run. Because piezoelectric harvesters generate energy by exerting force or pressure and because they must be placed close to kinetic living organs like the lungs and heart, these approaches are not able to be used in the vast majority of implantable devices. Because of its size and the amount of room it requires, the process of harvesting power is not as effective as it could be. Biofuel cells can be utilized in a form factor that is more compact whilst maintaining the same functionality and power output. Several of these approaches were only tested in vivo for a period of time that was less than one year; hence, additional study is required to determine how well they might function in vivo for longer time periods. order to perform long-term implantation in vivo, it is very necessary to locate a method that not only keeps the system stable but also provides great biocompatibility. The safety of the patient is compromised when energy is transferred from a harvester to a biological sensor without the use of any external wires or conductors, which is another disadvantage of this method, and this stipulation has not been investigated or researched to a significant degree as of yet.

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