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Study on Development of Power Supply System for Medical Implants using Thermoelectric Energy Harvesting from Human Body

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Abstract

This paper gossips on a development of power supply system using thermoelectric generator (TEG) used for medical implants. There are currently more implantable medical devices being used than ever before, with the best example being the implantable cardiac pacemaker. Thermal energy harvesting from the body may extend the use of biomedical devices beyond the lifetime of batteries. The proposed TEG is employed to harvest human body heat energy & was composed of a polydimethylsiloxane (PDMS) substrate and thermocouples. The use of PDMS provides flexibility to the TEG and low thermal conductivity that helps minimize losses in the effective heat flowing through the thermocouples. Thermoelectric energy generators are an excellent proposition for both wearable home healthcare solutions and implantable medical devices because of their solid-state nature, proven stability and energy harvesting efficiency from low-grade heat. While technological advancements in energy harvesting face equally difficult challenges as energy storage devices, developments in research and engineering will provide solutions to ultimately maintain the lifespan of medical devices. Also, Numerical modelling of bio-heat transfer is an essential tool to consider various thermal effects such as metabolic and perfusion heat sources.

Keywords: Human Body Heat, Implantable Medical Device (IMD),MEMS,PDMS, Thermoelectric Generator (TEG).

1. Introduction

Currently, all portable electronic devices are powered only by batteries. However, the energy harvesting from human or environmental sources has proved to be an effective alternative or complement. As the electronics' scale decreases, so does the energy consumption. In this sense, it is should expect that batteries were also produced in smaller size providing more energy storage availability. However, due to technical and technological issues, the batteries have not been following by the same evolution trend, limiting the operational time and performance of portable devices as it need to be replaced or recharged periodically, adding also unwanted weight and volume.

Among various energy harvesting methods, thermoelectric energy harvesting from human body has advantages that human body heat is steady and large. Energy harvesting gives the possibility to build autonomous microsystems. Especially, energy harvesting would be ideal for implantable microsystems because it can supply the electrical energy without replacement of the battery. At this point, it is possible to draw a distinction between active and passive harvesting methods. The active powering of electronic devices takes place when the user of the electronic device has to undertake additional actions to generate power. On the other hand, passive energy harvesting assumes that the user is not forced to change his habits in order to generate energy. There are several approaches to the energy harvesting scenario. The most common are electromagnetic, thermoelectric, electrostatic or piezoelectric generators.

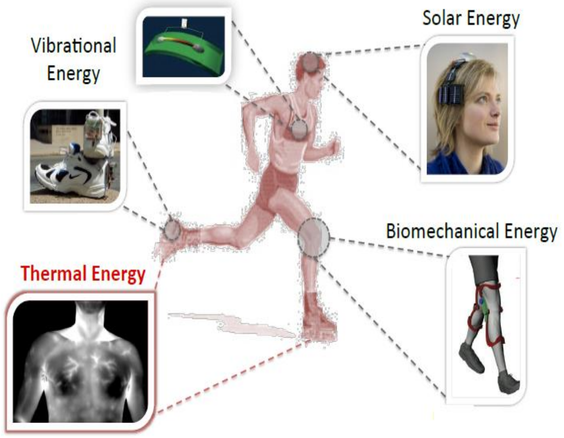

Fig.1 Sources of energy for energy harvesting in the human body[7].

However, from the viewpoint of the curvature of the human body, typical TEGs may be not suitable for applying to human body because most typical TEGs are composed of thermocouples on a rigid substrate. On the other hand, flexible TEGs transduce the human body heat efficiently since the flexible TEGs can be tightly attached on the skin [7].

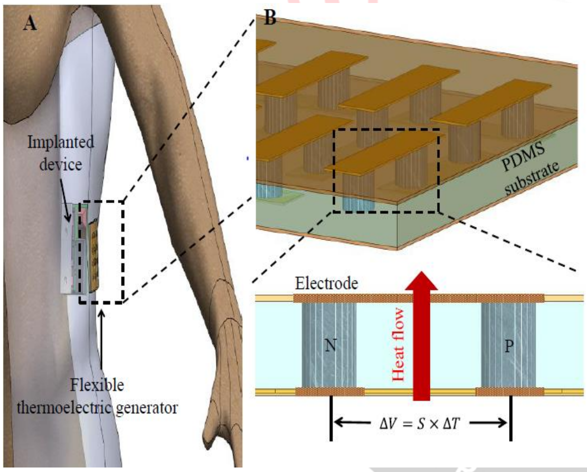

Fig.2 An implanted device with a flexible TEG & Schematic view of the proposed TEG [7].

Finite electrical battery life is encouraging companies and researchers to come up with new ideas and technologies to drive wireless mobile devices for an enhanced period of time. Batteries addto size and their disposal adds to environmental pollution. For mobile and miniature electronics devices, a promising solution is available in capturing and storing the energy from external ambient sources, a technology known as energy harvesting[8]. The objective of this work is to define analytical methods to study the effect of environmental and human factors on thermal energy generator (TEG) performance in a variety of use case scenarios [7].

2. Thermoelectric Generator

A thermoelectric generator (TEG), also called a Seebeck generator, is a solid state device that converts heat flux (temperature differences) directly into electrical energy through a phenomenon called the Seebeck effect[7]. In 1821 Thomas Johann Seebeck observed that when two dissimilar metals with junctions at different temperatures are connected in a circuit, a magnetic needle would be deflected. Seebeck initially attributed this phenomenon to magnetism.Devices are normally made up of semiconductor materials, the most common being bismuth telluride.

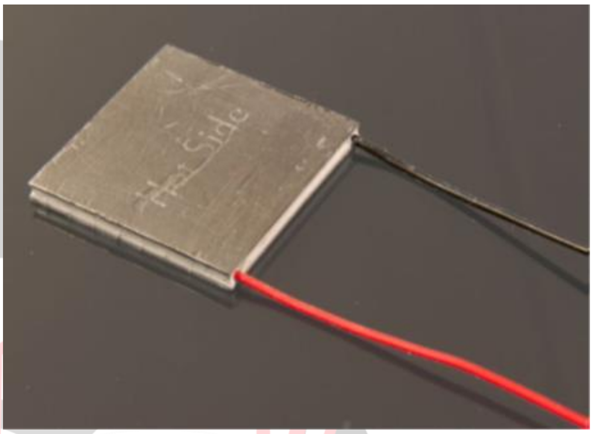

Fig.3 Thermoelectric Generator [3]

The extent to which electrons flow from hot to cold in an applied temperature gradient is governed by the Seebeck coefficient, also known as the thermopower .In order for a thermoelectric to establish a large voltage while in a temperature gradient, its thermal conductivity must be low[3].

2.1 Conventional materials

TEG materialscan be divided into three groups based on the temperature range of operation:

i. Low temperature materials (up to around 450K)Alloys based on Bismuth (Bi) in combinations with Antimony (Sb), Tellurium (Te) or Selenium (Se).

ii. Intermediate temperature (up to 850K): such as materials based on alloys of Lead (Pb).

iii. Highest temperatures material (up to 1300K): materials fabricated from silicon germanium (SiGe) alloys.

The power module is used for converting heat source directly into electricity.The module is Bi-Te based

Thermoelectric module that can work at the temperature of as high as 330 ˚C (626 ˚F) heat source continuously and up to 400 ˚C (752 ˚F) intermittently.

3. Current Practices

For MEMS devices with power consumption in the range of micro-watts, thermal energy harvesting becomes a viable candidate for power supply. Although the detailed analysis on the performance of thermoelectric generators affected by the internal irreversibility's such as Joule's heat and heat leak may be found in many texts many new results may be obtained when the influence of external irreversibility on the performance of thermoelectric generators is investigated further[5][1].The production of electricity using a thermoelectric generator placed onthe human body connected to a dc-dc converter. The small difference in temperature between the hot heat source (e.g. the human body, T_b = 37^{0}C) and the cold heat source (e.g. ambient air, T_a = 22^{0}C), associated with a poor quality thermal coupling (mainly with the cold source), leads to a very low temperature gradient at the thermoelectric generator terminals and hence low productivity. Under these use conditions, this the present article proposes an analysis of various ways to improve productivity given a surface capture system. Furthermore, we demonstrated, in this particular context that maximizing the recovered electric power proves to be a different problem from that of maximizing efficiency. Finally, this study highlights the benefit of sub-optimization of the power extracted from the thermoelectric generator to further improve efficiency of the overall system. We show that, given the conversion efficiency of the dc-dc converter, the maximum power point of the overall system is no more reached when the output voltage ofthe thermoelectric generator is equal to half of its electromotive force. [5]

4. Design and Fabrication

A schematic of the proposed TEG is shown in**Fig 2.** This TEG comprises thick PDMS film that includes thermocouples. PDMS is a flexible polymer with a low thermal conductivity. Thus, the use of PDMS reduces

thermal losses of effective heat flow that flows through the thermoelectric material. The thermocouples are

Composed of series connections between N-type and P-type thermoelectric materials. This series connection defines hot and cold junction. The defined hot junction is exposed to higher temperature, and the defined cold junction is exposed to lower temperature. When heat is applied to hot junctions, electrical potential is generated by See beck effect [7]. Basically, a rectangular meander made of the thermocouple materials deposited on a Si wafer. A barrier layer of SiO_2 insulates the thermopiles to prevent electrical short-circuit by the thermal contact structure fabricated in Module B. This concept allows to employ all kinds of thermoelectric materials that can be deposited on a Si substrate. For the fabrication of the thermocouple structures (Module A), a 300 m thick 4-in. silicon wafer serves as substrate. Thermal SiO_2 and LPCVD Si_3Ni_4 (each 300 nm thick) are subsequently deposited onto the wafer for electrical insulation and serve as supporting membrane. In situ n-doped poly-Si is deposited and structured by dry etching [3].

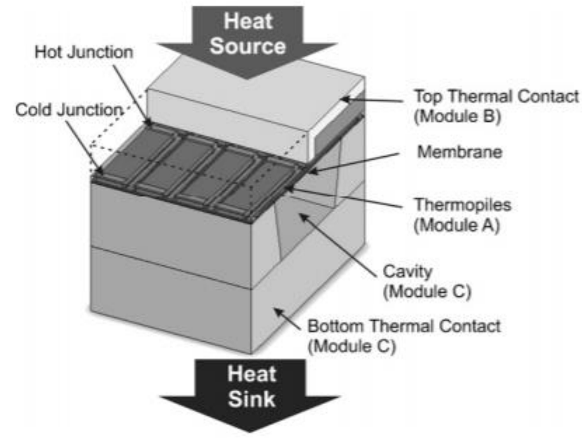

Fig. 4 Schematic of the microstructure TEG with optimized heat flow path. The prototype is fabricated with thermopiles made of n-poly-Si and Al[2].

When designing TEGs for wearable applications, it is important to consider the thermal resistance matching of the TEG to the human body. Proper matching of the high thermal resistance of the TEG to the high thermal resistance of the human body provides a maximum temperature difference across the generator. The thermal resistance model of a wearable TEG is shown in Fig. 4. Leonov et al demonstrated that by matching the thermal resistance of the TEG, RTEG, with the ambient environment, it can be shown as:[6]

$$R_{TEG} = \frac{(R_{body} + R_{sink})R_{air,0}}{2(R_{body} + R_{sink}) + R_{air,0}}$$ ....[6]

Where R_{body} is the thermal resistance of the human body at the TEG location, R_{sink} is the thermal resistance of the heat sink from convection and radiation and $R_{air,0}$ is the thermal resistance of the TEG if all the thermoelectric elements were removed and replaced with the surrounding insulator (usually air) . The thermal resistance of the generator can thus be designed based on the total resistance of the elements, $R_{elements}$, and the resistance of the empty space around the elements,

R_{space}, such that,

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$R_{TEG} = R_{elements}R_{space}/(R_{elements} + R_{space})$…………..[6]

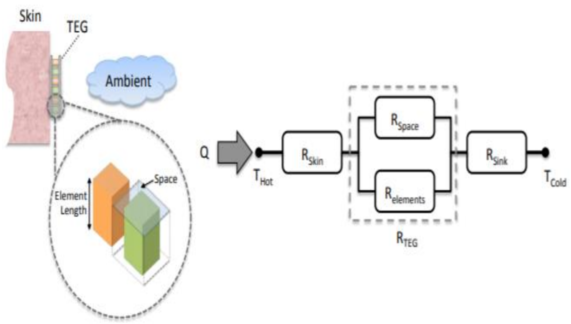

Fig.5 Schematic and thermal circuit of a wearable TEG[6].

5. Experimental Setup

The printed prototype device was tested by placing the device on a heater while carefully monitoring the temperature at both ends of the elements with thermocouples mounted with thermal joint compound (TIM-417, Wakefield Solutions). Once the device reached steady state, the open circuit voltage of the device was measured using a digital multimeter. A variable load resistance was then connected in series with the device and voltage measurements were taken at multiple load resistances. The power was then calculated based on the measured voltage and load resistance at various temperature differences. All testing of the device was performed in an insulated faraday cage to prevent thermal or electric interference from measurement. Fig shows an image of the experimental setup for characterizing the device [6].

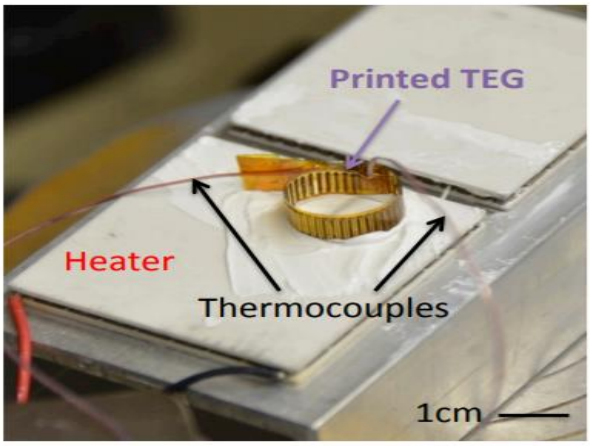

Fig. 6 Experimental setup for testing the printed TEG[6]

6.Result and Discussion

Fig.7 shows the temperature difference as a function of the temperature of the heat source when the ambient temperature was 25°C. It was possible to retain the temperature difference between top and bottom layer (ΔT) when the heat source temperature was close to the human body temperature.The fabricated TEG was finally attached on the human body. The ambient temperature and body temperature were measured by precision temperature sensor. It was confirmed that the skin temperature was constant at 32.5°C although the fabricated TEG was attached on the skin. When the temperature difference between ambient and body was 7°C, the output voltage and current of the attached TEG was 5 mV and 10 μA[7].

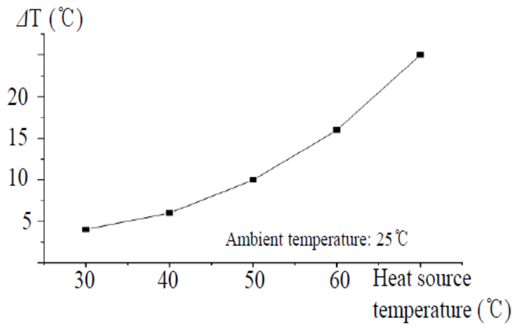

Fig.7 Temperature differences between top and bottom layer of the TEG as a function of the heat source Temperature(ΔT)[7].

The output power was 50 nWand it was very small value, but the TEG generated output voltage continuously with movement of the body. As stated earlier, the output power of TEG is proportional to the number of thermocouples, Seebeck coefficient and the temperature difference between hot and cold junctions.

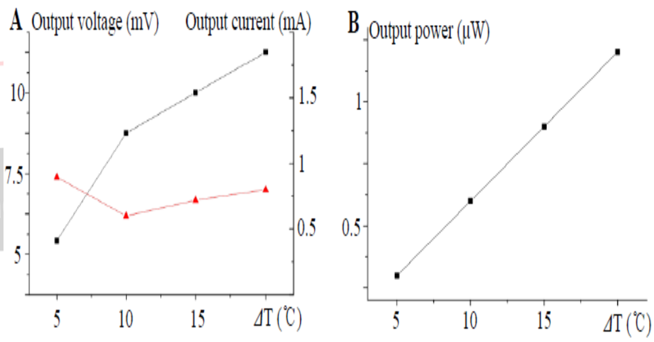

Fig. 8 Output voltage and current, (B)Output power as a function of top-bottom temperature difference

There are several ways to increase the output power of TEG such as enhancing of Seebeck coefficient of the thermoelectric materials or improvement of the TEG design. First, enhancing of the coefficient is material issue and it is difficult to change the material characteristic. However, the temperature difference and the number of thermocouples are relatively easy to change through improvement of the device design. In the view point of the design improvement, flexibility of TEG has great advantage because the flexible TEG can have large area with many thermocouples. The use of PDMS in this study gave flexibility to TEG and the temperature difference between each junction was large due to its low thermal conductivity. Although, the generated electrical power of the fabricated TEG on the human body was not large, the TEG showed feasibility of converting human body heat to electrical energy [7].

7. Medical Applications

The development of the first implantable artificial pacemaker over half a century ago spurred the phenomenal growth in the field of biomedical engineering within the last few decades. Embedding a thermoelectric generator (TEG) in a biological body is a promising way to supply electronic power in the long term for an implantable medical device (IMD). It can resolve the service life mismatch between the IMD and its battery. Implantable medical devices have had a long history of outstanding success in clinical practice. As employing thermoelectric generators (TEGs) to collect heat dissipated from the human body through the skin surface is a promising way to supply electronic power to wearable and pocket electronics, embedding a thermoelectric generator into biological body also can provide electronic power in the long term for the IMDs[9].

This study is dedicated to developing a real prototype, which consists of an implanted TEG and a specified boosted circuit. It was applied to support a clock circuit in the in vivo animal whose power consumption is much higher than an ordinary cardiac pacemaker. Meanwhile, the theoretical analysis implemented on such a real prototype is also established, which could serve as a valuable reference for future designs of the implanted TEG and its boosted circuit [6].

7.1Solid-state Heating & Cooling for Medical Applications

Thermoelectric heating and cooling utilize the Peltier effect to act as a solid-state heat pumpToday, the most ubiquitous biomedical uses of thermoelectric devices occur in modern polymerase chain reaction (PCR) thermal cycles for rapid heating and cooling of DNA. Developed in 1983 by Kary Mullis, who subsequently won the Nobel Prize in Chemistry in 1993 for his work, PCR has become a ubiquitous and indispensable method used in medical and biological laboratories for DNA amplification. The process of replicating DNA molecules using PCR requires thermally treating the DNA to three separate set points: (1) denaturation at 94°C, (2) annealing at 54°C and (3) extension at 72°C. These steps are then repeated multiple times with each cycle doubling the amount of DNA. This process naturally lends itself to using solid-state thermoelectric heater/coolers to speed up the thermal cycling time needed for these reactions. The reversibility, fast response and ease of deployment of Peltier devices make them ideal for PCR equipment. Thermoelectric manufacturers such as Marlow Industries and Nextreme have successfully commercialized thermoelectric devices in bench top PCR systems using standard Bi_2Te_3-based Peltier devices. Although PCR is a critical application of current thermoelectric devices in the biomedical industry, there have been few alternative uses of thermoelectric devices outside of PCR. It is thus of interest to explore various viable applications for thermoelectric devices.

7.2 Lab-on-a-chip Technology

Another potentially promising application of thermoelectric cooling and heating is its use in portable biomedical systems. With the future of healthcare focused on portability and on-site care, the field of Biological Micro-electromechanical systems (BioMEMS) has rapidly grown during the last decade. Advancements in micro-engineering adapted from the semiconductor Cooling' Blanket' 8 industry have opened the possibility of scaling laboratory-based systems such as PCR, electrophoresis, single molecular detection and disease diagnosis among many others. By utilizing MEMS techniques to make portable laboratory devices, commonly called "lab-on-a-chip" or micro-total analytical system (μTAS), such systems can be fabricated using low-cost and scalable methods while providing device portability and consuming less reagents.

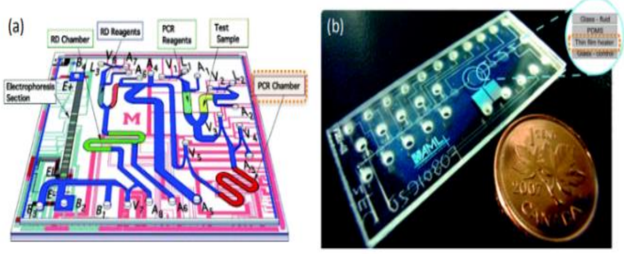

Fig. 9 Examples of fully integrated lab-on-chip devices:

(a) a microfluidic device for influenza andother genetics analyses. (b)an integrated microfluidic chip for chromosome enumeration using fluorescence in situ hybridization[6].

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7.3Thermoelectric Energy Harvesting for Biomedical Devices[6]

The history of medical diagnostics and treatments can be traced back millenniums to the ancient Egyptians and Greeks. With extraordinary advances in research and enabling technologies, modern medicine has come a long way from the clinical observations of Hippocrates. As diagnostic tools continuously evolve and improve, they tend towards miniaturization and mobility. Continuous patient physiological monitoring can now be performed outside the clinical environment, providing physicians with more thorough information. Life-supporting medical devices have transformed from bulky and invasive machines to portable implantable devices, freeing patients from the direness of permanent hospitalization. Mobility inevitably requires portable energy solutions, a role currently filled by energy storage technologies such as batteries. As it becomes clear that progress in energy research does not follow Moore's law, a multitude of energy harvesting approaches may eventually allow energy research to keep up. Thermoelectric energy harvesting in the biomedical realm can be divided into two sets of applications:

(1) Wearable

(2) Implantable applications.

This section will discuss developments and ongoing research in both sets of applications while focusing on the aspects of thermoelectric device design and integration. Thermoelectric devices, acting as solid-state power generators from temperature differences, may be suitable for harvesting the low quality heat emitted from the body. This recovered energy can potentially provide power for a new wave of diagnostic and medical tools.

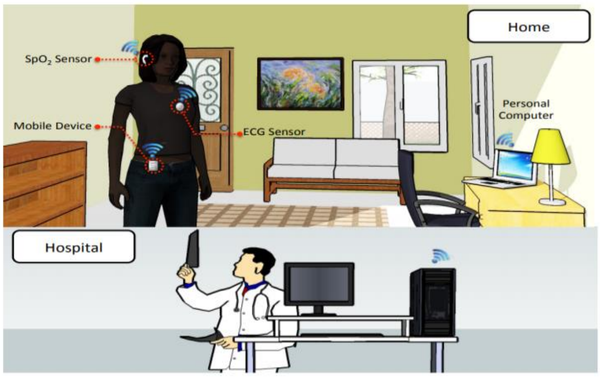

Fig.10 An illustration of a wireless physiological monitoring system, also frequently called a Body Sensor Network (BSN)[6]

7.3.1 Wearable Applications[6]

The increasing demand for low-cost and personalized wireless physiological diagnostic tools has increased research efforts in wireless body sensor networks (BSN's) and mobile health (mHealth). **Fig.8**illustrates an example of a wireless physiological monitoring system. These applications can include long-term (24/7) monitoring of the local/regional events in tissue or organs under investigation and personalized home health care. These tools can be applied to monitoring of patients with chronic diseases, hospitalized patients or the elderly. New generations of medical diagnostic "smart" probes often require high sampling rates resulting in high-energy consumption which has ultimately limited device lifetimes. Due to power constraints, there is often a trade-off between sensor resolution/sampling rate and device usability lifetime. Thermoelectric generators (TEG's) can provide a method to increase the energy storage capacity in BSN's by harnessing thermal gradients between the body and ambient environments. The power and voltage requirements of today's micro-electronic systems have significantly diminished to match the power output of TEG's at low temperature differences (between 5 and 20 K). Studies have suggested that a constant power source exceeding 100μW/cm^2 at 1V is an ideal energy harvester for practical wearable sensor networks. Some state-of-the-art ultra-low power radios have reported power consumptions <10μW with transmit/receive ranges of up to 10m. Advancements in TE materials and device fabrication technology have only recently been able to meet some of the power and voltage requirements of the radios and sensors within a constrained device footprint. It is thus important to understand the remote physiological monitoring systems and their applications to provide insight into the design and feasibility of wearable TEG's.

7.3.2 Implantable Applications [6]

Perhaps the earliest investigation of implantable thermoelectric generators surfaced during the late 1960's when zinc-mercury batteries were still the standard power sources for implantable pacemakers. To solve this problem, Medtronic, currently one of the largest implantable medical device manufacturers in the world, and Alcatel jointly designed a nuclear-powered pacemaker consisting of a Plutonium-238 (Pu-238) radioisotope and a thermoelectric generator. Even accounting for the degradation of the radioisotope and the TEG, the pacemaker still functions in patients after more than 35 years from its

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production. During the mid-1970's, radioisotope TEG powered pacemakers began to lose favor to lithium batteries which had calculated life-times of approximately 10 years. Physicians decided that it was more appropriate for patients to be updated with newer devices every 10 years instead of using devices with older technologies. Presumably, the inherent risks of plutonium were alsoreasons for switching to lithium-based batteries. Implants of radioisotope TEG pacemakers stopped in mid 1980's as lithium cells became the predominant power source for implantable medical devices.

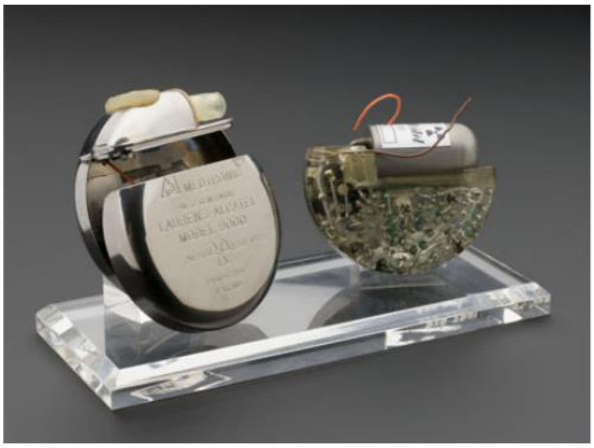

Fig.11 Image of an implantable pacemaker with a radioisotope TEG as the power source[6].

Lithium-based primary batteries have become the standard power sources for today's implantable medical devices. Their prevalence in the medical device industry has been attributed to their high energy density and high voltage, allowing single cells to last >10 years with

excellent stability and performance .This provides an unnecessary strain on patients as any surgical procedure includes additional risks and hazards. In fact, some devices such as implantable deep-brain neurological stimulators used for the treatment of Parkinson's disease, chronic headaches and depression, require replacement of batteries every few months. This results in significant scarring of the patient's skin near the collarbone where the battery is placed, creating additional stress for an already distressed patient. Some larger devices such as implantable ventricular assist devices (VAD), also known as implantable mechanical heart pumps, require more power than is possible for implantation. Once thought as a temporary device for patients awaiting heart transplants, implantable VAD's are becoming more prevalent among patients with heart failures. They provide patients with a life-supporting solution without the complications associated with transplants such as infection or organ rejection. However, to supply sufficient power to VAD's, a cable from the device connects to a control unit and large wearable battery packs through a small hole in the abdomen (Fig.10). The cable extruding out of the abdomen is coated in a biomaterial to allow tissue to heal around it without infection. Since the risk of a depleted battery is life threatening, patients must constantly worry about the battery life and many carry extra batteries for back-up. It is thus important to explore alternative strategies to powering implantable devices by either extending the lifetime of batteries or providing perpetual power to such devices. This opens a niche for new thermoelectric generators to harvest waste heat from the body for implantable applications [6].

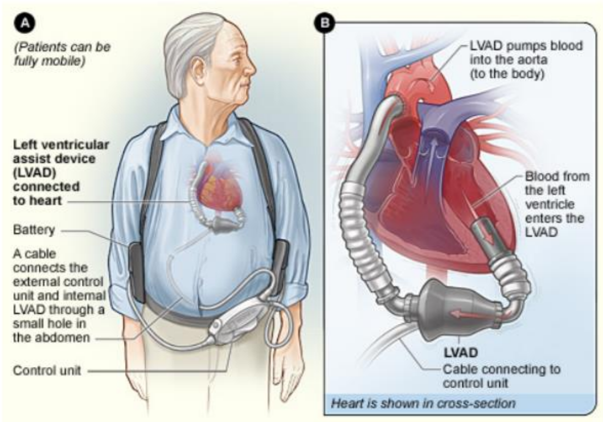

Fig.12 Schematic of an implantable left ventricular assist device [6].

Conclusions

From the experimental result, it was shown that the fabricated TEG could generate electrical power when the temperature difference between each junction was not large. Finally, the fabricated TEG was attached to human body and it showed the feasibility of harvesting human body heat. From an ultimate imagination, the interior composition of the IMD driven by the implanted TEG should contain three main parts: the functional circuit, the boost circuit, and the thermopile array. In order to guarantee the temperature difference crossing

the thermopile array, the electronic circuitry and thermopile array should be arranged in parallel and encapsulated in a shell which is provided with good thermal conductivity and biocompatibility with the human body. It was found that the highest temperature gradient occurs near the skin surface of the human body, which suggested a candidate site for implanting and positioning such a device. The performance of a thermoelectric generator is sensitively dependent on the degree of external irreversibility. It is thus clear that only if the influence of external and internal irreversibilities on the performance of thermoelectric devices is considered simultaneously, one can obtain more significant results for real thermoelectric generators. Also a new approach proposed to feed implantable neural recording system, which based on extracting electrical power from human tissue warmth in order to supply a biomedical neural recording system. Finally, the study of a complete energy recovery system has underscored the importance of optimizing overall system efficiency rather than the efficiency of each stage in the electric conversion chain. They have actually demonstrated that it was preferable not to optimize TEG output power by means of increasing voltage at its terminals, so as to minimize dc-dc converter losses and thus maximize overall system efficiency.

Future Scope

Thermoelectric energy harvesting from the human body will be employed to extend the operation time of battery-powered implants as used in e.g. deep brain stimulation. Comprehensive understanding of the temperature distribution at typical implant locations has to be acquired during the initial phase. Numerical modelling of bio-heat transfer is an essential tool to consider various thermal effects such as metabolic and perfusion heat sources. The implant will contain the generator, power management electronics and the control circuitry. Suitable power management electronic modules will also be evaluated and selected. We will assess the integration of the energy harvesting system and the electronics. Towards the end of the project an integrated prototype will be assembled and thoroughly tested.

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