The use of Nanogenerators to power Cardiac Pacemakers

S. Iyer & P. Jichkar

Abstract— Advances in medical technology have led to a substantial increase in the number of medical assist devices implanted in the human body. The pacemaker is one such device which aids cardiac functioning. Even as the number of pacemakers implanted each year reaches into millions worldwide, finding an efficient power source for them still remains a challenge. The average life span of a pacemaker battery is seven years. A cardiac patient thus requires several surgeries to replace the battery throughout his lifetime. The search for an alternate power source for pacemakers is hence critical.

This paper reviews the use of nanogenerators as a power source for pacemakers and is focussed on Piezoelectric nanogenerators using PMN-PT, ZnO and PZT. Based on a technology that converts mechanical or thermal energy from small-scale physical change into electricity, nanogenerators are an emerging option to power electronic devices. Nanogenerators have varied applications in bio-medical and other fields. The use of nanogenerators has enabled doctors to implant a new generation of devices. These devices have the capacity to stay powered for a long time with minimal body invasion. A major benefit of using nanogenerators is their ability to convert kinetic energy from bodily movement into electricity. Kinetic energy within the body is a naturally occurring and continuous source of renewable energy. Thus utilizing this source of energy to power devices proves to be beneficial to the body as well as to the environment.

Index Terms— Nanogenerators, Self powered implants, Piezoelectric Nanogenerators, Pacemakers, Lead zirconate titanate (PZT), Zinc oxide (ZnO), Lead magnesium niobate-lead titanate (PMN-PT).

INTRODUCTION

The rhythmic beating of the heart is due to the triggering pulses that originate in an area of the right atrium of the heart, called the sino-atrial node. In abnormal situations, if this natural pacemaker ceases to function or becomes unreliable or if the triggering pulse does not reach the heart muscle because of blocking by the damaged tissues, the normal synchronization of the heart gets disturbed. When monitored, this manifests itself through a decrease in the heart rate and changes the ECG waveform. By giving external electrical stimulus to the heart muscle it is possible to regulate the heartbeat. These impulses are given by an electronic instrument called a "pacemaker" [1].

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1.PACEMAKERS:

A pacemaker consists of two parts:

i) An electronic unit to generate impulses at a controlled rate and amplitude called 'pulse generator'

ii) The lead carrying these electrical pulses to the heart [1]

Pacemakers are of two types:

1) External pacemakers: They are used when the patient is recovering from cardiac surgery, awaiting implantation of a permanent pacemaker and in situations where short term pacing is required. They are more or less used as temporary solutions.

2) Implantable pacemakers: These pacemakers are implanted *In Vivo*, or within the body. Usually, a miniaturized pulse generator is powered by small batteries, designed to be implanted beneath the skin with its output leads directly connected to the heart muscles.

The implantable pacemakers improve survival rates in patients suffering from arrhythmias. But unfortunately, these life-savers do not provide a life-long service. They require batteries to operate which get exhausted. The life of a pacemaker is determined by the current consumption of the electronic circuit and the energy available in the unit. The first clinical application of an implantable cardiac pacemaker by Elmquist and Senning in 1960 used nickel-cadmium rechargeable cells [1]. These were abandoned as the battery life of the device was approximately similar to that of a primary cell. Other types of batteries used to power pacemakers are listed in table 1 given below. Modern day pacemaker batteries last for seven years on an average after implantation [2]. To continue using the device, the patient has to undergo surgery for battery replacement. This is not desirable as:

a) The surgery is highly invasive.
b) The procedure is expensive.
c) There is a risk of compatibility every time a pacemaker is implanted in the body.
d) Post surgical recovery is time consuming and may cause discomfort to the patient.

One approach to overcome the disadvantages associated with the use of replaceable batteries is by using nanogenerators to power pacemakers. Nanogenerators meet the power requirements of the batteries in the pacemakers by harnessing the energy generated due to mechanical movement of muscles. This mechanical energy is converted to electrical energy which is then used to power the pacemaker.

TABLE 1. Batteries other than Ni-Cd

	MERCURY BATTERIES	BIOLOGICAL POWER SOURCES	NUCLEAR BATTERIES	LITHIUM CELLS
HISTORY	Developed in 1960 by William Chardack and Wilson Greatbatch[1]	Developed by Racine and Massie(1971) and Schaldach(1971)[1]	Developed by Greatbatch and Bustard, 1973[1]	Developed in 1979 by John Goodenough and Koichi Mizushima [3] and first used in a pacemaker in 1972 [4]. Continue to be used till date.
WORKING	3-5 batteries were used with 1200 mAh. This battery produced 1.35V and was cast in epoxy, which was porous to the discharge of the battery, released hydrogen and permitted its dissipation, which required venting and hence could not be hermetically sealed. This allowed fluid leakage into the pacemaker at times that caused electrical shorting and premature failure.[4]	These were the Galvanic cells using body fluids as electrolyte. Unsuccessfully used once in a practical pacemaker.	The energy liberated from total decay of 1g of Pu238 with a power density of 0.56W/g was 780kWh. At 1% efficiency, if a pulse power needs to be provided, 20mg of Pu would be required. [1]	The electrochemical system Li-CF_x is a better choice for these types of cells. Theoretical value of energy density for this system is 2435 Wh/kg whichis 4 times the Li-I system.[5]
DRAWBACKS	Dendritic mercury growth, zinc oxide migration, leaky separators and corroded welds ,corrosive liquid electrolyte i.e. NaOH.[1]	Eventually cell becomes permanently electrically isolated becoming inoperative	Irrational fear of catastrophic dissemination of particulate matter. The plutonium emits alpha particles, which impact upon the container and generate heat. [1]	The lithium battery shows a gradual drop in voltage over a period of years due to slow increase in the internal resistance.

2. NANOGENERATORS (NG)

The word 'nano' implies one billionth part of the measured quantity. For the purpose of small size IMDs (implantable medical devices), nano-materials are of significance. These nano scale generators of electricity use piezoelectric materials to convert mechanical energy to electrical. Their greatest advantage is that they are self- sufficient, without any dependence on other power sources.

Materials such as PMN-PT, ZnO, PZT, ZnO-ZnS, GaN, CdS, $BaTiO_3$, PVDF are used in the manufacture of nanogenerators. Of these, the piezoelectric materials considered for this review are:

2.1 PMN-PT

The cardiac pacemaker operates at an input of 100 μA and 3V. Therefore, it is desirable to utilize materials with a high piezoelectric charge coefficient to increase the output current efficiency of flexible energy harvesters. The piezoelectric charge coefficient represents the piezoelectric capability of converting mechanical deformation into electric charges. One such piezoelectric material is single crystalline Lead magnesium niobate-lead titanate (PMN-PT). It has exceptional piezoelectric charge constant of d 33 up to 2500 pC/N, which is almost 4 times higher than that of PZT and 90 times higher than that of ZnO. [6]

PMN-PT NGs were first developed at Korea Advanced Institute of Science and Technology (KAIST) by G T Hwang and his team. They developed a flexible and highly-efficient energy harvester enabled by single crystalline piezoelectric PMN-PT thin film on a plastic substrate to achieve a self-powered artificial pacemaker with significantly increased electric output current. The flexible PMN-PT thin film harvester delivered a current of 145mA and a voltage of 8.2V, through the periodic mechanical motions of bending and unbending. Highest current reported to date was 223 μA, reported by finger tapping.[6] The converted electricity was used to directly turn on 50 commercial green LEDs and charge coin batteries for driving portable electronic devices. Finally, real-time functional electrical stimulation was performed to provide the artificial heart beating for a live rat using the high-performance flexible PMN-PT energy harvester. An overall schematic illustration of artificial cardiac pace-making using a flexible PMN-PT thin film stimulator is shown in figure 1a. The flexible cardiac stimulator was directly linked to stimulation electrodes to provide electrical stimuli to the heart of an anesthetized rat. Three sensing terminals were pinned to the rat, on the left posterior leg and both anterior legs, to monitor its (ECG). Figure 1b shows the animal experiment with opening the chest of a rat for stimulation of the heart and perception of the heartbeat. The rat had a typical QRS complex, P wave, and T wave in the ECG amplitude with a heart rate of about 6 beats per second as displayed in Figure 1c and its inset. In normal animals, external electric energy of 1.1 μJ is minimally needed to trigger the action potential for artificially contracting the heart. When the flexible PMN-PT stimulating device was bent and unbent cyclically, the corresponding spike peaks were observed on the natural heartbeat of the rat in the ECG, as seen in Figure 1d. The generated energy (2.7 μJ) from one bending motion of the flexible stimulator was larger than the threshold energy (1.1μJ) to electrically stimulate the living heart. This result shows that the thin film NG has potential biomedical use for the normalization of cardiac function [6].

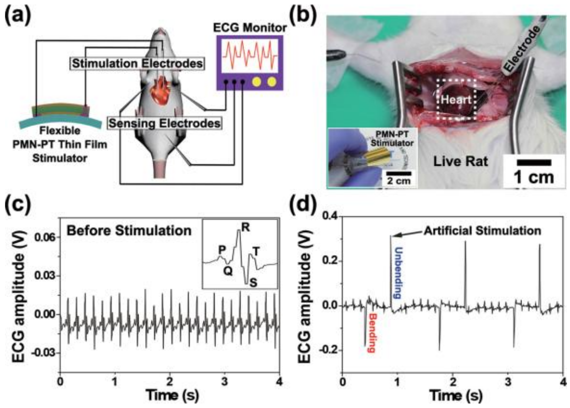

Fig 1: a) PMN PT thin film simulator. b) Implant in a rat's heart. c) The simultaneously recorded ECG in a normal rat heart before the stimulation. The inset presents a magnified heartbeat of the rat, which consists of typical

QRS complex, P wave, and T wave. d) Voltage current Characteristics. [6]

2.2 Zinc Oxide

Crystalline Zinc Oxide (ZnO) has a wurtzite crystal structure at ambient conditions. Fig (2) shows the crystalline structure of ZnO. ZnO is popularly used as a nanomaterial due to its vast areas of application. At the nano level, ZnO exhibits diverse configurations of nano structures including nanoparticles, nanowires, nanorods, nanotubes, nanobelts, and other complex morphologies[7].

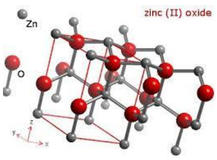

Fig 2: Crystalline structure of ZnO [8]

Due to its non-centrosymmetric crystallographic phase, ZnO shows piezoelectric property [6]. This along with its semiconductor properties form the basis of electromechanically coupled devices. ZnO is also bio-safe and bio-compatible and can be used for biomedical applications with little toxicity.

A ZnO Nanogenerator for cardiac applications was first invented by Zhong Lin Wang, professor of materials science at Georgia Tech and his team in the year 2009. They used aligned zinc oxide (ZnO) nanowires (NWs) embedded on an Al_2O_3 substrate. The NWs were formed using the vapour-liquid-solid process using Au as catalyst. In this process, ZnO is grown layer by layer on an Al_2O_3 substrate up to the desired length as shown in Fig 3 (A), (B). Ordinarily the positive and negative charges of zinc and oxygen ions in these crystalline nanowires cancel each other out. But when the wires, which are chemically grown to stand on end on top of an electrode, bend in response to mechanical forces, the ions are displaced. This unbalances the charges and creates an electric field that produces a current when the nanowire is connected to a circuit.

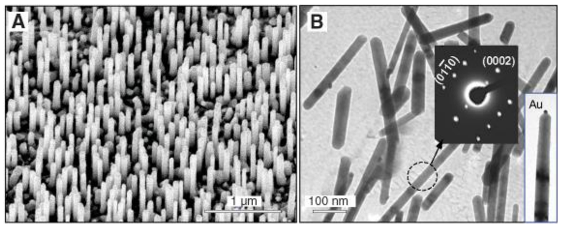

Fig 3: a) Scanning electron microscopy images of aligned ZnO NWs grown on an- Al_2O_3 substrate. b) Transmission electron microscopy images of ZnO NWs, showing the typical structure of the NW without an Au particle or with a small Au particle at the top. Each NW is a single crystal and has uniform shape. Inset at center: An electron diffraction pattern from a NW. Most of the NWs had no Au particle at the top. Inset at right: Image of a NW with an Au particle. [10]

The NG implemented at Georgia Tech university was a single NW generator (SWG) with a length of 100-500 micrometers and a diameter of 100-800 nanometers. The two ends of the NW were tightly fixed to the surface of a flexible polyimide substrate by applying silver paste and two lead wires, isolated from the environment, were connected to the ends. Because of the presence of bio-fluids under the in vivo working condition, the entire device was covered with a flexible polymer to isolate it from the surrounding medium and to improve its robustness [14]. It was implanted in a live rat and harnessed the rat's breath and heart beat as power sources. In the 1st experiment, the SWG was attached to the rat's diaphragm. The physical expansion and contraction of the diaphragm created a piezoelectric potential in the SWG. As seen from the figure (4d), a positive voltage current pulse was produced during inhalation and a negative pulse during exhalation. The SWG produced a voltage of 1mV and 1pA when the breathing was controlled by a respirator, and produced a voltage of 2mV and current of 4pA when the rat breathed normally.

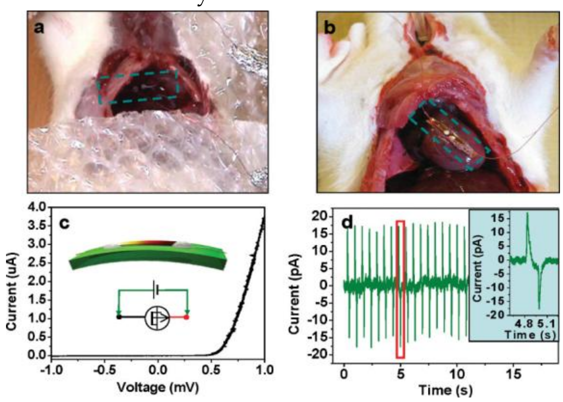

Fig 4: a,b) A SWG attached to a live rat's diaphragm (a) and its heart (b), which drives the SWG to periodically

bend and produce an AC power output. c) I–V characteristics of the SWG. The inset illustrates the schematic of the SWG and its connection configuration in reference to the measurement system. d) Typical current output recorded from a SGW under in vivo conditions [11]

In the second experiment, the SWG was attached to the rat's heart. The movements of the cardiac muscles created an AC current in the SWG. Figure 5 shows the open-circuit voltage and short-circuit current output. The different peaks on the graph represent the ventricular and auricular beating. On average, the voltage and current outputs were around 3mV and 30 pA, respectively. [14]

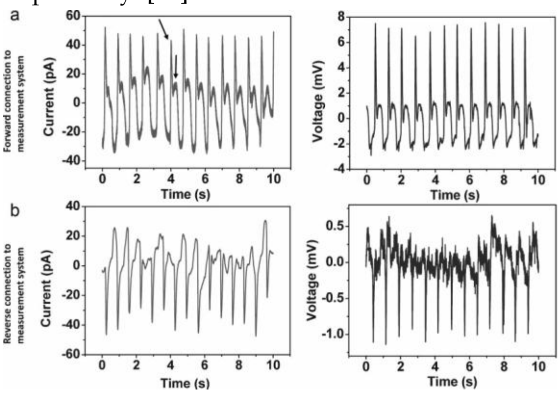

Fig 5: Energy harvesting from the heartbeat of a live rat by using a SWG. a) Electric power output (short-circuit current and open-circuit voltage) when the SWG is forwardly connected to the measurement system. b) Electric power output (short-circuit current and open-circuit voltage) when the SWG is reversely connected to the measurement system. [11]

Thus, these experiments have proven that ZnO can be used as NG with some success. Although currently each nanowire alone produces very little power, with simultaneous output from many nanowires, power high enough to run a small medical implant can be generated. The Team at Georgia Tech have also built a device that integrates hundreds of nanowires in an array. This device, which the researchers recently reported in the journal, Nature Nanotechnology, gives an output current of about 100 nA at 1.2 volts, producing 0.12 μW of power. Attempts are currently being made to integrate this array into an implantable electronic circuit. An additional advantage with ZnO is the low cost of production.

2.3 PZT

Lead zirconium titanate is an intermetallic inorganic compound with the chemical formula $Pb[Zr_xTi_{1-x}]O_3$ ($0 \leq x \leq 1$). Though PZT is among the most efficient piezoelectric materials known, it is an extremely brittle material, with a Young's Modulus half that of steel (50-100 GPa). Thus, the maximum safe strain for PZT is 0.2%, which means even small amounts of stretching will break them.

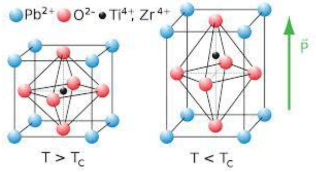

Fig 6: Crystalline structure of PZT. [12]

A research team at Princeton Headed by Yi Qi and Michael McAlpine worked in association with a research scientist, Prashant Purohit from the University of Pennsylvania to develop a PZT based nanogenerator which could withstand higher strain. They specially designed the PZT ribbons' shape into a wavy structure, so it could be stretched up to 10% strain. [14] To make the materials, researchers at Princeton University first made piezoelectric ribbons out of PZT (5-10 μm wide and 250-500 nm thick) and these were patterned on a magnesium oxide (MgO) host substrate. The ribbons were then released from the host substrate using Phosphoric Acid (85% conc.). A slab of poly(dimethylsiloxane), PDMS (2mm thick) was then elastically stretched and brought into conformal contact with the ribbons. Peeling off the PDMS allowed for complete transfer of the PZT ribbons to the elastomer via adhesive van der Waals forces in the surface dominated ribbons. Finally, releasing the prestrain in the PDMS led to a compressive force in the PZT ribbons as the PDMS relaxed to zero strain, leading to periodic de-adhesion and buckling. The resulting wavy geometry is a result of the transfer of mechanical compressive energy into bending energy.

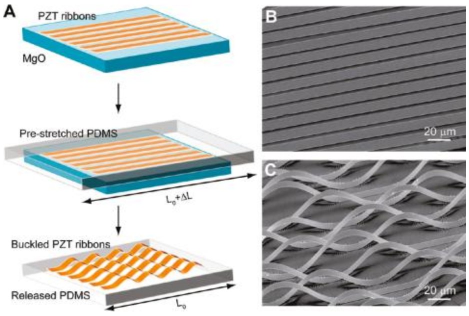

Fig 7: Formation of wavy/buckled piezoelectric PZT ribbons. (a) From top to bottom: PZT ribbons were patterned on an MgO substrate and undercut etched to release them from the mother substrate; a slab of prestrained PDMS was laminated against the ribbons and peeled off quickly; retrieved PZT ribbons were transferred onto PDMS and formed wavy/buckled structures upon strain relaxation. (b) SEM image of PZT ribbons transfer printed to PDMS with zero prestrain. (c) PZT ribbons spontaneously buckled under prestrained conditions. [14]

Researchers at the University of Illinois have utilized PZT ribbons to power NGs. The main element in the device is a capacitor-like structure comprising a layer of PZT 500 nm thick sandwiched between two electrodes – one made of titanium and platinum and the other from chromium and gold. The set-up consists of 12 groups of 10 such structures electrically connected in parallel. The researchers connect each of the 12 groups in series to its neighboring group to increase the output voltage. They then encapsulate the ensemble in a biocompatible material, such the polymer polyimide, to isolate it from body fluids and tissue.

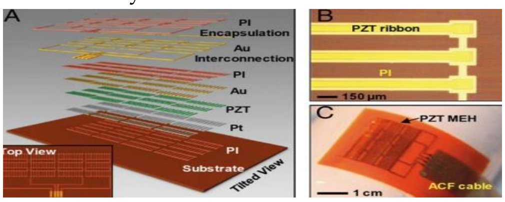

Fig 8 A) Exploded-view schematic illustration with a top view (Inset). (B) Optical microscope image of PZT ribbons printed onto a thin film of PI. (C) Photograph of a flexible PZT mechanical energy harvester with cable for external connection. [15]

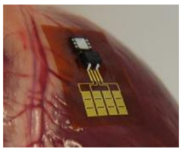

Fig 8 D) PZT mechanical energy harvester (co-integrated with a rectifier and rechargable battery), mounted on a rabbit heart. [15]

The Illinois researchers have already confirmed that the device is compatible with the major organs in several animal models. Experiments performed with a linear motor to periodically deform the device indicate electrical outputs as large as 1–2 V (open-circuit voltage) and 100 nA (short-circuit current). Initial in vivo tests on rabbit hearts yielded voltages and currents of
1 mV and 1 pA, respectively.

Efforts are being made to use the lung movement to power PZT Nano ribbon based NGs.

3. CONCLUSION

In conclusion, these types of energy harvesting and storage system could be used as potential candidates for the energy source in artificial pacemakers, thereby resolving intrinsic issues such as increment of battery size or even replacement of discharged batteries. The flexible energy harvester reviewed in the present work could lead to a robust and evolutionary energy source with longer operation time and miniaturization of batteries, especially in the restricted space of the human body.

They could be readily recharged by cyclic deformation behaviors of biomechanical energy source such as the heartbeat, diaphragm elevation, and lung movement or even the sound of heart beats.

By using nanogenerators, doctors could implant a new generation of devices with the capacity to stay powered for a long time with minimal body invasion. An additional benefit, is their positive impact on the environment since nanogenerators use a renewable resource: kinetic energy from body movement. Though the current impact of nanogenerators is small; they hold the promise to be an efficient power source for larger devices in the future.

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