Piezoelectric Energy Harvesting Optimization for an Extended Operation of Deep Brain Stimulator

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I. INTRODUCTION

Deep brain stimulation (DBS) is an accepted standard surgical treatment for Parkinson's disease and has been studied for a wide range of neurological and psychiatric disorders including depression, Alzheimer's disease, and other conditions that accompany disabling symptoms [1]. In the DBS system, electrodes are implanted into specific brain regions related to disease symptoms, and constant or intermittent electricity to stimulate targeted regions is delivered from a power source [2]. To supply power for neurostimulation, a battery is implanted in the body as an internal part of an implanted pulse generator (IPG).

Although current implantable DBS devices depend on a battery for operation, this battery-powered system has limitations; battery longevity is limited, and it is a component that restricts the miniaturization of IPG. The battery lifespan of current commercialized DBS devices, for example, is 3–4.6 years for Activa PC and 4.3–6.5 years for Kinetra [1]. Fixed battery longevity requires repeated replacement surgeries which accompany a high risk of infection, pain, and financial burden. To provide enough power for stimulation during the sufficient operating period of the DBS system, a large enough battery is needed, and this restriction in size results in bulky IPG. The bulkiness restricts the implantation of IPG on the specific body part such as the chest wall, which hinders variations and advancements of the DBS devices [1].

To address these problems, two different strategies to reduce the burden of using a battery in implantable DBS have been studied: (i) DBS with a rechargeable battery and (ii) battery-free DBS based on energy harvesting. Rechargeable IPGs have been proven to be able to provide the desired current for up to 9 years before replacement, which is longer than the lifespan of a fixed-life battery [3]. However, ineffective recharging may occur because ineffective communication between IPG and the recharging device can derive from inappropriate placement of the device [1]. In addition to the mechanical problem from device, the daily or weekly recharging process is another burden for some patients who have movement disorders or cognitive impairments [4]. Battery-free approaches using triboelectric [4] and piezoelectric [5] nanogenerators can convert biomechanical energy from the movement of internal organs such as the lung and heart to electrical output. Although energy harvesting totally removes battery-induced problems, this framework suffers from low power outputs which are insufficient to meet the need for implantable DBS. Elsanadidy et al. [4] proposed a battery-free, self-sustainable DBS system leveraging a bio-triboelectric nanogenerator which harvests energy from breathing motion of lungs. However, this device is insufficient to supply high power outputs so that its application is restricted to intermittent stimulation. It is also challenging to increase the size of the proposed device because of its thickness, which hinders implantation to target organ. Using flexible piezoelectric film, although Hwang et al. [5] proved that the harvester can generate sufficient power for operating DBS device with slight bending in a mouse model, its application for larger animal needs further analysis.

In this paper, we propose a piezoelectric energy harvesting efficiency optimization for an extended operation of a deep brain stimulator. By comparing the lung and heart as an energy source for a physical mechanical energy harvester based on the thin ribbons of lead zirconate titanate (PZT) [6], we decided to place the device on the right ventricle of the heart which generates higher power outputs. To maximize the efficiency of the proposed method, three approaches were combined: enlarging the size of the harvester, stacking multiple harvesters, and increasing the flexibility of the whole structure. As a result, the optimized piezoelectric DBS device provided higher power with a shorter charging time. It is expected to suggest a novel solution for a self-sustainable, consistent deep brain stimulator with miniaturized IPG.

II. RESULTS AND DISCUSSIONS

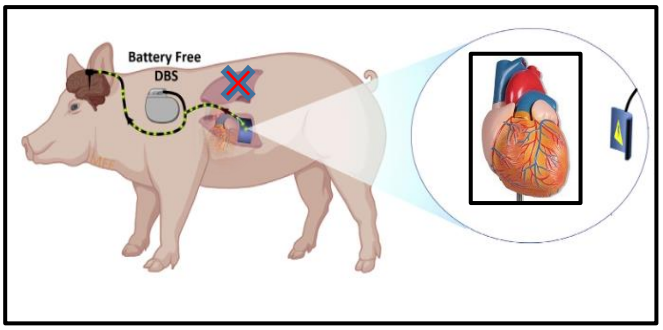


Fig 1. Concept and design of the self-sustainable DBS.

This system shows our standalone power system consisting of a Bio-TENG for harvesting biomechanical energy due to breathing and a bio-supercapacitor for the efficient storage of harvested electrical energy.

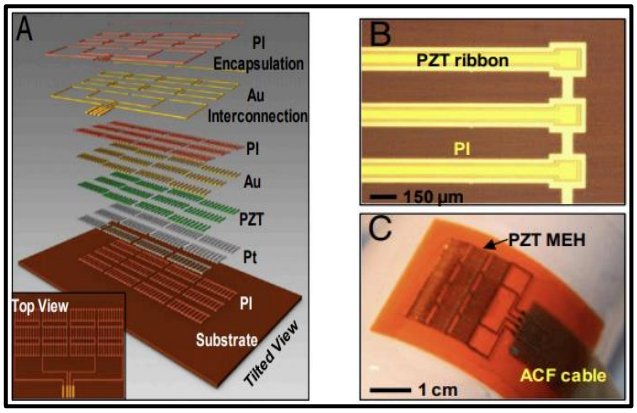


Fig 2. Flexible MEH based on thin ribbons of PZT.
(A) exploded-view schematic illustration with a top view. (B) Optical microscope image of PZT ribbons printed onto a thin film of PI. (C) Photograph of a flexible PZT MEH with cable for external connection. ACF, anisotropic conductive film.

The key functional elements of the piezoelectric device are a capacitor-type structure that consists of a layer of PZT (500 nm) between the bottom (Ti/Pt, 20 nm/300 nm) and top (Cr/Au, 10 nm/200 nm) electrodes. A MEH module consists of 12 groups of 10 such structures that are electrically connected in parallel. Each of the 12 groups is connected in series to its neighboring group to increase the output voltage. Encapsulation of these devices with biocompatible materials isolates them from bodily fluids and tissue, thereby minimizing the risks of failure or immune response. A thin spin-cast layer of polyimide (PI) serves effectively in this role, as flexibility. Here, we suggest fabricating the interconnect of the PZT ribbon with serpentine to make conformal contact of the device widely to the heart. Therefore, the Au interconnection and PI encapsulation layer were changed to serpentine. By using a serpentine interconnect, it can be conformally attached to the heart, and it can move according to the deformation of the heart and supply power stably. Figure 3 is a picture of the piezoelectric device attached to the heart. Due to the influence of the serpentine interconnect, the conformal contact is stably maintained even in the mechanical movement of the heart, and the electrical properties are also maintained. Evaluation of various mounting sites can identify locations for optimal power extraction (Fig. 3 A and B).

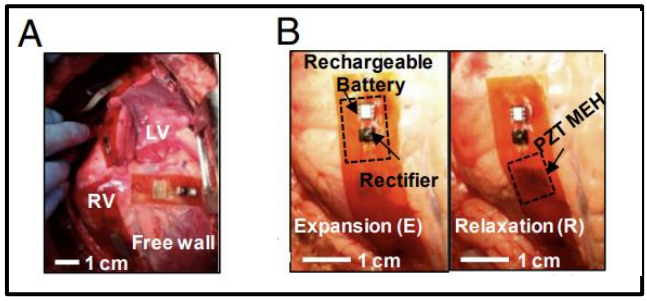


Fig 3. PZT MEHs on the heart.

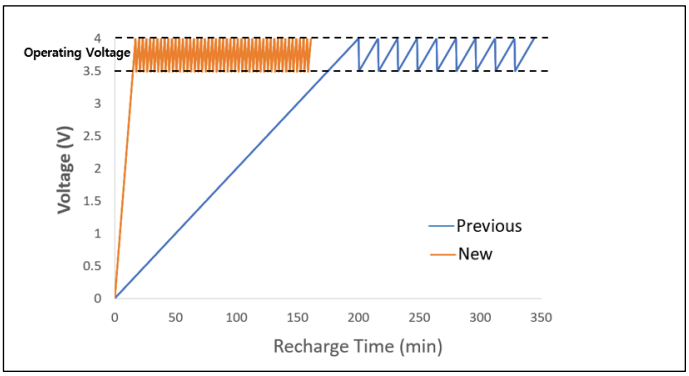


Fig 4. Recharging rate comparison chart.

While the previously reported triboelectric-based device with 16 minutes of recharging time stimulates the brain only once, our suggested design can stimulate the brain more than 5 times with 2.4 minutes of recharging time.

III. Conclusion

This approach could provide a novel method of implementing a complete self-powered DBS system that requires no additional incision surgeries. The expected result of significantly improved recharging time suggests a future research path for power optimization for a complete stimulation system without the need for a pause for recharging.

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