Nanogenerators to Power Implantable Medical Systems

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Replacing implantable medical devices (IMDs) is essential for their continuous operation, for which surgery is inevitable. Nanogenerators (NGs) have gained attention as potential power solutions owing to their compactness and safety compared with electromagnetic field-based energy transfer technologies. Their working principle, which involves the generation of electrical potential from body movement, is suitable for sustaining IMDs’ instant monitoring and sensor capabilities inside the body. In this regard, NGs hold promise for realizing self-powered IMDs that consume low power. For devices demanding a certain level of power required to operate sustainably, the realization of a powering system driven only by internal biomechanical energy has faced obstacles. Ultrasound referring to external mechanical energy has been found to have potential to noninvasively power IMDs that require relatively greater energy. This perspective discusses current NGs that are capable of coping with the IMDs’ power demand and thereof driven IMDs application. This paper also focuses on recent advances in ultrasound-driven NGs and their future opportunities and strategies to be a competitive powering device for IMDs.

INTRODUCTION

Implantable medical devices (IMDs) are designed to perform or augment the functions of existing organs by using monitoring,¹ measuring, processing units,² and the actuation control.³ Conventional IMDs are powered with primary batteries that require frequent surgeries for maintenance and replacement. Therefore, IMDs require a new reliable and safe powering system to avoid the need for frequent surgeries.¹ Wireless electromagnetic power transmission has been proposed as an alternative powering system. However, there is an issue of excessive tissue heating from these appliances, affecting the immune system and deoxyribonucleic acid (DNA) synthesis. Nanogenerators (NGs), on the other hand, have been proposed to harvest the mechanical energy produced by the human body. NGs based on piezoelectricity require a cyclic stress in order to generate electricity.⁵ Triboelectric nanogenerators (TENGs) are capable of generating electricity if there is a physical contact or rubbing.⁶–⁸ Unlike piezoelectric NGs (PENGs) relying on limited group of noncentrosymmetric materials (e.g., ZnO,⁹ GaN,¹⁰ Pb(Zr,Ti)O₃,¹¹ BaTiO₃,¹² and PVDF¹³), TENGs have gained attention in IMDs with the ease of fabrication and the IMDs-related benefits derived from the diversity of materials.¹⁴

Among the IMD features, diagnostic sensing and monitoring units enable accelerated medical care, identifying potential problems preemptively. Like an electrocardiogram (ECG) that measures the rate and rhythm of the heartbeat, a diagnostic tool that assesses the muscular function routine is of equal importance.¹⁵ Considering the working principle of NGs, they can serve as a biometric sensor by instantly...
converting mechanical energy (e.g., organ motion) into electrical signals (prognostic information). This feature of NGs is now attracting researchers from diverse fields of not only scientific community but also of medicine. Recent IMD-related NG research includes monitoring units and sensor application, with emphasis on sensitivity in recognizing the biomechanical behavioral characteristics. IMDs categorized as active devices (e.g., cardiac pacemaker) require a level of power to cope with multiple functions that include sensing, processing, and actuation. NGs have been studied as powering devices that generate electricity from any movement in a wide frequency range.

Over the past decade, NGs have intensively aimed at harvesting mechanical energy sources. Some NGs have studied not only detecting but also harvesting sound wave (referred to mechanical energy sources) propagating through air; however, there have been very few reports on harvesting sound waves traveling through the body to power IMDs. In 2019, there was a report that ultrasound transmitted through the skin or tissue generates electricity via TENG successfully demonstrated the practicability of charging rechargeable batteries. From this perspective, we discuss the developments of IMDs-related NGs devices for biomechanical energy conversion and their potential applications. Besides, this paper focuses on recent advances in ultrasound-driven NGs that harvest ultrasound energy aimed at powering IMDs, and we provide a discussion inspiring new perspectives on materials and devices to advance NGs in the future.

### POWER CONSUMPTION OF MODERN IMDs AND THEIR CHALLENGES

Figure 1A outlines power consumption requirements for modern IMDs. Among them, pacemakers are designed to moderate pulse rates by continuously stimulating the myocardium. These devices require a minimum amount of power (<0.1 mW). Neurostimulator and infusion-pump power consumption depends on the required stimulation thresholds and pulse characteristics measured by amplitude (measured as a voltage) and its duration (measured in milliseconds). IMDs have been developed for connecting all predefined sets of components, such as sensors, processors, and data transmitters and receivers, requiring high levels of power consumption. To achieve longer IMD-battery service life, the amount of energy required for data transmission should be reduced. Radio-frequency identification (RFID) pressure sensors consume 10 mW via bluetooth low energy.

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https://doi.org/10.1016/j.joule.2020.05.003*
IMDs capable of measuring physiological and spatiotemporal parameters demand high computation loads. Thus, their power consumption is often very high.

A Necessity of Power
Wireless energy transfer technologies can reduce power consumption, but most IMDs still require primary batteries. Batteries are nowadays routinely recharged or replaced using containers outside the body, connected through the body to the devices. Nonetheless, modern IMDs, including pacemakers, require internal power sources and mechanics that have to be replaced or repaired every 7–8 years. Surgical protocol is believed to be safe, but any invasive surgery may cause a risk of infection. Furthermore, the demand for pacing services is likely to continue to grow into diverse age ranges. In this respect, the power transfer from the external source in a wireless manner is truly preferred. Most power supply approaches have been based on radio frequencies, although they cannot address the following key challenges of IMDs: (1) extreme sensitivity to alignments and distances between source and receiver and (2) regulatory power thresholds for general safety concerns.

Research in Biomechanical Energy Harvesting
NGs have been explored to harvest biomechanical energy from various types of muscular movements. Figure 1B displays the amounts of power that can be harvested from joints or other body parts during walking. The potential power derived from the shoulder is 2.2 W, from the knee is 36.4 W, from a heel strike is 20 W, and from ankle joints is 66.8 W. Besides, biomechanical pumping (0.93 W) involving heartbeat and respiratory muscles movement (0.41 W) during breathing is also potentially harvestable. One interesting study reported the conversion of mechanical energy from walking into electrical energy using the inertial changes of the center-of-mass motion (20 W). The maximum amount of energy that can be harvested is approximately 1 W/kg, based on device weight. This technique is more appropriate to be realized outside the body. Furthermore, any solution should only minimally interfere with the natural function of body parts. This, in fact, makes NGs even more promising.

BIOMEDICAL APPLICATIONS BASED ON NGs POWERED BY BIOMECHANICAL ENERGY
Research in NGs and Emerging Thereby IMDs
PENG technology was first introduced in 2006. Since then, there have been extensive discussions on the piezoelectric properties of various materials and possible applications that could take advantage of the mechanical-electrical conversion. PENGs rely on mechanical strain on materials (Figure 2B). TENGs, on the other hand, are capable of generating electrical potentials through contact electrification, induced by mechanical impacts (Figure 2C) and electrostatic induction. The first TENG was reported in 2012, and since then, a great deal of research has been conducted on a number of high-performing materials (i.e., those with high surface charge density) and structures, theoretical predictions of systems, and applications in various environments. In particular, its application includes the internet-of-things sensors and self-powered electronics that convert mechanical energy from the environment into electrical energy. NGs are known to be suitable powering devices when mechanical conditions are apt to be triggered in places where there is no sustainable energy supply. The human body, likewise, cannot be easily accessible, but energy is primarily provided by only the intake of nutrients. Although various medical instrumentations are used to perform diagnosis and
analysis, conventional medical systems or protocols cannot keep track of patients’ heart rate, such as detecting an abnormal heart rhythm and restoring a normal heartbeat. In this regard, researchers have started paying attention to body-implantable systems to manage underlying risks in a more sustainable manner. In recent days, NGs have been studied as serving biomedical devices. NG studies have explored applications to organs (e.g., heart, lungs, and stomach) where continuous muscular events occur (Figure 2A). A level of electrical signal generated from NGs are used to clinically sense the signs of organs to evaluate the status, monitor other organs with powered medical devices, and to serve as a nerve stimulation device.

NG-Based IMDs: Sensors, Monitoring Units, and Stimulation Devices
Since NGs are able to convert mechanical motion into electrical signals, NGs can be developed as biomedical identifiers if the organs’ medical status can be determined by mechanical exercises. According to a study by Dagdeviren et al. (Figure 2D), PZT-based PENG was used as a dynamic mechanical-electrical energy converter. The level of the characterized output voltage was proportional to the measured displacement, which could be used to predict organ behavior. Consistent sensing characteristics were observed under different frequencies. Another study by Zheng et al. showed that the movement of the lungs could be identified by placing a TENG device on the diaphragm. As shown in Fig. 2E, TENG can precisely identify breathing behaviors, which is the required feature to be a medical sensor.

In addition to measuring, sensing, and understanding biological movements, research has shown that NGs can be used to treat the given measurable biometric identifiers as processible information that can be viewed or recorded for additional feedback responses. A study by Kim et al. (Figure 2F) showed that the electrical signals generated from PENG corresponded to ECG signals under cardiac oscillation.
from the heart. Their NG was also used as a telemetry device. The harvested mechanical energy was used to charge a capacitor, and it successfully powered a wireless data transmission system. Ouyang et al. (Figure 2G) showed that TENG-based cardiac pacemaker could monitor heart rates in vivo. Monitored heart-rhythm pacing was analyzed and regulated to confirm the controllability of physiological activities. Their TENG was featured as a mechanically stable device (tested 100 M times), making it suitable for monitoring devices that require long-term operation.

In biomedical applications, too-high currents can cause adverse effects on living organisms, including metabolic imbalances and DNA incompatibilities caused by heat generation. In this respect, an intriguing approach for NGs is the stimulation device, with emphasis on its relatively low-current and high-voltage characteristics. Hwang et al. (Figure 2H) demonstrated that PZT-based PENG devices, driven by minimal movement (e.g., bending), could send electrical impulses via implanted electrodes to specific target areas of the brain to treat behavior disorders, which refers to the deep brain stimulation (DBS). Besides, TENG-based vagus nerve stimulation (VNS) was also reported by Yao et al. (see Figure 2I), who found that stomach peristalsis could control the level of food intake. Their VNS system was designed as a TENG attached to the stomach, generating voltage pulses that effectively reduced food intake by stimulating vagal afferent fibers. They achieved 35% weight-loss results within 18 days. This development demonstrated that TENGs with instant responsivity can be well adapted to peripheral neuromodulation. Another interesting study by Lee et al. (Figure 2J) presented that TENG-based neurostimulation devices could generate sufficient electric field levels to activate muscles. Preferential stimulation of one or more nerve roots in a direct manner is required with modern neurostimulation technologies. Lee et al. showed that different muscle-activation patterns of gastrocnemius medialis and tibialis anterior muscles were successfully achieved. As introduced above, the benefits of NGs include instant response rates (i.e., mechanical-electrical energy conversion) and compatibility with existing biomedical systems, especially electrical nerve stimulation units, which make NGs an excellent treatment option for future medical applications.

NGs AS POWERING DEVICES FOR IMDs

Biomechanical Energy-Driven NGs

Apart from medical applications, PENG and TENG technologies can harvest mechanical energy to power various types of electronics. Figure 3 highlights a comparison of studies involving the conversion of mechanical energy triggered by muscular events inside the body into piezoelectricity and triboelectricity and other studies reporting generation of piezoelectricity and triboelectricity by externally applied mechanical energy that travels through the skin. A study by Dagdeviren et al. (Figure 3A) reported that PZT-based PENGs generated approximately 1 μW/cm² of output power when triggered by the mechanical deformations of heart pumping, providing a load displacement of ~10 mm. Another study by Ouyang et al. (Figure 3B) showed that an implantable TENG achieved ~10 μW/cm² output power. RFID tags and wireless sensors can be driven with 1–10 μW/cm². The amount of energy generated solely depends on working of the heart, which may raise concerns regarding the effectiveness and safety of TENGs in powering devices. Unlike various mechanical events occurring outside the body, very limited amount of mechanical energy (e.g., muscular displacement of the heart’s outer wall during heartbeat), extremely narrow space, and device dimension limitation inside the body present challenges for NGs in becoming a promising power source for IMDs. Accordingly, there is a need for noninvasive and sustainable NG-based powering system apart from organ motion-driven NG systems.
Ultrasound has been approved by FDA for treatment methods in various applications. Sound waves can travel through biological tissue (e.g., transcutaneous skin) to cause specific region to oscillate. The development of an ultrasound energy harvesting system based on piezoelectric materials has been discussed in previous studies. Because ultrasound transducers utilize the inverse piezoelectric principle, it may be possible to achieve high energy harvesting performance via advanced piezoelectric materials and resonance design. Shi et al. demonstrated that microelectromechanical system-based piezoelectric ultrasound energy could be used to power IMDs (Figure 3C). PENG-based PZT diaphragm array with a resonance frequency of 240–250 kHz, generating up to 3.75 mW/cm² at a distance of 1 cm and 1 mW/cm² of ultrasound intensity. To our knowledge, the supply of hundreds of milliwatts of power transcutaneously to an implant, using piezoelectric ultrasonic energy harvesting, has been reported. However, there are still several technical challenges such as limited materials option and long-term mechanical durability for PENG to be used as a power source for IMDs. Moreover, long-term stable operation is also required. As alternative candidates, TENGs have been studied as a promising implantable powering system because of their powering capabilities, regardless of materials and their superior mechanical stability. Additionally, TENGs are considered suitable for use in confined spaces (e.g., human body), because they can generate electricity as long as there is a minimal contact (<1 mm) between materials. As shown in Figure 3D, Hinchet et al. presented an ultrasound energy harvesting technology based on TENG intended to power IMDs. Ultrasound TENG (US-TENG) was triggered with an applied 20-kHz ultrasound at 3 W/cm² reaching 9.71 V_{root mean square (RMS)} and 427 μA_{RMS}. The measured output current was enhanced two orders of magnitude compared with conventional TENGs, with a similar level of σ₀ (surface charge density), triggered in low-frequency mechanical environments.
Because the output current is defined as \( i = \frac{dq}{dt} \), the relatively high output current of US-TENG (\( \approx 31.2 \, \mu A/cm^2 \)) is relevant to taking a short period of time (50 \( \mu s \)) for one full contact-separation. Interestingly, to experimentally simulate clinical conditions closer to human in the laboratory, Hinchet et al. inserted US-TENG under porcine tissue, showing that it fully charged a rechargeable Li-ion battery having a capacity of 0.7 mAh. From this aspect, the power generated was high enough to recharge small IMDs batteries (e.g., pacemaker and neurostimulators) that consume only 1–100 \( \mu W \).\(^2\)

**SUMMARY AND PERSPECTIVE**

By providing sustainable operational mechanical-electrical conversion using dependable muscular events inside the body, the use of NGs for IMDs sensor and monitoring units, and (neuro) stimulation devices has drawn significant attention in the fields of materials science and medicine in recent days. The energy harvesting property of NGs is an indispensable aspect of IMDs application, and a noninvasive solution would be a remarkable advancement. Since the level of electrical energy generated by NGs relies heavily on the input mechanical energy (i.e., given muscular event), taking matured theoretical models of NGs into account, first, measurable mechanical energy in various environmental scenario should be understood in a biomechanical aspect. Next, materials can be designed having an optimum level of surface charge density—(1) to achieve effective contact/separation even in confined space and evaluate their energy conversion property in device scale and
(2) to mechanically synchronize with the activity of the moving organs (e.g., heart and lung) to carry identical information. Based on this, concerning the efficiency and relevant applications, electrical engineers can be involved to develop applicable circuitry. Since biomechanical energy-driven NGs cannot generate electrical energy beyond measurable biomechanical energy inside the body, those could guarantee charging a limited range of IMDs batteries. In this respect, transcutaneous ultrasound through the skin has been proposed as an attempt to elevate NG energy output. This advancement promises the capability to generate higher power levels than conventional methods. To make desirable ultrasound-driven NGs that power IMDs, certain issues should be addressed in future studies (Figure 4). High NG efficiency is desirable under a certain level of ultrasound energy, which is required for miniaturization. Regarding US-TENG, dielectric layer design and surface charge density have been found to successfully improve output performance. There is a need to study the input ultrasound energy at certain depths. Implantation depth varies depending on the IMD application (e.g., mean implantation depth is ~10 mm), and mechanical energy should be estimated under different working environments in terms of mechanical properties of layers and implantation depths. Moreover, all media attenuate ultrasound due to absorption and scattering effects, which could potentially reduce NG input energy. Ultrasound field disturbances should be addressed with protective packaging materials in commercial IMDs. Finally, the stability of NGs over long periods should be tested. Performance data should be collected and analyzed under different working conditions, and the working and degradation mechanism of NGs should be statistically identified.

ACKNOWLEDGMENTS

This work was financially supported by the Basic Science Research Program (2018R1A2A1A19021947) through the National Research Foundation (NRF) funded by the Ministry of Science and ICT of Korea and the GRRC program of Gyeonggi Province (GRRC Sungkyunkwan 2017-B05).

AUTHOR CONTRIBUTIONS

S.-W.K. conceptualized this perspective. H.-J.Y. investigated the literature. All authors contributed equally to the writing of the manuscript. S.-W.K. revised the manuscript.

REFERENCES

from the patient’s perspective. Circulation 105, 2186–2188.


Development of battery-free neural interface and modulated control of tibialis anterior muscle via common peroneal nerve based on triboelectric nanogenerators (TENGs). Nano Energy 33, 1–11.


