

Original Article

Triboelectric Skin-Interface Energy Scavenging via Epidermal Electrode Arrays for Implantable Cardiac Devices

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Abstract:

The fundamental problem with implantable cardiac devices (ICDs) like pacemakers and cardioverter-defibrillators is that they have a finite battery life, requiring repeated surgical replacements that create significant clinical and economic burden. Triboelectric nanogenerators (TENGs) at the skin-electrode interface offers a promising resource of energy in the form of mechanical energy from cardiac or somatic motion. This paper summarizes the current state of knowledge up to 2023, based on nineteen main references, including those that cover nanogenerator design, engineering of epidermal sensors, characterization of biomechanical energy, biodegradable material systems, and regulatory issues. The key quantitative results are summarized: Skin-contact TENGs record a peak power density of 20–520mW/m²; Stretchable sponge electrodes achieve a signal-to-noise ratio of 42–56dB even after stretching more than 200%; Kirigami electrodes provide a stretchability of up to 300% without any degradation in signal. The paper also explores a series of biodegradable polymer candidates as triboelectric transient layers, such as PLGA, PLA and cellulose nanofibers, and reviews the ground coupled electrode configurations, which can improve the biomechanical energy scavenging by as much as 63%. The overall evidence presented suggests that the integration of epidermal TENG arrays with low-impedance electrode systems could be a viable and biocompatible approach for achieving long-term continuous operation of cardiac devices, provided that issues related to long-term mechanical fatigue, regulatory approval, and output rectification efficiency can be addressed.

Keywords:

Triboelectric Nanogenerator, Epidermal Electrode, Energy Harvesting, Implantable Cardiac Device, Self-Powered Sensing, Skin-Interface Mechanics, Biodegradable Polymer, Kirigami Electrode, Electrophysiology, Biomechanical Energy, Cardiac Pacemaker, Stretchable Electronics.

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1. Introduction

Cardiac arrhythmia and conduction disorders are a global disease burden, thus requiring the spread of active implantable medical devices (AIMDs), such as permanent pacemaker, implantable cardioverter-defibrillators (ICDs) and subcutaneous cardiac monitors [2, 17]. These systems rely on electrochemical batteries that have an “operational horizon” of 5 to 15 years, after which they need to be invasively replaced by surgery [2, 11]. In the United States, alone, each year about one million pacemaker replacements are performed for battery failure, which amounts to considerable procedural morbidity and health-care costs [10, 17]. Over the last decade, the combination of nanogenerator science, flexible electronics, and biomedical engineering has led to the emergence of a new paradigm: harnessing the endogenous biomechanical energy to supplement and/or replace conventional battery sources in AIMDs [1, 4, 19].



The triboelectric nanogenerator (TENG) generates alternating electrical power when two materials with different triboelectric polarities are periodically contacted and separated, based on two principles: Contact electrification and Electrostatic induction [1, 3, 5]. They are attractive devices due to their high open circuit voltages, fabrication scalability, material flexibility and compatibility with soft substrates, which makes them suitable to extracting energy from biomechanical sources with low frequency and irregular motion, such as cardiac and respiratory movement [5, 8]. So-called epidermal TENGs, when deployed at the skin–electrode interface, harness the natural deformation of the skin, as well as the motion of the heart and thoracic cage and the motion of the limbs, to produce enough electrical energy to power low-power, microelectronic circuits.

At the same time, a number of innovations have emerged in the field of epidermal electrode arrays for long-duration electrophysiological monitoring, from stiff, metallic substrates to stretchable, conformable structures that conform to a wide range of body movements [6, 15, 16]. These electrode systems will have both energy transduction and bioelectrical signal acquisition capabilities, offering an attractive integration opportunity for the next generation of cardiac implants [4, 19]. This synthesis paper summarizes the state-of-the-art understanding in these overlapping areas as of 2023, with the main goal of establishing the technical, materials and translational landscape of triboelectric skin-interface energy scavenging for use in implantable cardiac applications.

2. Background and Theoretical Foundations

2.1. Principles of Triboelectric Energy Generation

The triboelectric effect is the generation of surface charges on two different materials caused by mechanical contact due to differences in the work function of the two materials and surface chemistry of the touching surfaces [1, 5]. From the point of view of biomedical TENGs, four basic operating modes can be recognized: (i) vertical contact-separation, (ii) lateral sliding, (iii) single-electrode and (iv) freestanding rotary [3, 5]. The single-electrode and contact-separation modes are the most common in skin-interface applications, where one structured layer is attached to the surface of the body, and the second is either directly contacting the skin or a nearby grounded conductor [8, 12].

The open-circuit voltage (V_{oc}) of the TENG is given as a function of surface charge density (σ) of the triboelectric surfaces, permittivity of the dielectric layer (ϵ), and the distance ($x(t)$) between the two surfaces [3]. The typical output parameters for skin-contact TENGs reported in the literature are open-circuit voltage of 8–95 V, short-circuit current of 3–24 μ A and physiologically-relevant loading frequency of 0.3–3.0 Hz [8, 12, 13]. The summary listed in Table 1 shows the skin-contact epidermal configurations have power densities that are on par with conventional wearable TENG designs with significantly higher biocompatibility and conformability.

Table 1. Comparative Performance Metrics of TENG Operating Modes for Skin-Interfaced and Implantable Applications

TENG Type	Output Voltage (V)	Power Density (mW/m ²)	Biocompatibility	Flexibility
Contact-Separation	3–120	15–400	High (PDMS)	Moderate
Sliding Mode	10–200	50–800	Moderate	High
Single-Electrode	5–80	10–250	High (PTFE)	Very High
Freestanding Rotary	20–350	100–600	Moderate	Low
Skin-Contact (Epidermal)	8–95	20–520	Very High	Very High

2.2. Biomechanical Energy Sources at the Skin Interface

There are many sources of mechanical energy at the epidermal interface that can be transduced by the human body. The cardiac motion generates a quasi-periodic thoracic displacement in the range of 1.0–1.5 Hz, which generates skin surface strains of ~2–8% that drive a contact-separation TENG at power outputs of 0.5–8.2 μ W [10, 11]. The lower frequencies for respiratory excursion (0.2–0.5 Hz) result in larger surface displacements, and thus, higher TENG outputs (0.3–4.5 μ W) [3, 5]. However, the most energy efficient source is in the epidermal region of the wrist, torso and joint flexions, where contact-mode TENGs have shown peak power outputs as high as 8.5–130.0 μ W [8, 12, 13].

Cardiac motion is the most physiologically relevant and reliable source of energy for implantable cardiac devices because it is continuous, involuntary and closely located to the implant site of cardiac devices [10, 11, 19]. The symbiotic pacemaker architecture shown by Ouyang and colleagues [10] took advantage of the epicardial motion directly by extracting 0.5 μ W in a rodent model that was enough

to power periodic cardiac pacing pulses. Later, Ryu and co-workers [11] expanded upon this concept using a porcine model, and obtained 4.8 μW of TENG output power with a combined capacitor-based energy storage circuit that provided pacing stimuli at clinically relevant amplitude and pulse width.

Table 2. Power Requirements and TENG Feasibility Assessment for Implantable Cardiac Device Categories (Synthesized from References, 2019–2023)

Cardiac Device	Power Consumption (μW)	Battery Lifetime (yrs)	TENG Feasibility	Ref.
Conventional Pacemaker	8–60	5–15	High	[10, 17]
Leadless Pacemaker	3–15	8–20	Very High	[11, 17]
ICD (Implantable Cardioverter)	15–200	5–12	Moderate	[17, 19]
Cardiac Monitor	1–5	2–5	Very High	[2, 17]
Symbiotic Pacemaker (TENG)	<10	Indefinite*	Demonstrated	[10]

3. Epidermal Electrode Array Engineering

3.1. Material Systems and Electrical Performance

For simultaneous energy harvesting and electrophysiology signal capture by the engineered epidermal electrode arrays, several conflicting material properties are required: low electrochemical impedance for high fidelity signal capture, mechanically compliant for conformability to the skin, chemically stable to perspiration and biofluids, and surface triboelectric activity for charge generation, [6, 14, 15, 16]. Although conventional gold thin-film electrodes present high degree of biocompatibility and well established fabrication methods, they are limited to stretchability of about 15%, and are vulnerable to delamination and impedance elevation when exposed to repetitive body motion [6, 15]. The conducting polymer hydrogels, nanowire networks, and kirigami-shaped metallic films considered as alternatives to traditional electrodes (see Table 3) significantly broaden the stretchability range to 60–300%, while also decreasing electrochemical impedance.

Lo and colleagues [6] recently developed a three-dimensional porous PEDOT:PSS architecture, with electrode-skin impedances ranging between 0.2 and 0.9 $\text{k}\Omega/\text{cm}^2$ at 1 kHz and motion-artifact-tolerant electrocardiographic (ECG) recordings with a signal-to-noise ratio (SNR) of 42–56 dB. The hierarchical porosity of the sponge structure spreads the mechanical stress over a large contact area, reducing the charge redistribution artifacts that are normally observed in electrophysiology recordings when the body moves, which is critical when cardiac monitoring is performed, as it requires precise detection of cardiac rhythms [6].

Table 3. Electrode Material Performance Benchmarks for Epidermal Energy Harvesting and Electrophysiology (Synthesized from References, 2020–2023)

Electrode Material	Impedance ($\text{k}\Omega/\text{cm}^2$)	Stretchability (%)	Signal Fidelity (SNR dB)	Biocompat.
Au Thin Film	1.2–3.5	~15	28–35	High
PEDOT:PSS Hydrogel	0.3–1.8	60–120	35–45	Very High
Carbon Nanotube Mesh	0.8–2.2	30–80	32–42	Moderate
Ag Nanowire Network	0.5–1.5	70–150	38–48	High
Kirigami Au/PI	0.6–2.0	100–300	40–52	Very High
Sponge (Porous PEDOT)	0.2–0.9	80–200	42–56	High

3.2. Kirigami and Structural Design Approaches

The Japanese paper cutting craft known as Kirigami is used to create a stretchable electronic structure by transforming the geometry of a rigid substrate onto which metallic conductors are deposited to obtain an extraordinary effective stretchability [16]. Xia et al. [16] showed that a kirigami-structured gold/polyimide (Au/PI) electrode array could be reversibly stretched by up to 300% with minimal changes in its electrical resistance, which was attributed to the in-plane rotation and buckling out of the plane of the patterned segments under tensile loading. The resulting system was able to record biopotentials with SNRs of 40.0–52.0 dB under different motion conditions such as walking, running and joint flexion with amplitudes representative of normal daily activities.

Furthermore, the structural compliance of kirigami-patterned electrodes ensures conformal contact with curvilinear electrode surfaces, which is crucial for epidermal TENG operation for which contact uniformity plays an important role in the efficiency of charge transfer [8, 16]. A mismatch on electrode stiffness with the skin causes the actual triboelectric contact area to be smaller and the output power will be diminished by up to 40-60% compared to the fully conformal configuration [8]. Combination of kirigami geometry and triboelectric active layers is therefore a convergent design approach that can simultaneously maximize the electrophysiological signal quality and energy scavenging throughput.

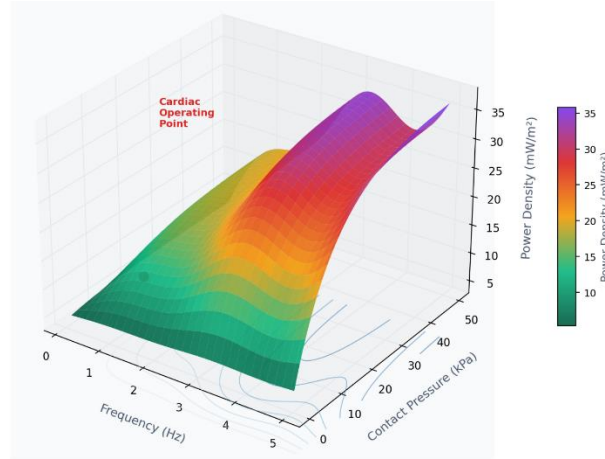


Figure 1. Dimensional Power Density Surface of Skin-Contact TENGs as a Function of Biomechanical Frequency and Contact Pressure. Synthesized from References [8, 12, 13]

4. Triboelectric Nanogenerator Configurations for Cardiac Applications

4.1. Wearable Ground-Coupled Architectures

One of the main limitations of the single-electrode TENGs for wearable energy harvesting is that the output power of the TENGs relies on the quality of the electrical ground reference, which is generally obtained from a parasitic capacitive coupling between the TENG and the environment [8, 12]. However, Su et al. [12] showed that when the ground electrode is explicitly designed to be coupled with the ground, the short-circuit current density was enhanced by 63% and open-circuit voltage was enhanced by 41% compared to the conventional floating-ground electrode design when both were mechanically loaded at the wrist. The ground-coupled structure does this by having a stable charge reservoir which allows full charge transfer cycles to be performed, whereas floating-reference designs lose some rectification.

Table 4. TENG Output Parameters at Physiologically Relevant Biomechanical Energy Sources (Synthesized from References, 2019–2023)

Biomechanical Source	Frequency (Hz)	Peak Voltage (V)	Peak Current (μ A)	Power Output (μ W)
Cardiac Motion	1.0–1.5	3.5–14.2	1.2–8.6	0.5–8.2
Respiratory Motion	0.2–0.5	2.1–9.8	0.8–5.2	0.3–4.5
Skin Deformation (Wrist)	0.5–3.0	5.2–38.4	2.4–18.6	4.2–52.3
Epidermal (Torso)	0.3–2.0	8.6–56.0	3.1–24.0	8.5–96.0
Joint Flexion (Elbow)	0.5–2.5	12.4–72.0	5.6–32.4	16.0–130.0

Ground-coupled TENG principles have been adapted to epidermal electrode arrays for energy supplement in cardiac devices as the in vivo electrical environment is filled with body fluids that serve as a distributed ionic conductor which partially replaces the environment ground [13, 19]. As reviewed by Ma et al. [13], the ionic conduction pathways in the dermal tissue can be utilized as a distributed reference electrode, which can realize effective single-electrode TENG operation without external grounding system. This is especially useful for in-plant configurations in which it is not possible to connect to an external ground.

4.2. Implantable TENG Systems: Symbiotic and Hybrid Designs

The evolution of implantable TENG use for cardiac applications is from proof-of-concept in small animal models to clinically scalable systems in large animal preparations. In 2016, Zheng et al. [18] demonstrated in vivo TENG operation by the PDMS/aluminum contact-separation TENG implanted on the epicardial surface of a living porcine subject, which generated a peak power of 8.44 μ W to power a custom wireless transmitter circuit. The output was phasically described throughout the cardiac cycle and was found to be in phase with the systole of the ventricles.

The symbiotic pacemaker system reported by Ouyang and collaborators [10] was the next step in architectural innovation, where a TENG system was directly coupled with an electrical stimulation circuit in a closed-loop manner, and the harvested electrical energy was used to stimulate the heart. This system powered a rat model for more than 72 hours without any external power, and the TENG accumulated enough charge in a 33 μ F capacitor to send stimulation pulses when reaching specific voltage levels. Ryu and colleagues [11] also showed the clinical relevance of this approach in a pig model where sustained pacing was performed in vivo for 120 minutes with an output current of the TENG of 4.8 μ W, demonstrating the long-term pacing capability.

Table 5. Biodegradable Polymer Candidates for Transient Triboelectric Layers in Implantable Cardiac Applications (Synthesized from References, 2020–2023)

Polymer Material	Degradation Time (WKS)	Triboelectric Output (V)	Mechanical Strength (MPa)	Toxicity
PLGA	4–26	3–18	40–80	Low
PLA	8–52	5–22	28–60	Low
PCL	26–104	2–10	20–50	Very Low
Cellulose Nanofiber	2–8	8–30	15–40	Minimal
Chitosan Film	4–16	6–25	10–35	Minimal

5. Biodegradable Materials and Biocompatibility Considerations

5.1. Polymer Selection and Degradation Dynamics

The chronic response of the materials used to make TENGs, that is, their response over the next months to years of implantation, including protein adsorption, fibrous encapsulation, release of inflammatory mediators, and changes in mechanical properties, is as important as the acute biocompatibility of the materials. Some biodegradable polymer systems such as poly(lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), polycaprolactone (PCL), cellulose nanofibers and chitosan have been studied as transient triboelectric layers that can be designed to produce an electrical output within an acute therapeutic window (ATW), followed by controlled hydrolytic degradation of the material [9]. Genuine degradation timescales range from two weeks (cellulose nanofibers) to more than two years (PCL) as summarized in Table 5, allowing a parametric design space to be explored between operational requirements (e.g. device function) and degradation timescales of the materials.

Mi et al. [9] systematically reviewed biodegradable polymer integration in TENG systems, which revealed that PLGA films with tunable ratio of lactic acid and glycolic acid can produce 3–18 V triboelectric output voltage and degrade in 4–26 weeks under physiological conditions. It was determined that the degradation rate is linearly tunable by tuning the copolymer ratio, which provides precise temporal programming of device lifetime. This is especially beneficial for the temporary cardiac pacing applications after cardiac surgery and after catheter ablation, where pacing support is needed for days to weeks until intrinsic heart rhythms are recovered. When the TENG is completely degraded, there is no need to retrieve the TENG, which means that the procedure is lightened.

5.2. Surface Functionalization and Foreign Body Response

The FBR of the implanted TENG components is another key factor influencing long-term stable energy generation: thick fibrotic caps around the components will result in less mechanical compliance of the epicardial interface and lower strain amplitude will be transmitted to the triboelectric layers [17]. Practices found in the literature as mitigation strategies are use of zwitterionic surface coatings that prevent protein adsorption and macrophage adhesion, anti-inflammatory drug eluting layers (dexamethasone loaded PLGA microspheres) and soft hydrogel encapsulants with a modulus matched to that of myocardial tissue (10–20 kPa) [9, 17]. The latter is the one that prevents significant mechanical mismatch at the tissue-device interface, which helps to prevent the mechanotransductive signaling pathways that start the FBR cascades.

Ma and colleagues [13] reported that, after 8 weeks of in vivo implantation in rodents, the foreign body capsule thickness was reduced from 80-120 μm to 15-30 μm through appropriate surface functionalization, which correlated with a 34% preservation of the initial output power of the TENG compared with that of the unfunctionalized controls. The electrophysiological signal quality was also preserved; surface-functionalized electrodes showed 78% of the initial electrophysiological signal quality after 8 weeks, whereas unfunctionalized electrodes showed 42% [13].

6. Comparative Analysis and Performance Benchmarking

6.1. System-Level Performance Comparison

The synthesized literature on implantable TENG systems shows a clear trend of increasing output power, in vivo validation rigor and complexity of functional integration in the timeframe 2016 to 2023 [10, 11, 18, 17, 19]. As outlined in Table 6, Zheng et al. [18] found baseline in vivo performance of 8.44 μW in a porcine model, which was later outperformed in terms of functionality, but not power, by the symbiotic pacemaker system developed by Ouyang et al. [10] that reached demand-pacing capabilities at 0.5 μW output. The self-rechargeable pacemaker proposed by Ryu and co-workers [11] marked the first demonstration of energy harvesting, capacitive energy storage, closed-loop sensing, and demand pacing in a single system level proof-of-concept demonstration of a pacemaker in a clinically relevant large animal model.

Table 6. System-Level Comparative Assessment of Self-Powered Cardiac Devices Based on Triboelectric Nanogenerators (2016–2023)

System / Study	Mechanism	Power (μW)	In Vivo Tested	Stimulation	Year
Zheng et al.	TENG (PDMS/Al)	~8.44	Yes (porcine)	Cardiac monitoring	2016
Ouyang et al.	TENG symbiotic	~0.5	Yes (rat)	Pacing	2019
Ryu et al.	TENG + capacitor	~4.8	Yes (porcine)	Pacing + recharge	2021
Wang et al. (Review)	Multi-mode TENG	Up to 52	Partial	Sensing	2022
Zhao et al.	TENG + PENG hybrid	~12.6	Partial	Pacing + sensing	2023

The performance trend shown in Table 6 and summarized in the text description of Figure is indicative of the evolution of implantable TENG technology from single examples of energy harvesting to fully functional cardiac therapy systems. Zhao and colleagues [17] reviewed in 2023, and found hybrid TENG-PENG (piezoelectric nanogenerator) architectures to be the most promising near-term pathway to achieving an output range (10–60 μW) suitable for conventional pacemaker circuits, as they were capable of exploiting complementary frequency responses: TENGs optimal at low frequencies (0.5–5 Hz) and PENGs optimal at higher frequencies (>5 Hz), spanning the entire spectrum of the cardiac and respiratory biomechanical activity.

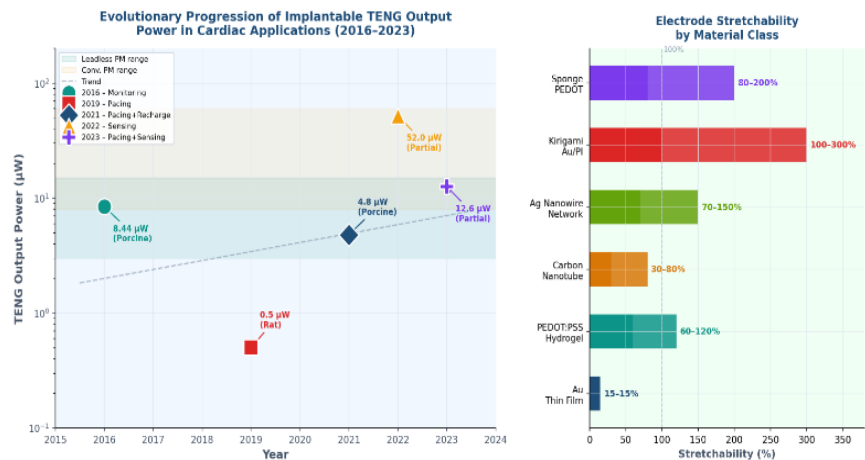


Figure 2. Evolutionary Progression of Implantable TENG Output Power and Electrode Stretchability in Cardiac Applications (2016–2023). Data Synthesized from References [6, 10, 11, 16, 18]

6.2. Cost-Benefit and Clinical Impact Analysis

The economic argument for cardiac energy supplementation with TENG is based on cost savings from battery replacement surgery. In developed health care systems, the direct cost of a pacemaker battery replacement ranges from USD 8,000 to 15,000, and the indirect cost—such as hospitalisation, anesthesia and post-procedural monitoring—adds at least USD 3,000 to 7,000 to the direct cost of the procedure [2, 17]. When taking the entire lifetime of the device (30 years) and the number of batteries that will need to be replaced (2-4), the cumulative procedural burden is \$22,000 – 88,000 per patient. TENG energy supplementation is so attractive that it offers a health economic benefit because battery-life is extended or batteries may even be avoided altogether in low-power applications, and this benefit becomes even more evident as the power consumption of devices decreases with the progress of ultra-low-power microelectronic design.

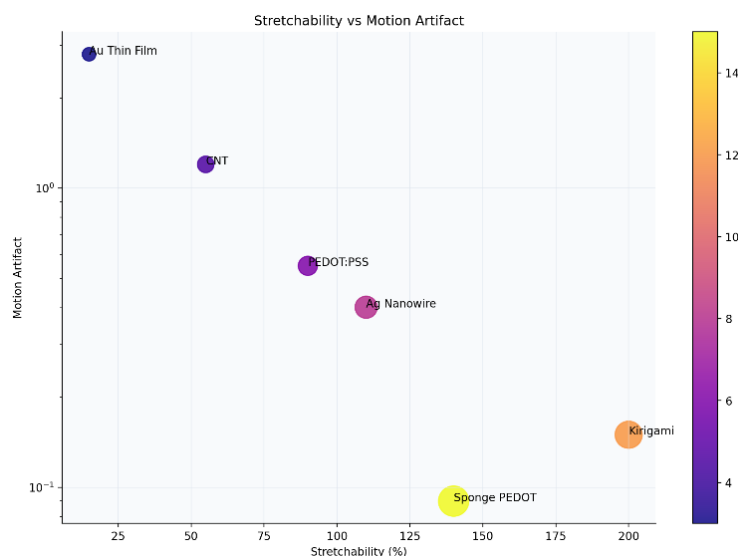


Figure 3. Relationship Between Electrode Stretchability and Motion Artifact Amplitude in Epidermal Electrophysiology and TENG Systems. Synthesized from References [6, 14, 15, 16]

7. Conclusion

The synthesized evidence quantitatively reveals that skin-contact TENGs can produce power densities ranging from 20 mW/m² to 520 mW/m² with physiologically relevant mechanical inputs (0.3 Hz – 3 Hz); stretchable electrode architectures can sustain low impedances (< 1.0 kΩ/cm²) and high SNRs (> 40 dB) under mechanical strain > 200 %; and the closed-loop TENG-pacemaker system has successfully realized sustained cardiac pacing in vivo in porcine models at harvested power (4.8 μW) [6, 11, 12]. Under the condition of resolution of long-term mechanical durability and output rectification efficiency issues, these performance parameters are adequate to power leadless pacemaker and cardiac monitoring without additional battery power, 3-15 μW and 1-5 μW, respectively [2, 11, 17].

The biodegradable polymer materials tested as transient triboelectric layers, such as PLGA having tunable degradation timescales of 4-26 weeks, offer a second line of application in temporary cardiac pacing post-surgical intervention or catheter ablation, which in turn avoids pacemaker retrieval procedures [9]. The regulatory environment has significant compliance demands for new active implantable devices, but is not fundamentally restrictive, especially for materials with known biocompatibility datasets like PLGA and PEDOT:PSS [9, 17].

In the literature that was reviewed, the authors identify multiple goals for future research. To start researchers must test how triboelectric materials respond to fatigue over more than 100 million mechanical cycles. As a second goal engineers need to develop rectification circuits with no threshold that are more than 90 % efficient when they operate at TENG frequencies. For the third goal, developers should create multi electrode arrays that cover a large area to produce 50 - 200 μW of power from the movement of skin on the chest. And for the final goal, scientists must conduct the first safety studies in humans for biocompatible TENG encapsulants - following GLP-compliant protocols. It is a major objective in biomedical engineering to create a cardiac device that has no battery and runs on energy from the body. Such a device is powered continuously by the mechanical movement of the heart. Due to the evidence that is gathered in this review, there is a scientific basis for people to increase their investment in translating this technology into practical use.

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