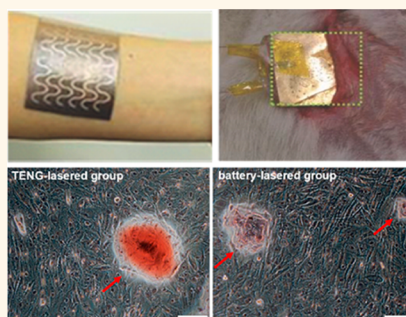


Wearable and Implantable Mechanical Energy Harvesters for Self-Powered Biomedical Systems

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ABSTRACT In this issue of *ACS Nano*, Tang *et al.* investigate the ability of a triboelectric nanogenerator (TENG) to self-power a low-level laser cure system for osteogenesis by studying the efficiency of a bone remodeling laser treatment that is powered by a skin-patch-like TENG instead of a battery. We outline this field by highlighting the motivations for self-powered biomedical systems and by discussing recent progress in nanogenerators. We note the overlap between biomedical devices and TENGs and their dawn synergy, and we highlight key prospects for future developments. Biomedical systems should be more autonomous. This advance could improve their body integration and fields of action, leading to new medical diagnostics and treatments. However, future self-powered biomedical systems will need to be more flexible, biocompatible, and biodegradable. These advances hold the promise of enabling new smart autonomous biomedical systems and contributing significantly to the Internet of Things.



The recent development of small biomedical systems and microelectronic devices for healthcare and medical applications^{1,2} illustrates the power and the potential of such a futuristic concept. Possible applications are vast, but they need reliable and safe energy sources to operate. Especially in the fields of biology and medicine, batteries can be dangerous, bulky, and difficult to change—for example, replacing a pacemaker battery can be problematic. However, great progress has been made in energy harvesters over the past decade. In the body, where there is little light and there are only small thermal gradients, mechanical energy harvesting is needed to power new medical devices. Biomedical systems are consuming less and less power, and new harvesting technologies like piezoelectric³ and triboelectric⁴ nanogenerators have the potential to supply the power needed for the safe operation of medical devices.

MOTIVATION AND OVERVIEW

New Medical Microelectronics Technology. New biomedical systems have enormous potential and are motivating active research. These technologies are smaller and more

autonomous and, therefore, are wearable or implantable. Thus, every patient with one of these microelectronic devices would be able to receive personalized treatment that is adapted to their case. The medical possibilities are booming; this new technology has enormous potential and could offer new control, diagnostic, and treatment possibilities.

The first applications developed were mainly aimed at controlling malfunctions of the body or restoring lost function (*e.g.*, pacemakers, cochlear implants, retinal implants, brain implants, neurostimulators, and prosthesis controllers). These applications opened new horizons for integrating new features into the body, such as radio frequency identification (RFID) and near-field communication (NFC) microchips. In addition, diagnostic microchips have also been developed to facilitate medical tests at lower cost. These are lab-on-a-chip and micro total analysis systems (μ TAS). Recent research demonstrated the benefit of *in vivo* biomedical systems to treat,⁵ to help,^{6,7} and to accelerate⁸ the healing process of body tissue. Patches can fulfill many roles, including disinfecting wounds,^{7,9} monitoring some patient parameters,¹⁰ and transmitting

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this information.^{11,12} More impressively, in this issue of *ACS Nano*, Tang *et al.*⁸ show that wearable, self-powered laser treatments can accelerate bone remodeling.

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Energy Rations. Biomedical systems are intensely researched and are quickly evolving new functions. However, they are also progressing toward more integration onto and into the body, which requires autonomous systems. These devices need power to operate, and despite recent advances, batteries still take up a lot of space, can be dangerous, and have short-to-medium lifetimes. In addition, because of the strict constraints in biomedicine, batteries' use of risky materials like heavy metals has made them even more difficult to integrate into biomedical systems. Finally, the need to control and to replace batteries periodically generates necessary maintenance, often involving surgery, which increases the number of critical steps and risks. Therefore, there is a growing need for new power sources for independent and continuous operation of biomedical systems. Importantly, small-sized microelectronics operating with ultra-low-power consumption may be able to power biomedical devices by using body energy. This is one way to achieve self-powered implantable systems, and that is why the development of energy harvesters has recently drawn much attention. Energy harvesters first aim to complement batteries and next will develop self-powered biomedical devices

for *ex vivo* and *in vivo* medical applications.

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Harvesting the Body's Mechanical Energy. Among the different types of energy that we can harvest, there are little light and only small thermal gradients in the human body. It is full of various forms of chemical energy like glucose and adenosine triphosphate (ATP), but their use remains questionable. However, the body is a fabulous source of mechanical energy. It is a widespread product of our muscles and abundant, which makes it a good energy source to power autonomous biomedical systems. To harvest mechanical energy, diverse technologies have been developed. In particular, recent emphasis has been placed on the use of nanomaterials and nanotechnologies following the development of piezoelectric nanogenerators (PENG) in 2006.³ They can be efficient, but they are complex to fabricate and difficult to integrate. Nevertheless, in 2012, triboelectric nanogenerators (TENG)⁴ were invented and quickly developed on the basis of electrostatic and contact electrification (also named triboelectrification) physics.^{13,14} Triboelectric nanogenerators present numerous advantages, including high output voltage, efficiency, low cost, high versatility, simplicity in structural design and fabrication, stability and robustness, and environmental friendliness.¹⁵ They also enable designs and structures that are robust, less troublesome, and better suited to harvest body movements. They facilitate the integration of such devices into wearable and implantable biomedical systems.

For all these reasons, flexible TENGs have recently received particular interest.

One *in vivo* experiment has been accomplished in a rat by using a small and flexible planar TENG.¹⁶ The device structure is basic and inexpensive, made of a micropatterned polydimethylsiloxane (PDMS) layer, aluminum (Al) foil, and flexible polyethylene terephthalate (PET) spacers (Figure 1a), and its operation is simple. When compressed, the foils (Al and PDMS/PET) are bent between the spacers and touch, generating opposite triboelectric charges at their surfaces. Then, when they move, they create electrostatic induction, producing an electrical signal to supply power to any small, low-consumption device. The goal of Zheng *et al.* was to power a human pacemaker. The prototype fabricated was small (1.2 cm × 1.2 cm, Figure 1b) to fit *in vivo* in rats. The PET spacers (400 μm thick) fully enclosed the gap in the device to protect the inner structure from the surrounding bioenvironment. In addition, the entire device was covered with a thin and flexible PDMS layer (50 μm thick) as the encapsulation material because of its flexibility, resistance to leaks, biocompatibility, and mild inflammatory reaction upon implantation. Moreover, this polymer layer protects the device from biofluids and increases its robustness. Because of the spacers and all of the packaging, the active surface of the device was estimated to be 0.8 cm × 0.8 cm. The open-circuit voltage reached 12 V, and the short-circuit current was 0.25 mA, which is equivalent to a power density of 0.844 μW·cm⁻². For realistic characterization of the planar flexible TENG as an *in vivo* pacemaker energy source, it was implanted under the thoracic skin of a rat (Figure 1c) to serve as a breathing energy harvester. The open-circuit voltage generated by the breathing of the rat was 3.73 V, and the short-circuit current was 0.14 mA. This voltage is sufficient to power a commercial pacemaker. Because of the low

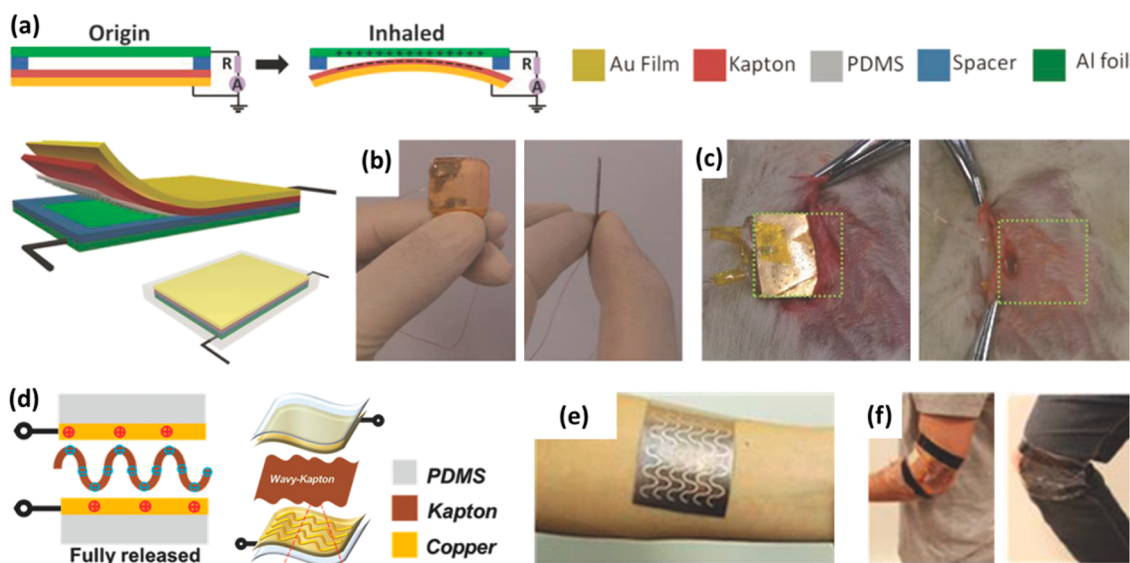


Figure 1. (a) Schematic structure of an implantable planar flexible triboelectric nanogenerator (TENG). (b) Photo of a TENG before and (c) after implantation into a rat under its thoracic skin. (d) Schematic structure of the flexible TENG skin patch. (e) Photos of the serpentine-patterned electrodes on human skin and (f) under elbow and knee stretching. Reproduced with permission from refs 16 and 17. Copyright 2014 and 2015, respectively, Wiley.

output current, five breaths are necessary to activate a commercial pacemaker. However, considering the small size of the planar flexible TENG due to the rat's size, implanting a larger device in the human body should allow a commercial pacemaker to be powered with each breath.

Concerning *ex vivo* TENG devices and patches, a recent paper proposed a TENG skin patch¹⁷ to harvest energy from skin deformation. The patch can be rather large, up to 40 cm², and was attached to the skin with tape. Here again the substrate used was PDMS (Figure 1d) because of its stretching ability. The PDMS is a good material with which to embed biomedical devices because it is biocompatible, inexpensive, easy to prepare, and more robust than other stretchable medical polymers like Ecoflex. To ensure that the electrodes had low resistance and high stretching capacity, serpentine-patterned copper electrodes were deposited on the flexible substrate (Figure 1e). Under stretching (up to 22%) or compression, the TENG can generate an open-circuit voltage and short-circuit current up to 700 V and 75 μ A, respectively. Under realistic situations,

when bending the elbow, knee (Figure 1f), neck, or bicep, it can generate tens of volts, which is enough energy to power low-energy-consumption biomedical devices.

It is in this important and encouraging context that Tang *et al.*⁸ demonstrate that flexible TENGs attached to human articulations can generate enough electricity to supply periodic power to a medical laser. The aim is for this laser to accelerate bone remodeling treatments.⁸ Of course, such a flexible TENG equipped with a small capacitance as an energy buffer does not have the same ability to power a device over time compared to a battery. The specifications and behaviors of TENGs are different: batteries deliver continuous power until they are empty, while flexible TENGs deliver a pulse of power every time they are activated. Therefore, the performance of the powered medical laser varies, such as producing a continuous light emission during 60 s when powered by a battery, compared to a series of 100 light pulses when powered by a flexible TENG. As a consequence, we might expect significantly different medical results. However, Tang *et al.* show that even if the laser powered

by the TENG is a little less efficient than the battery-powered laser, both treatments work and have good results (Figure 2b–d). This finding is important because it proves that TENGs with a small energy buffer like a capacitance can be sufficient to power small biomedical devices. Thus, batteries are not mandatory in these devices, and instead, TENGs are strong candidates to power future biomedical systems.

OUTLOOK AND FUTURE CHALLENGES

Biomedical systems and nanotechnologies are revolutionizing healthcare and medicine; their synergy could be extremely powerful, and they could play key roles in near-term medical technologies. Taking into account the decreasing power consumption of microchips and the increasing efficiency of nanomaterials-based mechanical energy harvesters such as PENGs and TENGs, it should be possible to power autonomous biomedical systems. Reaching energetic independence from batteries is a first important step for their development. However, to reach their full potential in the field of healthcare, autonomous biomedical systems

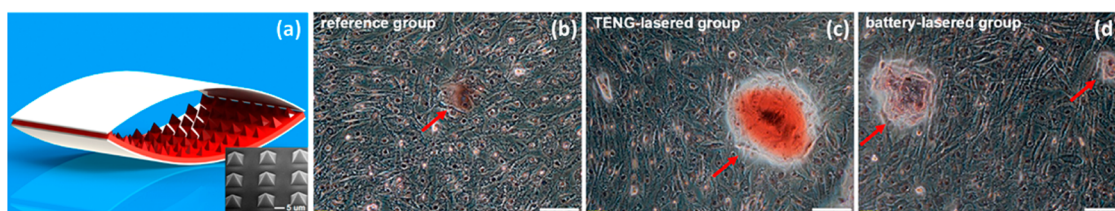


Figure 2. (a) Schematic illustration of a flexible arch-shaped triboelectric nanogenerator (TENG). (b–d) Images reveal that the quantity of calcium nodules and mineralized area in both TENG-lasered and battery-lasered irradiation groups are larger than those in the reference group. Reprinted from ref 8. Copyright 2015 American Chemical Society.

need to continue to evolve more flexibility and biocompatibility to be fully operational in the human body.

To be easily used *ex vivo* and *in vivo*, future autonomous biomedical systems will need to be wearable and implantable. In order to achieve this, they will need to be fully flexible to fit the shape of organs,⁶ including skin, closely.^{11,12} Thus, the devices will be more discrete and comfortable, which is important for the patient, and will be better adapted to their target, which will increase their sensing ability and the amount of energy harvested. For example, to sense the heart, it is better to fit its shape⁶ in order to get higher mechanical deformations and, thus, better sensing and energy harvesting. This trend has already started and is progressing quickly. Flexible electronics are currently used, flexible microelectronics are under development,^{6,11,12} and flexible TENGs are progressing.¹⁸ Therefore, flexible autonomous biomedical devices are possible, and the challenge will be to integrate all the parts into one small, flexible device. Then the device will need to be embedded into a flexible, biocompatible package to be patched on or implanted into a patient. Improving and facilitating this last step is another important goal for biomedical systems.

Conflict of Interest: The authors declare no competing financial interest.

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REFERENCES AND NOTES

- Menon, K.; Joy, R. A.; Sood, N.; Mittal, R. K. The Applications of BioMEMS in Diagnosis, Cell Biology, and Therapy: A Review. *Bionanoscience* **2013**, *3*, 356–366.
- James, T.; Mannoor, M. S.; Ivanov, D. V. BioMEMS – Advancing the Frontiers of Medicine. *Sensors* **2008**, *8*, 6077–6107.
- Wang, Z. L.; Song, J. Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays. *Science* **2006**, *312*, 242–246.
- Fan, F.-R.; Tian, Z.-Q.; Lin Wang, Z. Flexible Triboelectric Generator. *Nano Energy* **2012**, *1*, 328–334.
- Jeong, J.-W.; McCall, J. G.; Shin, G.; Zhang, Y.; Al-Hasani, R.; Kim, M.; Li, S.; Sim, J. Y.; Jang, K.-I.; Shi, Y.; et al. Wireless Optofluidic Systems for Programmable *In Vivo* Pharmacology and Optogenetics. *Cell* **2015**, *162*, 662–674.
- Xu, L.; Gutbrod, S. R.; Ma, Y.; Petrossians, A.; Liu, Y.; Webb, R. C.; Fan, J. A.; Yang, Z.; Xu, R.; Whalen, J. J.; et al. Materials and Fractal Designs for 3D Multifunctional Integumentary Membranes with Capabilities in Cardiac Electrophysiology. *Adv. Mater.* **2015**, *27*, 1731–1737.
- Tao, H.; Hwang, S.-W.; Marelli, B.; An, B.; Moreau, J. E.; Yang, M.; Brenckle, M. A.; Kim, S.; Kaplan, D. L.; Rogers, J. A.; et al. Silk-Based Resorbable Electronic Devices for Remotely Controlled Therapy and *In Vivo* Infection Abatement. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111*, 17385–17389.
- Tang, W.; Tian, J.; Zheng, Q.; Yan, L.; Wang, J.; Li, Z.; Wang, Z. L. Implantable Self-Powered Low-Level Laser Cure System for Mouse Embryonic Osteoblasts' Proliferation and Differentiation. *ACS Nano* **2015**, *10*, 1021/acs.nano.5b03567.
- Hwang, S.-W.; Tao, H.; Kim, D.-H.; Cheng, H.; Song, J.-K.; Rill, E.; Brenckle, M. A.; Panilaitis, B.; Won, S. M.; Kim, Y.-S.; et al. A Physically Transient Form of Silicon Electronics. *Science* **2012**, *337*, 1640–1644.
- Hwang, S.-W.; Lee, C. H.; Cheng, H.; Jeong, J.-W.; Kang, S.-K.; Kim, J.-H.; Shin, J.; Yang, J.; Liu, Z.; Ameer, G. A.; et al. Biodegradable Elastomers and Silicon Nanomembranes/Nanoribbons for Stretchable, Transient Electronics, and Biosensors. *Nano Lett.* **2015**, *15*, 2801–2808.
- Kim, J.; Banks, A.; Cheng, H.; Xie, Z.; Xu, S.; Jang, K.-I.; Lee, J. W.; Liu, Z.; Gutruf, P.; Huang, X.; et al. Epidermal Electronics with Advanced Capabilities in Near-Field Communication. *Small* **2015**, *11*, 906–912.
- Kim, D.-H.; Lu, N.; Ma, R.; Kim, Y.-S.; Kim, R.-H.; Wang, S.; Wu, J.; Won, S. M.; Tao, H.; Islam, A.; et al. Epidermal Electronics. *Science* **2011**, *333*, 838–843.
- McCarty, L. S.; Whitesides, G. M. Electrostatic Charging due to Separation of Ions at Interfaces: Contact Electrification of Ionic Electrets. *Angew. Chem., Int. Ed.* **2008**, *47*, 2188–2207.
- Wang, Z. L. Triboelectric Nanogenerators as New Energy Technology for Self-Powered Systems and as Active Mechanical and Chemical Sensors. *ACS Nano* **2013**, *7*, 9533–9557.
- Wang, Z. L.; Chen, J.; Lin, L. Progress in Triboelectric Nanogenerators as a New Energy Technology and Self-Powered Sensors. *Energy Environ. Sci.* **2015**, *8*, 2250–2282.
- Zheng, Q.; Shi, B.; Fan, F.; Wang, X.; Yan, L.; Yuan, W.; Wang, S.; Liu, H.; Li, Z.; Wang, Z. L. *In Vivo* Powering of Pacemaker by Breathing-Driven Implanted Triboelectric Nanogenerator. *Adv. Mater.* **2014**, *26*, 5851–5856.
- Yang, P.-K.; Lin, L.; Yi, F.; Li, X.; Pradel, K. C.; Zi, Y.; Wu, C.-I.; He, J.-H.; Zhang, Y.; Wang, Z. L. A Flexible, Stretchable and Shape-Adaptive Approach for Versatile Energy Conversion and Self-Powered Biomedical Monitoring. *Adv. Mater.* **2015**, *27*, 3817–3824.
- Hinchet, R.; Seung, W.; Kim, S.-W. Recent Progress on Flexible Triboelectric Nanogenerators for Self-Powered Electronics. *ChemSusChem* **2015**, *8*, 2327–2344.