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Piezoionic artificial nerves for tactile sensing and neuromodulation

Meng Xiao[1] and Zhou Li[1,*]

As soft, self-powered, and biocompatible ionic current generators, piezoionic hydrogels are suitable candidates for implantable neuromodulation applications. In a recent issue of *Device*, Dai et al.[1] describe an artificial nerve that combines sensing and synaptic functions for neuromodulation. The success of piezoionic artificial nerves can inspire next-generation neuromorphic devices with sensing, storage, and computing properties.

The pressure perception systems of human skin are composed of pressure receptors, afferent nerves, and synapses to perceive stimuli efficiently. Inspired by nature, artificial sensory nerves with synaptic behavior are required for seamless communication between biological and artificial systems.[2] Artificial nerves with ionic synaptic transistors are capable of processing stress information in parallel without intensive information processing units. However, the energy consumption of artificial nerves with both sensor and transistor units is huge, posing a challenge for long-term portable operation. Based on force-induced ion fluxes in the hydrogel network, piezoionic hydrogels can be used as self-powered artificial sensory nerves.[3] In a recent issue of *Device*, Dai et al. provide new insight into ionic artificial nerves with integrated sensing and synaptic functions for neuromodulation (Figure 1).[1] With a fiber/hydrogel composite structure, their artificial nerve can sense pressure similarly to skin and mimic the spatiotemporal integration functions of synapses.

In this work, a piezoionic hydrogel is developed based on the artificial sensory nerve. The structured piezoionic hydrogel device comprises an oriented poly(ethylene terephthalate) (PET) microfiber structure to provide a directional ion migration path under pressure in the ionic hydrogel. Benefiting from ion hysteresis generated by electrostatic interaction between charged PET fibers and ionic gels, the artificial nerve can mimic the spatiotemporal signal integration function of synapses. Also, the generated piezoionic current is large enough to directly stimulate the sciatic nerves for neuromodulation, showing potential for bionic interface. This piezoionic device can be used as an ionic tool for sensing, computation, and neuromodulation.

Like a bionic system that relies on mechanosensitive ion channels to convert pressure information into action potential, the artificial nerve relies on force-induced ionic flow. The generated potential of the artificial nerve is comparable to biological potential in both value and spike shape. Similar to action potential, the shape of the spike can be divided into four stages: resting state, depolarization state, repolarization state, and hyperpolarization state. When pressure is applied on one side of the piezoionic hydrogel, a net potential difference is generated due to the discrepancy in diffusion speed between Li^+ and Cl^- along the pressure gradient. After the pressure releases, the generated potential decreases rapidly as a result of the ionic flow in the opposite direction, akin to the repolarization state of an action potential. Additionally, a small negative spike occurs due to the quicker diffusion speed of cations compared with anions, corresponding to the hyperpolarization of an action potential. The negatively charged PET fibers provide micrometer channels for ion transport, resulting in much higher potential output and quicker rebalancing of ion distribution compared with pure poly(acrylic acid)/lithium chloride hydrogels. Meanwhile, the piezoionic output potentials are enhanced in the parallel direction, demonstrating the importance of microscale fiber structure for piezoionic performance and synaptic behavior. Furthermore, finite element simulations based on Darcy's law confirm the proposed mechanism of piezoionic potential generation caused by pressure-induced ionic flow.

The artificial sensory nerve exhibits high sensitivity to both the magnitude and pressing speed of pressure. For instance, a faster pressing speed can cause the accumulation of Li^+ opposite to the pressing site, generating a higher piezoionic potential. Furthermore, the artificial nerve exhibits a pressure sensitivity of 0.043 mV/kPa with a pressure range from 17.4 to 174.3 kPa, while the sensitivity decreases to 0.020 mV/kPa at a larger pressure. The artificial nerve can detect dynamic and static forces in the absence of external voltages, which is different from traditional piezoelectric materials that can only detect dynamic forces. When a static force is applied, the artificial nerve can sustain the generated piezoionic potential due to the slow diffusion speed of the free ions. Additionally, the artificial piezoionic nerve exhibits stable sensing performance without signal attenuation and baseline drift because of the strong water-absorption ability of Li^+ and the hydrophobicity of polyethylene encapsulation films.

[1]Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China
*Correspondence: zli@binn.cas.cn
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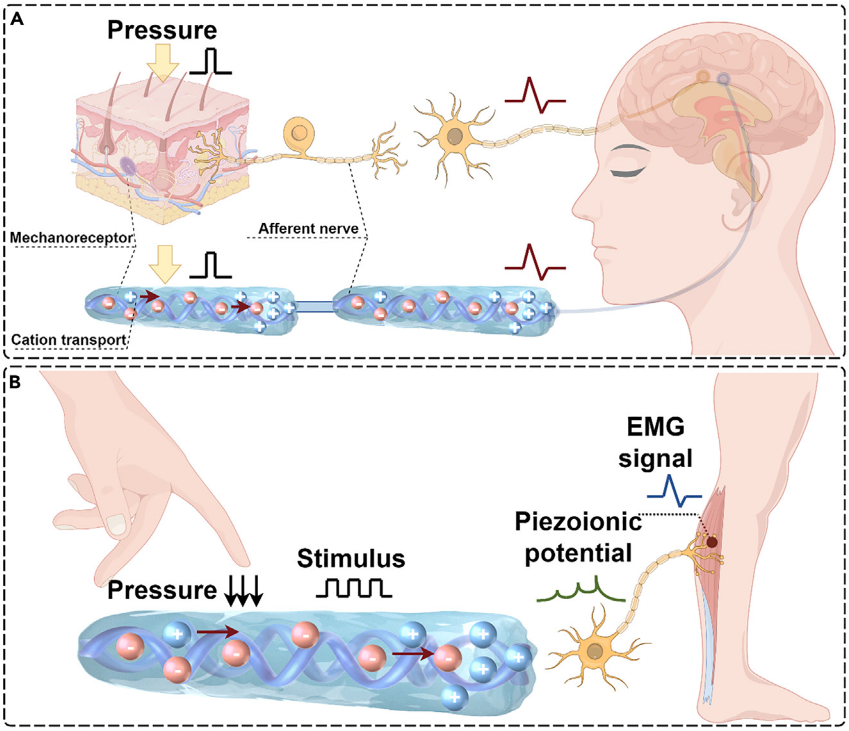

Figure 1. Self-powered pressure sensing and neuromodulation of the hydrogel-based piezoionic artificial nerve

(A) The schematic shows a comparison between the hydrogel-based piezoionic artificial nerve and a human sensory nerve.

(B) Piezoionic potentials generated by hydrogel-based artificial nerves can stimulate the sciatic nerves and activate the muscle nearby.

Figure created by Figdraw.

The electrical signal transmission induced by ion transportation is the foundation of vital human activities. Physical signals can regulate life activities by adjusting the ion transportation process in the ion channels on the surfaces of cell membranes. A physical stimulus unit, such as the mechanical stimulus device, can act on the corresponding proteins in the cell, such as mechanoresponsive PIEZO proteins, to regulate the cell's physiological functions. Similarly, physical stimuli can directly act on and alter the structure and function of tissues, cells, organelles, and molecules. By exploring the biological regulatory effects and mechanisms of physical stimuli, theoretical guidance for therapeutic strategies based on physical stimuli can be developed.[4]

The artificial nerve has similar functions to bionic sensing and synaptic behavior. The artificial nerve can integrate the potential and current signals of the former ones, demonstrating its spatial integration functions. In addition, the artificial nerve shows frequency-related properties comparable to the function of biological synaptic junctions. With a decrease in stimulus interval from 10 to 0.5 s, the piezoionic potential gradually increases by 1.8 times compared with the original signal. The combination of sensory functions and synaptic behaviors of the afferent nerves shows the potential for neuromorphic computing.

The artificial nerve combines sensing and synaptic behavior, making it an appropriate choice for neural interfacial applications.[5] In specific neural stimulation applications, the operating voltage must be kept low for safety concerns, and high injection currents are needed at the same time.[6] Unlike piezoelectric devices, piezoionic devices can output large currents at small voltages, making them ideal candidates for these types of neural stimulation. In this work, Dai et al. demonstrate the functionality of artificial nerves as self-powered neural interfaces that can stimulate the sciatic nerves and activate the muscle nearby without the need for external amplifiers and encapsulation. A high output performance of piezoionic current up to 66 μA/cm^2 and a potential above 21 mV can be achieved to stimulate the sciatic nerves. The waveform and duration of piezoionic potential can be generated by adjusting the frequency and duration of the input stimuli. Clear electromyogram signals are recorded, indicating that the muscle near the sciatic nerves can be activated with the input stimuli of artificial nerves.

Piezoionic hydrogels are simple materials that are composed of polymers and salts and are amenable to scalable fabrication through advanced printing techniques. In the future, the performance of piezoionic devices, including in areas such as maximum output voltage, sensitivity, and power density, needs to be further improved to meet the demands of specific applications. For instance, the output performance of piezoionic devices can be improved by exploring the ion-polymer interactions,[7] phase and interface structure,[8] and integration of piezoionic units.[9] Materials options for piezoionic devices, aside from hydrogels, are largely unexplored. Piezoionic elastomers with dynamic network structures and durable mechanical properties may be suitable alternatives.

In Dai et al.'s work, the generated piezoionic currents are converted into electronic currents by Pt wires and the electronic currents are converted back into ionic signals at the tissue-electrode interface. In the future, piezoionic devices with hydrogel-stimulating electrodes can form all-hydrogel stimulating circuits.[10] The biological effects

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and mechanisms of piezoionic signals with relation to biosystems, such as inhibition of inflammation, promotion of angiogenesis, and regulation of osteogenesis and osteolysis, have not yet been explored. In the future, more medical devices based on piezoionic effects will be developed to fulfill the requirements of closed-loop and autonomous treatments.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Unveiling passive design to enable synergistic water harvesting and irrigation

Changmin Shi,[1,*] Brian W. Sheldon,[1] and Meijie Chen[2,*]

Developing passive water collection strategies offers us an opportunity to address global water scarcity and energy shortages. In a recent issue of *Nature Water*, Zou et al. introduced a novel solar-driven hygroscopic gel to efficiently recycle water for irrigation from plant transpiration and soil evaporation, offering a promising energy-saving solution for agricultural water management.

Water scarcity is a growing global concern, particularly in the agricultural sector, which accounts for about 70% of the world's freshwater consumption.[1] As the demand for food production increases with the rising global population, sustainable water management in agriculture has become a critical challenge.[2] Traditional irrigation methods are often inefficient and wasteful, exacerbating water scarcity issues. To address this, innovative solutions that can enhance water use efficiency and sustainability are urgently needed.[3]

Conventional irrigation methods in agriculture often result in significant water loss due to evaporation and inefficient water distribution. In many regions, water resources are already stretched thin, and the impacts of climate change are likely to exacerbate these issues further. Sustainable irrigation solutions that can reduce water usage, minimize losses, and recycle water are essential for ensuring food security and protecting water resources. Atmospheric water harvesting (AWH) technologies have emerged as promising solutions to augment water sustainability in agriculture.[4] These technologies capture moisture from the air and condense it into liquid water using solar energy. Despite their potential, existing AWH methods in greenhouses face challenges such as inefficiency, high costs, and integration issues with current greenhouse structures.[5] Addressing these challenges is essential for maximizing the benefits of AWH in

[1]School of Engineering, Brown University, Providence, RI 02912, USA

[2]School of Energy Science and Engineering, Central South University, Changsha 410083, China

*Correspondence: changmin_shi@brown.edu (C.S.), chenmeijie@csu.edu.cn (M.C.)

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