Integration of Soft Electronics and Biotissues

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The collection of physiological signals as well as the electrical stimulation to the biotissues are significant but challenging. There is a huge gap between the living systems and electronics. Biotissues are wet and soft, while electronics are dry and relatively stiff; biotissues conduct ions, while electronic materials often conduct electrons. As a result, forming a stable interface for bidirectional electrical communications between electronics and the living systems is difficult. In this perspective, we review recent landmark progresses made in this field, and propose a few future directions that scientists may further work on.

The integration of flexible electronics and biotissues is a transformative technology that advances the fields of healthcare, human-machine interfaces, and internet of things by enabling devices with the capability to interact with the human body. Typically, biotissues are soft and wet, while electronics are rigid, dry, and non-bioactive (Figures 1A and 1B). The significant differences between biotissues and electronics, as well as the special bio-environments in the body, will lead to unstable bioelectronic interfaces and thereby dysfunction of the devices. The huge gap between the two different systems therefore calls for new demands in material science, electronics, and biomedical engineering.

Emerging materials that allow for the rapid formation of robust and conformable bioelectronic interfaces are required to address this challenge. It is extremely difficult for an artificial material to form tough adhesion on wet and dynamic tissue surfaces, while enabling bidirectional

Figure 1. The Integration of Biotissues and Electronics (A) Schematic illustration for the integration of biotissues and electronics. (B) Young’s modulus of different materials including biotissues, hydrogels, and electronic materials. Panels (A) and (B) are reprinted with permission from Ref. 2, copyright 2019, Royal Society of Chemistry. (C) Structure of bilayered tough hydrogel consisting of an adhesive surface and a dissipative matrix. Reprinted with permission from Ref. 5, copyright 2017, American Association for the Advancement of Science. (D) Schematic of the electrical bioadhesive interfaces. (E) Comparison of electrocardiogram (ECG) signals detected using conventional electrodes and the bioadhesive electrode. (D) and (E) Reprinted with permission from Ref. 8, copyright 2020, Springer Nature. (F) Photograph of the highly sensitive pressure sensor. Reprinted with permission from Ref. 9, copyright 2020, Springer Nature.
electrical communications. Hydrogels are a type of materials that present high biocompatibility and tissue-like mechanical properties, and thus are promising in tissue engineering. This class of materials has been successfully implanted in the body to bridge electronics and biotissues. Li et al. developed a bilayered hydrogel consisting of an adhesive surface and a dissipative matrix (Figure 1C): the former forms strong adhesion with the tissue surface via electrostatic bonds within a few minutes, while the latter dissipates energy upon deformation by significant hysteresis. Very recently, Zhao and Guo developed a new conducting hydrogel behaving like a double-sided tape that forms much faster and stronger bonds with wet and dynamic biotissues in a few seconds, enabling tough skin-electronic interfaces (>400 J m⁻²) for stable physiological signal recording or electrical stimulation (Figures 1D and 1E). On-demand detachment of devices from biotissues is another big challenge that needs to be addressed, and this can also be achieved by applying a solution that is destructive to the interfacial bonding between the electrical bioadhesive and the tissue. The electrical bioadhesive interface presents clear advantages over traditional suturing or physical attachment, which suffers from either extra damage to the biotissues or poor interfacial adhesion. Future electrical bioadhesive materials are expected to present higher electrical conductivity with significant anisotropic conducting only along the z-direction. Such materials may be achieved by doping aligned conductors in the matrix or by printing conductive pixel arrays.

The improvement in performance of bioelectronic devices is another challenge in this field. Implants often need to record physiological signals, some of which are too weak to be detected. For example, the fetal heartbeat signal is critical in evaluating the health conditions of the fetus. However, the fetal heartbeat is often weak, and thus highly sensitive sensors are required to detect such weak signals. Sensitivity is a parameter of sensors that is probably overstressed. It is often defined as \( S = \frac{A(\Delta X/X_0)}{A P} \), where \( X_0 \) is the initial signal amplitude, \( \Delta X \) is the change in signal amplitude, and \( P \) is the pressure applied on the device. From its definition, sensitivity is a relative amount highly related to \( X_0 \), which may not be a stable value for many measurements. In comparison, pressure resolution is a parameter that directly reflects the capability of a sensor to resolve pressure at different pressures, and thus has more significant practical uses. However, this parameter has seldom been discussed in the community, until recently, Bai et al. reported a highly sensitive flexible pressure sensor (Figure 1F) that resolves pressures of 0.08 Pa at very low pressures and ~18 Pa at high pressures up to 3.2 atm. A special structure called graded intrafillable architecture could well improve the compressibility of a layer of ionic gel in the sensor, and thus high pressure resolution can be achieved in the high-pressure region. In addition, electric double layers that form at the electrode-gel interface also help improve the sensing performance. Sensors with such a high pressure resolution over a wide pressure range are desired to be implanted on organs for pressure mapping, or integrated in medical catheters or guidewires to measure pressure variations in blood vessels, heart, and other organs.

Bioelectronics should achieve high spatial resolution for some applications. For example, Neuralink Inc. used a multi-channel brain-machine interface that was able to record electrical signals from 1,024 electrodes, which are at least two orders of magnitude more electrodes than those used in clinically approved devices. Of course, ideal brain-machine interfaces also need to be soft and highly sticky to biotissues. For bioadhesive soft electronics, electrical hydrogels that conduct along the z axis (out-of-plane direction) will be of great significance in developing high-spatial-resolution bioelectronics. However, the synergy of compatibility, conformability, electrical conductivity of the bioadhesive interface, as well as the spatial resolution and sensing performance of the device still needs great efforts.

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DECLARATION OF INTERESTS

The authors declare no competing interests.