Soft Electronics

Configuring hard, inorganic functional materials into thin, open mesh microarchitectures and embedding them in soft, elastomeric films provides a route to electronic systems, such as circuits and sensors, and optoelectronic systems, such as light-emitting diodes and photodetectors, that combine state-of-the-art operational characteristics with soft, elastic mechanical properties, even under large-strain deformations. Such devices can be bent, twisted, folded, stretched, and conformally wrapped onto arbitrarily curved objects, without significant change in performance.1 When implemented with biocompatible interface materials, this mechanics enables intimate integration with the soft, curvilinear surfaces of major organ systems such as the brain, heart, and skin, without constraint and in ways that would be impossible using conventional wafer-based devices built and packaged on standard, rigid, printed circuit boards. Examples include balloon catheters with surface-mounted arrays of electronic sensors and actuators configured for use in high-resolution mapping of endocardial electrophysiology and in pulmonary vein ablation therapy for atrial fibrillation.2

Related embodiments involve 3-dimensional elastic membranes similarly instrumented and specially shaped to envelop the entire 3-dimensional surface of the heart, as an electronic artificial pericardium capable of performing spatially and temporally programmable pacing, low-energy defibrillation, and other forms of cardiac electrotherapy.3 Thin, flexible sheets of dense collections of actively amplified sensors constructed using these same concepts can perform multiplexed electrocorticography with a resolution that far exceeds that of passive electrode arrays currently used to guide surgical interventions for treating certain forms of epilepsy.4

The process of releasing the injection needles described above involves bioresorption of a thin adhesive layer upon contact with cerebrospinal fluid. Recent work demonstrates that this concept of bioreabsorbable materials in biointegrated electronics can be extended to entire functional systems, where all of the materials, both active and passive, dissolve completely in a controlled fashion and with programmable rates when immersed in biofluids.8 Wide-ranging options...
in sensing, wireless data transmission, power supply, and actuation are now available in devices that exhibit good biocompatibility in cell-level toxicity studies and animal trials. Demonstrated examples with clinically relevant utility include electronic appliances designed to eliminate infections at surgical sites, intracranial pressure, and temperature monitors for patients with traumatic brain injury, nerve stimulators that mitigate pain and accelerate regeneration, pacemakers for use during postsurgical recovery, and electronically programmable vehicles for drug release. Such devices provide high-performance, stable operation for a desired time frame, and then completely resorb to eliminate unnecessary device load on the body. Successful animal studies of these and other bioresorbable electronic systems demonstrate capabilities of relevance to unmet clinical needs.

**Outlook**

New opportunities afforded by biocompatible electronics have the potential to profoundly affect the future of biomedical research and clinical care. The scalability and diversity of options in multifunctional operation create a rich range of promising directions for further development and deployment. An important perspective is that the materials and device designs of many of the component building blocks align well with those found in the consumer electronics industry, thereby offering synergies for accelerated improvements in performance and scale. In this way, it is possible to realistically contemplate biocompatible transistors, light-emitting diodes, photodetectors, electrodes, and interconnects formed at submicron dimensions, in multilayered formats, with levels of integration that approach billions of devices, over areas of hundreds of square centimeters.

The most significant near-term opportunities are in surgical and diagnostic devices and in skin-mounted, continuous health monitors. Bioreabsorbable sensors and therapeutic devices, sometimes referred to as bioelectronics medicines, or electroceuticals, represent additional areas with significant promise. A longer-term vision involves the use of biocompatible electronics as long-term implants, for which a key additional technical challenge is in the development of thin flexible layers of materials that can serve as robust long-lived barriers to biofluids. This topic and others in chemical sensors, active microfluidics, and power-harvesting devices represent promising directions that can be pursued in parallel with more immediate efforts in translating proven technologies into clinical practice.

**ARTICLE INFORMATION**

**Conflict of Interest Disclosures:** The author has completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest and reports that he has received grants and personal fees from MC10 Inc and has patents, several of which through the University of Illinois are licensed.

**REFERENCES**


