A taste of bioelectronics

Transient and ingestible electronic devices could play a valuable role in the development of personalized healthcare.

Artificial cardiac pacemakers, which use electrical signals to correct abnormal heart rhythms, were first developed around 1930 (ref. [1]), but it was only after the invention of the transistor in 1947 that practical devices started to appear. In 1957, Earl Bakken, the co-founder of Medtronic, created a wearable, battery-operated pacemaker that used a two-transistor circuit[2]. The device had leads that passed through the skin and connected to electrodes attached to the heart. Shortly after, in 1958, the first fully implantable pacemaker, which had been designed by Rune Elmqvist and Åke Senning, was tested on a patient[1].

Since then a range of increasingly complex and miniaturized pacemakers, as well as other implantable devices such as cochlear implants, have been built[3]. However, these devices are still based on hard, rigid materials. The development of electronics made from flexible and stretchable materials is now expanding the potential capabilities of implantable devices. The nature of these flexible materials means that they can form an intimate connection with tissue or organs, creating potentially powerful systems for health monitoring and therapy. Furthermore, while pacemakers should ideally last a lifetime, for certain applications an implantable device is only required for a short, defined period. Therefore, the recent emergence of flexible devices that can also degrade after they have performed their medical function, and thus avoid the need for additional surgery to remove them, has created exciting possibilities.

A range of potential applications for such transient, or bioresorbable, electronics in the diagnosis and treatment of medical conditions has already been demonstrated. It has, for example, been shown that silicon-based sensors that dissolve after use are capable of monitoring temperature and pressure within the brain[4] — measurements that are vital in the treatment of traumatic brain injury. Similar devices have also been used to map electrical activity from the brain[5], which could be of value in post-operation monitoring. Alternatively, strain and pressure sensors, which incorporate biocompatible and biodegradable polymers, have been built that could track the healing of tendons in real time, before naturally decomposing after their useful lifetime[6]. Such sensors could allow rehabilitation programmes to be personalized to each recovering patient.

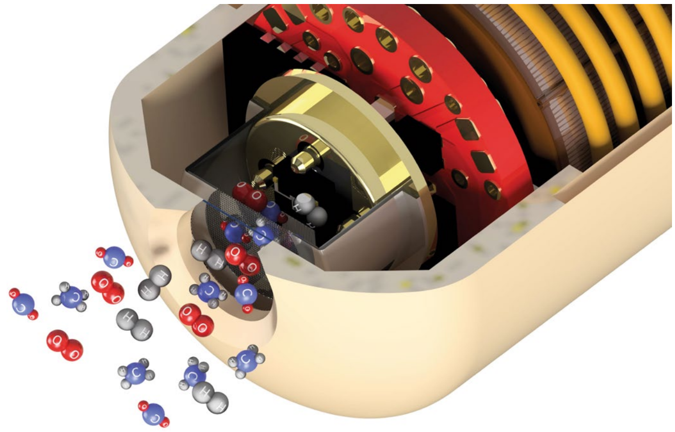

Illustration of an ingestible electronic sensor that can detect different gases in the gut. Credit: adapted from ref. [9], Springer Nature Ltd.

In trying to develop biomedical devices that minimize the invasive procedures required to get them in and out of the body, an attractive option is to have devices that can be simply swallowed. Such devices can be traced back to 1957, when an ingestible electronic capsule that had a radiofrequency transmitter, and could transmit internal pressure and temperature readings, was reported[7]. But it was in the 1990s, after a sustained period of electronic miniaturization and expansion, that research activity in the field began to gain momentum[8].

Commercial ingestible sensors are now available that can, for example, measure body temperature, or pH and pressure levels in the gut; there are also devices that can monitor the taking — or not — of medication[8]. A variety of more sophisticated systems are also beginning to emerge from the research community. Earlier this year, a human pilot trial of an ingestible electronic sensor (pictured) that can measure different gases in the gut was reported[9]. As these devices travel along the length of the gut they sense oxygen, hydrogen, and carbon dioxide, transmitting gas concentration data to external pocket-sized receivers. The sensors can, in particular, distinguish changes in a person's diet and could potentially be used to help develop individualized diets.

Ingestible electronic sensors that can detect gastrointestinal biomolecules with the help of biosensing bacteria have also recently been demonstrated[10] (see a Research Highlight in this issue of *Nature Electronics*). The sensors are currently a little too large for a person to comfortably swallowed — they are capsules with a length of around 4 cm (in comparison, the gas sensing capsules recently used in a human pilot trial[9] had a, not insignificant, length of 2.6 cm). They were, though, shown to be capable of detecting gastrointestinal bleeding in pigs.

The public's appetite for such devices is still an open question. Ethical and legal concerns have, for example, been raised about ingestible sensors, including worries about data privacy and security[11]. The growth of wearable devices that provide activity and fitness tracking suggests that, on one level at least, there is an interest in continuous digital monitoring. And as ingestible and transient electronic devices continue to improve, and their capabilities expand, the role they could play in the development of personalized healthcare is likely to become increasingly compelling. ❐

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