Cell Press REVIEWS

Biohacking

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Biohacking is a do-it-yourself citizen science merging body modification with technology. The motivations of biohackers include cybernetic exploration, personal data acquisition, and advocating for privacy rights and open-source medicine. The emergence of a biohacking community has influenced discussions of cultural values, medical ethics, safety, and consent in transhumanist technology.

Epidermal electronics, biosensors, and artificial intelligence have converged as healthcare technologies to monitor patients in point-of-care settings within the Internet of Things (IoT) [1]. These technologies have created a community of hobbyist software developers involved in the quantified-self movement [2]. The self-experimentalist community is primarily interested in tracking their daily physical and biochemical activities to build a library of personal informatics in order to maintain a healthy lifestyle or improve body performance. The growing interest in this 'tech-savvy' community has motivated questioning the possibility of experimenting with implantable technologies. The emergence of implantables for biometric animal identification has encouraged self-experimentalists to chipify themselves in order to interact with computers in the IoT [3]. Inspired by transhumanism, which advocates the enhancement of human body and intelligence by technology, the overlap between self-experimentation and medical implant domains has created a vision to modify the human body and document their experiences in social media for open-source medicine [4].

The movement of biohacking has begun with a self-experimentation project (Cyborg 1.0, 1998) of Kevin Warwick who implanted a radio frequency identification (RFID) tag to his arm in order to control electronic devices. In another experiment, a multielectrode array was implanted in Warwick's arm to create a neural interface, which allowed controlling a robotic arm and establishing telepathy system with another human implantee via the Internet [5]. Self-experimentation with biomaterials has also been popularized with the performance art works of Stelarc, who had a scaffold implanted in his arm (Third Ear, 2007) [6]. The synergy of cybernetics, biopunk, and citizen science has led to the formation of a media-activist biohacking community. Figures in this transhumanist community include Amal Graafstra (tagger), Tim Cannon, Lepht Anonym, and Neil Harbisson. These technology activists, also known as grinders, implant chips in their bodies or have them implanted. Their primary motivations include human–electronic device communication and self-quantification, and cosmetic enhancement [7]. Another overarching goal of this community is to increase scientific literacy as citizen scientists. The biohacking community is actively engaged in the development of off-the-shelf protocols at low cost, open access research and collaboration by creating individual pursuit of inquiry [8]. Biohackers document and share their protocols, equipment designs, and experiences on the Internet (i–vii).

Implantable Technologies

Commercial or homemade implants are commonly inserted to the body via hypodermic needles or surgical incision. A common feature of these implants is that they are coated with a layer that reduces the immune reaction (bioproofing). These protective coatings include cylindrical medical-grade borosilicate glass capsules, Parylene C, polytetrafluoroethylene, titanium nitride, and silicone. Table 1 lists implants used by biohackers.

Neodymium Magnets

A wide range of species in nature (including homing pigeons and bats) are known to use magnetoreception for sensing orientation and navigation [9]. Inspired from magnetoreception, implantable neodymium magnets (N52 Gauss) have been developed for *in vivo* use (Figure 1A). These implantable magnets allow feeling electromagnetic forces by tactile sensation. They can be also used to activate magnetic reed switches and Hall effect sensors. Subdermal implants have been tested in seven humans and compared to a control group in which the implants were superficially attached to their skin. The implanted group required less force than the control group to perceive an electromagnetic stimulus (I.M. Harrison, PhD Thesis, University of Reading, 2014). In another case, the biohacker Rich Lee implanted magnets into the tragus of his ears to receive audio signal from a coil of an electromagnetic wire connected to a smartphone (Figure 1B).

RFID/NFC Chips

Implantable RFID tags are powered by an external energy source [10]. However, active RFID implants feature an embedded battery that can communicate within a body area network. They also have the ability to connect to IoT via Bluetooth in a continuous or on command mode at long distances. Former Verichip Corporation (now PositiveID) has offered an FDA-approved RFID chip for implantation in human body to reveal biometric information (Figure 1C) [11]. This passive implant consisted of a RFID circuit, a capacitor, and an antenna encapsulated in a medical-grade glass coated with antimigration film. This technology was designed to identify the medical history of unconscious patients in an emergency situation. Early biohackers mainly employed uncoated RFID capsules such as EM4102 (FAREAD) and HITAG 2048S (NXP) (Figure 1D). The Supplemental

Table 1. Implants Used by Biohackers, and Their Properties

Implant	Features	Geometry/size	Implantation method	Implantation site
Neodymium magnets	Coated with titanium nitride	Disc (3 × 1 mm)	Surgical incision	Fingers
MF1 IC S50 (NXP)	13.56 MHz (ISO14443A) Emulates MF1ICS50 1k chip 7 byte UID & writable sectors	Cylindrical glass capsule (3 × 13 mm)	Hypodermic needle (9 g)	Hand webbing
NTAG216 chip (NXP)	13.56 MHz (ISO14443A) and NFC Type 2 7 byte UID and 880 bytes of user read/write memory	Cylindrical glass capsule (2 × 12 mm)	Hypodermic needle (11 g)	Hand webbing
ATA5577 RFID chipset (Atmel)	125–134 kHz (ISO11784/785) EM41xx/EM4200/HID/Indala compatible	Cylindrical glass capsule (2 × 12 mm)	Hypodermic needle (11 g)	Hand webbing
I-CODE SLI RFID chipset (NXP)	13.56 MHz (ISO15693) 8 byte UID and 112 bytes of user read/write memory	Cylindrical glass capsule (2 × 12 mm)	Hypodermic needle (11 g)	Hand webbing
Bio-Thermo LifeChip RFID tag (Destron Fearing)	134.2 kHz (ISO11784/11785) Temperature sensor (25–43°C)	Cylindrical glass capsule (2 × 12 mm)	Hypodermic needle (11 g)	Skin near the arm pit
DESFire EV1 RFID chip (NXP)	13.56 MHz (ISO14443A and NFC Type 4)	Polymer coating (10 × 22 × 0.5 mm)	11 mm wide incision	Arm
NTAG216 RFID chip (NXP)	13.56 MHz (ISO14443A and NFC Type 2)	Polymer coating (8 × 22 × 0.4 mm)	9 mm wide incision	Arm
Tritium lighting implants (Cyberise.me)	Radioluminescent tritium gas	Cylindrical borosilicate glass and lead oxide capsule (3 × 5 × 21 mm)	Hypodermic needle (8–9 g)	Hand webbing
LEDs (Northstar, Grindhouse Wetware)	Chip containing a processor, LED, and embedded batteries	Polymer coating	Surgical incision	Hand/forearm

Information online describes the implantation experience showing the procedures used by biohackers to implant active and passive devices, and it discusses RFID communication technologies.

Light Sources

Optical materials and devices have been subcutaneously implanted for cosmetic purposes. One such implant utilizes the decay of tritium gas that emits β particles. This effect combined with phosphor emits photons and produces radioluminescence (Figure 1E). Layers of lead oxide glass and medical-grade glass have been used to coat the surface of a tritium capsule to minimize the emitted radiation. Additionally, Grindhouse Wetware biohackers have implanted an active optical device (Northstar V1) in their hands (Figure 1F). This optical device featured light-emitting diodes (LEDs), an embedded battery, and a magnetically activated switch. Next-generation implantable devices may offer a rechargeable battery, gesture recognition, and Bluetooth connection.

Implantable Sensors

Temperature sensors have been utilized to measure body temperature by biohackers. For example, originally designed for veterinary applications, Bio-Thermo (LifeChip, Destron Fearing) continually temperature data with a detection range of 25–43°C. This sensor has an antimigration coating (BioBond) and is implanted through a hypodermic needle to the arm near the armpit. A Grindhouse Wetware biohacker surgically implanted a battery-powered microchip (Circadia 1.0) in his forearm (Figure 1G). The implant transferred temperature data to a tablet computer via Bluetooth connection. Such implants can be designed to measure other physical and biochemical parameters such as pressure and biomarkers in real time.

Safety Implications

Medical devices need to be sterilized before implantation to the body to kill pathogens. Sterilization of implants can be achieved by autoclaving or

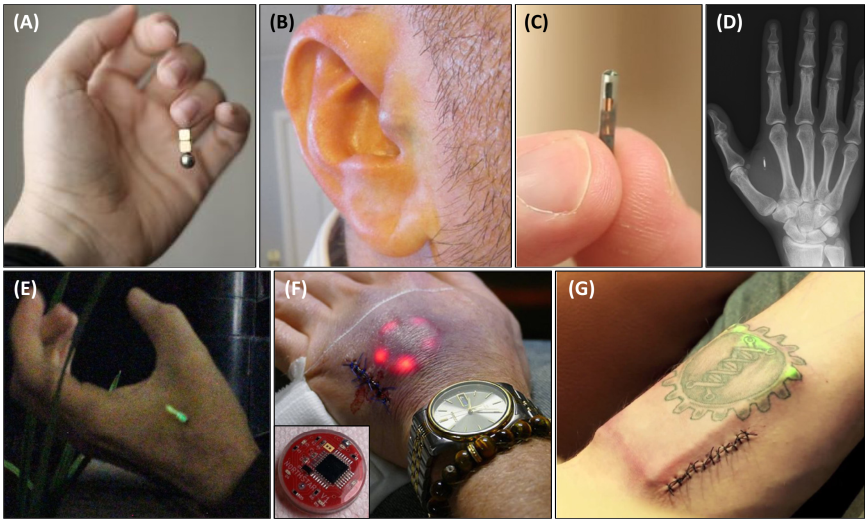

Figure 1. Implants Used by Biohackers. (A) A neodymium magnet in a finger. (B) Magnets in the tragus of an ear. (C) A RFID tag. (D) RFID tags implanted in the webbing between the metacarpal bones of the index finger and thumb, positioned parallel to the index metacarpal. (E) Tritium lighting implants. (F) LEDs in hand. (G) Continual temperature sensor in forearm.

submerging them in antiseptic solutions. Implants having an antiremoval coating (e. g., BioBond) attaches to the subcutaneous tissue to prevent device migration in the body. This antimigration cap consists of a porous polypropylene sheath, which promotes the growth of fibrocytes and collagen fibers around the device. Their removal is an invasive process and may result in complications. Nonbiocompatible implants or implant parts (e.g., neodymium cores) may be rejected or becoming encapsulated in highly dense fibrous tissue. Such implants also pose a risk if they are physically exchanged between biohackers, which may lead to the transmission of microorganisms. Although at this stage, passive tags are popular, active tags with batteries are being increasingly used in biohacking community and the potential structural compromise and hence leakage of material from these devices is a risk factor. Additionally, long-term behavior and biocompatibility of electronic and optical implants in human body is unclear. Rat model studies showed that implants may cause sarcomas based on foreign-body induced tumorigenesis; however, the risk was factor was limited to 1% [12].

Privacy Concerns

The increasing systematic use of personal data surveillance (überveillance) in the investigations or mass monitoring of citizens by law enforcement agencies is a significant concern among biohackers [13]. This may involve real-time geotagging of an individual's location and activities. The biohacking community actively discusses mass surveillance implications of implantable devices that may be used to control citizens. For example, in 2017, Ross Campton of Ohio was convicted of arson and insurance fraud after law enforcement used heart function data from his pacemaker as supporting evidence to prosecute him. European Group on Ethics in Science and New Technologies has published a guideline (2005) that described the ethical and legal challenges associated with electronic implants. Such implants may be used by state authorities to obtain personal information to justify security reasons within democratic principles. In the United States, laws in a few states (Wisconsin, North Dakota, and California) protect citizens from involuntary or incentivized chip implantation. For example, Wisconsin Act 482 prohibits caregivers to coerce a patient to involuntarily have a chip implanted for their safety. Furthermore, the American Medical Association drafted an ethics code (2007) for active RFID tag implants that highlighted the importance of protecting the implantees from stigmatization, social discrimination, or loss of health care or insurance coverage.

The Rise of Open Medicine

The implications of experimenting with implants and the development of new applications are immense to broader communities. Biohacking also raises questions about the limits of medical data privacy, and it opens up the possibility of cryptography use for medical data storage. The motivations of biohackers are aligned with the healthcare advocates who want patients to access their own implant-generated data, which are considered proprietary by device manufacturers [14]. Citizen scientists who are interested in experimenting with their own bodies should not be marginalized but supported by non-profit organizations, research institutions, biotechnology companies, and social services. Based on the positive outcomes of needle exchange scheme in HIV patients, the involvement of medical professional to provide consultations, access and disposal of medical safety equipment to biohackers will reduce the risks of infection and self-harm. The emergence of biohacking as a citizen science initiative has set a remarkable precedent for our understanding of what it means to be human in the context of open medicine.

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Disclaimer Statement

The author does not endorse or recommend any material, equipment, or procedures discussed in this article. Licensed medical professionals may perform the procedures described in this article. The author declares no competing financial interests.

Resources

[i]https://sapiensanonym.blogspot.co.uk/
[ii]https://www.youtube.com/watch?v=2Ex51kc3pOs
[iii]https://biohack.me
[iv]https://dangerousthings.com
[v]www.grindhousewetware.com
[vi]https://cyberise.me
[vii]https://futuregrind.org

Supplemental Information

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Forum

Designing Reactor Microbiomes for Chemical Production from Organic Waste

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Microorganisms are responsible for biochemical cycles and therefore play essential roles in the environment. By using omics approaches and network analysis to understand the interaction and cooperation within mixed microbial communities, it would be possible to engineer microbiomes in fermentation and digestion reactors to convert organic waste into valuable products.

Mixed Culture Fermentation

Most biotechnological processes use pure culture fermentations because process parameters can be optimized for specific strains of microorganisms. However, pure culture fermentation has some fundamental disadvantages – it requires sterile operating conditions and high-quality and high-purity raw materials. Mixed culture fermentation does not rely on specific microorganism strains and can be operated in nonsterile conditions without a significant risk of contamination. The mixed microbial consortia are able to perform more complex activity than the pure cultures. Therefore, they are able to utilize more complex substrates and consume a variety of organic chemical compounds.

One of the most common commercially applied processes that uses undefined mixed cultures is anaerobic digestion (AD) [1]. This process plays a crucial role in waste management systems and produces renewable energy in the form of methane. AD entirely depends on the complex syntrophic activity of microorganisms belonging to several functional groups. In general, this process can be divided into hydrolysis, acidogenesis, acetogenesis, and methanogenesis, where most organic matter (carbohydrates, lipids, and proteins), except for lignin components, is degraded into methane and carbon dioxide in the absence of oxygen. The main drawback of the AD process is a low market price for methane and therefore difficulties in economic feasibility of the biogas plants, especially where there are no subsidies or supporting governmental policies [2]. Diversification of products may help to overcome this shortcoming. Volatile fatty acids such as acetic, propionic, butyric, and valeric acids, which are key intermediate products in AD, can be also considered as intermediates for currently emerging bioprocesses such as polyhydroksyalkanoates or medium chain fatty acids generation, among others [2]. However, the full potential of mixed microbial community is still not truly understood, and understanding the behavior of mixed microbial communities might open new possibilities for commercial applications, for instance, towards converting organic waste into commodity chemicals such as medium chain fatty acids. The biggest challenge to a commercialization of mixed microbial processes will be low product concentration and therefore difficult downstream processing and product recovery.

Reactor Microbiome

A reactor microbiome can be defined as a group of microorganisms living in a certain setting adapted to the artificial (bioreactor) environment. Through natural selection,