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Implantable Bioelectronics – Editorial Introduction

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The integration of electronic elements with biological systems, resulting in novel devices with unusual functionalities, attracts significant research efforts owing to fundamental scientific interest and the possible practical applications of such devices. The commonly used buzzword ''bioelectronics'' highlights the functional integration of two different areas of science and engineering – biology and electronics, to yield a novel subarea of biotechnology [1, 2]. Bioelectronics is a rapidly developing, multidisciplinary research direction, combining novel achievements from electronics miniaturization allowing devices to operate with ultralow power consumption [3], the development of flexible devices for interfacing with biological tissue via advances within materials science [4], bio-inspired unconventional computing for mimicking biological information processing [5], and many other highly innovative science and technology areas. One of the most advanced applications benefiting from the development of bioelectronics is the rapidly progressing area of biosensors technology [6]. The use of novel nanostructured materials integrated with biomolecular systems [7–9] tremendously contributes to the rapid progress of bioelectronics, especially in regard to biosensor applications [10]. The novel electronic systems based on flexible supports [11] for direct interfacing with biological tissues are very promising for use in implantable bioelectronic devices [12] (Figure 1.1).

The most challenging developments in bioelectronics are related to biomedical applications, particularly advancing the direct coupling of electronic devices/machines with living organisms, where electronics operates in a biological environment implanted within a living body. This technology is already highly advanced, at least in some medical applications such as implantable cardiostimulators [13, 14] and various other implantable prosthetic devices [15, 16]. The most important issue in the biotechnological engineering of implantable devices is the interface between living tissues and artificial man-made implantable devices. Cardiac defibrillators/pacemakers, deep brain neurostimulators, spinal cord stimulators, gastric stimulators, foot drop implants, cochlear implants, insulin pumps, retinal implants, implantable neural electrodes, muscle implants, and other implantable devices must perform their functions by directly interacting with the respective organs to improve their natural operation

Implantable Bioelectronics, First Edition. Edited by Evgeny Katz.

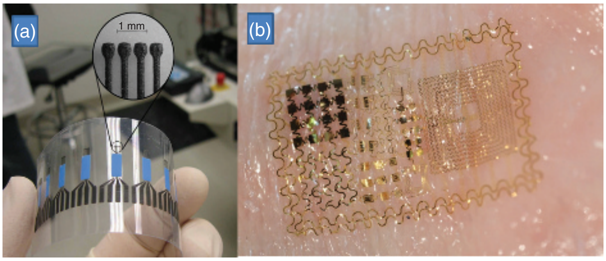

Figure 1.1 (a) Flexible bioelectronic devices allow interfacing with a biological tissue. (b) A new type of biosensor uses flat, flexible electronics ("tattoo"-bioelectronics) printed on a thin rubbery sheet, which can stick to human skin for at least 24 h. (Photos "a" and "b" were kindly provided by Prof. Joseph Wang, University California San Diego, USA, and Prof. John A. Rogers, University of Illinois at Urbana-Champaign, USA, respectively.)

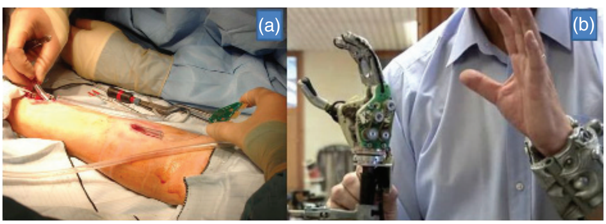

Figure 1.2 Prof. Warwick had his nervous system wired to a robotic hand allowing its remote control. (a) A 100-electrode array surgically implanted into the median nerve fibers of the left arm allowed electrical reading of nerve signals. (b) The robotic hand was remotely controlled by signals from the researcher's nervous system. (Photos "a" and "b" were kindly provided by Prof. Kevin Warwick, University of Reading, UK.)

or substitute the missing function. Implantable medical devices can also restore function by integrating with nondamaged tissue within an organ. The artificially generated electrical and sometimes electromechanical activity in each of these cases must be engineered within the context of the physiological system and its biological characteristics. For example, in one of the recent research projects [17], a nervous system was wired to a robotic hand, allowing its remote control (Figure 1.2). Neural signals were transmitted to various technological devices to directly control them, in some cases via the Internet, and feedback to the brain was obtained from, for example, the fingertips of the robot hand [17].

Highly integrated systems also make possible the development of implantable devices that can sense their biological environment in real time and properly respond to the changing conditions. Integrated "*Sense-and-Act*" systems for intelligent drug delivery have emerged, contributing to the novel concept of personalized medicine and appear particularly important for advancing point-of-care and end-user applications [18]. Although very sophisticated digital electronics can provide perfect internal operation of the implantable devices, their interfacing with the biological environment requires further advancement. New materials and novel

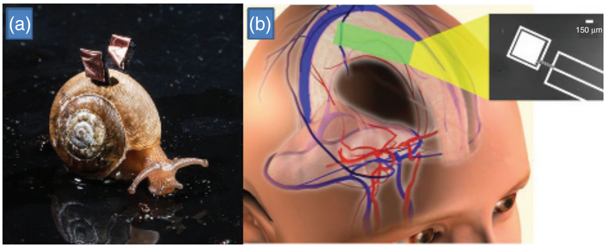

Figure 1.3 Implantation of biofuel cells in a living tissue can provide electrical power harvested from metabolic species for activating implantable bioelectronic devices. (a) A biofuel cell implanted in a free moving snail. (b) Conceptual schematic design for an implanted biofuel cell harvesting power from the cerebrospinal fluid, showing a plausible site of implantation within the subarachnoid space. The inset is a micrograph of one prototype, showing the metal layers of the anode (central electrode) and cathode contact (outer ring) patterned on a silicon wafer. (Photo "a" originates from Prof. E. Katz laboratory, Clarkson University, NY, USA. Part "b" is adapted from Ref. [23] with permission.)

concepts are needed for improved interfacing of the biological and electronic systems. Improving biocompatibility, via surface chemistry, is critical for enabling future implantable bioelectronic devices. Information processing by the integrated biological/electronic system requires novel computational approaches because natural information processing is conceptually different from the digital operation used in modern electronics. New methods for harvesting and managing energy to power implantable devices are required [19, 20]. They can be based on bio-inspired approaches using, for example, implantable biofuel cells harvesting energy from the internal physiological resources [21–23] (Figure 1.3). Revolutions in miniaturized electronic devices, cognitive science, bioelectronics, bio-inspired unconventional computing, nanotechnology, and applied neural control technologies are resulting in breakthroughs in the integration of humans and machines. The interactions of electronic computing elements, wireless information processing systems, advances in prosthetic devices, and artificial implants facilitate the merging of humans with machines. These exciting advancements lay the foundation for the development of bionic animal/human–machine hybrids [24] (Figures 1.4 and 1.5). Apart from biomedical applications, one can foresee bioelectronic self-powered "cyborgs" capable of autonomous operation using power from biological sources, utilized in environmental monitoring, homeland security, and military applications.

The present book summarizes the diverse subareas of implantable bioelectronics including the modification of biological cells, interfacing tissues, and particularly nervous systems with electronics, harvesting energy from biological sources using implantable biofuel cells and creating "cyborgs" where the function of biological organisms is highly integrated with electronic systems and machines. The variety of systems described in the book and their possible applications are really impressive! While some systems and their applications represent the present level of technology, others are at the interface with future advancements. Possible revolutionary changes in a human's life can be expected on the basis of the rapid progress in the

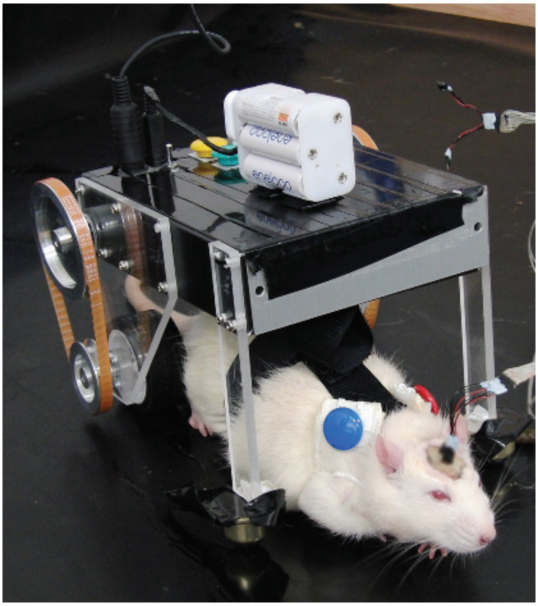

Figure 1.4 Brain–machine interface allowing control of moving robotic vehicles. Rat–robot hybrid involves implanted neural electrodes that allow the rat's brain signals to control a motorized vehicle. (Photo was kindly provided by Prof. Kunihiko Mabuchi and Dr. Osamu Fukayama, The University of Tokyo, Japan.)

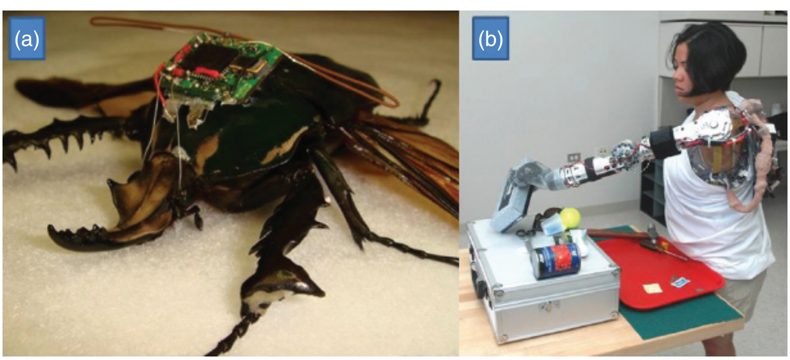

Figure 1.5 "Cyborgs" with electronically integrated biomachine parts: (a) A giant flower beetle wears an electronic backpack that allows researchers to wirelessly control its flight. (b) A robotic hand controlled by brain signals can substitute for the missing hand of a disabled person. (Photos "a" and "b" were kindly provided by Prof. Michel M. Maharbiz, University of California, Berkeley, USA, and by the Rehabilitation Institute of Chicago, USA, respectively.)

technology integrating the human body with machines. This requires not only novel technological solutions but also careful ethical considerations. This book aims at summarizing the achievements in this rapidly developing multifaceted research area providing background for further progress and helping in understanding of various aspects in this complex scientific field.

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