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7.8. NEURAL IMPLANTS AND BRAIN–MACHINE INTERFACES

Another exciting application of bionanotechnology is the use of nanomaterials to improve biomedical devices such as neural implants and brain–machine interfaces. The brain remains the most physically untouched part of the human body, and a complete understanding of how it functions is still lacking. The brain controls the nervous system, which is the most complex system in the human body. The nervous system is composed of nerves and neurons which communicate signals between different parts of the body. Each neuron forms part of a neural network and produces an electric signal when triggered by internal or external stimuli. When there are abnormalities in communications between neurons, the human body can fall to severe illnesses such as movement disorders and changes of consciousness. To cure or control such illnesses, it is important to obtain and understand the electrical signals generated by neural activity in the targeted neurons and nerves. Such information can be obtained from neural implants. A neural implant is a surgically-implanted device containing micro- or nano-electrodes that can both record nerve signals in real time as well as stimulate nerves. Neural implants can provide either continuous nerve stimulation or only necessary nerve stimulation to restore lost body functions such as hearing or limb movement.

By interfacing neural implants with a computer, we can create a brain–machine interface (BMI). BMIs allow the human brain and by extension the nervous system to communicate with a computer. BMIs can interact with neural signals via microelectrodes so that we can obtain information about how the brain works. These neural signals occur when an action potential is triggered due to any stimulus from the internal or external environment. Each neuron forms part of a neural network and produces an electric signal when triggered (such as an action performed by a human). The signal can be measured by microelectrode threads placed extremely close to the neurons. Variations in the strength of neuronal electric signals are reflected in spikes, and the timing of these spikes provides useful quantitative information that needs to be analyzed. Once analyzed, the reverse can be achieved by synthesizing the signal and sending them back to specific parts of the brain.[71]

Cochlear implants are a well-known example of a BMI. To offset hearing loss, the implanted device produces electrical currents to relay audio signals past the inner ear to stimulate the cochlear nerve. Important issues to be considered are the biocompatibility of materials, and how the implant affects nearby tissue. High-intensity stimuli can cause permanent damage to the auditory nerve. Another example is the U.S. FDA–approved Utah array, which can record and stimulate a group of neurons. The Utah array is used to control a prosthesis. The problem is that the array can neither be inserted for too long nor be constantly reinserted because tissue scarring and neural damage can occur.[72]

Safety and long-term integration with the human brain are the main concerns when designing these micro-/nano-electrodes. Unfortunately, the typical instability of interfacing the brain with electrodes can render the electrodes useless due to cellular and vascular damage, inflammation, tissue response, neuronal degradation, and scar formation. If the electrodes are too large, they may cause glial scarring in the brain. However, if the electrodes are too small, they can easily break and be rendered useless. Figure 7-34 shows the effect of microelectrodes on the safety and long-term integration with brain or neural tissue. When a hard and noncompliant electrode is inserted into healthy tissue, inflammation is visible since many astrocytes and microglia are seen around the microelectrode (Figure 7-34b).[73]

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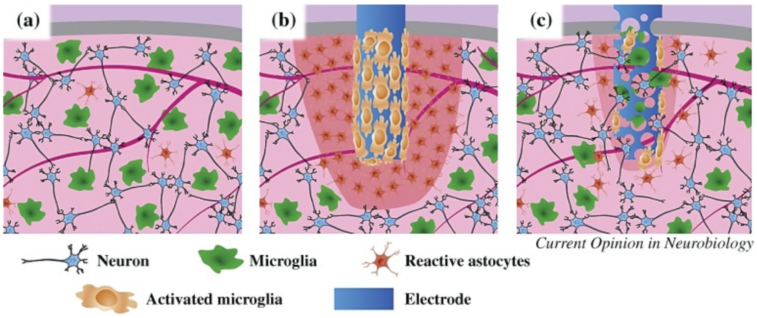
Figure 7-34 The effect of microelectrodes on the safety and long-term integration with brain or neural tissue. (a) healthy tissue; (b) inflamed tissue resulting from a noncompliant microelectrode; (c) non-inflamed tissue integrated with a porous and soft microelectrode. (The illustrations are reprinted with permission from D. Scaini and L. Ballerini.[73])



To reduce the negative long-term impact of electrodes on neural tissue, nanomaterials including carbon nanotubes and various nanowires integrated with hydrogels are applied. Since the initial insertion of microelectrodes must be delicate and precise as local cells can be damaged during the insertion, soft conductive materials or ultra-thin and flexible electrodes can be used.[73] Figure 7-34c shows that porous and soft microelectrodes can achieve high biological integration with minimal inflammation.

Other important examples of BMIs are computer or microprocessor-controlled neural implants used for deep brain stimulation (DBS), vagus nerve stimulation, and mind-controlled prosthesis. DBS was first used in the 1990s. To implement DBS, a small and portable neurostimulator device is used with electrodes inserted into specific brain areas to deliver electrical pulses for suppressing abnormal nerve signals which cause symptoms. For instance, DBS can be effectively used to reduce uncontrollable movements with a neurostimulator device connected to electrodes inserted in the basal ganglia network of the brain (which controls motor behavior). Through insulated wires, the DBS electrodes are connected to a small battery-powered pulse generator controlled by a built-in microprocessor. The insulated wires and pulse generator are implanted under the skin near the collarbone or at other places in the body. DBS treatments have been used for patients with movement disorders such as Parkinson's disease, dystonia, essential tremor, and Tourette syndrome. The efficacy of DBS treatments depends on the appropriate target region of the brain as well as the stimulation settings which include intensity, pulse width, and frequency. The local field potentials (i.e., transient electrical signals) recorded by the electrodes are used to analyze the nervous system response to the stimulation, which can be used to determine optimal settings for individual patients. Even when DBS treatments are successful, the efficacy can be limited. A deeper understanding of the DBS mechanism of action in the brain is required to improve this therapy and avoid the side effects associated with DBS.[74]

Increasing the number of electrodes is being considered to improve DBS treatment. As electrodes are used to record the activity of neurons, the application of more electrodes will enable the collection of more signals from a greater number of neurons. Recently, Neuralink—a company focusing on BMIs—developed a device which has 3072 microelectrodes. These electrodes are distributed on 96 polymer threads, with each thread having 32 electrodes. The device is small, with 3072 channels (electrodes) in a space of 23 mm × 18.5 mm × 2 mm. The polymer threads are ultra-fine and flexible, offering greater biocompatibility compared to those made from metals or semiconductors. Since the microelectrodes are not stiff enough to penetrate the skull, a neurosurgical robot is used to implant the threads at a speed of 6 threads (i.e., 192 microelectrodes) per minute. The data collected is processed by an integrated circuit. At present, this device is mainly used as a research platform. Rodent studies using the device may pave the way for future applications in humans.[75]

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In addition to DBS, BMIs can also be used for vagus nerve stimulation (VNS). The vagus nerve is located in the neck and regulates the functions of many internal organs as well as reflexes. VNS is a treatment for non-motor diseases such as epilepsy, pain, and neuropsychiatric disorders. It was first used for epilepsy treatment in 1988. In addition to vagus nerve electrodes inserted into the neck, the implantable VNS device includes a microprocessor-controlled pulse generator, lead wires, and a handheld magnetic controller accessory. Although the pulse generator is programmed by software, it also can be manually controlled by the user through the magnetic controller accessory. The magnetic accessory allows the user to increase or stop the vagus nerve stimulation. Increasing the stimulation level with the magnet right before the onset of seizures can shorten or stop the seizures. Unlike DBS neurostimulator devices, the battery-operated pulse generator of a VNS device is usually implanted in the upper chest or in the armpit. The vagus nerve is connected to the VNS pulse generator through lead wires. For the VNS device, the lead wires are positioned at the cervical portion of the trunk of the left vagus nerve above the clavicle. Due to its highly invasive nature and potentially serious side effects, VNS is usually used to treat drug-resistant epilepsy and treatment-resistant neuropsychiatric disorders.[76]

Finally, a mind-controlled prosthesis (e.g., an artificial limb, hand, or foot) can be used to restore extremity functions. In the 1900s, body-powered prostheses able to perform intended movements were developed. By the 1960s, myoelectric prostheses came into use. These prostheses could translate residual muscle electrical activity into movements. In myoelectric prostheses, surface electromyography electrodes are placed above residual muscles of the residual limb to record the muscle's electrical activity, which is used by the patient to control the prostheses. The accuracy of prostheses control can be improved using multichannel surface electromyography electrodes or implanted electromyography electrodes.[77]

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