The current range of neuromodulatory devices and related technologies

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Summary

The pace of technology dictates changes in every aspect of human life. Medical profession is not an exception. The development of sophisticated electronic devices has radically influenced diagnosis and therapy. Today neurosurgical science is revolutionized with numerous implanted and non-implanted devices that modulate and stimulate the nervous system. Physicians, patients and non-technical experts involved in this field need to understand the core mechanisms and the main differences of this technology so that they can use it effectively. It will take years until clinicians reach a "consensus" about the use of these devices, but in the course of action objective information about the current status of the methods and equipment, and the technical, biological, and financial complications that arise in practice will speed up their public approval and acceptance.

Keywords: Neuromodulation; neurotechnology; neurostimulation; neurodevices; neuroprostheses; brain-computer interface (BCI); assistive technology (AT); functional electrical stimulation (FES).

From neurotechnology to neuromodulation

According to the International Neuromodulation Society, "Neuromodulation is defined as the therapeutic alteration of activity in the central, peripheral or autonomic nervous systems, electrically or pharmacologically, by means of implanted devices" [13]. In this usage, neuromodulation is another form of technology where the knowledge about the nervous system is used to create specially designed implantable devices to serve a therapeutic or rehabilitation purpose. On the other hand our current efforts combine technical methods, skills, processes, equipment, and information from biology (biochips, genetic engineering, and cellular implantation), neuroscience, mechanics, electronics, computing, and pharmacology in order to surpass the field of neuromodulation. This interdisciplinary nature of the fields combined is reflected in the term "neurotechnology", a multi-billion dollars industry that includes three sectors [17]:

1. Neurodiagnostics (neuroimaging, in vitro diagnostics, neuroinformatics).
2. Neuropharmaaceutical (cogniceutical, emoticeutical, sensocentical).

More specifically, recent advances in the fields of neuroscience, robotics, and electronics have caused a resurgence to develop neurodevices for interaction with the impaired neuro-muscular and sensory system in order to restore or decrease the impact of a disease or injury on the individual. For example, in an attempt to bypass pathological motor or sensory nerve circuits, implantable or non-implantable devices have been invented to restore vision, hearing, motor, and sensory function.

In this review, we classify and summarize the current state of neuromodulation related technologies i.e. neurostimulation and neuroprosthetics. The third category, neurosurgical devices for navigation, radiosurgery, and endovascular intervention is beyond the scope of our review. Apart from the classification criteria in the next sections we define terms related to the technology used for the development of neurodevices and we present a short description for each type of device, an abridgment of the surgical operation required and an application example. In addition, we give a short description of the similarities of Assistive Technology (e.g. wheel chairs, artificial limbs, augmentative-alternative communication) with the neurodevices and we conclude our review with frequently met issues i.e. complications and risks, financial implications, and future prospects.
Classifications of neurodevices

Rehabilitation is an application field for implantable neural devices. Diseases and traumatic incidents may lead to damage or lesions in the central or peripheral nervous system. When the information flow between any of the following: brain, spinal cord, nerves, biological sensors and actuators, or muscles, is interrupted, sensoric inputs are lacking and vision or hearing is lost. If motor commands from the brain do not reach the muscles, paralysis occurs. The objective of neural rehabilitation is the restoration of lost functions using therapeutic programmes and technical aids. Because of the tremendous complexity of the human nervous system, technical aids only lead to restricted restoration in function. However, what may seem to be a small improvement to a healthy person may be a great improvement in quality of life for a disabled person.

Neurodevices can be classified according to the following criteria:

- stimulation (i.e. pharmacological vs. electrical);
- application (i.e. neuroprosthesis vs. neuro-orthosis);
- purpose (i.e. therapeutic vs. assistive vs. rehabilitation);
- site (i.e. implantable vs. external);
- invasiveness (i.e. invasive vs. non-invasive);
- communication channel (i.e. unidirectional vs. bidirectional);
- effect on the nervous system (i.e. central nervous system damage vs. denervation).

Pharmacological vs. electrical

This distinction fits with the definition of neuromodulation and leads to two of the main categories for neurodevices namely “stimulators” and “pumps”. In particular, stimulators are devices that use electricity to stimulate the brain, the cord, and the peripheral nerves, whereas pumps refer to implantable devices that inject a pharmacological substance into the nervous system (e.g. baclofen for spasticity or morphine for pain).

Neuroprosthesis vs. neuro-orthosis

In terms of the application of neurotechnology, devices can be categorized to those that couple an artificial system with the physiological system in order to replace or supplement a neuromuscular or sensory function (vision, hearing, tactile), i.e. “neuroprosthesis”, and are contrasted to those that influence/modulate the neural controller to achieve an ample relief of symptoms of a disease and/or to train the physiological system until the function is performed adequately without any support, i.e. “neuro-orthosis”. Characteristic type for this kind of devices is the neurostimulation devices.

Therapeutic vs. assistive vs. rehabilitation

Perhaps the most important criterion for distinguishing neurodevices is the purpose of their development, i.e. neurostimulation may be used for muscle contraction to assist in breathing, grasping, reaching, bladder and bowel function. On the other hand TENS (transcutaneous electrical nerve stimulation), does not involve moving muscles, but prevents secondary complications and is aiming at a relief of symptoms (i.e. spasticity, tremor, atrophy).

Yet other devices are applied for rehabilitation, usually after the therapy, and their objective is full restoration or improvement of recovery with some form of training. A third type of device may be complementary to the other two or self-contained and is targeted to supplement, replace or even enhance a function. This type is commonly referred in the literature as an assistive technology device. Therapeutic and assistive technology devices may permanently accompany the patient for the rest of his life.

Implantable vs. external

There are two types of implantable devices: one that is completely internal and one with both internal and external components. In the first, the power source (battery) and lead(s) are surgically implanted, whereas in the second a receiver is implanted and detects radio-frequency signals through the skin from an external power source [17]. On the other hand external devices may be “worn”, e.g. electrodes are attached on the skin and have either a wired or wireless connection to the device [24].

Invasive vs. non-invasive

Devices that require surgery can be implanted at some point in the body and are considered invasive (e.g. deep brain stimulation, DBS) in contrast to those that may operate externally with surface electrodes attached on the surface of the body (e.g. peripheral nerve stimulation, PNS).

Unidirectional vs. bidirectional communication

The human nervous system is a two-way communication system. It has two main types of signals, those that