Prosthetics, Sensory Systems

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Introduction

This article concerns sensory prostheses, in which information is collected by electronic sensors and delivered directly to the nervous system by electrical stimulation of pathways in or leading to the parts of the brain that normally process a given sensory modality. In principle, all of the senses could be replaced or even augmented by such technology. In practice, only some sensory modalities seem amenable to currently available approaches; the status for each sense is summarized below:

- Hearing—widespread clinical success with the use of cochlear implants over the past decade.
- Vision—long-standing goal, with a recent resurgence in preclinical research plus some pilot human experiments.
- Touch—some clinical research on peripheral restoration in conjunction with functional electrical stimulation (FES; see PROSTHETICS, MOTOR CONTROL).
- Proprioception—little research under way, despite eventual importance to FES.
- Balance—some theoretical potential and early-stage analysis of feasibility.
- Smell—some theoretical interest because of the clinical significance of anosmia in the elderly, but hampered by the complexity of the natural senses and the unavailability of prosthetic sensors.
- Taste—no research under way; little clinical interest.

The general problem in constructing and implementing sensory prostheses is to understand and emulate the relevant parts of the neural code used by normal sense organs to encode and transmit sensory information to the brain. In practice, this means identifying a surgically accessible site through which to apply a complex temporospatial pattern of electrical stimulation. The general biophysical and electronic considerations can be found in PROSTHETICS, NEURAL. This article describes current research on auditory and visual prostheses.

Cochlear Prostheses

Current Technology

Cochlear prostheses use direct electrical stimulation of auditory nerve cells to bypass absent or defective hair cells that normally transduce acoustic vibrations into neural activity. They are the most sophisticated and the most successful neural prostheses to date, and they are still evolving. The currently available devices generally use multicontact electrodes inserted into the scala tympani of the cochlea so that they can differentially activate auditory neurons that normally encode different pitches of sound (for a historical review, see Loeb, 1990). A much smaller number of patients with bilateral degeneration of the auditory nerve have been treated with modest success by stimulation of the cochlear nucleus in the brainstem. In all currently available systems, an external, wearable control unit (Figure 1) determines a pattern of electrical stimulation in which the stimulus amplitude in each channel depends on the spectral content in the acoustic input and a previously stored map of auditory sensations that can be elicited by electrical stimulation of each channel in that patient. Many algorithms have been developed over the years, employing both analog and pulsatile electrical waveforms delivered sequentially and/or simultaneously to fixed or dynamically changing channels.

Clinical results with cochlear implants have improved steadily, to the point that they are the treatment of choice for most cases of severe to profound sensorineural hearing loss in both adults and children. Most patients with adult-onset deafness are devastated by

the loss of social interactions and find it difficult to develop alternatives such as lip-reading and sign language. Cochlear implants provide essentially immediate restoration of awareness of sound in all patients and functional levels of speech recognition in the majority, suggesting that the goal of replicating the salient natural encoding of sound has been achieved in most but not all patients (see below).

For prelinguistically deafened children, the trend is to implant a cochlear prosthesis at an early age, generally under 6 and increasingly under 2 years old. Young children appear to benefit from the increased plasticity of the young nervous system and the ability to participate in conventional verbal educational programs (Svirsky et al., 2000). In general, they acquire language skills at the same rate as normal children, but they remain delayed by the preimplantation period. Individuals who have received no acoustic stimulation in the first few years of life appear to lose much of their ability to learn to process such information by adolescence (Busby et al., 1991), consistent with the notion of "critical periods" in the training of biological neural networks.

Current Research

Improved temporospatial representations of speech sounds. The replacement of 10,000 independent hair cell transducers with 8 to 20 sources of stimulation current necessarily results in distortions of both the temporal and spatial patterns of neural activity received by the brain. The spatial problem is further aggravated by the tendency of stimulus currents to spread radially from their source in the volume-conductive tissues of the cochlea, resulting in "cross-talk," whereby a stimulus targeted to one spatial subgroup of spiral ganglion cells exerts modulatory effects on distant subgroups that are the target of another stimulation channel. The extent of this problem has been appreciated relatively recently through both clinical studies (Lawson et al., 1996) and computer modeling (Frijns, Briaire, and Grote, 2001). It is particularly severe for apical (low-frequency) sites. This has led to renewed development and testing of novel cochlear electrode arrays intended to position the contacts closer to the target spiral ganglion cells and reduce spread of stimulation currents.

The temporal distortions are more complex and their significance and amelioration less obvious. As the strength of an electrical stimulus is increased to represent increasing loudness, it recruits more and more auditory neurons, as would occur with an acoustic stimulus, but the electrically evoked activity tends to be much more highly synchronized. This results in a form of "beating" or "aliasing" among the repetition rates of the stimulation pulses (typically 400–800 pps), the modulation bandwidths of the acoustic information (typically 100–400 Hz), and the relative refractory periods of auditory neurons (probably 1–3 ms, corresponding to 300–1,000 Hz). The effect is most severe for low-frequency (apical) percepts, which are normally decoded from both temporal and spatial cues in the neural activity. It appears to be possible and useful to break up such beating by employing stimulation pulse rates that are far higher than those that can be followed by individual neurons (e.g., 1,500 up to 5,000 pps). This reduces beating and aliasing and results in a more randomized temporospatial representation, which many patients find to be subjectively less annoying and functionally more useful (Wilson et al., in press).

Combined electrical and acoustic stimulation in patients with residual hearing. There are many more patients with severe than with profound hearing loss, and most of these tend to have preferential preservation of low-frequency (apical) acoustic perception. This is the band in which cochlear implants tend to produce the greatest spatial and temporal distortions (see above). Clinical testing in a limited number of such subjects suggests that it is usually possible to preserve acoustic hearing apical to an electrode array that has been inserted shallowly into the scala tympani. The simultaneous presentation of amplified low-frequency acoustic information together with a multichannel electrical representation of the higher frequencies produces substantial improvements in performance, particularly for complex tasks such as perception of speech in highly noisy environments (Wilson et al., in press).

Bilateral cochlear implants. Individuals with normal hearing use binaural cues to distinguish desirable signals from noise sources that are located at different positions. Differences in relative loudness and arrival time at the two ears are decoded in the auditory brainstem so that the cognitive centers of the cortex can focus on spectral information from a single source. At least some of the few patients who have received cochlear implants in both ears have experienced substantial improvements in speech perception in noisy environments (Wilson et al., in press). This has motivated additional research on methods to synchronize the stimulation of the corresponding channels in the two ears, which might lead to performance that would warrant the additional expense and invasiveness of two cochlear implants.

Psychophysical correlates of performance variability. The development and testing of cochlear implants has been plagued by large variability of results among patients with no distinguishing characteristics. This complicates the design and interpretation of studies comparing the performance of different devices and speech-processing strategies. It also makes it difficult to justify implantation in the many patients whose residual hearing provides function comparable to that obtained by the poorest implant recipients. Enhanced psychophysical tests enabled by more flexible stimulation systems have started to identify neurophysiological correlates of cochlear implant performance (Wilson et al., in press). This bodes well for the development of speech-processing strategies to overcome these individual limitations and to fit them to the appropriate patients.

Fully implanted systems. Cochlear implants have been following a development track similar to that of hearing aids, their technological predecessors. Both started with relatively large and power-hungry circuitry that had to be worn on the body, including large, heavy, rechargeable batteries. Both used improvements in low-power integrated circuitry and battery technologies to miniaturize the sound-processing systems so they could be worn behind the ear (or even in the ear canal, in the case of hearing aids). Because one component of a cochlear prosthetic system must be surgically implanted, an obvious goal is to eliminate the external components entirely. This poses three major challenges that seem likely to be overcome within the next 2–3 years:

- The power consumed by the stimulation pulses themselves is substantial in a high-speed, multichannel implant, necessitating the development of high-performance batteries that can be recharged rapidly and frequently by inductive coupling of RF energy applied outside the body. More efficient electrodes closer to the spiral ganglion cells should also help.
- The microphone in present cochlear implant systems is usually located with the external headpiece that transmits power and data to the implanted electrodes. Novel technologies are in development for an implanted microphone that will function electrically and acoustically in a surgically suitable site.
- The dynamic range of electrical stimulation (from perceptual threshold to uncomfortably loud) is very narrow compared with that of acoustic hearing (6–20 dB versus 100 dB). Speech processors employ sophisticated digital algorithms for dynamic gain control and stimulus intensity mapping, but many patients find it necessary to make frequent adjustments to the manual loudness control on their externally worn speech processors. An alternative strategy is to have the implant monitor the electromyographic activity associated with the stapedius reflex and use it to make automatic adjustments of stimulation intensity. This is a protective reflex that comes on when the brain perceives the sound to be uncomfortably loud; it is intact in most cochlear implant recipients.

Visual Prostheses

As in the early days of auditory prostheses, there is not yet any general agreement on the most promising site to apply electrical stimulation to the visual pathways. Sites that have been considered

include subretinal (microelectronic array of photodiodes between the retina and the sclera), epiretinal (thin film electrode array on the vitreous surface of the retina), optic nerve (nerve cuff electrode), optic radiations (probes with multiple contacts inserted stereotactically), surface of striate cortex (arrays of contacts on the pial surface), and striate intracortical (see below). The obvious difference between auditory and visual prostheses is that auditory information requires a small number of channels with high data rates and the visual system requires a large number of channels with low data rates. This would seem to favor the two sites described below, which offer large, fairly flat surfaces on which to deploy retinotopically mapped electrode arrays.

Cortical Approach

Attempts to provide useful visual sensations in the blind by direct electrical stimulation of visual cerebral cortex began in 1966 (Brindley and Lewin, 1968). The initial devices used arrays of small electrodes (about 1 mm diameter) on the pial surface. Relatively high stimulus currents (about 1 mA for a 200 μs pulse) were required to produce sensations of light called phosphenes. Because of current spread by volume conduction, such stimulation presented to a single electrode presumably recruits neurons scattered over many adjacent cortical columns, but the surround inhibitory mechanisms actually result in a surprisingly small, well-formed dot of light. This seems to suggest that a complete, if coarse-grained, picture could be built up from a sufficient number of such phosphenes. The problem is that the processes responsible for the focusing operate quite slowly, so that stimulus trains presented concurrently but interleaved between even two such sites produce unpredictable, nonlinear interactions (Girvin, 1988). A useful image will require hundreds, if not thousands, of independently controllable phosphenes.

More recently, intracortical microelectrodes have been employed successfully to create similar phosphenes with stimulus currents (5–20 μA) that would tend to recruit only a few neurons within the immediately vicinity of the electrode tip (Bak et al., 1990). When two sites spaced less than a millimeter apart are stimulated concurrently, their phosphenes seem to combine and fuse in a predictable and desirable manner. Silicon fabrication (Wise and Najafi, 1991; Normann et al., 1996) may make it feasible to build dense arrays of contacts and associated electronic circuitry that are safe to implant and operate continuously for long periods of time.

Retinal Approach

Recent improvements in low-power integrated circuitry and intraocular surgical techniques have sparked interest in the possibility of placing an array of microelectrodes on the inner retinal surface. This approach requires viable retinal ganglion cells, so it is limited to blindness caused by photoreceptor degeneration, such as retinitis pigmentosa and macular degeneration.

Human research to date has employed intraoperative probes and small electrode arrays to determine suitable stimulation parameters and the percepts that they evoke. Data are inconclusive because of the severe limitations on intraoperative experiments and because of uncertainties about the positioning of the electrodes and the condition of the retinal circuitry. The following is a tentative interpretation of the biophysics of retinal stimulation and their implications for the design of a functional visual prosthesis.

In the intact retina, photoreceptors maintain a polarization level that maximizes sensitivity to incident photons, which results in changes in the release of transmitter and in the background spontaneous activity of bipolar and ganglion cells. Even tiny transretinal currents in the μA range can change the bias levels of these photoreceptors, resulting in perceptions of light and dark phosphenes. In the absence of photoreceptors, electrical stimulation pulses must produce sufficiently intense voltage gradients to depolarize neurons from the resting potential to the threshold for the propagation of action potentials. Retinal neurons are relatively small and unmyelinated, so they would be expected to have high thresholds and long membrane time constants. The output axons of retinal ganglion cells are the largest structures and lie on the vitreous surface

of the retina, immediately under the stimulating electrodes, so they would be expected to have the lowest thresholds. However, the axons at a given location originate from a wedge-shaped sector of the retina, so their activation would be expected to produce elongated and overlapping phosphenes. Bipolar cells are more localized and tend to be preserved in most retinopathies, but their electrical thresholds are somewhat higher. Because bipolar cells have longer membrane time constants than ganglion cells (1–2 ms versus 0.5 ms), they can be activated selectively by long-duration pulses (Greenberg et al., 1999). However, such stimulation applied to a large array may result in cross-talk between channels and unacceptable levels of power dissipation.

Information Processing

The introduction of information directly into the CNS, bypassing the natural sensory encoding, raises interesting questions about how that information will be interpreted by the CNS.

Temporal Patterning

Classical neurophysiology is grounded in the notion that the output of each individual neuron represents an independent channel in which the mean spike rate encodes unidimensional information. There have been various theories regarding the encoding and decoding of information in the fine temporal details of activity patterns in ensembles of neurons. One theory of pitch perception held that the acoustic frequency information encoded in the phase-locked activity of auditory afferents could be decoded by cross-correlation of delayed and undelayed versions of this signal. However, patients reported pitch sensations that were dominated by place of electrical stimulation rather than frequency for stimulation rates above about 500 Hz (Eddington et al., 1978). Electrical stimulation of the visual cortex would seem to offer a powerful technique to test current theories regarding the significance of widespread synchronization among neurons responding to a single object in a complex scene.

Neuronal Plasticity

There have been dramatic demonstrations of remapping of both sensory maps and motor representations in primary cortex in response to various surgical, electrical, and behavioral modifications of cortical input (Merzenich and Grajski, 1990). Abrupt or gradual loss of signals from failing sense organs is likely to induce various reorganizations of the ascending pathways, as well as the general atrophy that has been noted. The use of electrical stimulation to restore sensory information inevitably results in somewhat unphysiological temporospatial patterns of neural activity that are likely to induce further reorganizations. For example, recent evidence suggests that the tendency of cochlear implants to produce a better representation of high (basal) versus low (apical) acoustic frequencies may result in a remapping of the central representations and consequent improvements in speech perception (Svirsky et al., 2001). Because of the complex precortical processing of auditory information, the locus of such plasticity will be difficult to identify. Similar experiments in the much simpler visual system have the potential to provide important insights into cortical information processing.

General Conclusions

The growing clinical application of neural prosthetics should provide a major catalyst for the expansion of basic knowledge about the nervous system. The devices themselves provide unique opportunities for psychophysical testing of current theories of neural computing and immediate incentives for improving those theories when their limitations are revealed. The technology that is being developed to build these prostheses has considerable spin-off potential as neurophysiological research tools. Conversely, the nervous system embodies tried and proven solutions to computational problems that have resisted conventional algorithmic approaches of robotics and artificial intelligence. It is difficult to

imagine a more appropriate application of electronic neural networks than in the repair of the biological systems that have inspired them.

Roadmap: Applications
Related Reading: Prosthetics, Motor Control; Prosthetics, Neural

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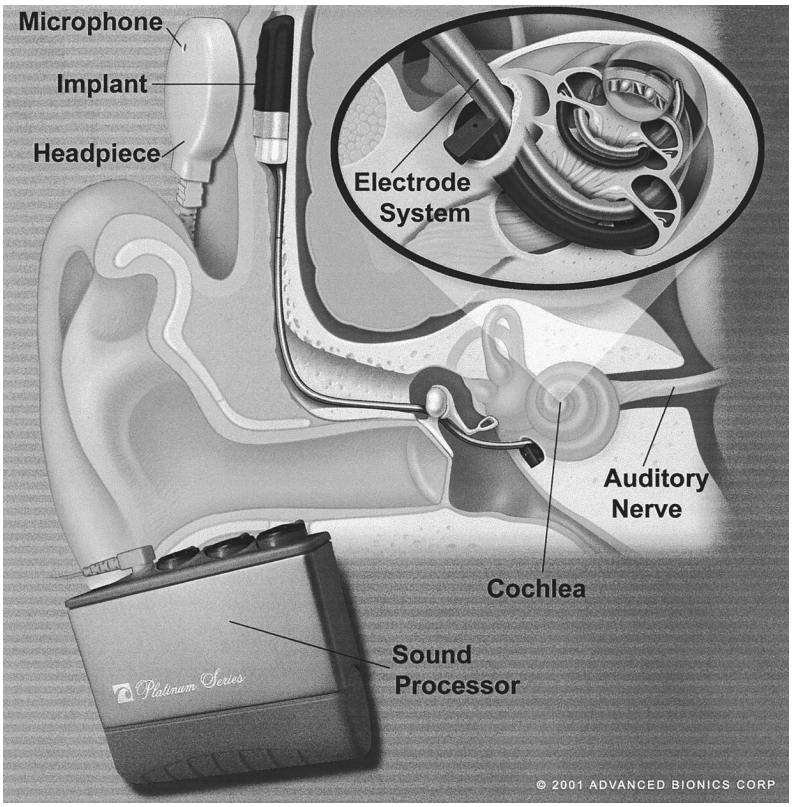

Figure 1. Clarion cochlear prosthesis showing external (left foreground) and implanted (right) components. The implanted components include a 16-contact intracochlear electrode (wedged into the spiral shape of the first one-and-a-half turns of the scala tympani by the dark blue positioner; see insert) and hermetically encased electronics (labeled implant: 25 mm wide by 6 mm thick). The external sound processor contains patient-operated controls, a rechargeable battery, a microprocessor, and a digital signal processor, and connects to a headpiece with a microphone and the antenna that transmits power and data to the implant. Acoustic signals from the microphone are filtered and converted into 8 to 16 channels of stimulus waveforms; these are delivered by the electrode contacts to recruit tonotopically arranged subsets of the spiral ganglion cells that comprise the auditory nerve. (Photograph courtesy of the manufacturer, Advanced Bionics Corp., Valencia, Calif.)