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Advances in Auditory Prostheses

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Abstract

Purpose of the Review—Auditory prostheses use electric currents on multiple electrodes to stimulate auditory neurons and recreate auditory sensations in deaf people. Cochlear implants have restored hearing in more than 200,000 deaf adults and children to a level that allows most to understand speech. Here we review the reasons underlying these results and describe new directions in restoring hearing to additional patient populations and the design of new devices.

Recent findings—From their early development about 50 years ago, cochlear implants (CIs) have been well received and beneficial to people who had lost their hearing. Although those first implants did not allow high levels of speech understanding, they provided auditory information that worked synergistically with lip reading to improve communication. Present day CIs provide excellent speech understanding in children and in postlingually deafened adults. Research is focused on improved signal processing and new electrode designs. Electric stimulation of the auditory brainstem can also produce excellent hearing in some children and adults.

Summary—Auditory prostheses, both at the level of the sensory nerve and at the brainstem, can restore patterns of neural activation that are sufficient for high levels of speech understanding. These prostheses are not only clinically successful but also are important tools for understanding sensory processing in the brain.

Keywords

cochlear implants; auditory brainstem implants; speech recognition; hearing

Introduction

Artificial prosthetic stimulation of the nervous system has long been a dream and a goal of biomedical engineering. However, studies of sensory systems showed a complexity of processing that seemed impossible to replicate in a prosthetic device. Recreating the complex spatial and temporal pattern of neural firing on 30,000 auditory nerve fibers did not appear to be possible. In spite of this, early attempts at restoring hearing sensations by electrically activating a single electrode placed in the cochlea were surprisingly successful

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[1]. Later devices with multiple electrodes were able to produce high levels of speech understanding, in spite of the crude pattern of nerve activation (compared to acoustic hearing). It is now apparent that the brain's pattern processing is robust enough to recover speech even from a coarse pattern of electrical stimulation. Auditory prostheses have progressed to the point that more than 200,000 people have gone from deafness to the ability to converse on the telephone. Here we review the state of the art and future directions in auditory prostheses: cochlear implant (CIs), auditory brainstem implants (ABIs) and auditory midbrain implants (AMIs).

Cochlear Implants

Restoration of hearing by electric stimulation started in France in the 1950s, when a surgeon and an engineer teamed up to put a wire into the inner ear of a deaf patient [2, 3]. Although the device was crude, the patients reported useful auditory sensations and were able to distinguish sounds. The device also aided their lip-reading. Further development of cochlear implants moved from single wires [4] to multiple wires inserted into the scala tympani of the cochlea [5–10]. By the 1970s several companies were manufacturing cochlear implants in the US and Europe. Patient results improved dramatically over the next 20 years as electrode designs and signal processing improved [11, 12, 13]. By 2004 the average adult cochlear implant recipient could understand more than 90% of words in sentences [14].

In spite of the coarseness of the spectral and temporal representation, a multichannel cochlear implant clearly provided sufficient cues to an experienced brain to allow pattern recognition of speech sounds at a high level. Would that same coarse input be sufficient for a developing brain to learn those patterns with no prior history of acoustic hearing? Early implantation of young children showed dramatic plasticity in adapting to the prosthetic auditory input [15]. Multichannel cochlear implants in congenitally deaf or early deafened children eventually proved to be highly successful; measures showed children developing speech and language at a normal rate following implantation [16, 17]. Obviously, the coarse activation patterns of a cochlear implant are sufficient to allow the brain to learn to identify words and sentences. Over the last 10 years there has been a trend to implant younger and younger children, to take advantage of the amazing plasticity of the early developing brain [18, 19*]. Results show faster auditory development and higher asymptotic levels of performance with earlier implantation.

As performance with cochlear implants has improved, patient selection criteria for adult populations has also changed dramatically. Whereas early implanted patients were profoundly deaf in both ears, new guidelines allow considerable hearing in either ear [20, 21], and even normal acoustic hearing in one ear [22–25]. Combining residual acoustic hearing with electric hearing requires that the implant be tuned to match the acoustic hearing to achieve the greatest synergy. Residual acoustic hearing alone may be insufficient for understanding speech, but combined with a CI the outcomes are excellent. The acoustic hearing may allow perception of harmonic pitch, something not well-represented in a CI. Harmonic pitch allows better perception of music and voice quality.

Cochlear implants are now commonly performed bilaterally to restore directional hearing [26, 27], which requires signals from two ears, just as visual depth perception requires two eyes. Binaural hearing is especially important in noisy listening conditions, so that the listener can separate the talker from the interfering sounds. Interaural loudness cues are relatively well used by CI listeners, but interaural timing cues are not preserved in CIs. Bilateral CIs allow listeners to localize the source of sound, and a small improvement in speech recognition in noise. However, full binaural hearing is not restored by bilateral CIs because CIs do not preserve interaural timing differences.

While cochlear implants can restore speech understanding to a high level, they are poor at restoring music and voice quality. The broad activation patterns produced along the cochlea are adequate for speech patterns, but do not have sufficient spectral resolution to convey harmonic pitch, which is essential for music and voice quality. The identity of talkers and the emotional content of speech require access to subtle changes in the fundamental frequency of the voice, which requires access to the harmonics of the voice frequency [28–31]. Voice pitch intonation is also important for tonal languages, in which the voice pitch contour conveys lexical meaning [32–33]. To improve music and voice quality in a cochlear implant will require substantial improvements in spectral resolution, which is the goal of most research and development.

One of the main limitations of cochlear implants is due to the physics of the electrode location relative to the auditory nerve. The electrode resides in the scala tympani of the cochlea and is separated from the nerve by the boney medial wall of the cochlea and by about 1 mm of fluid-filled space. Electric current injected into the CI electrodes spreads out in the fluid and is diffused by the bone before activating the nerve. Stimulation on a single electrode at a comfortable listening level activates neurons across a cochlear region of several mm, corresponding to ½ to a full octave acoustic equivalent. Two methods for improving the selectivity of neural activation are current field focusing [34–39] and placing the electrodes closer to the nerve. Current focusing uses the overlap of current fields from multiple electrodes to shape the overall current field to make it more localized at the point of stimulation than a single electrode's field. This technique has promise, but is ultimately limited by the physics of the fields and the distance to the nerve. If the nerves are too far from the electrode then the fields from different electrodes overlap so much that sharpening is not practical.

The only method of assuring better stimulation selectivity is to place the electrodes as close as possible to the nerve. In the cochlea this can be accomplished by placing the electrode array into the nerve trunk in the modiolus of the cochlea. This will require a new electrode design and a new surgical approach and both are currently under development [40]. Highly selective nerve activation may allow better representation of spectral features and there is evidence that it may also improve the temporal representation in nerve firing patterns [41]. If successful, the intraneural CI could provide sufficient spectral resolution to convey complex harmonic sounds that would improve the perception of music and voice quality [42].

Auditory Brainstem Implants (ABI)

Some deaf patients cannot use cochlear implants because they have no remaining auditory nerve to stimulate. This includes people with bilateral temporal bone fractures, bilateral vestibular schwannomas (from neurofibromatosis type 2, NF2), or from severe ossification of the cochlea and modiolus. For such patients a new implant was developed intended to stimulate the cochlear nucleus, the first auditory relay nucleus in the brainstem [43, 44, 45]. ABI patients received useful auditory information, but they mostly don't understand speech without lip-reading, unlike cochlear implants [46, 47]. It was originally thought that, similar to CIs, the ABI was also limited by stimulation selectivity; the positioning of the electrode on the surface of the brainstem allows large electric field interactions between electrodes. In addition the ABI doesn't align well with the underlying neural tonotopic map; neurons representing high frequencies are below the surface and so not accessible from surface electrodes.

A new ABI was designed with penetrating microelectrodes (PABI). The PABI used 10 microelectrodes to penetrate 1–2mm into the cochlear nucleus in addition to the normal surface electrode array, now containing 12 electrodes. Penetrating electrodes achieved the goals of lower thresholds, more selective stimulation, and activation of high pitch sensations. However, overall speech understanding was no better in the 10 PABI patients than in previous ABI patients with traditional surface electrodes [48, 49].

Since 2005, new results from Europe have demonstrated that CI-like speech understanding can be obtained by an ABI. Colletti [50, 51, 52] showed high levels of speech understanding in ABI patients who did not have NF2. These patients lost their VIIIn from trauma or disease or severe ossification in the modiolus of the cochlea. Some of these non-NF2 ABI patients could recognize speech well enough to converse on the telephone; a level of performance similar to that of good CI users [53]. From this it appeared that the poor performance of ABIs in NF2 was related to the deleterious effects of the NF2 vestibular schwannomas. However, more recent results show excellent speech recognition even in NF2 ABI patients [54, 55]. Excellent speech recognition with the ABI in both NF2 and non-NF2 patients suggests that the good outcome is not related to the disease process or to the tumors *per se*, but to the surgical approach and procedure.

If the ABI can provide sufficient auditory information that post-lingually deafened adults can recognize high levels of speech, can it provide sufficient information for congenitally deaf children to learn speech and language? At present there are more than 75 children worldwide who have received an ABI. These children had no cochlear nerve, either from bilateral fracture of the temporal bone or due to congenital malformations of the cochlea and absent cochlear nerve [56, 57, 58*]. There is a wide range of acoustic ability in these children, with some showing a normal rate of auditory development [59, 60, 61]. These children constitute an existence proof that the ABI can provide sufficient auditory information to the brainstem to allow relatively normal development of complex auditory perception. Even in children with an ABI who have less than optimal speech outcomes there is evidence that the ABI allows improvements in general cognitive development [62]. The ethics of applying the ABI in children depends on the relative risk of the surgery compared to the benefits. Complication rates in children and adults from ABI surgery are no different from the low rate observed in thousands of cases using a similar surgical approach for microvascular decompression [63*]. The higher complication rate in many ABI surgeries in NF2 patients is clearly due to the complications of NF2.

Based on the success of cochlear implants and ABIs, additional auditory prostheses have been developed targeting a higher level in the auditory pathway; the inferior colliculus (IC) in the auditory midbrain. These devices are called the auditory midbrain implant (AMI) [64, 65, 66] or Inferior Colliculus Implant (ICI) [67]. The IC is a relatively large nucleus with a known tonotopic organization that is surgically accessible either from the infratentorial supracerebellar median surgical approach (used to access pituitary tumors), or from the same retro-sigmoidal approach used for NF2 tumor removal. It is possible that, at least in some NF2 patients, the cochlear nucleus is damaged by the tumor and/or it’s surgical removal. In some cases brainstem damage might occur from fractionated radiation approaches to tumor management. However, if good outcomes can result from application of electrodes to the brainstem, it might also be possible to achieve functional hearing from stimulation of the midbrain. Six patients have been implanted with AMI or ICI and the results are somewhat disappointing. While most of these patients hear sounds from stimulation, and hear different pitches on different electrodes, the speech perception outcomes are more similar to the earlier outcomes of ABI in NF2 patients. However, even this limited outcome is of great benefit to these patients. Even though they cannot understand words, the midbrain implants provide useful sound awareness, some sound discrimination, and a significant help to lip-reading. In a face-to-face conversation these patients show a large improvement in speech understanding with the auditory help from the device. For patients with brainstem damage the AMI may provide the only option for obtaining useful auditory information.

Implications for Neuroscience

One of the great surprises of auditory prostheses is the degree of success we have achieved. Researchers in the 1970’s thought that restoration of functional hearing by stimulating a few wires in the cochlea would never work. Those researchers were focused on the complexity of cochlear mechanics and the complexities in spatial and temporal firing patterns of 30,000 auditory neurons. They were astounded when the earliest single channel cochlear implants were enthusiastically adopted by the first CI patients. They were even more astounded when multichannel CIs provided excellent word and sentence recognition. The pattern of nerve activity produced by these devices was crude compared to the complex pattern of normal hearing, yet patients achieve a high functional level of hearing. And now we see excellent speech recognition even by stimulation of the brainstem and in children who have never heard before.

We shouldn’t have been surprised. In the aftermath of World War II auditory researchers set out to discover a method of encrypting communications by corrupting speech on the transmitting end and reversing the corruption on the receiving end. To their surprise they found that speech remained intelligible even under the most severe types of distortion, including the removal of all amplitude information in the temporal waveform – reducing speech to a rectangular time waveform [68]. It proved to be very difficult to degrade speech in a way that rendered it unintelligible. Indeed, infinite clipping is actually beneficial to intelligibility in conditions of high noise! Once trained, the pattern recognition of the brain is powerful. From auditory prostheses we re-learned the lesson of those earlier studies: that, with sensory systems, the powerful neural network of the brain is trained over many years and millions of repetitions to recognize the complex patterns of sound and speech. Even when those patterns are badly distorted by an auditory prosthesis or a distorted communication channel, speech is intelligible. In auditory prosthesis research we have learned much about how the ear and brain work together for pattern recognition and those new insights allow us to design better prostheses. The success of auditory prostheses has changed the way we think about hearing and sensory processing. Some of these lessons are still evolving, but some of the knowledge gained from auditory prostheses can now help guide the design of new sensory prostheses in vision and balance [69–72]. The interface between electronics and biology has a bright future.

Conclusions

Auditory prostheses are the most successful sensory prosthesis. Although the prosthetic representation of information is crude in comparison to the normal system, the pattern recognition of the brain can overcome the lack of fidelity and reconstruct the message. The adult brain has been trained over a lifetime for auditory pattern recognition, so that even the distorted patterns provided by the prosthesis are highly intelligible. In congenitally deaf children with cochlear implants and brainstem implants we have seen that even this crude pattern of prosthetic stimulation is sufficient for a previously untrained brain to learn speech and language.

Key Points

- Cochlear implants and auditory brainstem implants allow recognition of speech.
- Cochlear implants and auditory brainstem implants provide sufficient auditory information to allow congenitally deaf children to develop speech and language.
- Auditory prostheses have improved our understanding of the ear-brain system.

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