New horizons in auditory prostheses

By Fan-Gang Zeng, PhD

Modern multi-electrode cochlear implants have restored partial hearing to more than 200,000 deaf people worldwide today. About half of these are children, with many of them having now developed language capabilities on par with their normal hearing peers.[1] For cochlear implants to achieve this remarkable level of success, they not only had to compete against other devices such as tactile aids and hearing aids, they also had to overcome doubt from the mainstream and deaf communities in their early years of development.

All contemporary cochlear implants use similar signal processing that extracts temporal envelope information from a limited number of spectral bands, and delivers these envelopes successively to 12-22 electrodes implanted in the cochlea. As a result, these implants produce similarly good speech performance: 70-80 percent sentence recognition in quiet, which allows an average cochlear implant user to carry on a conversation over the telephone. Interestingly, though, sentence recognition in quiet has essentially remained at this same level since 1994. (Figure 1.)

Judging by the number of cochlear implant-related publications in PubMed, research output has been on a fast track, roughly doubling the number of papers every eight years in the past three decades, but what's been cooking? Where will the next breakthrough be? How will these advances affect the way we view and treat hearing loss and its related disorders?

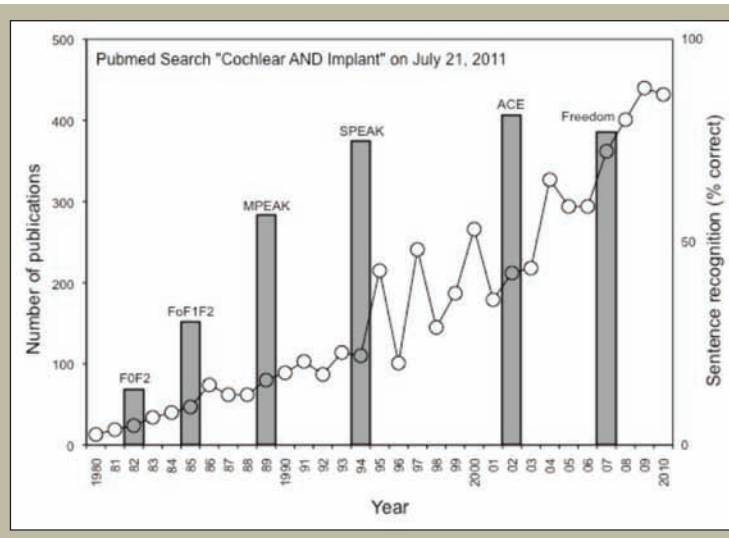

Figure 1. *Annual number of cochlear implant related publications available in PubMed as of July 21, 2011.*

HOT AREAS

The number of publications related to bilateral cochlear implants has doubled in the past five years. Compared with single cochlear implantation, bilateral implantation guarantees that the better ear is implanted. Although bilateral speech perception in noise and sound localization are improved by bilateral implants, the improvement is still modest and mostly comes from the acoustic head shadow effect that uses interaural level differences. Little evidence suggests that bilateral implant users take advantage of the interaural time difference to improve their functional binaural hearing, partly because of scarce data on these users and the lack of encoding of low-frequency fine-structure information in current cochlear implants.[2,3]

One means of providing such low-frequency, finely structured information is to complement the cochlear implant with a contralateral hearing aid in subjects who have residual acoustic hearing. This area of research known as hybrid hearing has been red hot as its number of publications increased fourfold in the past five years. Compared with the typical 1-2 dB improvement in speech perception in noise with bilateral implants over unilateral implants, electroacoustic stimulation (EAS) can improve speech perception in noise by as much as 10-15 dB, depending on noise type and quality of residual hearing.[4-6] The mechanisms underlying the improvement are also totally different between bilateral implantation and EAS, with the former relying on loudness summation and the latter on voice pitch to separate signals from noise or glimpsing signals at time intervals with favorable signal-to-noise ratios. EAS, with its promising initial outcomes, improved surgical techniques, and signal processing will likely continue to expand its candidacy criteria to include those who have significant residual hearing, and possibly become the treatment of choice for presbycusis in the future.

Implantable middle ear devices have received relatively less attention but have more than satisfactorily filled the gap between hearing aids and cochlear implants. Middle ear implants avoid several pitfalls associated with the use of ear molds in most conventional hearing aids, such as the so-called occlusion effect where the hearing aid wearer's own voice sounds louder than normal, feedback squeal due to acoustic leakage between the microphone and speaker,

and undesirable blockage of residual hearing at low frequencies. For those with conductive or mixed conductive and sensorineural loss, chronic ear infections, or severe to profound hearing loss, hearing aids cannot be applied and cochlear implants are not likely as effective as the implantable middle ear devices.

Ironically, cochlear implants may eventually be used to treat tinnitus. We all know that cochlear implants have been developed to restore the world of sounds to those who cannot hear, but can they also restore the world of silence to those who have too many unwanted sounds in their head? Traditionally, cochlear implants have been used to treat deafness with tinnitus suppression as a secondary effect, but recently, they've been used specifically to treat patients with unilateral tinnitus and deafness. A cautious note is that using cochlear implants to treat deafness and tinnitus may require different speech processor fitting as one unilateral tinnitus patient was reported to require surprisingly low-rate electric stimulation to suppress his tinnitus.[7-9]

The final hot area in auditory prosthesis is electric stimulation, which is now being used to treat other major inner ear-related diseases such as dizziness and balance disorders. Modifying a commercial cochlear implant from the Cochlear Corporation, Rubinstein and colleagues turned the device into a vestibular neurostimulator, and last year researchers at the University of Washington successfully implanted such a device in the first human volunteer with Ménière's disease.[10] Another successful vestibular implant was reported in one bilaterally deaf patient with bilateral vestibular loss who received a custom-modified Med-E1 cochlear implant. The patient was able to adapt to continuous vestibular electrical stimulation and generate smooth eye movements with modulated vestibular stimulation.[11] Compared with cochlear implants, the enterprise of vestibular implants is small but ready to take off because of clinical need, encouraging animal studies, and borrowing similar cochlear implant technologies. Sophisticated sensor-based vestibular implants, totally implantable devices, and even vestibular brainstem implants, are likely to be developed and tested by those with severe balance disorders in the near future.

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NEW HORIZONS

New technologies are also being developed to address significant problems associated with current cochlear implants that use electrodes inserted in the scala tympani to stimulate the auditory nerve. With a bony wall separating the electrode and the nerve, the current implant not only requires high currents to activate the nerve, but it is also severely limited by broad spatial selectivity and lack of access to apical neurons. Several new approaches address this spatial channel interaction problem.

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Richter and colleaguesat Northwestern University have been using infrared light to optically stimulate the auditory nerve, and have shown that optical stimulation can significantly improve spatial selectivity over electric stimulation. They have presented promising chronic animal data and evaluated surgical techniques for the feasibility of an optical cochlear implant.

Middlebrooks and Snyder at the University of California took an alternative approach that uses traditional electric stimulation, but placed the electrodes in direct contact with the neural tissue to achieve selective stimulation. In a cat model, this approach produced not only low stimulation thresholds and sharp spatial selectivity, as expected, but more importantly, access to apical neurons that are more capable of transmitting temporal information than basal neurons. Optical and intraneural stimulation approaches have the potential to improve current cochlear implant performance by quantum steps, but are likely years away from human clinical trials because they have to overcome challenging technical issues such as size (for optical stimulation) and stability (for both).

In patients lacking a functional cochlea or auditory nerve, as is the case with bilateral acoustic tumors, higher auditory structures have to be stimulated to restore hearing. The first stage of the central auditory system is the cochlear nucleus, which can be electrically stimulated by auditory brainstem implants (ABI). ABI performance in patients with bilateral acoustic tumors is generally poor, limited to mostly help in lip reading. But recently, the ABI has emerged as a viable option for adults and children without tumors but with a malformed inner ear or damaged auditory nerve, with many ABI users producing surprisingly good performance similar to cochlear implants.[12] The other direction for ABI is to coordinate surface and penetrating

electrode stimulation to achieve lower thresholds, finer pitch, and hopefully better speech recognition than either alone.[13]

Because of its well-defined laminated structure and easy access in humans, the inferior colliculus has also been targeted as a potential site of stimulation. Researchers at Hannover Medical University in Germany designed and implanted an auditory midbrain implant (AMI) to stimulate the inferior colliculus in three patients.[14] In theory, the AMI should produce better results than the ABI, but the actual performance from the three AMI patients so far is limited to help in lip reading only. Compared with 1,000 ABI users worldwide, the AMI is still in its infancy but has the potential to push the technological and surgical envelope and expand the horizon for wide acceptance and high efficiency of central auditory prostheses. If AMI is successful, then a natural extension would be to develop a cortical auditory implant to take advantage of the high-density penetrating electrode array and overcome spatial channel interaction problems associated with peripheral implants.

Cochlear implants may eventually be used to treat tinnitus.

NOT READY FOR PRIME TIME

Although none of the following ideas is feasible for immediate human application, several highly innovative ideas have been proposed that can and will fundamentally change the current paradigm of auditory prostheses. One of these is to use microelectromechanical system (MEMS) technology to engineer an artificial cochlea that is similar in size and power consumption to the natural cochlea. Several groups in the United States have been working on a micro-machined cochlea, but a Japanese group seems to be the closest to making a practical MEMS device for human use.[15]

The researchers deposited a piezoelectric layer on a silicon base, producing an acoustic sensor that has similar frequency selectivity to a natural basilar membrane while generating a small amount of voltage in response to sound stimulation. Although at present this small amount of voltage has to be amplified by 1,000 to activate the auditory nerve, the idea of replacing the damaged cochlea with an artificial MEMS device is at least feasible in principle.

In most sensory systems, chemical transmitters released from sensory receptors are the driving force to activate a neuron. Neuroengineering efforts have been underway to power a novel neuroprosthetic interface that can locally release and recycle chemical transmitters to mimic natural sensory transduction function. One possible application is to use the MEMS cochlea as a switch to control the flow of these chemical transmitters, producing an ultra low-power and highly natural means to restore impaired sensations, including hearing.

The most exciting of these approaches is to target and express neurons genetically with light-sensitive ion channels; lasers of certain wavelengths could then specifically stimulate chR2-expressed neurons. Tobias Moser at the InnerEarLab in Germany is exploring an optogenetic cochlear implant that, if successful, could provide not only similar temporal precision to the current cochlear implant but also much more selective spatial stimulation. The new-generation implant could activate low-frequency neurons that are spirally intertwined with high-frequency neurons. This selective stimulation is difficult, if not impossible, with the current approach.

In the near future, we can expect to apply the principles and successes of cochlear implants to treat not just one symptom of hearing loss, but address the whole spectrum of the condition, including tinnitus, dizziness, and depression. The auditory prostheses can also be combined with other well-established neural prostheses, such as the vagus nerve and deep brain stimulation, to treat multiple disabilities and neurological disorders from Parkinson's disease to seizures at the same time. The application of modern technologies will revolutionize the way that sensory, neural, and even cognitive functions can be restored and enhanced.

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