Cochlear and Brainstem Auditory Prostheses "Neural Interface for Hearing Restoration: Cochlear and Brain Stem Implants"

Successes with ear implants have been followed by hearing improvement for some patients with brain stem implants; investigation of midbrain implants shows promise but is still in early development.

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ABSTRACT | This paper discusses the development and implementation of three novel implantable technologies that have advanced the communication abilities of hearing-impaired individuals who cannot benefit from conventional hearing aids. This paper will discuss clinical indications and outcomes and include current technological limitations and future research efforts.

KEYWORDS | Auditory brainstem implant; cochlear implant; neurofibromatosis type 2

I. INTRODUCTION

Cochlear implants (CIs), auditory brainstem implants (ABIs), and auditory midbrain implants (AMIs) represent a triumph of bioengineering. CI electrode arrays are implanted in the cochlea, ABI electrode arrays stimulate the cochlear nucleus complex in the lower brainstem, and AMIs stimulate auditory neurons in the inferior colliculus. Of these auditory implants, cochlear implants have been particularly successful. Conversing on the telephone, for example, is now routinely possible with modern cochlear implants. This paper discusses the development and implementation of these technologies designed for hearing loss, their clinical indications, and outcomes, and includes current technological status and future research efforts.

II. COCHLEAR IMPLANTS

In 1957, French researchers A. Djourno and C. Eyriès, with the help of D. Kayser, provided the first detailed description of the effects of directly stimulating the auditory nerve in a human subject [1], [2]. The individual described chirping sounds at a high frequency when stimulation was performed and was able to distinguish basic monosyllabic words [3].

W. F. House at the House Ear Clinic implanted several experimental CI devices in deaf volunteers in the early 1960s. Initial devices were not successful in the long term due to rejection of the electrode insulation material [4]. B. Simmons at Stanford University reported studies in 1965 and 1966 in which multiple electrodes were implanted into the modiolus of the cochlea in a patient with profound hearing loss. In his study, the patient heard the different electrodes as differences in pitch, and on a single electrode they could detect a

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change in pitch up to stimulation frequencies of 300 Hz. The study prompted further research into multichannel electrode devices [1], [3].

The first portable cochlear implant system in an adult was implanted in 1972 at the House Ear Clinic. In 1980, children began to be implanted with single-channel devices. The U.S. Food and Drug Administration (FDA) formally approved the marketing of the House-3M cochlear implant in November 1984 [4]. By the late 1980s, more studies were emerging that showed the safety and efficacy of cochlear implantation [5]. However, while single-channel devices did provide significant auditory benefit, they did not allow word understanding without lipreading cues [6].

While FDA approval of the House-3M device was occurring, in 1984, Clark and colleagues in Australia were developing what would become the Nucleus-22 multichannel cochlear implant, and initial U.S. studies were performed at the University of Iowa [6]. This work would eventually spawn Cochlear Corporation, and their multichannel cochlear implant would be approved one year later [7]–[9]. Initially, this approval was only for adults with profound hearing loss, but in 1990, approval was widened to include children over two years of age. In 1995, criteria were again broadened to include adults with severe hearing loss and reduced speech discrimination scores. In the early 1980s, another implant group was active in Austria, and their work eventually lead to production of the Med-El multichannel cochlear implant, which has achieved worldwide use. Another implant manufacturer, Advanced Bionics, received FDA approval for its Clarion device in 1997 [10]. In 1998, Cochlear Corporation's Nucleus 24 was approved for use in children ages 12 months and older [4].

III. HOW COCHLEAR IMPLANTS FUNCTION

CIs, ABIs, and AMIs all function with somewhat similar hardware (except for the electrode arrays) and sound-processing techniques. For the sake of brevity, cochlear implant function will be discussed specifically.

In contrast to traditional hearing aids that amplify acoustic energy and deliver it to the external ear, cochlear implants process sound and convert it into electrical energy for subsequent delivery to the auditory nerve. The implanted electrode array is positioned via the scala tympani of the cochlea, near the osseous spiral lamina and the spiral ganglion. By stimulating the spiral ganglion, diseased or absent cochlear hair cells and peripheral processes are bypassed and sound information may be relayed to the auditory nerve and subsequently to the cerebral cortex.

The external components of a cochlear implant (and ABI/AMI) consist of the microphone and the speech processor (which may be combined in a behind-the-ear unit) and the external transmitter coil [Fig. 1(e)]. The internal implanted components include the receiver/stimulator and the electrode array [Fig. 1(a)–(d)].

The microphone of the CI receives analog sound from the external environment and sends it to the speech processor, which converts the sound into a digital signal. The signal is filtered into separate frequency bands that

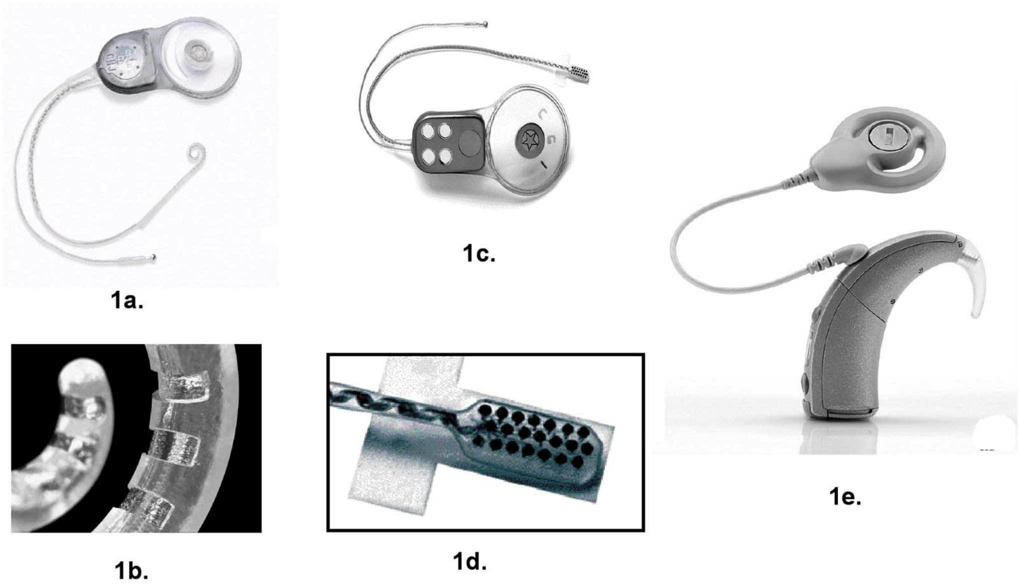

Fig. 1. *(a) and (b) Cochlear implant and (c) and (d) auditory brainstem implant receiver/stimulators and electrode arrays and (e) ear-level Freedom model sound processor used with the implants.*

are sent to the appropriate tonotopic regions in the cochlea that approximately correspond to those frequencies. The external processor also compresses the typical 60 dB dynamic range of acoustic amplitudes into a smaller 10–20 dB range of electrical current typical in a cochlear implant.

The digital electric signal is then sent by radio-frequency transmission from the external transmitter coil through the skin to an internal receiver/stimulator. The signal is then decoded and sent to the implant electrode array in the cochlea. Signal transmission is achieved via modulation of a high-frequency carrier signal between 600 kHz and 5 MHz. In the Cochlear N24 and Med-El Pulsar devices, all stimulation information (pulse-phase duration, pulse amplitude, interphase gap, source electrode, sink electrode) is transmitted for each pulse. In the Clarion CII device and in the high-speed mode of the N24 device, some parameters are fixed and stored in the internal portion of the device, and the transmitted signal only sends amplitude and electrode information for each pulse. This type of transmission is capable of specifying pulses at speeds up to 90 000 pulses/s, even though the speed of the telemetry link is considerably slower. When all parameters are passed for each pulse, the overall pulse rates are limited to about 15 000 pulses/s. Reverse telemetry signals are transmitted from the implanted device to allow monitoring of electrode impedances and for monitoring electrophysiological signals from neural activation. Most of the power consumption in cochlear implant devices is due to the inefficiency of the coil data link and not due to the actual stimulation.

A number of sound- and speech-processing algorithms may be used to process sound information before it is sent to the internal receiver/stimulator. These include spectral peak processing, continuous interleaved sampling (CIS), and advanced combination encoding. Cochlear implant manufacturers continue to develop new processing strategies with the goal of improving speech and music perception [11], [12].

IV. SIGNAL PROCESSING FOR AUDITORY PROSTHESES

When cochlear implants were first developed in the 1960s, researchers thought that they would not be able to provide sufficient sensory information to enable speech recognition. This perception was based on the idea that the pattern of neural activity from the cochlea was too complex to be accurately reproduced by a relatively small number of electrodes (relative to the 30 000 hair cells and neurons). We now know that high levels of speech recognition can be obtained with modern multichannel cochlear implants [13] and that only four spectral channels are sufficient for speech recognition under optimal listening conditions [14], [15]. It is clear that the auditory brain's pattern-processing system does not require all of the fine structure in the neural responses coming from a normal cochlea. The following section reviews the history of signal processing for implants and the developments in processing that resulted in improved performance.

A. Feature Extraction

The initial signal-processing strategies for auditory prostheses were based on pessimism. It was widely believed that the limited number of electrodes in a cochlear implant was not sufficient for understanding speech, so it was thought that the most important features of speech should be extracted and presented to the electrodes. Rather than "overwhelm" the system with the full speech information, it was thought that the best use of this limited channel would be achieved by only presenting the core features and discarding everything else. It was known that the voice fundamental frequency was useful for supplementing lipreading [16], [17], and that the second formant was the most important feature for vowel identity. Early speech processors—F0F1F2 and Multipeak, for example [18], [19]—attempted to extract the fundamental frequency of the voice and the second formant frequency of vowels and stimulate the electrodes that corresponded to those frequencies. These processing strategies worked fairly well and produced a modest level of speech recognition of unfamiliar sentence materials presented with no lipreading cues. Even this modest level of performance was surprising at the time because the pattern of neural activation was quite sparse and quite unlike the natural acoustic pattern of activation for that same speech. Unfortunately, the algorithms that extracted speech features failed quite badly in noisy listening conditions, especially in conditions with competing talkers. Although these early cochlear implants were highly successful prosthetic devices, the results were actually limited by the signal-processing algorithms rather than by the electrode neural interface.

B. Biomimetic Signal Processing

During the 1980s and 1990s, signal processing for cochlear implants attempted to incorporate more and more speech features and to present patterns of stimulation that mimicked known patterns of activity in a normal cochlea. Strategies were implemented that mimicked the traveling wave in the cochlea, in which high-frequency activation occurs prior to low-frequency activation and the activation appears to "travel" along the cochlea. Strategies were implemented that attempted to mimic the fine temporal structure (phase-locking) in nerve responses. In general, these attempts all failed to improve speech recognition. For most of these manipulations, implant listeners could not detect a qualitative difference when the feature was present or not. This result suggested that while these "fine structure" features of the normal acoustic neural response may be necessary for some specialized functions of hearing, these were not necessary for speech recognition.

C. Minimalist Signal Processing

The most significant advance in implant processing occurred when the signal processing was minimal [20]. The CIS processing strategy analyzed sound into spectral bands that were each assigned to one electrode. The energy in each band was averaged over a few milliseconds, and then that amplitude was mapped onto an electrical level that was presented to that electrode. Each electrode was stimulated with a continuous stream of brief biphasic current pulses that changed in amplitude based on the speech energy from that spectral band. Across electrodes, the pulses were interleaved in time to avoid direct summation of the electric current fields from each electrode. This type of processing resulted in a dramatic improvement in speech recognition with cochlear implants. No specific speech features were extracted and no attempts were made to mimic the biophysical patterns of the normal cochlea. Indeed, in many cases, the electrodes were positioned in the cochlea at a tonotopic location that was more than one octave higher than the information being presented to that electrode. In spite of the mismatch between the electrode information and its location, and in spite of the absence of normal acoustic fine timing structure, implant listeners with CIS processors were able to achieve high levels of speech recognition without lipreading cues. Most implant patients were able to achieve a level of performance that allowed them to converse easily on the telephone, even with its reduced bandwidth and the absence of any visual cues. Subsequent research has shown that speech recognition is resistant to distortions in the spectral/tonotopic pattern of up to 40% [21]–[23] and to shifts in tonotopic location of about one-half octave [24].

D. Summary of Signal Processing

Improved performance in cochlear implants depended not only on understanding the physical and biophysical limitations of implant stimulation but also on an understanding of the brain's pattern processing requirements. Modern signal processing represents the most important speech information while also providing the brain the pattern recognition information that it needs. Pattern recognition in the brain is more effective than algorithmic preprocessing at identifying important features in speech. A combination of engineering, signal processing, biophysics, and cognitive neuroscience was necessary to produce the right balance of technology to maximize the performance of auditory prostheses.

V. IMPLANT CANDIDACY

Indications for cochlear implantation have undergone changes since originally being approved by the FDA. The indications gradually have become more inclusive of patients with severe hearing loss.

In the early 1980s, patients considered candidates for CIs included postlingually (that is, after development of substantial speech and language skills) deafened adults with a profound hearing loss who could get no benefit from conventional hearing aids. Today, pediatric candidates for cochlear implantation must have bilateral, severe to profound sensorineural hearing loss with a pure-tone average of 90 dB in the better ear. Implantation may be performed as young as 12 months of age (Nucleus device).

Presently, CI candidates must generally demonstrate little significant benefit from hearing aids (less than 51% correct on a standardized sentence test) and have no medical contraindications. Perhaps equally as important as audiological criteria are appropriate motivation, psychological fitness, and willingness to participate in postoperative CI testing and programming. Patients as well as parents must have appropriate expectations, and there must be appropriate support in the home and school environments.

VI. PRELINGUAL AND POSTLINGUAL CONSIDERATIONS

Historically, adult CI recipients who were deafened at a very early age, essentially prelingually, have had a higher nonuser rate. This has been the case since the very early history of CIs at the House Ear Institute (HEI) [25]. Approximately 30% of adult patients who were implanted with the House/3M device before the age of 5 years chose not to use the implant, compared with a 10% nonuser rate in patients whose hearing loss occurred later [26]. Later studies have also failed to show substantial ability to understand speech using only implant sound (no lipreading cues) in prelingually deafened adults [27]. This is thought to be related to the lack of stimulation of the central auditory pathways in childhood. This issue must be addressed in preoperative counseling with such patients.

VII. AUDIOLOGICAL/MEDICAL EVALUATION

Patients being evaluated for a CI should undergo a full audiometric and medical evaluation to determine if they meet the indications required by the FDA and the manufacturer, as well as any additional criteria required by the implant center. For adults, this is somewhat less rigorous than for very young children. Implant centers equipped to manage pediatric CI recipients must have a very experienced pediatric team.

Implantation is generally achieved via a postauricular incision and after a mastoidectomy. The CI electrode array is then placed into the scala tympani of the cochlea via the cochleostomy using the technique recommended by the manufacturer. The electrode array can be manipulated to hug the modiolus so that stimulating electrodes are in close proximity to remaining axons or spiral ganglion cells. In the advance-off stylet technique in the Nucleus CI, a stiffening wire (stylet) is removed as the electrode is inserted into the cochlea which allows the array to coil snugly around the modiolus (Fig. 2).

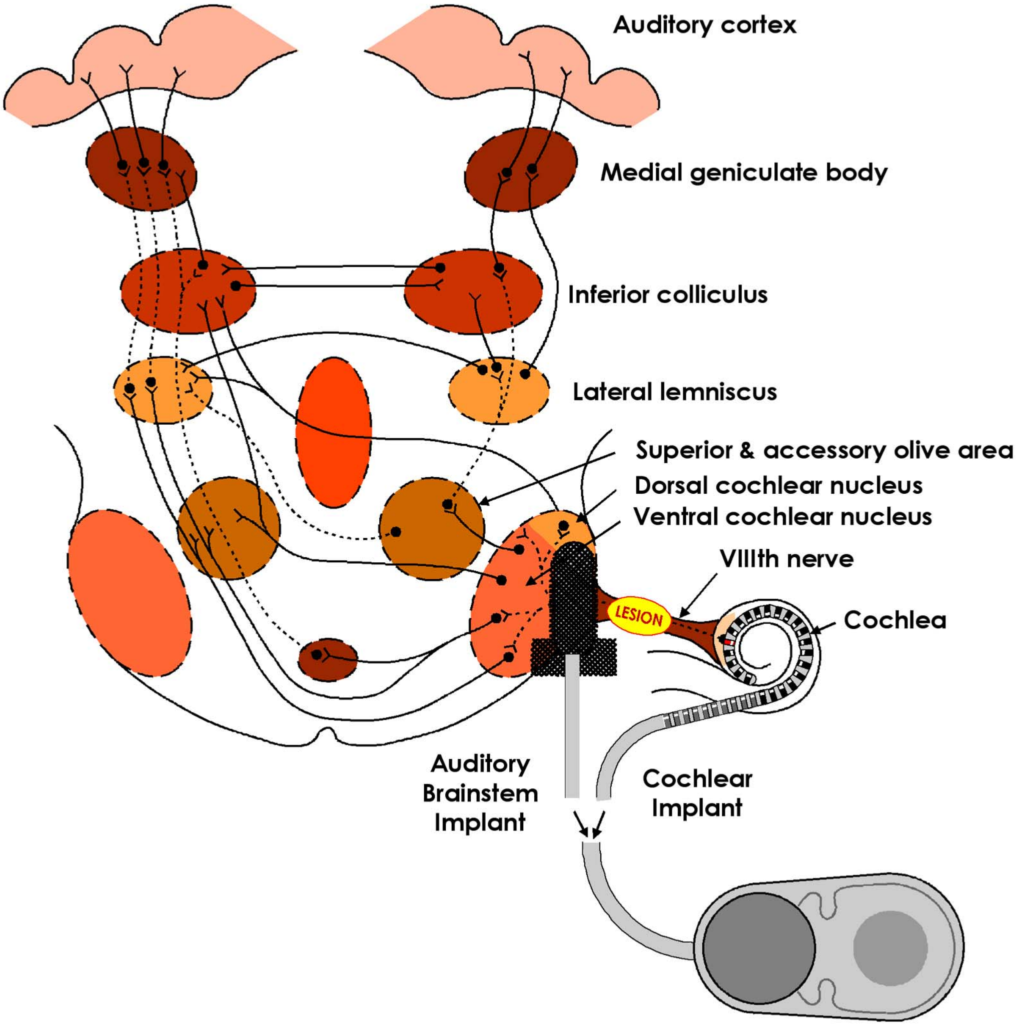

Fig. 2. ***Schematic illustration of the central auditory pathways showing the relative locations of the cochlear implant and auditory brainstem implant electrode arrays.***

Intraoperative neural response telemetry (NRT) is employed at some centers to help verify the presence of auditory neural responses and proper electrode impedances. In this technique, an electrode is activated and the resulting neural response (action potential) is measured from an adjacent electrode on the array. It probably is effective because the only neurons in the cochlea are auditory neurons. This technique also has been used to help program the CI in very young children [28].

VIII. SPECIAL SITUATIONS

Neuroanatomic difficulties such as acoustic tumors (vestibular schwannomas), anomalies in cochlear development, or infiltration of bone in the cochlea after meningitis may preclude cochlear implantation. ABIs (or AMIs) can be a beneficial option in these cases because they stimulate the central auditory pathways directly (Fig. 2).

As newborn hearing screening continues to expand, increasing numbers of infants are being found to be potential candidates for cochlear implantation. Implantation in the United States is currently approved for patients as young as 12 months, with some even younger cases implanted [29], [30]. Studies have shown that very early implantation may facilitate the development of key central auditory pathways critical to the development of speech [31], [32].

CIs may even be performed on both ears simultaneously or sequentially [33]–[36]. Results of studies examining bilateral CIs reveal that such recipients perform better on sound localization tests and in noisy situations.

IX. ACTIVATION AND REHABILITATION

Depending on the implant center, initial stimulation and programming of the implant may occur very soon postoperatively, even as early as the first postoperative day. Generally, the goal of programming is to measure threshold for electrical stimulation on each electrode, as well as the maximum level of comfortable sound, and then assign the frequency analysis bands in the sound processor to the specific electrodes in a reasonable pattern. A standard pattern typically is used in CI programming, and this has provided very good auditory performance in most cases. In individuals with ABIs or AMIs, the programming process may be complicated by individual differences in auditory percepts such as pitch and the presence of mild nonauditory sensations. For further details on the programming and adjustment of auditory implants, the reader is referred to manufacturer software manuals from the various implant manufacturers (e.g., Cochlear Corporation, Advanced Bionics, and Med-El). Skill and experience are necessary to properly program these devices and to optimize performance.

Modern cochlear implants can allow deafened individuals to communicate so well that it is possible to speak on the telephone with such a person and never suspect he/she has a hearing problem or a cochlear implant. Also, deaf children, implanted at an early age, can develop very good speech and language and be integrated into regular classrooms where they develop academically along with their peers.

X. FUTURE EVOLUTION OF COCHLEAR IMPLANTATION

A. Short Electrode "Hybrid" Implants and Implantation With Residual Hearing

Since the early 2000s, an FDA clinical trial has been under way to examine the usefulness of cochlear implantation in patients with residual low-frequency hearing. This device, termed the "hybrid" cochlear implant, utilizes a shorter electrode than the standard cochlear implant, a 10-mm-length modified device from Cochlear Corporation [37].

Since the electrode is shorter, it stimulates the basal region of the cochlea and hence the high-frequency tonotopic region. The theorized advantage of such devices is to benefit patients with significant low-frequency residual hearing who have lost perception in the speech frequency range and hence have decreased speech discrimination scores. Patients implanted with a hybrid cochlear implant may wear both a hearing aid and a cochlear implant in the same ear [38].

B. Totally Implantable CI

Research is progressing on a totally implantable cochlear implant device that would not require the use of an external processor, microphone, or transmitter coil. This obviously would have tremendous practical appeal. Periodic charging of the device would occur transcutaneously, using a charging module [39]. This technology would also require the implantation of a microphone [40].

XI. CI SUMMARY

Cochlear implantation has undergone major advances since its introduction. Devices continue to become smaller, more technologically complex, and implanted through smaller incisions. Candidacy criteria have also expanded, and children as young as 12 months of age are currently candidates for CIs, with some patients younger than a year being implanted on study protocols.

It is anticipated that CIs will continue to improve as understanding of the auditory system and its stimulation increases. Future developments in CIs include the totally implantable cochlear implant, improved processing strategies to facilitate speech understanding in noisy listening conditions, music appreciation, increasing sound-only word and sentence understanding, and the use of CIs in patients with significant residual hearing.

XII. AUDITORY BRAINSTEM (AND AUDITORY MIDBRAIN) IMPLANTS

House Ear Institute developed the ABI for patients with neurofibromatosis type 2 (NF2) in order to electrically stimulate the cochlear nucleus complex. Cochlear implants, which electrically activate peripheral neural processes within the cochlea, are not an option for patients with NF2 because of their loss of integrity of the auditory nerve due to bilateral vestibular schwanommas (acoustic tumors).

Dr. W. House and Dr. W. Hitselberger first used the ABI in such a patient in 1979 [41]–[43]. The ABI is introduced into the lateral recess of the fourth ventricle (Fig. 3) and placed on the brainstem surface over the area of the ventral and dorsal cochlear nuclei (CN) after tumor removal. The ABI is similar in design and function to multichannel CIs except for differences in the design of the stimulating electrode arrays [44]–[46]. The present Nucleus ABI24 device (Cochlear Corporation, Englewood, CO) uses 21 stimulating electrodes on a 2 × 8 mm pad-shaped array. Med-El also produces an ABI (Pulsar ci100) that has been approved for use in the cochlear nucleus (and inferior colliculus) in European countries.

The programming of ABI (and AMI) devices differs in several important aspects from cochlear implant programming. Due to the close proximity of other nuclei in the brainstem, nonauditory sensations (most commonly mild tingling, dizziness, and eye sensations) are more common with ABIs and must be managed. Also, since multichannel CIs and ABIs were developed to capitalize on the frequency tuning of neurons in the auditory system, variable electrode-specific pitch percepts encountered with ABIs must be evaluated and accommodated.

In multichannel CIs, consistent placement of the electrode carrier and its depth of insertion are assured in normal cochleas. However, in ABI recipients, anatomical landmarks that are used in electrode array placement may be altered or obscured due to the presence of tumors, making accurate electrode array placement more

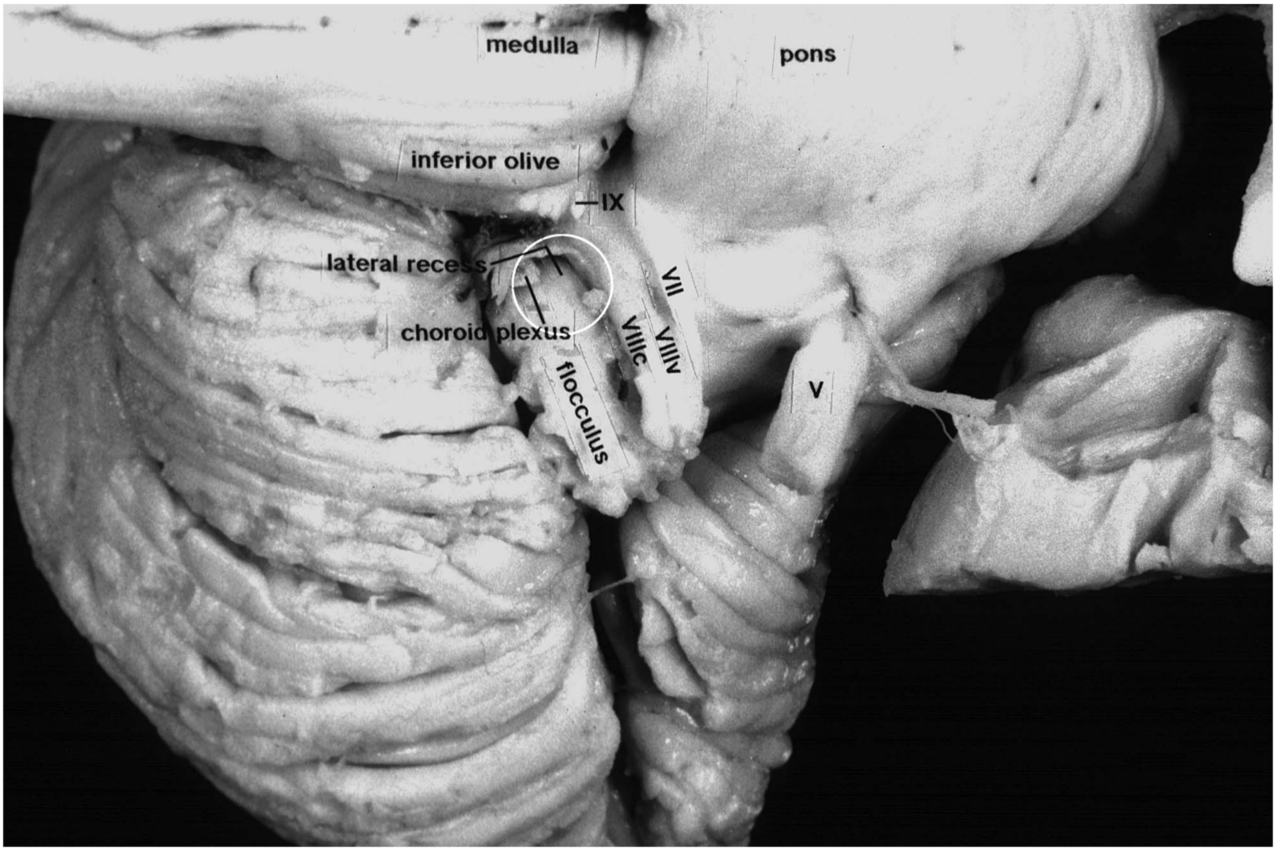

Fig. 3. ***Cadaver preparation showing the lateral recess opening (LR, circled) where the auditory brainstem implant electrode array is placed, as well as nearby neuroanatomical structures used to help identify the LR.***

challenging. Even under ideal circumstances, slight variations in placement occur.

XIII. THE “PENETRATING” ABI (PABI)

The ABI was originally developed to stimulate the CN, the first auditory nucleus in the brainstem, using electrodes that were in contact with the CN surface [44]. In 2003, a clinical study using needle-like penetrating microelectrodes (PABI) was initiated at HEI. The PABI is designed to stimulate the tonotopic interior of the CN [47]. The PABI device has both surface and penetrating electrodes, and the two types can be used in combination. Penetrating microelectrodes have resulted in auditory sensations at lower levels of current than conventional surface electrodes, which potentially could reduce the power requirements of ABI systems.

XIV. AUDITORY MIDBRAIN IMPLANT (AMI)

It is possible that ABI patients who lose their auditory nerve due to tumors have limited performance with the ABI because of damage to the brainstem region either due to the tumor, or during tumor removal. If this is the case, then it may be necessary to bypass this damaged region to provide these patients with good speech recognition. Recently, two projects have investigated the possibility of prosthetic stimulation of the inferior colliculus (IC), an auditory nucleus in the midbrain. The inferior colliculus implant (ICI) places a surface electrode on the IC [48], and the AMI uses a penetrating electrode array to access the deep layers of tonotopic organization within the IC [49]. Both the AMI and ICI have been implanted in NF2 patients as of spring 2007, and the preliminary results are encouraging. Patients hear different pitch sensations on the different electrodes and can use the sounds from the devices to supplement lipreading [48], [50]. At the present time, these patients are not able to understand speech without lipreading, but it is still too early to assess the long-term capabilities of these midbrain implants.

XV. ABI PATIENT SELECTION AT HEI

With two exceptions, only patients with NF2 and bilateral vestibular schwannomas have received the ABI at HEI. In these patients, the goal is to restore some auditory function in order for these individuals to continue to be a part of the hearing world and to improve their quality of life. The ABI may be placed during removal of their first acoustic tumor even if they have hearing on the other side, which is usually the case. This approach allows patients to become familiar with the use of the device and prepares them for when all hearing is lost. Appropriate preoperative counseling is required so that ABI candidates understand the potential benefits and limitations of the device, and the need for regular postoperative testing to keep the device programmed properly to match the changes that usually occur in their hearing over time. We have found that ABI speech perception performance can improve for more than 10 years with regular ABI use [51]–[54].

Other possible indications include bilateral transverse skull fractures and avulsion of both cochlear nerves. More recently, in Europe, the indications for the ABI have included cochlear nerve aplasia and severe cochlear malformations in children and complete ossification of the cochlea or cochlear nerve disruption due to cochlear trauma in adults [55]–[58].

XVI. SURGICAL IMPLANTATION AND THE ANATOMY OF THE COCHLEAR NUCLEUS

The cochlear nucleus complex (dorsal and ventral cochlear nuclei) lies in the lateral recess of the fourth ventricle (Fig. 3). It is partially obscured by the cerebellar peduncles. A surface electrode introduced in the lateral recess crossing the tinea choroidea will stimulate viable cochlear nuclei.

At HEI, we have exclusively used the translabyrinthine approach for placement of the ABI [59]. The translabyrinthine approach provides direct access to the cochlear nuclei. Location of the ventral cochlear nucleus, the main target for placement of the ABI, can be problematic due to individual differences in anatomy and anatomical distortion caused by the tumor. Anatomical placement is confirmed using electrophysiological monitoring. Electrically evoked auditory brainstem responses are elicited by stimulation of the nucleus, and the position of the ABI electrode is optimized using information derived from the monitoring, which is interpreted by an experienced auditory physiologist. Others have used the retrosigmoid approach to implant the cochlear nucleus complex with similar success and results [57].

XVII. RESULTS WITH ABI

A number of articles have been published detailing results obtained using the ABI [42], [45], [51]–[54]. To date, more than 228 individuals have been implanted using this device at HEI, and more than 650 recipients worldwide. Although ABI and PABI devices produce auditory sensations (and often distinctive electrode-specific pitch) for individuals with NF2, high levels of speech recognition without lipreading generally have not been achieved. While ABI recipients obtain an average of 30% improvement in sentence understanding over lipreading alone [51], only about 16% of such recipients at HEI can recognize some words using sound only (an even smaller percentage scoring at 50% correct or better). One exception is that higher levels of speech recognition have recently been observed in ABI recipients who do not have NF2, but who do not have viable auditory nerves as a result of other etiologies [57]. This result suggests that the limited speech-recognition performance of most ABI patients may be related to their etiology and not to limitations inherent in the device or electrode placement.

XVIII. ABI RESULTS IN COMPARISON WITH CIs

HEI now has a small series of patients (four) who have had both CIs and ABIs in the course of their treatment. Two patients have used these devices simultaneously. Fig. 4 shows comparative speech-perception results in such individuals. On average, patients scored somewhat higher on speech perception tests using their CIs than their ABIs; however, one patient scored better with his ABI than his CI, and another patient scored comparably. Also, the figure shows that CI performance in this group did not reach the generally high levels seen in CI recipients without NF-2. Perhaps the cochlear nerve and brainstem pathology observed in NF2 limits what can be achieved with auditory implants both in the cochlea and cochlear nucleus. Vestibular schwannomas have long been known to negatively affect acoustic psychophysical abilities and speech perception.

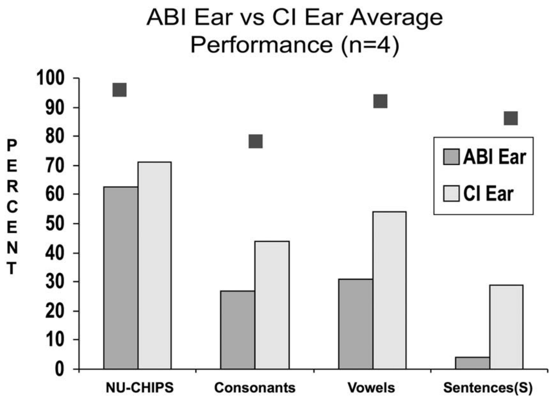

Fig. 4. ***Auditory brainstem implant (ABI ear) versus cochlear implant (CI ear) speech perception performance in 4 individuals with NF2 that have had both devices. The NU-CHIPS test is a four-alternative rhyming monosyllabic word test. All tests were administered in sound only (no lipreading cues). The squares at the top of the graph indicate typical good cochlear implant performance in individuals who do not have NF2.***

XIX. RESULTS USING THE PENETRATING ELECTRODE ABI

The PABI was developed in an effort to improve the precision of stimulation of brainstem auditory neurons and also hopefully improve speech recognition over the regular surface ABI. Patients have generally performed best on speech perception tests when using a speech processor program that combines surface with penetrating electrodes. The two types of electrodes seem to work synergistically, and each offers advantages. Surface electrodes generally create a larger current field that increases the likelihood of activating auditory neurons, ultimately resulting in beneficial hearing sensations.

Penetrating electrodes have generally provided auditory sensations at lower current levels (1-2 nC) than surface electrodes, and they have resulted in a wide range of pitch percepts. In comparison with the larger surface electrodes, however, the incidence of failing to achieve auditory sensations has been higher with penetrating electrodes. Also in some instances, stimulation from penetrating electrodes has reached the maximum charge limit without achieving a comfortable level of sound. The combination of arrays in the PABI was very valuable to one recipient who did not experience any auditory sensations on his surface electrodes. He did receive auditory sensations on six of ten of his penetrating electrodes, and he is now able to use his PABI with benefit.

It is clear that placement of the penetrating electrode array is more critical than the surface electrode array and requires considerable accuracy. A slight deviation (only a millimeter or so) from the target region can result in no auditory responses on penetrating electrodes. The electrical ABR monitoring that is used intraoperatively to assist with placement of the surface ABI array has been of little use in penetrating electrode placement because the microelectrodes do not typically generate a sufficient neural response for detection by scalp monitoring electrodes. Also, NRT, which has been useful in the near-field detection of cochlear nerve action potentials generated by cochlear implants, does not appear to be useful in ABI implantation because of difficulty differentiating auditory from nonauditory action potentials. In postoperative testing with awake patients, NRT waveform morphology often appeared the same regardless of whether patients reported hearing sensations, nonauditory side effects, or no sensations at all [59].

XX. ABI SUMMARY

The ABI is implanted using a translabyrinthine approach into the lateral recess of the fourth ventricle and placed over the area of the ventral and dorsal cochlear nuclei after vestibular schwannoma (acoustic tumor) removal. Most recipients receive beneficial auditory sensations and improve their communication abilities over lipreading only. A small number achieve substantial speech understanding using only ABI sound. ABI recipients typically enjoy using the device regularly and find that it improves their quality of life. One of the most encouraging findings is that ABI recipients, with regular device use, can continue to show improvements in auditory performance for more than ten years after implantation.

XXI. OVERALL SUMMARY

Implantation of the auditory pathways for the purpose of restoring useful hearing has progressed beyond basic cochlear implantation to other sites in the central auditory system. These developments have resulted in considerable benefit to those who previously faced only complete and permanent deafness. CIs now typically provide remarkable performance, and in some instances, so do ABIs. AMI devices are at the fledgling stage; however, it appears that this site of implantation in the midbrain holds promise in the rehabilitation of deaf individuals as well. This progress has been made possible through the cooperative effort of many individuals with wide-ranging specialties working together over many years. It is an outstanding example of how cooperative scientific effort can greatly benefit humankind. ■

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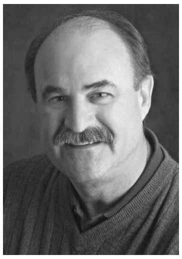

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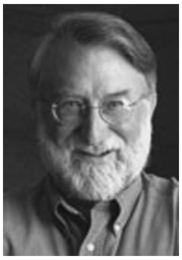

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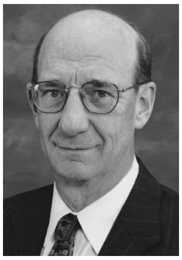

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