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Combined Acoustic and Electric Hearing: Preserving Residual Acoustic Hearing

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Abstract

The topic of this review is the strategy of preserving residual acoustic hearing in the implanted ear to provide combined electrical stimulation and acoustic hearing as a rehabilitative strategy for sensorineural hearing loss. This chapter will concentrate on research done with the Iowa/Nucleus 10mm Hybrid device, but we will also attempt to summarize strategies and results from other groups around the world who use slightly different approaches. A number of studies have shown that preserving residual acoustic hearing in the implanted ear is a realistic goal for many patients with severe high-frequency hearing loss. The addition of the electric stimulation to their existing acoustic hearing can provide increased speech recognition for these patients. In addition, the preserved acoustic hearing can offer considerable advantages, as compared to a traditional cochlear implant, for tasks such as speech recognition in backgrounds or appreciation of music and other situations where the poor frequency resolution of electric stimulation has been a disadvantage.

Keywords

Acoustic Plus Electric (A+E); Cochlear Implant; Sensorineural Hearing Loss

Introduction

In recent years, a novel approach in the treatment of severe high-frequency sensorineural hearing loss has been under investigation. Unlike more long-range goals, such as regenerating hair cells in human patients, this new approach is a modification of already-existing techniques and has already been implemented in over one hundred patients worldwide. The approach involves preserving existing residual acoustic hearing (low-frequency) in an ear to be implanted with a cochlear implant, and then adding electrical stimulation via this cochlear implant for the missing high frequencies to produce speech understanding (and other hearing sensations) via combined acoustic and electric hearing (A+E). In this article, we will review some of the rationale and background for the A+E approach, and briefly summarize some of the published results, including a brief summary of our results to date from the Iowa/Nucleus Hybrid Project, in which 87 subjects have participated in an ongoing FDA clinical trial.

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Limits of Hearing Aid Benefit

The underlying purpose and function of a cochlear implant is to stimulate the auditory nerve directly, replacing the receptor inner hair cells that have been lost. In the case of profound or severe hearing loss, usually few functioning inner hair cells are present in the cochlea and very little, if any, usable speech information can be received through acoustic input to the cochlea; thus hearing aids are not an effective treatment strategy. In these cases, the traditional standard-electrode cochlear implant (approximately 20–25 mm) attempts to replace the function of all, or nearly all, the inner hair cells across the frequency range.

However, most hearing losses are not total, and the severity of hair cell loss usually varies by frequency (location along the basilar membrane) with the basal end of the cochlea most susceptible to hair cell loss. In these cases of partial hearing loss, which speech cues are available to the patient via acoustic stimulation and which are not? This depends upon the type of speech cue and also the severity of hearing loss in each frequency region.

Speech cues can be roughly divided into 3 features that correspond to various actions in the vocal cords or vocal tract when a speech sound is produced. The 3 features are: Voicing, Manner and Place. Voicing cues are the presence or absence of periodic vocal fold vibrations and are signaled by the overall intensity of the speech sound, which is dominated by the low-frequency regions of the spectrum. Examples of a voiced versus un-voiced consonant sound pair is /z/ versus /s/. Manner cues involve the timing, intensity and the frequency of speech sounds, and signal the general mechanism of producing the speech sound. For example, some different “manner” categories are fricatives, stop consonants, or nasals. Manner cues are generally located across the broad frequency spectrum of speech. Place cues, otherwise known as “place of articulation” cues are specifically related to the position of the tongue and other movable parts of the vocal tract. These movable articulators determine the shape of the short-term speech spectrum (i.e., formants, bursts, etc) and are signaled by the specific frequency locations of spectral peaks. Two consonant sounds that differ in the place feature are /b/ versus /d/. Place of articulation cues are generally located in mid- to high- frequency regions of the spectrum.

Research in animals with hearing loss has shown that losses less than approximately 60 dB usually involve primarily outer hair cells, which are responsible for sensitive thresholds and narrow frequency tuning. When sensorineural hearing loss begins to exceed approximately 60 dB, substantial inner hair cell loss is present (Lieberman and Dodds, 1984). However, even severely hearing-impaired patients can perceive voicing cues, since they are generally signaled by low-frequency intensity differences. If the low-frequency speech is amplified to be above threshold, even a few functioning inner hair cells should be capable of transmitting these general intensity cues. On the other hand, the place of articulation cue is difficult for most listeners with severe to profound high-frequency hearing loss, since substantial inner hair cell loss prevents the cochlea from transmitting the frequency cues (presumably via place coding) to the brain. Speech recognition research in patients with varying degrees of hearing loss by Hogan and Turner (1998), Ching et al. (1998) and Turner and Brus (2001) supports these conclusions. Vickers et al. (2001) refers to these regions of inner hair cell loss as “Dead Regions” and has also shown that speech recognition is affected. Thus a severe to profound high-frequency hearing loss often cannot be successfully remedied by simple amplification.

Shortcomings of Electrical Stimulation

The current generation “standard-electrode” cochlear implants are capable of providing very high levels of speech understanding (in quiet backgrounds) to many patients. Although not all patients implanted with these devices do as well as the top performers, this is usually not a fault of the device, but rather related to patient characteristics such as duration of deafness and/or pre-operative cochlear status (Rubinstein et al., 1999). One might reasonably ask then, why

not just implant every patient with a long-electrode if they are not receiving an acceptable level of assistance from a hearing aid? The arguments against this strategy arise from some apparent shortcomings of the present techniques for electrical stimulation of the auditory system. These shortcomings are a direct result of the limited ability of cochlear implants to provide adequate frequency resolution (i.e. spatial selectivity along the cochlear array) necessary for some special listening situations.

In quiet backgrounds, Shannon et al. (1995) has shown that a few as 3–4 independent frequency channels of speech information are adequate for high levels of speech understanding. Thus for the entire speech range, which is approximately 200–8000 Hz, each channel can encompass nearly 2 octaves. Fishman et al. (1997) demonstrated that the top-performing cochlear implant users are receiving at least these 3–4 independent channels of stimulation from their devices. However, once a noise background is present along with the target speech (certainly a common situation in the real world), the requirements for frequency resolution increase dramatically. Fu et al. (1998) demonstrated that performance in noise kept improving as more channels were added for normal-hearing listeners listening to cochlear implant simulations, even as many as 16–20 channels. However, even the top-performing implant users could not take advantage of more than 6–8 channels of electrical stimulation (Friesen et al., 2001), presumably due to spatial interactions between channels within the cochlea for electrical stimulation. Nelson et al. (2003) showed that implant users have tremendous difficulty in recognizing speech when the competing signals are speech or speech like in nature, and that the culprit is reduced frequency resolution. When the background is other competing talkers, the frequency resolution requirements can be even more demanding (Qin and Oxenham, 2003), as better frequency resolution allows listeners to separate the various talkers.

Henry et al. (2005) directly compared the behaviorally measured frequency resolution of normal-hearing, hearing-impaired and cochlear implant listeners in a task requiring the discrimination of spectral peaks in a broadband stimulus. Normal-hearing listeners had the best frequency resolution, followed by listeners with sensorineural hearing loss, and the poorest resolution was observed in implant users. In normal-hearing listeners, exquisite frequency resolution is provided by the fine tuning of the basilar membrane and the function of the outer hair cells. Some additional frequency resolution may even be provided by as yet unknown temporal coding mechanisms as well (e.g., Loeb et al., 1993). In listeners with hearing impairment, the outer hair cells are usually damaged, but moderate frequency resolution is still provided by the passive vibration patterns of the basilar membrane. In the implant listener, who listens through electrical stimulation with no involvement of the basilar membrane, the frequency resolution is even poorer.

The same subjects who were tested in Henry et al. (2005) were also tested in their ability to understand speech in competing backgrounds. The two types of backgrounds used were 1) steady-state speech spectrum noise and 2) two competing talkers. The spondee target words were, in the absence of a background, quite easy for all subjects to recognize (see Turner et al., 2004 for details on these methods). Thus the test primarily measures the ability of the subject to resist a competing background noise, rather than an overall ability to recognize speech in general. The signal-to-noise ratio (in dB) at which each subject could correctly recognize 50% of the target words is the dependent measure. In Figure 1 (from Turner, 2006), the results of normal-hearing, sensorineural hearing loss and cochlear implant subjects are plotted for both types of background. The listeners with sensorineural hearing loss are sorted according to their average pure-tone thresholds. It is clear that the speech recognition in noise results for the three groups of subjects follow the pattern of results seen in the Henry et al (2005) frequency resolution study, with finer frequency resolution linked to an increased ability to resist the masking effects of background noise. Two particularly striking aspects of these data also appear. First, compared to normal-hearing listeners, the cochlear implant users have

tremendous difficulty in understanding speech in noise (similar to the results of Nelson et al. 2003 and Friesen et al. 2001). This is particularly evident for the competing-talkers background. Second, even the listeners with severe sensorineural hearing loss are able to resist competing backgrounds better than the cochlear implant listeners, presumably due to their better frequency resolution abilities.

Normal-hearing listeners show a large advantage for the competing talkers condition, because they can take advantage of various cues that allow them to separate (or "stream") the multiple sound sources allowing them to focus on the target speech (Duquesnoy, 1983). These can involve pitch, timing, and in some situations, localization cues. Cochlear implant listeners, on the other hand, are presumably unable to perceive some of these cues, making the competing-talker situations particularly difficult for them since they may not be able to segregate the various talkers. Instead the competing talkers may serve as a type of "informational masking", where the linguistic content of the background talkers is confused with the target speaker's content (Brungart, 2001). The fluctuating and irregular nature of the competing talker background also allows for normal-hearing listeners to potentially listen for the target speech in the temporal and spectral "dips" of the background. While implant listeners are not generally known for temporal acuity deficits (Shannon, 1990), their poor frequency resolution would impair their ability to listen in spectral "dips" as compared to normals. Nelson et al. (2003) and Qin and Oxenham (2003) demonstrated that reducing the frequency resolution of speech presented to normal-hearing listeners produced deficits in speech recognition in fluctuating backgrounds similar to those observed in cochlear implant listeners. Thus, the primary deficit of cochlear implant listeners in resisting the effects of competing background signals when listening to speech appears to be related to the poor frequency resolution provided by current electrical stimulation devices.

Another consequence of poor frequency resolution in cochlear implants is seen when the listening task involves the perception of pitch as the primary task. Certainly listening to music is one situation where implant listeners have been shown to have severe perceptual deficits (e.g. Gfeller et al, 2002; Kong et al, 2004). For example in Gfeller et al (2002), while normal-hearing listeners had no difficulty in discriminating piano notes one semitone apart (adjacent piano keys, approximately 6% frequency difference), implant listeners' ability to discriminate pitches was generally much poorer, the typical threshold was 1/2 octave (6 semitones), with some listeners requiring as much as 2 octaves difference between notes for discrimination. This poor pitch perception affects the typical implant patients' ability to recognize melodies.

Some Asian languages use tonal cues (variations in fundamental frequency) for word identity. These are called Lexical tones and they are found in Mandarin and Cantonese. It would be expected that poor pitch discrimination (i.e. poor frequency resolution) would affect the ability of implant listeners to correctly identify these tonal speech sounds. However, in one study (Fu et al., 1998), subjects who were native speakers of Mandarin could identify lexical tones, despite pitch information that was limited by simulated cochlear implant processing. Fu et al. concluded that, along with the tonal cues for these sounds, distinguishing temporal envelope cues were also present, and that listeners were able to rely on these. A study by Xu et al. (2002) supported this explanation when they found that temporal cues could compensate for reduced spectral cues in Mandarin tonal patterns for subjects listening to cochlear implant simulations with varying degrees of temporal and spectral resolution. In contrast, other researchers such as Ciocca et al. (2002) have found that for the Cantonese language, where pitch cues are not typically supplemented by temporal cues, cochlear implant listeners showed a distinct deficit in recognizing these lexical tones, with only a few patients able to score above chance levels.

Intonation cues for speech recognition are also present in other languages such as English, but at the suprasegmental level, for example the distinction between a statement and a question in a sentence. Peng et al. (2007) measured the perception of intonation cues by normal-hearing and cochlear implant listeners and found that, on average, the implant listeners could distinguish only half as many of the question-statement pairs as normal-hearing listeners. This finding should remind researchers to consider that the speech communication abilities required in many real-world situations go beyond simple identification of the words themselves.

In summary, the poor frequency resolution abilities of the vast majority of traditional cochlear implant patients appear to be a major remaining hurdle in improving the listening abilities of these patients. Some of the deficits that implant patients suffer from in their everyday life are not revealed by employing simple word-list-in-quiet testing. It is also interesting that the frequency resolution provided by acoustic hearing, even when there is a severe hearing loss, is often better than that provided by a cochlear implant. For these reasons, preserving residual acoustic hearing in patients who will receive a cochlear implant has some potential advantages.

Preservation of Hearing following Cochlear Implant surgery

Can acoustic hearing be preserved following the implantation of a cochlear implant? One well-known and obvious case is when the contralateral ear has usable hearing and implantation is monaural; this topic will be reviewed very briefly in the next section. More recently, however, preservation of residual acoustic hearing in the implanted ear has received attention. Preservation of hearing within the implanted ear has been reported in several animal studies from the 1990's. Ni et al. (1992) found that placement of a short electrode in animals did not induce additional tissue damage distal to the region of the electrode. Xu et al. (1997) reported similar results. Maintenance of near-normal click evoked ABR thresholds in the majority of cochleae in these studies suggested that hair cells, at least apical to the implanted electrode array, not only survive, but also can function at a near normal sensitivity.

Moderate hair cell survival has also been documented in a human temporal bone that was implanted with a long intracochlear electrode seven months prior to the subject's death (Zappia et al., 1991). Hodges et al. (1997) reported that one-half of patients examined following implantation with a cochlear electrode had at least some behavioral response to acoustically-presented tones. Von Ilberg et al. (1999) reported preservation of hearing in a human patient following implantation of a standard long-electrode device, and that, although poor, the residual acoustic hearing was capable of understanding speech above chance levels. Also in the late 1990's, our group at the University of Iowa began implanting a newly designed cochlear implant with a modified intracochlear electrode that was much smaller in diameter and 6mm in length, in subjects with usable residual low-frequency hearing. Based on these early reports of preservation of hearing following implantation, a number of centers have specifically attempted to preserve residual hearing in implanted ears of their patients.

Some groups have attempted to preserve residual acoustic hearing using a standard-length electrode that is partially inserted into the cochlea, combined with "soft surgery" techniques designed to minimize trauma. Gstoeftner et al. (2004) described full or at least partial preservation of hearing in 18 of 21 patients using this technique. Kiefer et al. (2005) reported that at least partial preservation of hearing was accomplished in 11 out of 13 patients. The mean threshold change for those 11 patients was approximately 15 dB at the lower frequencies, while the remaining 2 patients suffered essentially total losses. James et al. (2005) reported approximately an average of 25 dB loss in the lower frequencies for 12 patients implanted with a long electrode, including the data for two patients who suffered total losses. James et al. (2006) followed up with additional data, showing that 10 out of 37 patients initially had residual

hearing preservation immediately following surgery; several months later, this number had decreased to 7.

Another approach to preservation of hearing in the implanted ear has been to use a specifically-designed “short electrode” (The Iowa/Nucleus Hybrid device) which is 10 mm in length. Using this approach, Gantz et al. (2006) reported preservation of hearing initially after surgery in 47/48 patients; an additional two patients lost hearing a few months following surgery. Like the reports of James et al., it seems that the loss of residual hearing can occur several months after surgery. The underlying reasons for a delayed loss of hearing are unclear at this time. In general, a 15–30 dB loss of low-frequency acoustic hearing in the implanted ear did not usually affect the patients’ acoustic speech discrimination; the amplification provided by a hearing aid was sufficient to restore acoustic speech understanding to pre-operative levels. In summary, the short electrode approach may offer better preservation of acoustic hearing than more invasive devices; the potential downside of this approach is that the electric stimulation provided by the shorter device may not be capable of providing as much information to the auditory nerve as a longer electrode array. However, some evidence, reviewed in a subsequent section of the present article, suggests that this may not necessarily be the case.

Hearing Aids in the Contralateral Ear

As the eligibility criteria for implantation has expanded, more cochlear implant recipients have various degrees of usable hearing in the contralateral ear. Thus these patients have the opportunity of combining acoustic plus electric hearing. In the present article, in which our primary task is to review preservation of hearing in the implanted ear, we will briefly summarize the topic of contralateral hearing only to the extent that it reflects upon the potential benefits of combined acoustic and electric hearing. In these contralateral ear studies, the patients were implanted with a standard-length electrode in one ear, and generally used a hearing aid in the contralateral ear. Dooley et al. (1993) reported benefits from providing amplified (and signal-processed) speech to the contralateral ear. Mok et al. (2006) reported benefits when amplification was provided to the contralateral ear for approximately one-half of their 14 subjects. Interestingly, they also reported several instances where the addition of the acoustic stimulation actually decreased performance. Presumably, some sort of interference between the two presentation modes was occurring. Kong et al. (2005) measured the benefits of this arrangement in several subjects. The contralateral (acoustic) ears did have measurable pure-tone thresholds, however speech presented to these ears could not be recognized. Nonetheless, when compared to listening with the cochlear implant alone, the combined condition achieved better speech recognition in backgrounds, presumably because the acoustic hearing assisted in the separation of target voices from background due to its more precise pitch perception. Similar results, only with a much larger group of subjects, are reported in Ching et al (2006). Some additional advantages of the combined mode were also reported; however, they were related to overcoming head shadow effects when listening through two ears. The acoustic ear was found to also contribute to speech recognition in quiet by providing some low-frequency speech information in Ching et al. (2001); the low-frequency acoustic hearing provided increased perception of voicing and manner, which, as discussed previously, are dependent upon low- and mid-frequency cues. Gifford et al. (2007) reported similar advantages in speech recognition from acoustic hearing contralateral to the implanted ear. They also reported that speech recognition for these patients (listening with both ears) was generally comparable to the published results from other studies where patients had preserved acoustic hearing in the implanted ear and listened in the A+E mode. One factor to keep in mind when reviewing these studies is the hearing status of the acoustic contralateral ear. If, as is often the case, the ear contralateral to the implant is the “better” ear, then improved speech recognition performance in the binaural condition may have little to do with combined acoustic plus electric hearing, and instead be primarily a reflection of the better ear’s status. Even when this factor

is taken into account, the evidence is clear that combining acoustic and electric hearing across ears can provide a substantial advantage for many patients.

A+E results for Speech Presented in Quiet

When evaluating the success of the A+E (in the implanted ear) approach in actual patients, several factors need to be considered. The first is that making comparisons across various devices, clinics, or patient populations is potentially confounded by numerous uncontrolled variables. The degree of residual hearing in each patient can certainly influence the A+E speech recognition score, with very low Acoustic-alone scores perhaps indicating poor nerve survival, and high Acoustic-alone scores limiting the potential for improvement that the added electrical stimulation can provide. Thus some of the earliest patients' data for A+E listening, who often had little residual hearing pre-operatively, may not represent the best performance that the A+E approach has to offer. On the other hand, there certainly will be an "upper limit" to the degree of pre-operative acoustic hearing that would qualify for implantation surgery. As Rubinstein et al. (1999) and others have demonstrated, the success of electrical stimulation is also strongly influenced by such variables as duration of deafness, etiology and pre-operative speech recognition abilities. Thus different patient selection criteria across studies can strongly influence the outcome measures and uncontrolled comparisons across studies or devices are most likely not valid. Recent data from the FDA Iowa/Nucleus Hybrid clinical trial suggests that those with more than 35 years of severe-profound hearing loss above 2000 Hz often do poorly with the added electric stimulation, suggesting that they may not have sufficient ganglion cell survival in the base of the cochlea to be able to take advantage of a 10-mm electrode.

Second, merely showing an increase in speech recognition performance above the acoustic-alone pre-operative score when the electrical stimulation is added does not, by itself, validate the A+E approach. The combined score must also be better than the electric-alone score, in order to demonstrate that preserving residual hearing was beneficial. A third caution in interpreting these data is that although monaural testing of the implanted ear by itself is a logical measure of the success of the same-ear A+E approach, in real life, many patients actually listen through both ears, and the speech cues can presumably be combined across ears, as discussed in the preceding section on Hearing Aids in the Contralateral Ear. The contribution of the contralateral ear often depends on whether the poorer or better ear was chosen for implantation, which could serve as a confounding factor when using binaural data for comparison. Keeping these possible complications in mind, the results of some published studies on A+E speech recognition in quiet are briefly reviewed below.

Von Ilberg et al. (1999) reported the speech recognition in quiet results for one patient implanted with a long electrode inserted 20mm into the cochlea who had some preserved residual hearing 2 months following implantation, this patient's sentence recognition scores were 7% with the acoustic hearing alone, and increased to 56% with the addition of electric stimulation. Interestingly, sentence recognition with the CI alone was only 2%, suggesting a strong synergistic effect of the two modes of stimulation. Gantz and Turner (2003) reported results from a group of 6 A+E patients, 3 implanted with a 6mm electrode and the remainder with a 10mm electrode. The 6mm-electrode patients demonstrated approximately 10 percentage points improvement in the recognition of consonants with the addition of electric stimulation, whereas the patients implanted with the 10mm device improved nearly 40 percentage points. The greatest improvement was noted for the perception of the speech feature place of articulation, which is in agreement with the high-frequency range of speech information assigned to the short-electrode. These authors also noted a strong effect of experience following implantation, with some patients continuing to improve as long as 10 months following implantation.

Skarzynski et al (2003) described the speech recognition results for one patient listening under A+E conditions after being implanted with a long electrode of 20 mm insertion depth. Monosyllabic word scores increased from 25% (acoustic alone) to 90% (A+E). The electric-only score was 23%, again suggesting a strong synergistic effect for this patient. Gstoeftner et al. (2004) reported speech results for one patient implanted with a 22mm electrode who improved from 38%-recognition of monosyllables in the acoustic-only mode to 90% with the addition of electric stimulation.

Kiefer et al. (2005) reported monosyllabic word understanding a group of 11 patients with preserved residual hearing. Mean acoustic-alone scores were 7%-correct, and the addition of electric stimulation increased this to over 60%, with several patients showing scores increasing to over 75%. Of these 11 patients, only 4 obtained A+E scores higher than the electric-alone score, suggesting that for many patients, the electric stimulation was providing the primary contribution to speech understanding.

James et al. (2006) reported word recognition scores for 7 subjects whose residual hearing was preserved 6 months postoperatively to 60 dB HL or better at the low frequencies. The mean pre-operative score was 22%, CI-alone score 6 months after surgery was 56%, and combined A+E scores averaged 68%. For two of these subjects, the implant-alone score was equal to the A+E score, suggesting that the bulk of speech recognition was provided by the electric stimulation. At the other end of the spectrum, in two other patients, the implant provided little or no speech recognition alone, nor did it provide an increase over the acoustic-alone score in the A+E condition. These two patients had long durations of deafness prior to implantation.

Gantz et al. (2006) reported the preliminary results of 47 subjects enrolled in the FDA multicenter clinical trial of the Iowa/Nucleus Hybrid 10 mm implant. Nineteen subjects had 9 months of experience with their device and 16 of these demonstrated significant improvement with the addition of the implant when listening with both ears (combined mode). A group of 11 subjects had 12 months of experience and averaged 72% correct on the CNC word test in the combined mode compared to 32% CNC word understanding with 2 hearing aids preoperatively. It was also interesting to note that one subject who lost almost all acoustic hearing 4 months postoperatively more than doubled his preoperative word understanding score and achieved 69% correct using the Hybrid implant in one ear and his acoustic hearing in the other. Four of the 47 subjects did not derive benefit from the combined acoustic plus electric speech processing.

In Reiss et al. (2007b), we reported results using /aCa/ consonant speech materials. 25 patients who have used the short-electrode (Hybrid) device for at least 12 months were tested. The mean acoustic alone scores were 44%-correct; after 12 months of implant use, the addition of electric stimulation increased the scores to 58%, after 24 months the score increased to 62%. The range of improvements across patients was from 0 to nearly 60 percentage points. The mean electric-only score was 38% for these consonants at 12 months of implant use.

It was also interesting to note in the Reiss et al. data that many short-electrode subjects continued to improve their performance as measured when listening thru the implant alone. After 24 months of implant experience, the mean score was 51%-correct for electric-only speech recognition, with several individuals scoring over 70%-correct on this rather difficult consonant test. These average scores compare very favorably to the best long-electrode patients measured on the same consonant test, and the best short-electrode patients actually score above the range observed in long-electrode patients. Although patient selection criteria are different between the two groups (with Hybrid patients having more residual hearing), it is still quite interesting to see that very high recognition scores are possible even with a short (10mm insertion, 6 channels in the distal 6 mm) electrode. Reiss et al. (2007b) hypothesize that these

patients are capable of learning a highly compressed and shifted frequency map over time and that this may correspond to a perceptual change over time in the pitch sensation associated with each electrode (Reiss et al., 2007a).

A+E Results for Speech in Noise

Turner et al. (2004) demonstrated, using simulated Hybrid processing of speech presented to normal-hearing subjects, that high-frequency electrical stimulation along with acoustic low-frequency hearing (as compared to full speech range electric stimulation alone) had the potential to provide a significant advantage for understanding speech in background noise, particularly when the competing signal was other talkers. As shown by Qin and Oxenham (2003), better frequency resolution aids the recognition of speech in backgrounds; and the Turner et al. findings demonstrate that improving frequency resolution in only the low-frequency speech region can show this advantage. Turner et al (2004) also tested three Hybrid patients using speech in backgrounds. When those three subjects were compared to a group of long-electrode patients (whose speech scores in quiet were matched to the Hybrid subjects), a significant advantage was observed.

Gstoettner et al. (2004) reported results from one A+E patient tested on sentence recognition in noise. Performance was best for the A+E condition, as compared to either the acoustic-alone or electric-alone condition. Kiefer et al (2005) updated this report with speech-in-noise data from a total of 12 patients showing a significant improvement (as much as 60 percentage points) for 7 of the 12 patients when listening in the A+E mode as compared to the acoustic-alone or electric-alone mode.

James et al. (2006) reported recognition scores for words presented in a multitalker babble for 7 A+E patients. A substantial advantage for A+E stimulation as compared to either acoustic-alone or electric-alone was found on average for the seven subjects.

In Turner et al. (2007) a Hybrid subject group was tested for speech recognition in competing talkers. The speech-in-background test used was the same as described earlier in Figure 1. The group consisted of 19 individuals who had been previously implanted with the 10-mm Nucleus Hybrid electrode and had preserved residual low-frequency hearing (within 30 dB of pre-operative values). All had worn their device for at least 6 months. Their low-frequency residual hearing ranged from mild-moderate hearing loss to severe-profound. The Hybrid group mean speech recognition scores for consonant recognition (in quiet) was 62%-correct (range 32–85%), when they were listening using the acoustic and the electric hearing in the implanted ear only. Two additional Hybrid patients who lost significant amounts of acoustic hearing post-operatively (> 30 dB) were also included in some analyses. A long-electrode group was used as the comparison. It consisted of 20 traditional implant users who had been implanted previously and had worn their device for at least 2 years. Their average consonant recognition score was 47%-correct when using only the implanted ear. A subgroup of the top-performing individuals was selected from the larger long-electrode group for some comparisons. This smaller (n=11) comparison group was selected from the larger group in order to match the speech recognition in quiet abilities of the Hybrid group. Subjects were chosen starting with the highest-performing long-electrode user of the larger group on the same consonant recognition task and proceeding downward until the group mean score matched the Hybrid group. This top-performing long-electrode subgroup's mean speech recognition scores (implanted ear only) for the consonant recognition task was 61%-correct (range 45–74%).

When the speech in noise performance for the Hybrid users is compared to the larger group of long-electrode users, there is a considerable advantage for the Hybrid users. The larger (n=20) long-electrode's group mean SRT was +6.7 dB, and the Hybrid group was –2.3 dB, for an advantage of 9 dB. In this comparison, the “electric-only” speech recognition of the two groups

was nearly equivalent (47% vs. 44%), however it is likely that the large long-electrode group included some subjects with poor nerve survival or other negative eligibility factors that the Hybrid group did not contain, so this advantage is most likely overstated in this particular comparison.

The speech in noise performance for the Hybrid subjects was also compared to the smaller “matched” group of 11 long-electrode users. As noted above, the mean SRT (signal-to-noise ratio) for the matched Hybrid group of 19 subjects was -2.3 dB, whereas the smaller select long-electrode comparison group mean was 1.9 dB, for a mean advantage of 4.2 dB. The distribution of individual SRT values for this comparison is displayed in Figure 2. The individual results also show that for a few Hybrid individuals, SRT values were considerably better than any of the long-electrode subjects. Keep in mind that these two groups had equivalent speech recognition in quiet (when Hybrid users were allowed to use both electric and acoustic hearing). It should be noted that even though these two groups were matched for speech scores in quiet, other potentially important factors could not be matched, such as audiograms in the implanted ear (due to the different criteria for implantation between the two types of electrodes). With these cautions in mind, these results appear to further support the value of preserving residual low-frequency acoustic hearing during cochlear implantation for the recognition of speech in a background of other talkers. It is likely that the better frequency resolution of the low-frequency residual acoustic hearing, as compared to electrical stimulation via an implant, accounts for this advantage.

How much residual acoustic hearing is worth preserving?

Also of practical interest is to examine how much residual low-frequency hearing is required to provide the advantage for speech in a background over the traditional long-electrode strategy. Kong et al. (2005) showed that residual hearing in the contralateral ear could assist cochlear implant users in understanding speech in background noise, even when that contralateral ear was not capable of speech recognition by itself. In Figure 3, the filled squares represent the SRT values for each of the 19 Hybrid subjects plotted as a function of their pure-tone acoustic thresholds (average of 125, 250 and 500 Hz). In addition, two open-circle data points are included; these are 2 Hybrid patients whose residual hearing shifted more than 30 dB following implantation. Looking at just the subjects with preserved residual hearing (filled squares), the relation between thresholds and SRT is mild ($r = 0.36$, not quite significant at $p > .05$). If the two additional subjects (open circles) are included, the correlation becomes significant ($r = 0.56$; $p < .05$). There are two dashed horizontal lines in the graph as well. The upper represents the mean SRT value ($+6.7$ dB) for the larger group of long-electrode patients ($n = 20$); the lower line represents the mean SRT value ($+1.9$ dB) for the select, matched group of long-electrode patients shown in Figure 3 ($n = 11$). A regression line drawn through all the data points suggests that, on average, the advantage of preserving residual hearing exists unless the hearing loss approaches profound levels, although there is only one data point for hearing losses greater than 75 dB HL. Additional data in this range of hearing loss would be helpful. However, the eligibility criteria for the Hybrid do not permit recruiting such patients, and such data will most likely have to come from the occasional patients who exhibit a shift in their hearing after implantation, or perhaps from long-electrode patients who have preserved hearing.

A+E Results for Music

As mentioned previously, the generally poor frequency resolution and pitch perception of the traditional cochlear implant can lead to deficits in music perception. While implant listeners generally are quite good at perceiving the rhythmic cues in music (Gfeller et al., 1998; Kong et al., 2004; McDermott, 2004), their recognition of melodies is usually much poorer than normal, especially when the rhythmic or lyrical cues are not available (Gantz et al., 2005; Kong

et al. 2004; Gfeller et al., 2002). The residual low-frequency acoustic hearing of A+E patients can provide assistance in pitch perception in these patients. Gfeller et al. (2006) tested normal-hearing, traditional long-electrode, and Hybrid (short-electrode) patients on melody and instrument recognition and found that Hybrid patients were nearly as accurate as normals for melody recognition, whereas the long-electrode patients performed very poorly. For instrument recognition, the Hybrid patients did show a deficit compared to normals, but this was primarily for instruments in the higher-frequency ranges, where the signal was transmitted via the cochlear implant rather than the acoustic hearing.

Summary and future questions

The preservation of residual hearing has been shown to be practical and effective solution for severe high-frequency hearing loss. It can overcome some of the inherent disadvantages of traditional, electric-only, long-electrode cochlear implantation. These advantages of the A+E approach are primarily a result of the better frequency resolution provided by the residual hearing as compared to electric stimulation. Thus the advantages of the A+E approach are most evident in situations where frequency resolution is important, such as recognizing speech in backgrounds and music perception.

The clinical trials of A+E patients are still in their early years; therefore the issue of long-term success rates still deserves attention. How stable are residual acoustic hearing thresholds over longer periods of time? Yao et al. (2006) retrospectively looked at the changes in thresholds over time of non-implanted ears that had audiograms that at one time fit the criteria for the short-electrode. They found that in adults, low-frequency thresholds were relatively stable and consistent (changing only 1-dB per year over periods as long as 25 years), however for children the rate of hearing loss was generally larger and much more variable across patients. Future research looking at the stability of low-frequency thresholds in actual A+E patients over long periods of time remains a project for the future.

The “optimal” length of the implanted electrode for A+E patients is also a matter of debate. Although it would seem to be a logical assumption that longer electrodes would present more risk to residual hearing, this has not been conclusively demonstrated. Hearing preservation must be balanced against the possibility that shorter electrodes may (or may not) provide as much information to the auditory system as a longer electrode, particularly in the few unfortunate cases where residual acoustic hearing is not preserved. It is possible however, to successfully reimplant those few who do not benefit from a short electrode with a standard length implant (Fitzgerald et al, 2007). In addition, future developments in electrode design or surgery may serve to reduce the risk of damage for any electrode insertion.

In a somewhat related issue, the ability of the auditory system to adapt to mismatches in the frequency-place map may influence the choice of electrode length. Longer electrodes would theoretically offer a better opportunity to present low- and mid-frequency information to the “proper” place along the cochlea. However, the ability of implant listeners to adapt to new frequency maps (Fu et al, 2002), and the changes in pitch perception over time observed in short-electrode patients (Reiss et al, 2007) suggests that this may not be a crucial issue. The Hybrid patients in the Iowa studies continue to improve their performance over periods as long as 2 years; this is longer than typically observed in traditional long-electrode patients, and suggests that: 1) the stimulation pattern currently provided to these patients is not optimal to begin with, and 2) over time, the auditory system does adapt itself at least to some extent over time. Further research in this area is certainly needed.

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Figure 1.

The signal-to-noise ratio (in dB) for 50%-correct recognition of spondee words in competing backgrounds of steady noise or competing talkers. Subjects are sorted according to degree of hearing loss (average of 500, 1000 and 2000 Hz) and also if they are listening through a traditional long-electrode cochlear implant. Figure reprinted with permission (Turner. C.W.; *Audiol Neurotol*; 2006; 11:2–5) courtesy of S Karger AG, Basel.

Figure 2. Distribution of SRT (signal-to-noise ratios) values for the Hybrid group and the smaller, matched long-electrode group. From Turner et al. (2007).

Figure 3.

SRT (signal-to-noise ratios) for the recognition of spondees in competing talkers as a function of the low-frequency average pure-tone thresholds. The two dashed lines at the top represent the average long-electrode SRT values for the large, unselected group ($n=20$) and the smaller, matched group ($n=11$). Open symbols represent the subjects who lost residual hearing. From Turner et al. (2007).