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Research Paper

The cochlear implant and possibilities for narrowing the remaining gaps between prosthetic and normal hearing

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Abstract *Background:* The cochlear implant has become the standard of care for severe or worse losses in hearing and indeed has produced the first substantial restoration of a lost or absent human sense using a medical intervention. However, the devices are not perfect and many efforts to narrow the remaining gaps between prosthetic and normal hearing are underway.
Objective: To assess the present status of cochlear implants and to describe possibilities for improving them.
Results: The present-day devices work well in quiet conditions for the great majority of users. However, not all users have high levels of speech reception in quiet and nearly all users struggle with speech reception in typically noisy acoustic environments. In addition, perception of sounds more complex than speech, such as most music, is generally poor unless residual hearing at low frequencies can be stimulated acoustically in conjunction with the electrical stimuli provided by the implant. Possibilities for improving the present devices include increasing the spatial specificity of neural excitation by reducing masking effects or with new stimulus modes; prudent pruning of interfering or otherwise detrimental electrodes from the stimulation map; a further relaxation in the criteria for implant candidacy, based on recent evidence from persons with high levels of residual hearing and to allow many more people to benefit

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from cochlear implants; and "top down" or "brain centric" approaches to implant designs and applications.

Conclusions: Progress in the development of the cochlear implant and related treatments has been remarkable but room remains for improvements. The future looks bright as there are multiple promising possibilities for improvements and many talented teams are pursuing them.

Introduction

I had the distinct privilege and honor to present the opening keynote (and plenary) address for the *10th Asia-Pacific Symposium on Cochlear Implants and Related Sciences (APSCI 2015)*, which was held in Beijing from April 30 through May 3, 2015. Some weeks later, Fan-Gang Zeng kindly asked me to contribute a brief synopsis of the lecture for publication in *The Hearing Journal*, which I did.[1] The synopsis (similar to an extended abstract) was indeed short and included only two figures from among the 16 images ("slides" prior to the advent of PowerPoint) that were presented. The purpose of the present paper is to provide a full exposition of the lecture, as it was presented and including nearly all of the figures.

The lecture began with the photo shown here in Fig. 1. With the photo I recalled with the greatest fondness a trip Fan-Gang, Steve Rebscher, Bob Shannon, Gerry Loeb, and I made in 1993 to participate in the *Zhengzhou International Symposium on Electrical Hearing and Linguistics*, which I believe was the first conference of its type in China. Approximately 130 persons attended the conference. Fan-Gang, Steve, Bob, and I are shown in the photo, one that brings back happy memories indeed, including memories of all the wonderful people we met at the conference and our marvelous tour of China afterward.

Everyone in the photo was at the *APSCI 2015*, which was a lovely reunion for us. We noticed that we are a bit younger in the photo!

1993 was at about the time that new and highly effective processing strategies were introduced into clinical practice and after implants with multiple sites of stimulation in the cochlea had been developed. 1993 was near the clear onset of what later would prove to be an exponential growth in the number of implant recipients worldwide, a growth that continues to this day (Fig. 2).

The cochlear implant (CI) is by far the most successful neural prosthesis to date, both in terms of restoration of function and the number of people helped. Indeed, the CI has become the foremost model for the development or

Fig. 1 Fan-Gang Zeng, Steve Rebscher, Bob Shannon, and Blake Wilson in China in 1993.

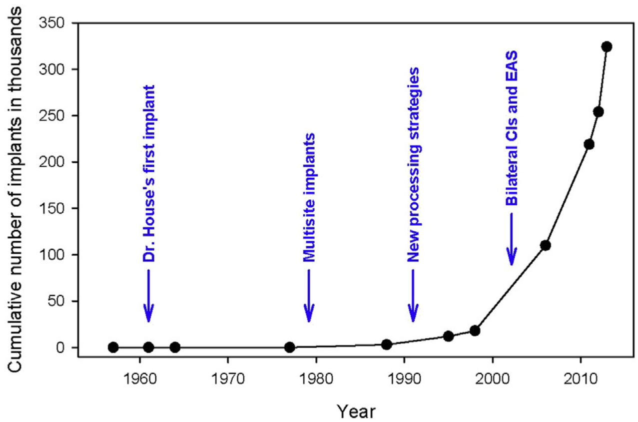

Fig. 2 Cumulative number of implant recipients over the years. The dots represent published numbers. Unpublished industry records indicate that the number exceeded half a million in early 2016. An exponential fit to the published data has a correlation that is higher than 0.99 and the half-million figure continues that exponential increase. Major events in the development of the cochlear implant (CI) are also indicated in the figure. Dr. House is Dr. William F. House, MD, DDS, who contributed strongly to the development of the CI and performed his first implant operation in Los Angeles, CA, USA, in 1961. EAS = combined electric and acoustic stimulation. Adapted from Wilson and Dorman,[2] with permission.

further development of other types of neural prostheses, e.g., visual and vestibular prostheses.[2]

In the remainder of this article, I present a snapshot of where we are with the CI devices now in widespread use and then offer some suggestions for narrowing the remaining gaps between prosthetic and normal hearing. I note that we now have a happy problem to solve, in making highly effective devices even better.

Where are we?

The data presented in Fig. 3 are still largely representative of the performance of the present-day unilateral CIs, even though the data were collected in the mid 1990s (The data are from a multicenter study conducted in Europe by Helms et al[3]). Percent correct scores are shown for 55 adult users of the COMBI 40 CI, for recognition of speech using their restored hearing alone and without any visual cues such as those provided with speech reading (principally lip reading). The top panel shows scores for recognition of sentences, and the bottom panel shows scores for recognition of isolated monosyllabic words. The columns in each panel present scores for various times after the initial fitting of the device for each of the subjects. The means of the scores for each time and test are shown with the horizontal lines.

Sentence recognition is high for most subjects. Scores are lower for the recognition of monosyllabic words, and those scores are more broadly distributed across subjects compared with the distributions for sentences. The differences between the sentence and word scores can be attributed at least in part to the lack of contextual cues for the words.

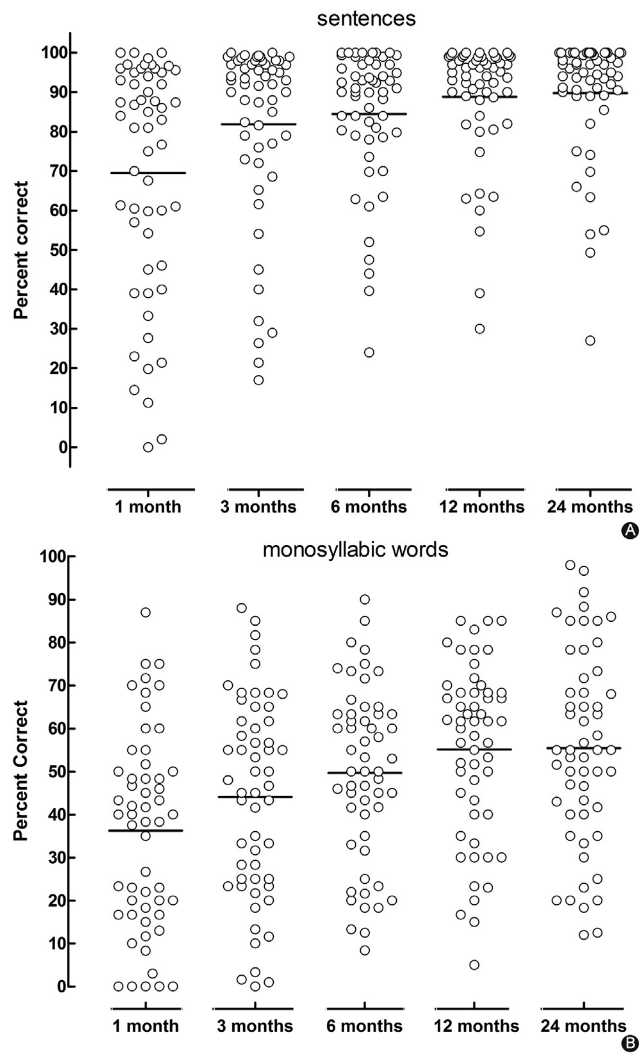

Fig. 3 Percent correct scores for users of the COMBI 40 implant. Circles show scores for the individual subjects and columns present scores at different times after the initial fitting of the device for each of the subjects. The horizontal lines indicate the means of the scores for each of those times. Results from tests of sentence recognition are shown in the top panel (A), and results from tests of word recognition are shown in the bottom panel (B). The data are from Helms et al,[3] along with further data from that study first reported in Wilson.[4] The figure is from Wilson and Dorman,[5] used here with permission.

The upward progression of the horizontal lines in each of the panels seems to indicate improvements in the scores with increasing experience with the implant. This aspect is easier to see in Fig. 4, where the means and standard errors of the means (SEMs) for the two tests are plotted (More intervals were included for the sentence test than for the word test). Significant improvements in the scores for the sentence test are observed out to 3 months after the initial fitting, and for word test out to 12 months. These long time courses are consistent with plastic changes in brain function and inconsistent with changes at the periphery, which would be far more rapid. As such, the improvements over time indicate a key role of "hearing brain" in determining outcomes with CIs.

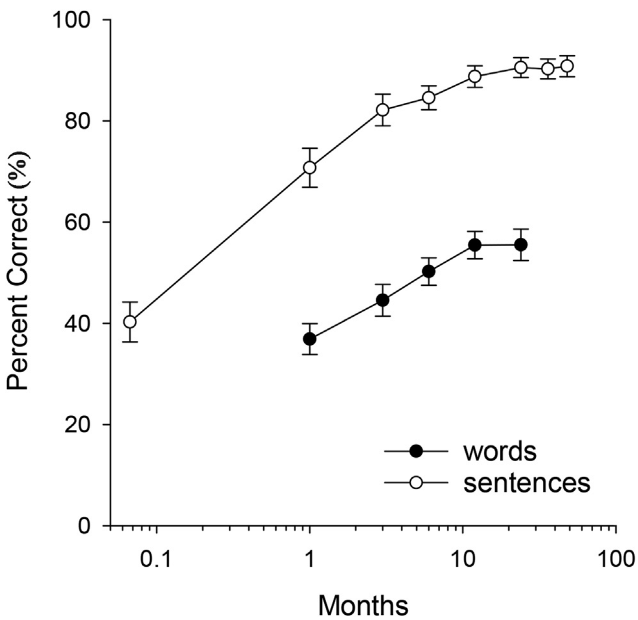

Fig. 4 Means and standard errors of the means for the data in Fig. 3 plus data from additional times after the initial fitting of the device for the sentence tests. Note that the scale for the abscissa is logarithmic. From Wilson,[4] used with permission.

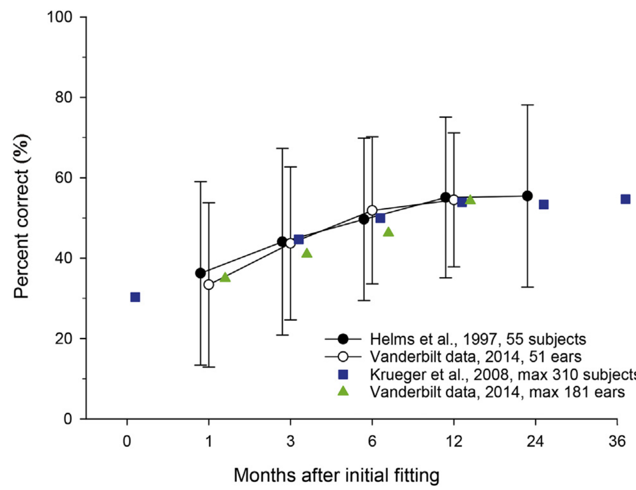

Fig. 5 Means of percent correct scores for the recognition of monosyllabic words by users of unilateral cochlear implants. Sources of the data include Helms et al[3]; Krueger et al[9]; and René Gifford, PhD, from the Vanderbilt University Medical Center in Nashville, TN, USA (The latter data also have been published in Wilson[6] and Wilson et al[10]). Standard deviations are shown for the sets of subjects who took the tests at all of the indicated times after the initial fittings of the devices. Some of the symbols are offset slightly in time for clarity. The figure is from Wilson,[6] used here with permission.

At two years of experience, the median and mean scores for sentence recognition are 95 and 90 percent correct, respectively. Those scores demonstrate a remarkable restoration of auditory function and indeed most users of CIs today routinely use the telephone or cell phones for conversations even with previously unfamiliar persons and even with unpredictable and changing topics.

In contrast, scores for prior devices and processing strategies were very much lower that the scores shown in Fig. 3.[6,7] And indeed, only about 1 in 20 of the users of the best of those prior devices and strategies could carry out a normal conversation without the assistance of speech reading, and the scores for the 1 in 20 were far below the top scores in Fig. 3 and usually well below the average scores in the figure.[6–8]

The COMBI 40 used only eight intra cochlear electrodes, a number that is small in comparison to the 30,000 neurons in the healthy auditory nerve or the 3500 inner hair cells distributed along the length of the cochlea. And yet that number of electrodes is adequate for high levels of speech reception. That was a surprise at the time and is no doubt a testament to the power of the brain to utilize a decidedly sparse input and to make progressively better sense of the input over time.

Results like those shown in Figs. 3 and 4 propelled the CI into widespread use. It is now the standard of care for persons with severe or worse losses in hearing.

Despite many efforts to produce further improvements in the performance of unilateral CIs, only modest progress has been made since the mid 1990s. This fact is illustrated in Fig. 5, which shows the means of scores for recognition of monosyllabic words by post lingually deafened adults who received their CIs in the mid 1990s, the mid 2000s, or recently, up to early 2014. The scores were obtained with the CI alone and each of the studies included large cohorts of unselected patients (Scores can be higher for small groups of subjects or for selected subjects). The error bars in the figure show standard deviations for the two sets of subjects who were tested at all of the indicated intervals after the initial fitting. The scores for the mid 1990s are from Helms et al and are the same as the word scores shown in Figs. 3 and 4.

As is evident from Fig. 5, no improvement was made across the decades, at least for the recognition of monosyllabic words and for large cohorts of post lingually deafened adults, even though many changes were introduced during the period including: (1) more channels of sound processing and associated intracochlear electrodes; (2) newer processing strategies; and (3) substantial relaxations in the criteria for implant candidacy. Even the standard deviations are same between the mid 1990s and 2014. These results indicate the broad clinical experience with unilateral CIs to date and the results are especially informative as the word tests are still largely immune to possible ceiling effects (the exception is the relatively few subjects who score at or near 100 percent correct in the tests). The means of the word scores asymptote at about 55 percent correct for all devices in widespread use since the mid 1990s. Sentence scores are much higher, of course, and those scores (and the word scores) are fully consistent with fluent verbal communications with and by CI users.

A vexing limitation

A likely roadblock to further improvements is illustrated in Fig. 6, which shows speech reception scores as a function of the number of processing channels and associated intracochlear electrodes for users of unilateral CIs. The top panel presents data from one of my earlier laboratories (at the Research Triangle Institute in North Carolina, USA) and the bottom panel presents data from Garnham et al.[11] The data in both panels are representative of findings from other studies. The subject in the top panel used a Cochlear Ltd (Nucleus) implant with its 22 intracochlear electrodes, and the 11 subjects in the bottom panel used MED EL GmbH implants with 12 intracochlear electrodes (Today's CIs use 12—24 intracochlear electrodes). Tests of consonant identification in quiet and in noise were administered for the subject in the top panel, and various tests of speech recognition in quiet and in noise were administered for the subjects in the bottom panel. The panels show the means and SEMs of the scores for the tests.

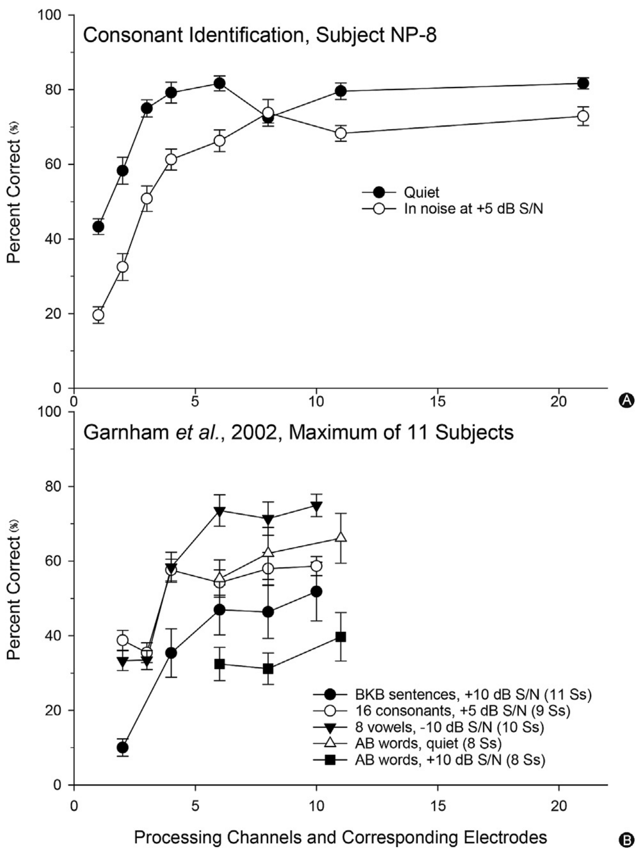

Fig. 6 Means and standard errors of the means for tests of speech reception conducted in one of the author's earlier laboratories, at the Research Triangle Institute (RTI) in North Carolina, USA, and by Garnham et al.[11]The subjects were users of unilateral cochlear implants and the tests included identification of consonants in quiet and in noise; recognition of the Bamford-Kowal-Bench (BKB) sentences in noise; identification of vowels in noise; and recognition of the Arthur Boothroyd (AB) monosyllabic words in quiet and in noise. The speech-to-noise ratios (S/Ns) for the tests in noise are indicated in the legends. Scores for sound processors using different numbers of channels — and the electrodes associated with those channels — are shown. The tests of consonant identification at the RTI included 24 consonants. Additional information about the tests at the RTI is presented in Wilson.[12] The figure is from Wilson and Dorman,[5] used here with permission.

Both panels indicate an asymptote in the scores once the number of channels rises above 3—6 depending on the test. Indeed, no implant subject tested to date has reached more than eight channels in any test before encountering asymptotic performance. That means that the number of effective channels with the present-day unilateral CIs is below, and often far below, the number of intracochlear electrodes and the maximum possible number of channels.

The reason(s) for the limitations in the numbers of effective channels remain to be identified. A lack of discrimination among electrodes is not a candidate reason, as many subjects can discriminate most or all of their intracochlear electrodes when the electrodes are stimulated in isolation, one after the other and with a substantial delay in between. For example, the subject in the top panel could reliably discriminate any two electrodes from the available 22 and yet the number of effective channels for the subject was three for consonant identification in quiet and four for consonant identification in noise. That is, an apparent disconnect exists between the number of discriminable electrodes on the one hand, and the number of effective channels on the other hand. Possibly, temporal interactions that are produced in the speech processor context, with rapid sequential presentations of overlapping electric fields, and that are not produced in the electrode discrimination context, may provide a partial or complete explanation for the disconnect. However, that is speculation at this point and more research is needed to learn why the numbers of effective channels are so low and why those numbers are so different from the numbers of discriminable electrodes.

Given what we know now, the eight electrodes used in the COMBI 40 CI may have been the ideal number, in that no more than eight electrodes can be effective, at least with the existing devices and processing strategies. In addition, limiting the number to eight allows for a relatively wide spacing between the intracochlear electrodes, which would be expected to reduce interactions among the electrodes, compared with the interactions produced with shorter inter-electrode distances.

An increase in the number of effective channels up to eight for all cases that fall short of that mark would be expected to produce high scores in even the most difficult tests of speech reception in quiet for most or all users of unilateral CIs.[13] In addition, increments beyond eight, even as small as 1—3 more channels, would be expected to produce substantial improvements in speech reception in noise for the same users.[13] Such gains — however achieved — would be a breakthrough in implant design and performance.

According to some measures, e.g., critical bands, there are more than 20 effective channels in normal hearing across the range of frequencies in speech. The 20 is far greater than the maximum of eight that we have with the present-day CIs.

Benefits of adjunctive stimulation

As noted previously, the performance of unilateral CIs has remained relatively stable since the mid 1990s. Fortunately, however, another way has been found to improve performance and that is to present stimuli in addition to those provided with a unilateral CI. This can be done in either of two ways and one is to present electric stimuli on both sides with bilateral CIs and the other is to present acoustic stimuli on one or both sides, the latter for persons with useful residual hearing at low frequencies. For the combination of electric plus acoustic stimuli (combined EAS), the electric stimuli represent high frequencies in the sound input and the acoustic stimuli represent low frequencies in the input.

An example of the benefits of such adjunctive stimulation is presented in Fig. 7. In this case, acoustic stimuli were delivered to the ear contralateral to the ear with a fully inserted CI (This arrangement of electric and acoustic stimuli is often called "bimodal" stimulation). The middle column in the figure shows scores for recognition of monosyllabic words with the CI alone for 15 subjects, and the right column shows scores for the same subjects and test but with electric plus acoustic stimuli. The left column reprises the word scores at the two-year interval for the 55 subjects in the Helms et al study, who were tested in the mid 1990s. The 15 subjects in the other two columns were tested by Michael Dorman and his coworkers a little more than a decade later.[14]

The scores in the left and middle columns are indistinguishable, again showing the same performance for unilateral CIs between the mid 1990s and the mid-to-late 2000s. In contrast, the scores in the right column are significantly higher than the scores in the middle and left columns.

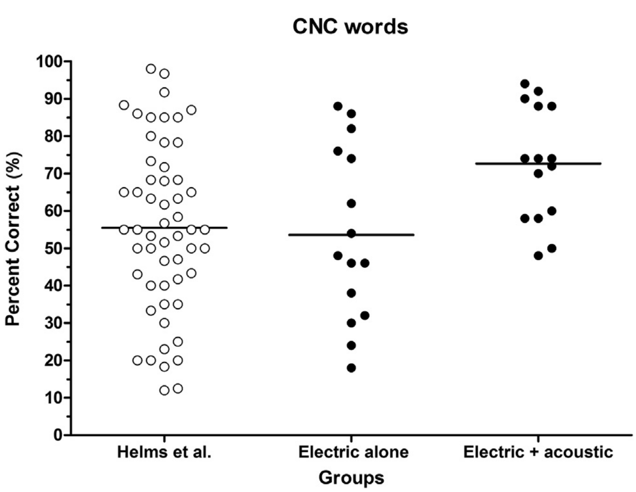

Fig. 7 Percent correct scores for the recognition of monosyllabic words by users of unilateral cochlear implants (CIs) and additional acoustic stimulation for some of the users. The left column shows scores from the 2-year test interval in the study by Helms et al,[3] reprised from the rightmost column in the bottom panel of Fig. 3. The middle and right columns in the present figure show scores from 15 other subjects studied by Dorman et al.[14] The subjects in the left and middle columns used their CIs only. Each of the subjects in the middle and right columns had a fully inserted CI on one side and residual hearing at low frequencies on the contralateral side. The right column shows scores for electric plus acoustic stimulation, with the acoustic stimuli delivered to the acoustically sensitive ear. The horizontal line in each column indicates the mean of the scores for the column. The figure is from Dorman et al,[14] used here with permission.

Of course, the top scores obtained with just the single CI (middle column) can't be improved much if at all for this particular test, as those scores approximate 85 percent correct. The effect of the adjunctive stimulation is to "bring up the bottom" such that the number of subjects with scores below 55 percent correct is greatly diminished compared with the number for electric stimulation alone. Results from further studies by Dorman et al[15] have shown that the greatest benefits of combined EAS generally are obtained when: (1) the CI-only scores for a given test are below 60 percent correct; (2) the pure tone average (PTA) of thresholds in the hearing ear(s) for the frequencies of 125, 250, and 500 Hz is better than 60 dB HL; and (3) the test material is sentences presented in competition with noise or other talkers.

Bilateral electrical stimulation can produce similar gains in speech reception and additionally can reinstate to a limited but useful extent sound localization abilities through a representation of the interaural level difference (ILD) cues that can indicate the lateral positions of sound sources.[16–20] Combined EAS also greatly enhances music reception,[14] perhaps through a better representation of fundamental frequencies and the first several harmonics of those frequencies for periodic sounds.

Preliminary evidence also suggests that combining the two types of adjunctive stimulation — with bilateral CIs plus acoustic stimulation on both sides for persons with useful (and more or less symmetric) residual hearing on the two sides — can be especially beneficial.[21] In particular, speech reception in a complex listening environment (with interfering sounds at different locations simulating restaurant noise) was better for the three tested subjects using the combination of the two types of adjunctive stimulation, compared with the scores for larger separate groups of subjects using bilateral CIs, bimodal stimulation, a single CI with acoustic stimulation on both sides, or a unilateral CI. The number of subjects studied with the acoustic plus electric stimulation for each ear was small and studies with a much higher number of such subjects are needed to evaluate the generality of this initial result.

The continued importance of unilateral implants

Despite these wonderful gains with adjunctive stimulation, unilateral CIs are still vitally important. In particular, not all patients have useful residual hearing (although many do); not all patients or prospective patients have access to bilateral CIs due to national health policies or restrictions in insurance coverage; and the unilateral CI and its performance is the "bedrock" of the adjunctive stimulation treatments. With respect to the last point, improvements in the performance of unilateral CIs would be expected to boost the performance of the adjunctive stimulation treatments as well.

Remaining gaps

Although the present-day CIs and related treatments are great, they are not perfect. Some of the remaining gaps between prosthetic and normal hearing are that:

- Some users of CIs still do not have high levels of speech reception
- Speech reception in adverse acoustic environments such as noisy restaurants or workplaces is worse for even the best CI users compared to listeners with normal hearing
- The averages of scores for difficult tests in quiet, such as recognition of monosyllabic words, are still far lower for CI users than for listeners with normal hearing, although some CI users score at or near 100 percent correct in these tests
- Sound localization is absent or nearly so for users of unilateral CIs
- Reception of sounds more complex than speech, e.g., most music, is impaired for CI users

In addition, some experts have suggested that reception of tone languages may pose special difficulties for CI users, in that perception of fundamental frequencies (and therefore the tone contours in the tone languages) may be at least somewhat impaired with the present-day devices. However, results from the recent clinical trial in China of the Nurotron device indicate that recognition of sentences in Mandarin (a tone language) is just as good as recognition of sentences in languages that do not use tone contours to convey phonetic information.[22] Possibly, the perception of tone contours is at least adequate with the present-day CIs for robust reception of tone languages, or co-varying cues convey the necessary phonetic information in any case. The CI works similarly well for all languages tested to date.

Possibilities for narrowing the gaps

Each of the gaps listed in the preceding section can be narrowed but not eliminated with adjunctive stimulation. Combined EAS is especially helpful for music reception, and bilateral CIs are especially helpful for restoring sound localization abilities. Either mode can produce substantial improvements in speech reception in noise and in the recognition of difficult speech items in quiet.

Additional possibilities for narrowing the gaps include: (1) identifying the mechanism(s) underlying the difference between the number of discriminable electrodes and the lower number of effective channels; (2) an increase in the latter number, perhaps with a greater spatial specificity of stimulation at different sites in the cochlea or auditory nerve; (3) prudent pruning of interfering or otherwise detrimental electrodes; (4) a further relaxation in the criteria for implant candidacy, based on recent evidence from persons with high levels of residual hearing; and (5) "brain centric" approaches to designs and applications of CIs that take the brain into account and make appropriate adjustments for persons whose hearing brains have been compromised by long periods of sensory deprivation or a myriad of other causes. Many other possibilities could be suggested and indeed are being pursued. However, the listed possibilities are the most promising in my opinion.

Understanding the apparent disconnect between the number of discriminable electrodes *versus* the number of effective channels is vital for guidance in increasing the latter number. Modeling studies are underway to evaluate various possible mechanisms for the observed effects.[23] Results from the studies may inform the design of electrodes or stimuli or both that will produce increases in the number of effective channels. As noted previously, even small increases would be a boon to CI users.

Based on what we know now, increases also might be produced with greater spatial specificities of stimulation at different sites in the cochlea or auditory nerve. Three promising possibilities along these lines are optical rather than electric stimulation in the cochlea[24]; delivery of electrical stimuli within the auditory nerve rather than in the scala tympani (ST) of the cochlea[25]; and promotion of the growth of neural processes ("neurites") from the spiral ganglion cells toward electrodes in the ST.[26,27] Each of these approaches may sharpen the neural excitation fields.

Pruning of interfering or otherwise detrimental electrodes makes great sense for the present-day CIs, in that those devices can support only a maximum of eight effective channels. Choosing the best eight among the higher numbers of available electrodes, and deactivating the other electrodes, may produce improvements in performance compared with using most or all of the available electrodes. Certainly, deleterious interactions among electrodes would be reduced in each case with the smaller number.

New evidence in support of this "prudent pruning" possibility is presented in Fig. 8 which shows results from Vanderbilt University Medical Center in Nashville, TN, USA, comparing speech reception scores obtained with conventional fittings of CIs (open bars) *versus* modified fittings with a subset of the previously utilized electrodes deactivated (gray bars). A computed tomography (CT) imaging and analysis technique was used to identify the electrodes that were relatively far away from the putative neural target for CIs, the spiral ganglion cells, and therefore likely to have higher thresholds for neural activation and greater spatial extents of excitation for supra-threshold stimuli. Those identified electrodes, or subsets of them, were deactivated. The technique is described in detail in the initial paper on the topic by Noble et al[28] and results from studies with implant patients are presented in subsequent papers also by the Vanderbilt group.[29–31]

Gains in speech reception from application of the technique can be large. For the four subjects in Fig. 8, for instance, gains in the recognition of the Arizona Biomedical (AzBio) sentences presented in competition with noise, at the speech-to-noise ratio (S/N) of +10 dB, ranged from 22 to 44 percentage points. Results vary across subjects and not all subjects have similarly large gains if any significant gain at all. However, gains like those shown in the figure are large and clearly indicate the promise of the approach.

Alternatively, electrodes could be deactivated on the basis of direct measures of electrode interactions. The electrodes that produce the greatest interactions would be eliminated. Also, electrodes that are associated with relatively poor sensitivities to modulation of a pulse train

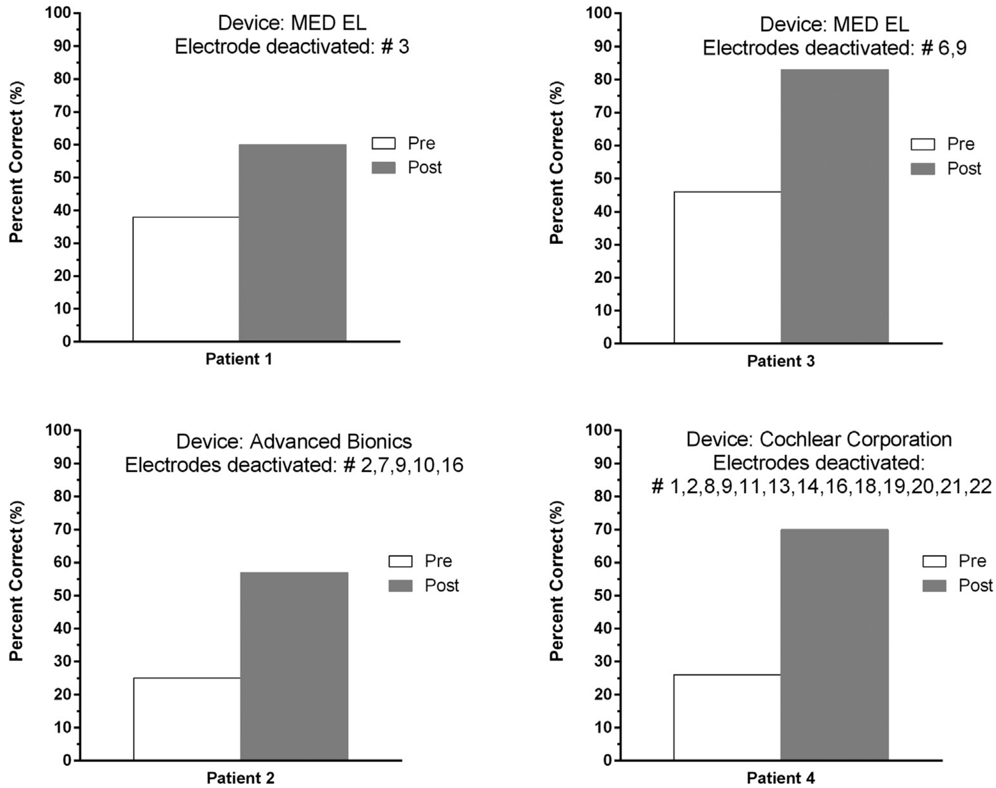

Fig. 8 Percent correct scores for recognition of the Arizona Biomedical Institute (AzBio) sentences by users of unilateral cochlear implants (CIs). The sentences were presented in competition with noise at the speech-to-noise ratio of +10 dB. Scores are shown for conventional fittings of the CIs (pre) *versus* fittings in which electrodes were deactivated (post), for each of four subjects. The devices used by the subjects and the electrodes that were deactivated are indicated in the title lines for each panel. The subjects are identified by patient number, patients 1—4. These data were kindly provided by René Gifford, PhD, of the Vanderbilt University Medical Center in Nashville, TN, USA, and have been published in Wilson et al.[10] The figure was first presented in that publication and is used here with permission.

carrier could be eliminated,[32] as the sensitivity to modulation is strongly correlated with speech reception scores.[33] And most simply, electrodes could be eliminated to produce the maximum spatial separation among the retained electrodes, again to reduce interactions. For example, alternate electrodes in a 16-electrode array could be deactivated to produce the maximum spatial separation.

More than eight electrodes were retained for each of the subjects in Fig. 8. Even better results might have been obtained if the numbers were further pruned to eight.

Future research might include the use of within-subject controls to evaluate the relative efficacies of the different techniques for electrode selections and deactivations. For example, the CT imaging technique, direct measures of electrode interactions, measures of modulation sensitivity, and selection to maximize the spatial separation among the retained electrodes could all be compared (in randomized orders of presentations) in tests with the same subjects. In that way, the best technique(s) might be identified.

A further relaxation in the criteria for implant candidacy would make CIs available to many more persons who could benefit from them. In addition, the newly included persons would have even more residual hearing than the present CI users and candidates for CIs. The average scores would increase, through the demonstrated benefits of combined EAS, which also include better reception of sounds more complex than speech. Even a slight relaxation in the criteria would increase the number of candidates substantially. Possibly, for example, persons who now suffer from the debilitating effects of the more severe forms of presbycusis may become candidates for a CI and the benefits of combined EAS.

I note that the present criteria for implant candidacy in China are stricter than in many other countries, including the USA, all countries in Europe, and Australia to name some among the many. In China, a person must have a severe or worse loss of hearing in both ears to become a candidate.[34] Elsewhere, a person can become a candidate for combined EAS with a moderate loss in either or both ears, including normal or nearly normal hearing at low frequencies in those ear(s). Additionally, persons with a severe or worse loss on one side and normal or nearly normal hearing on the other side (so-called single-sided deafness patients) may now qualify in many countries for an implant on the severe-or-worse loss side. Relaxation of the criteria for implant candidacy in China also would increase the number of candidates there substantially (and would further impact the number worldwide, given China's large population).

Evidence in support of broadened candidacy is presented in Fig. 9, which shows results from a retrospective chart study of 159 persons with residual hearing who were implanted at the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, from mid December 2002 to late June 2007.[35] The amount of residual hearing for each of the subjects was characterized by her or his audiogram for the better hearing ear. Two measures were used: the PTA for 125, 250, and 500 Hz, and the threshold for 500 Hz only. The categories included relatively good, moderate, and poor levels of residual hearing and are labeled in the figure as "PDCI," "EAS," and "Neither," respectively. Prospective patients in the categories might be regarded as candidates for a "partial deafness cochlear implantation" (PDCI) procedure, for combined EAS, or for neither procedure, again on the basis of each person's residual hearing. Persons in the PDCI category had thresholds at 500 Hz that were equal to or better than 55 dB HL *or* a PTA equal to or better than 45 dB; persons in the EAS category had thresholds at 500 Hz in the range from 80 to 56 dB HL *or* PTAs in the range from 70 to 46 dB HL; and persons in the "Neither" category had thresholds at 500 Hz that were worse than 80 dB HL *and* PTAs that were worse than 70 dB HL. All of the subjects used their residual hearing in conjunction with the CI in their daily lives.

The figure shows the means and standard deviations of the scores for the recognition of Polish monosyllabic words presented in quiet and in noise, the latter at the S/N of +10 dB. The conditions included tests with the residual hearing only (RH only) and with the CI plus the residual hearing (CI + RH). The acoustic stimuli were delivered to either or both ears, depending on which choice produced the best recognition of the monosyllabic words in quiet for each subject using her or his residual hearing only, with amplification as appropriate (some of the PDCI subjects did not need and did not use amplification).

The addition of the CI produced large and highly significant improvements in speech reception in all cases. The improvements for the subjects with relatively high levels of residual hearing (the PDCI subjects) were just as great as the improvements for the other subjects, with lower levels of residual hearing. That was a surprise, as the conventional wisdom at the time was that patients with such good residual hearing might be harmed by cochlear implantation and that there must be a point of diminishing returns at which the residual hearing is so good that it can't be augmented with the addition of a CI. In contrast, the data show that enormous benefits are conferred by the CI even for the PDCI subjects. In addition, the highest scores in the study were obtained by the PDCI subjects in each of the experimental conditions. The data presented in Fig. 9, along with other similar data,[36] strongly support a further relaxation in the criteria for implant candidacy and indeed the point of diminishing returns has yet to be identified.

And last but not least, brain centric approaches to designs and applications of CIs and related treatments may be especially helpful for patients presently at the low end of the performance spectrum.[37] Indeed, accumulating evidence is indicating that a large portion of the remaining variability in outcomes with CIs and the related treatments may be due to differences in the function of the hearing brain among the recipients.[37–40] If so, then a better match between what the prosthesis provides and what the compromised brain can process may improve performance for the relatively small proportion of patients (roughly 10 percent) who are still struggling. Help for them would be another breakthrough.

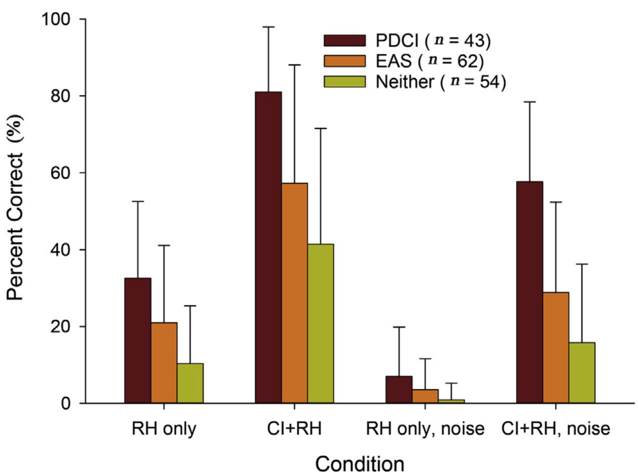

Fig. 9 Means and standard deviations of percent correct scores for the recognition of the Pruszewicz monosyllabic words (in Polish) by users of unilateral cochlear implants (CIs) who were implanted at the International Center of Hearing and Speech in Kajetany, Poland, from mid December 2002 through most of June 2007. All 159 subjects had residual hearing (usually at low frequencies only) in one or both ears. The words were presented in quiet and in noise, the latter at the speech-to-noise ratio of +10 dB. Results are shown for acoustic stimulation using the residual hearing only (RH only and RH only, noise) and for electric plus acoustic stimulation using the CI plus the residual hearing (CI + RH and CI + RH, noise). The results for subjects with relatively good residual hearing are shown with brown bars; results for subjects with moderate residual hearing are shown with the orange bars; and results for subjects with relatively poor residual hearing are shown with the olive-colored bars. These categories of residual hearing are described further in the text. Adapted from Wilson,[35] with permission.

Concluding remarks

The modern CI is a triumph of engineering, otology, and neuroscience, among other disciplines. It is now widely regarded as one of the great advances in medicine and in technology. Most users today converse routinely with their cell and landline phones.

Performance with unilateral CIs has remained relatively stable since the early 1990s, when new and highly effective sound processing strategies were first introduced into widespread clinical applications.

In the early 2000s, adjunctive stimulation — either with bilateral CIs or combined EAS — produced further and highly significant gains in speech reception. In addition, bilateral CIs could reinstate to some extent sound localization

Fig. 10 The author with cochlear implant user Lilo Baumgartner at a picnic table on the campus of the Research Triangle Institute in 2003. The shared joy in the exchange is evident from the photo, and Lilo like other users of cochlear implants is not having any difficulty in understanding me even though she is not using any visual cues. The figure is from Wilson,[41] used here with permission.

abilities and combined EAS greatly improved reception of sounds more complex than speech such as most music.

However, not all candidates for CIs have access to bilateral CIs or enough residual hearing for effective use of combined EAS. In addition, room still exists for improvements even with the adjunctive stimulation treatments.

Additional steps forward might be achieved in any of multiple ways, including broadened indications that would allow many more people to benefit from combined EAS.

In conclusion I would like to say that the greatest joy for me in my 3+ decades of work to help develop the CI has been in my interactions with patients and seeing them flourish with their restored hearing (Fig. 10). I have been blessed to have had the grand opportunities to meet these magnificent people, work on an important problem, and to do that work in the company of spectacular colleagues. We all did something wonderful together, and the journey toward perfect or nearly perfect hearing for CI users continues.

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