Future Directions for Cochlear Implants

Orientations futures pour les implants cochléaires

Richard S. Tyler
Department of Otolaryngology—Head & Neck Surgery
Department of Speech Pathology and Audiology
University of Iowa

Jane M. Opie, Holly Fryauf-Bertschy, and Bruce J. Gantz
Department of Otolaryngology—Head & Neck Surgery
University of Iowa

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Abstract

Cochlear implants have provided the opportunity for many postlingually deafened adults to hear. Results from sophisticated multichannel implants show a very wide range of performance across patients. We review some of these findings and present a method for measuring lipreading enhancement by considering the percentage of possible enhancement. Prelingually deafened children with cochlear implants are able to recognize some of the important speech features, although their progress is slow. Future improvements in understanding signals and noise, in signal processing, in optimizing device adjustments, in surgical procedures, and in rehabilitation will contribute to the development of this field.

Résumé

Grâce aux implants cochléaires, de nombreux adultes atteints de surdité postlinguistique peuvent entendre. Les résultats d'implants multi-canaux perfectionnés révèlent des performances très variées chez les patients. Nous examinons certaines de ces constatations et présentons une méthode pour mesurer l'amélioration de la lecture labiale en considérant le pourcentage de l'augmentation possible. Les enfants avec surdité prélinguistique qui ont un implant cochléaire sont en mesure de reconnaître certaines des caractéristiques importantes de la parole, bien que leurs progrès soient lents. Les améliorations futures au niveau de la compréhension des signaux et du bruit, du traitement des signaux, de l'optimisation des ajustements des appareils, des interventions chirurgicales et de la réadaptation vont contribuer au développement de ce domaine.

Introduction

Cochlear implants have made a dramatic impact on the rehabilitation of profoundly deafened adults and children. Over the past 30 years, researchers and clinicians have witnessed many developments in the field of cochlear implantation. Early work focused on the benefits of single channel cochlear implants provided to profoundly hearing impaired adults. Currently, both adults and children worldwide are implanted with multichannel cochlear implants. As the devices have evolved and the implant population has grown, researchers and clinicians have broadened their understanding of the benefits of cochlear implants. In addition, aural rehabilitation strategies have become more sophisticated and have taken advantage of new technology in audiovisual equipment. In this article, we first briefly review some of our recent findings from adults and children using cochlear implants. This provides a current perspective in which to place our following discussion of future directions in cochlear implants.

Overview of Recent Findings

In our initial studies at the University of Iowa (Tyler et al., 1984; Gantz et al., 1988; Tye-Murray & Tyler, 1989), we focused primarily on postlingually deafened adults using single channel and multichannel cochlear implants. In an examination of speech perception measures, we demonstrated that, on an average, patients using the multichannel Nucleus (Clark, Tong, & Martin, 1981) and Ineraid (Eddington, 1980) devices outperformed other patients using the single channel (3M/House et al., 1976) and Vienna (Hochmair & Hochmair-Desoyer, 1985) cochlear implants. No statistically significant differences were observed between the speech perception results of two groups of patients who used the two multichannel systems. Speech perception performance increased rapidly over the first 12 months of implant use, and then reached an asymptote or increased more slowly (Tye-Murray, Tyler, Woodworth, & Gantz, 1992).

We have also investigated several other areas related to the overall effects and benefits of the cochlear implants. These studies have focused on psychological, electrophysiological, speech production, and aural rehabilitation factors.

We have analyzed our data to examine individual differences and variables predictive of successful cochlear implant use. In general, younger patients and patients who had been deafened recently performed better than older patients and patients who had been deaf for several years (Tyler, 1991; Gantz, Woodworth, Knutson, Abbas, & Tyler, 1992), although virtually all the patients benefited from their implant. In addition, in one of our previous studies, Lansing and Davis (1988) reported that patients who received speech perception training one month after implantation outperformed those who received training nine months after implantation.

Our psychological studies revealed that multichannel cochlear implant users were significantly less depressed, lonely, socially isolated, and suspicious following implantation than before (Knutson et al., 1991). Similar observations were reported by investigators at other implant centers (Crary, Berliner, Wexler, & Miller, 1982; Miller, Duvall, Berliner, Crary, & Wexler, 1978; Vega, 1977). It would appear that cochlear implantation contributes to the improved emotional outlook and social functioning of profoundly hearing impaired patients.

In recent electrophysiological work, our studies have examined the viability of using the electrically evoked whole nerve action potential to estimate peripheral auditory nerve survival rates in multichannel (Ineraid) cochlear implant patients (Brown, Abbas, & Gantz, 1990). This research suggested that evoked whole nerve action potentials correlated moderately with word recognition performance. Current research is underway to determine the extent to which a variety of measures of peripheral nerve activity correlate with psychophysical and speech perception performance. Preliminary results suggest electrophysiological measures have the potential to provide preimplant data important in predicting the possible future success of implantation for a particular implant candidate.

We have also tested speech production with children who have cochlear implants. The vowel and diphthong speech production repertoire of prelingually deafened children expands and becomes more diverse after 24 or 36 months of cochlear implant use (Tye-Murray & Kirk, 1992), and their productions become more accurate (see also Tobey, 1992, for a review of this topic).

In an examination of the effect of cochlear implantation on communication effectiveness among family members, we have revealed that families do not always change their communication styles after a child receives a cochlear implant. They are uncertain about how to integrate auditory speech cues into their communication modes and could benefit from training about how to repair breakdowns in communication (Tye-Murray & Kelsay, 1992, in press).

Overall, our work and the research of others (e.g., Waltzman, Cohen, & Shapiro, 1986; Dowell, Mecklenburg, & Clark, 1986; Dorman et al., 1989) support the overall success of the cochlear implant program. A wide range of speech perception abilities is evident across patients, some receiving only limited lipreading enhancement and everyday sound recognition. However, scores greater than 50% correct in word recognition have been obtained by some patients (Dorman et al., 1989; Tyler, Moore, & Kuk, 1989; Wilson et al., 1991). Promising results such as these are encouraging for clinicians and researchers working with cochlear implant patients.

Postlingually Deafened Adults

Here we review some of our current speech perception results from adults using the Nucleus and Ineraid multichannel cochlear implants. None of these patients had significant word recognition when listening through hearing aids preoperatively. These results include patients having about 18 months of experience with their implants. All patients received implants at the University of Iowa. Implant type was assigned randomly, alternating between the Nucleus and Ineraid devices depending on the order in which they were seen in our program.

Word Recognition

One of the most important measures of performance is the ability to recognize words in an open set format. This resembles some difficult listening situations in everyday life and provides a good measure of the benefit provided by the implant.

Figure 1 shows individual performance on the NU-6 word recognition test (Tillman & Carhart, 1966). The 24 Nucleus patients averaged 17.5% correct word recognition ($sd = 18.0$), and the 25 Ineraid patients averaged 10.5% correct word recognition ($sd = 10.8$). There were no statistically significant differences between the two groups ($t = -1.66$, $df = 47$, $p = .103$). When scoring for percent correct phoneme recognition, the 24 Nucleus patients averaged 36.8% correct ($sd = 21.3$), and the 25 Ineraid patients averaged 29.3% correct ($sd = 17.2$). There were no statistically significant differences between the two groups ($t = -1.37$, $df = 47$, $p = .178$).

Lipreading Enhancement

Lipreading enhancement is one of the most important benefits provided by cochlear implants. Most cochlear implant patients require audiovisual information to communicate in typical situations. Therefore, it is critical to document lipreading enhancement accurately and in a manner that can be

Figure 1. Performance of postlingually deafened adults on the NU-6 word recognition test. The results are scored for percentage of phonemes and words correctly identified. The top panel shows results from the Nucleus patients and the bottom panel shows results from the Ineraid patients.

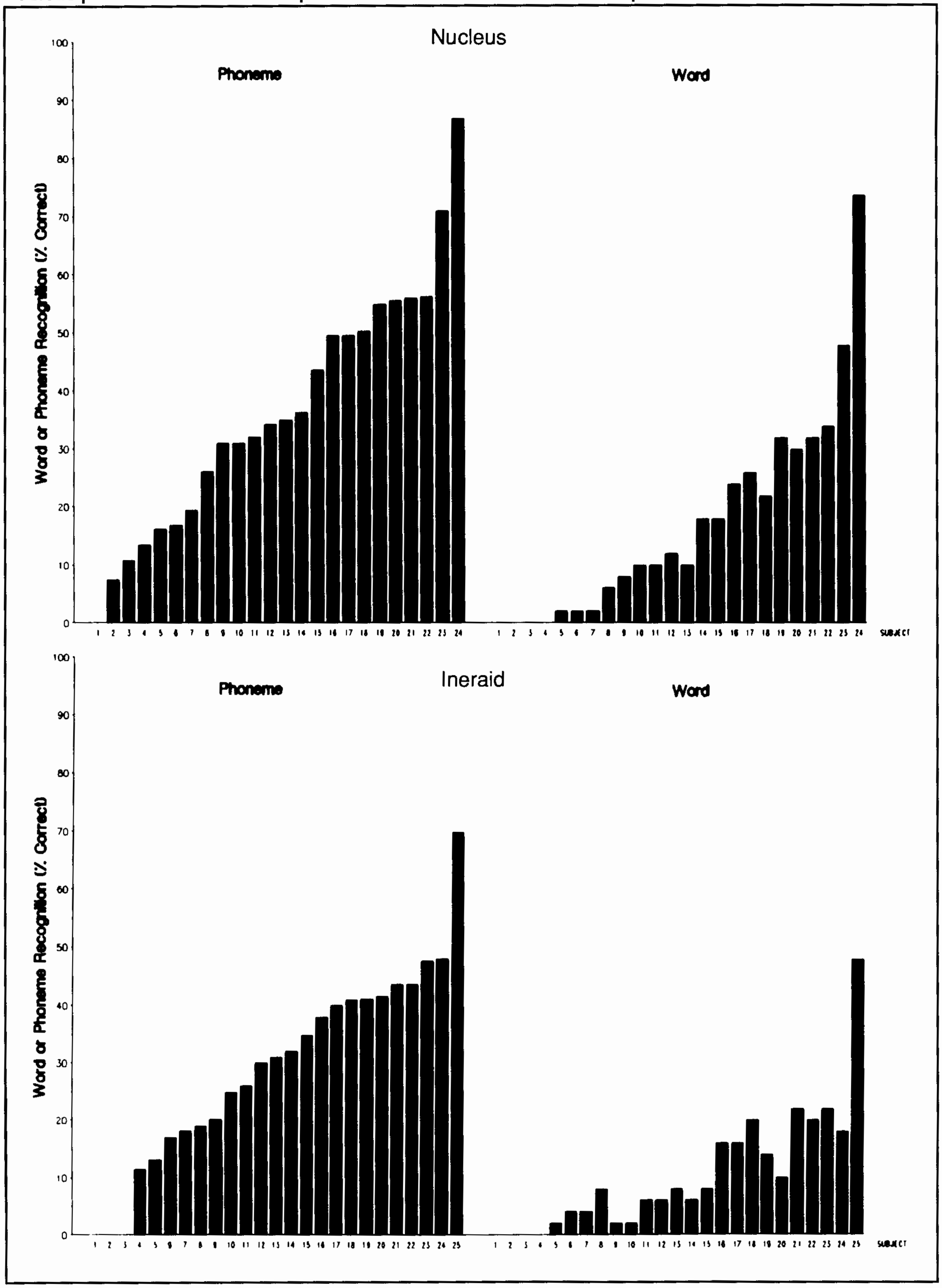
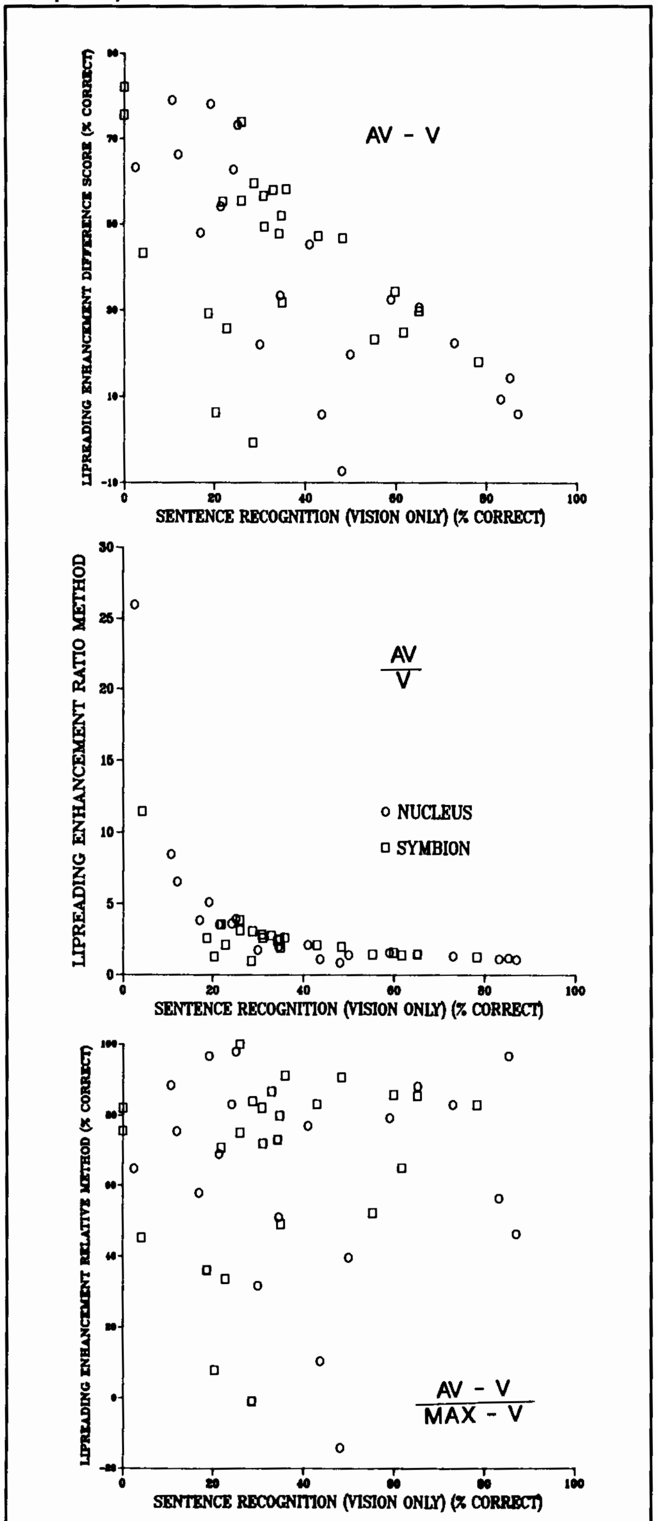


Figure 2. Three different methods of scoring lipreading enhancement. The performance of postlingually deafened adult cochlear implant users is presented based on a difference score (top panel), a ratio score (middle panel), and the percentage of possible improvement (bottom panel).



compared across different patients with different baseline lipreading abilities.

There are two common ways of examining lipreading enhancement. First, a difference score can be obtained by subtracting the score obtained in the vision condition from the score obtained in the audition-plus-vision condition. For example, a change from 20% to 30% represents a 10% increase. Second, a ratio score can be obtained by dividing the audition-plus-vision score by the vision score. For example, a 20% to 30% increase represents a 1.5 ratio increase (30/20).

A third alternative is to consider the amount of potential improvement. One possibility is to divide the difference score (audition-plus-vision minus the vision score) by the amount of possible improvement, defined as the maximum score (usually 100%) minus the score on vision alone (Walden, Erdman, Montgomery, Schwartz & Prosek, 1981; Tyler, 1991). This result can be multiplied by 100 to convert it to a percentage. For example, a change from 20% correct vision-alone to 30% correct audition-plus-vision represents an enhancement of 12.5% $[((30 - 20)/(100 - 20)) \times 100]$ of the possible enhancement.

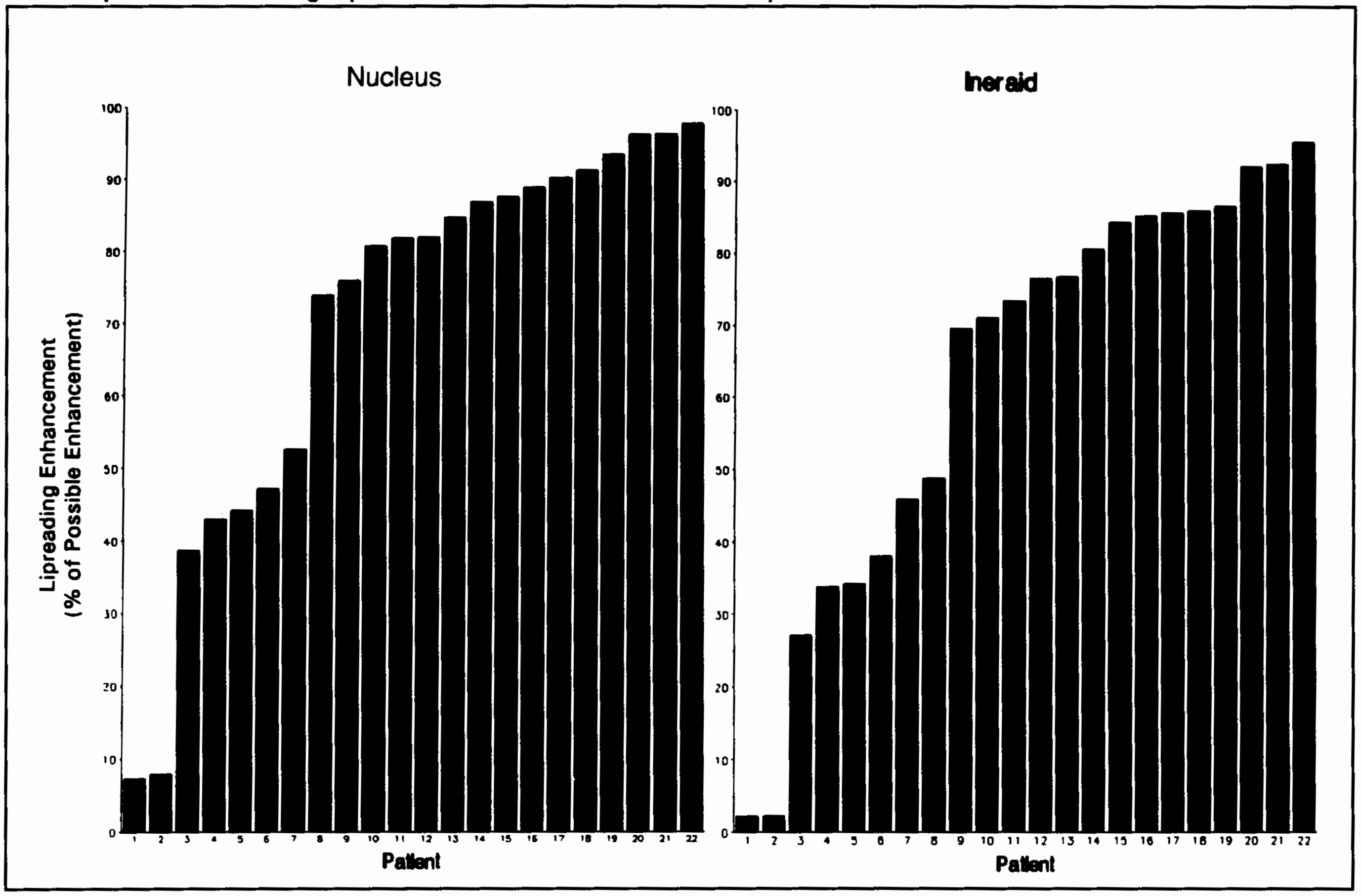
One way to determine the most appropriate lipreading enhancement metric is to examine the relationship between the lipreading enhancement score and a person's lipreading (vision-alone) condition. The two scores should be independent. That is, the enhancement that the patient obtains from the auditory prosthesis should not depend on whether they are a good or poor lipreader.

Figure 2 shows the relationship of lipreading performance to each of the three measures of lipreading enhancement obtained from a number of cochlear implant patients. The difference score (top) shows that lipreading score sets a limit on the amount of enhancement that can be measured. The higher the score, the lower the limit is. Patients whose score is 20% in the vision-only condition cannot have a difference score higher than 80%.

The ratio score is shown in the middle panel of Figure 2. Patients who have a very low vision-only score have an advantage because they can have a very large ratio score. For example, someone who scores 5% correct in vision-alone and 50% correct on audition-plus-vision conditions would have a ratio score of 10. However, someone who scores 80% correct in vision alone could never achieve a ratio greater than 1.25 (100/80).

The bottom panel shows the results using the percentage of maximum possible enhancement approach. There is no relationship to baseline lipreading ability. Thus, we conclude that this method of scoring lipreading enhancement is more appropriate than the others.

Figure 3. Performance of postlingually deafened adults on the Iowa Audiovisual Consonant Confusion Test. Lipreading enhancement is scored as a function of the percentage of possible enhancement. The left panel shows results from the Nucleus patients and the right panel shows results from the Ineraid patients.



We have contrasted the lipreading performance of our patients using this method. The percentage of possible lipreading enhancement for the Ineraid and Nucleus patients is shown in Figure 3 on the Iowa Consonant Confusion Test (Tyler, Preece, & Tye-Murray, 1986). The 22 Nucleus patients averaged 70.4% of the possible lipreading enhancement (sd = 27.8), and the 19 Ineraid patients averaged 66.2% of the possible enhancement (sd = 27.0). There were no statistically significant differences between the two groups (t = -0.49, df = 39, p = .63).

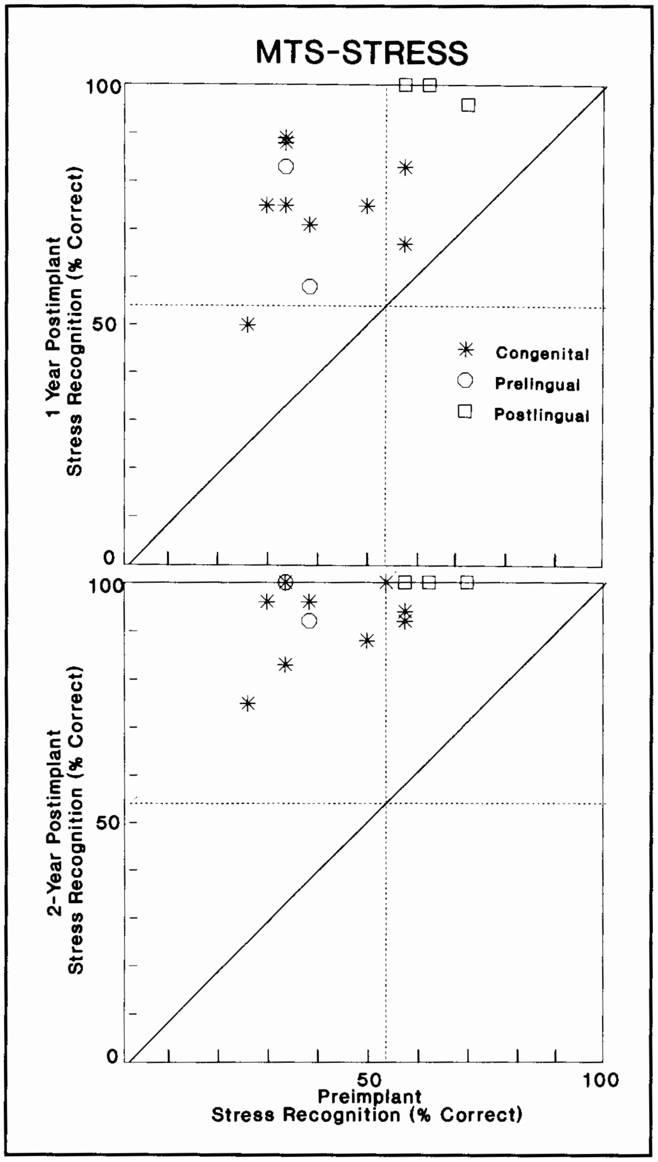
Prelingually and Postlingually Deafened Children

The provision of cochlear implants to children represents both an exciting and controversial area (House & Berliner, 1982; Tyler, Davis, & Lansing, 1987; Owens & Kessler, 1989; Miyamoto & Osberger, 1991). Preliminary results indicate that the acquisition of new auditory skills by young prelingually deaf children is slow and gradual (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992; Staller, Dowell, Beiter, & Brimacombe, 1991; Osberger et al., 1991). We do not yet know what average level of speech perception ability implanted children ultimately will realize. However, among children who currently use cochlear implants, some have demonstrated the ability to perceive significant segmental information (Tyler, 1990b, 1991; Osberger et al., 1991). Some implanted children have developed oral and auditory skills that allow them to rely primarily upon spoken communication (Boothroyd, Geers, & Moog, 1991). Other implanted children have demonstrated less dramatic gains in speech perception ability, but most of these children are still able to benefit from using an implant by obtaining improved sound awareness skills and improved lipreading ability.

Performance Over Time

We present recent results of our assessment of performance of children with cochlear implants on a relatively simple perceptual test, the Monosyllable-Trochee-Spondee Test

Figure 4. Performance of children with cochlear implants on the Monosyllable-Trochee-Spondee Test. Preimplant performance is compared to 1 year (top panel) and 2 year post-implant performance (bottom panel) for individual subjects. Data values higher than broken lines indicate a significant difference above chance at the 0.05 confidence level using a one tailed *t*-test of the binomial model.



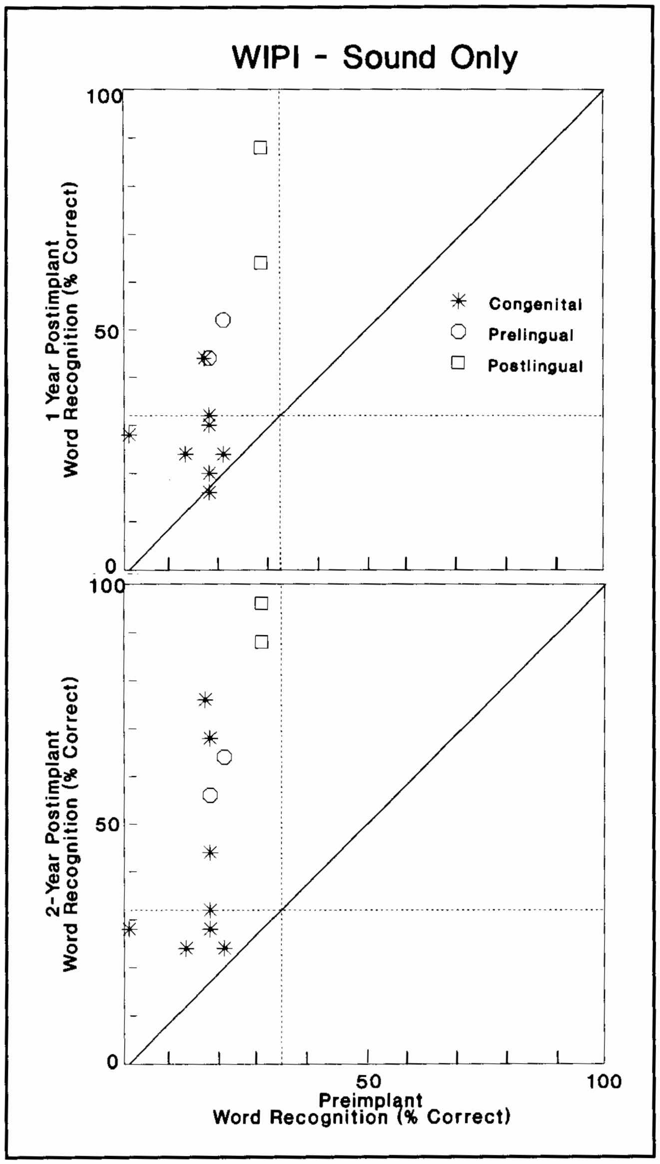
(MTS) (Erber & Alencewicz, 1976). This test assesses the ability to recognize the stress patterns of words, information provided by gross changes in the waveform amplitude of the speech sounds. Scoring is based on the percent correct stress recognition for 12 words: 4 monosyllables, 4 trochees, and 4 spondees. The top panel of Figure 4 presents data for 14 children with various onsets of hearing loss and compares preimplant performance with performance after 1 year of implant use. Preimplant performance is also compared with performance after 2 years of implant use (bottom panel). Chance performance is 33% correct. An examination of the two panels suggests that after two years of use, most children achieve very good performance on pattern recognition on the MTS Test, which suggests that they are able to use envelope cues provided by the cochlear implant. In a comparison of the performance for children categorized according to onset of hearing impairment, the data in Figure 4 suggest that the postlingually hearing impaired children achieve good performance more quickly than the congenitally hearing impaired children, but that congenitally hearing impaired children are also able to perform well on the test after 2 years of implantation. This indicates that envelope cues are perceived by the implant patients, although congenitally impaired children may require more experience with the implant to use the cues (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992).

We also present recent results on a more difficult perceptual test, the Word Intelligibility by Picture Identification (WIPI) Test (Ross & Lerman, 1971). This test assesses the ability to recognize words from 25 sets of six pictured words. Because all the words are monosyllables, this test requires the ability to recognize spectral differences. The top panel of Figure 5 presents data for 12 children with various onsets of hearing loss and compares preimplant performance with performance after 1 year of implant use. All children were in total communication programs. Preimplant performance is also compared with performance after 2 years of implant use (bottom panel). Chance performance is 17% correct. With regard to performance over time, an examination of the two panels suggests that most children show some improvement with continued implant use. This suggests that some children are able to learn to use spectral cues provided by the implant, although performance varies greatly. In a comparison of the performance for children categorized according to onset of hearing impairment, the data in Figure 5 suggest that postlingually hearing impaired children perform better than do the other children, and that some congenitally impaired children are able to perform above chance on the word recognition test, although they may require more experience with the cochlear implant. In general, the results suggest that the cochlear implant can provide useful spectral cues to speech perception such that word recognition improves over time.

Audiovisual Speech Feature Perception

It is important to establish which speech features are perceived by children with cochlear implants. One powerful approach is to present a closed set of syllables that differ in only one feature. We (Tyler, Fryauf-Bertschy, & Kelsay, 1991) have developed a closed set Audiovisual Feature Test to this end. Specifically, it consists of ten items in a conso-

Figure 5. Performance of children with cochlear implants on the Word Intelligibility by Picture Identification Test. Preimplant performance is compared to 1 year (top panel) and 2 year post-implant performance (bottom panel) for individual subjects. Data values higher than broken lines indicate a significant difference above chance at the 0.05 confidence level using a one tailed *t*-test of the binomial model.



nant-vowel syllable. Figure 6 shows an example of the response form. Before the test begins, the audiologist ensures that the children can label all items. In the test proper, the children are presented with one stimulus and must select their response from ten options.

Here we report preliminary data obtained from twelve congenitally deaf children who have been using the Nucleus cochlear implant from 1 to 4 years. Figure 7 presents the results from children who were divided into two groups; children who do not perform above chance (23% correct) in the sound-only condition (top panel), and children who perform above chance in the sound-only condition (bottom panel). An information transmission analysis of the errors was performed using the feature categories of Miller and Nicely (1955). For the group of children who performed well in the audition-alone condition, the features of voicing and nasality were best perceived. Observe that the vision-alone scores are similar across the two groups for voicing, nasality, and place. Note that the audition-plus-vision scores are higher than the vision-alone scores for both groups of children. This is particularly important for the group who did not score above chance on the overall audition-alone scores because it suggests that they received useful auditory information from their implant. Furthermore, both groups were able to integrate the auditory signal and the visual signal provided by the lips.

These preliminary results suggest that this test provides a useful technique to determine which speech features are utilized by young cochlear implant patients. In addition, the closed set format allows for audiovisual testing without complications of unequal lists or learning (memorization) of the test items. The test can be used successfully on many five-year-olds with equality among test lists.

Future Directions

We have identified several areas of importance that should be considered for the future development of cochlear implants in children and adults.

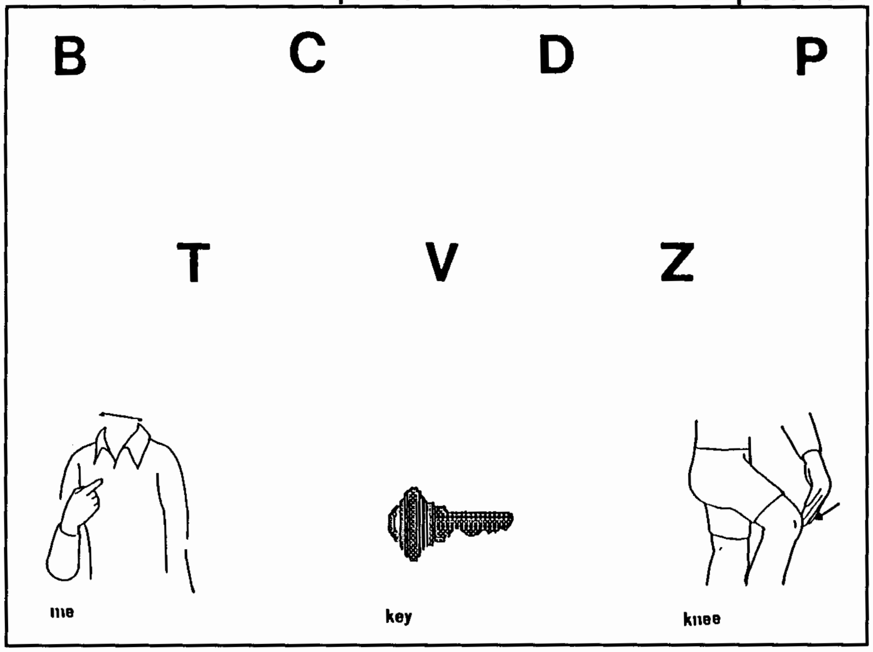
1. Expand Our Knowledge of the Acoustics of Speech, Background Noise, and Everyday Sounds

Designing signal processors and adjusting the processors for individual patients requires a detailed understanding of the signal and the noise. The signal might be speech, everyday sounds, or music. Background noise can be periodic or aperiodic and can include background voices. Listeners often attend to one signal while monitoring another in the background. For example, one might have a conversation while listening to music.

Study Speech Acoustics and How They Are Affected by Signal Processing Algorithms

Much is known about speech acoustics, but little is known about how signal processing changes speech features. One important example involves multichannel, full-range, amplitude compression circuits. These circuits are needed to re-

Figure 6. Response form from the Audiovisual Feature Test. The child hears one of the 10 items and must point to the one that he thinks was presented.



duce the 40-50 dB dynamic range of speech into the restricted dynamic range of the hearing impaired listener. Compression circuits are particularly useful for cochlear implant patients for whom the electrical coding of intensity often has a very limited dynamic range of 5-10 dB. These circuits change the temporal and spectral characteristics of speech. In addition, because the circuits are nonlinear, it is sometimes difficult to predict how they change the speech signal. For syllabic compression to be effective, the influence of various compression variables on speech acoustics must be determined. For example, the effect of different compression release times on various speech sounds should be studied.

Document Noise Characteristics

In order to develop effective noise suppression circuits, detailed information is required about the temporal and spectral composition of typical noises. Information is needed about the spatial and spectral characteristics of noise relative to speech. For example, data about noise amplitude fluctuations in different frequency bands will guide the development of circuits needed for noise recognition, the critical first stage of processing to separate the signal and the noise.

Determine Salient Acoustic Characteristics of Everyday Sounds and Music

More information is also needed about features salient for music perception and the effects of hearing impairment on music perception. As the speech perception skills of implant patients improve with rehabilitation, experience, and new signal processing designs, many patients will desire enhanced perception of music and other sounds that heighten their quality of life.

2. Determine How the Hearing Impaired Auditory System Codes Sound and Which Transformations Improve Coding

There are physiological constraints imposed on auditory perception. These include, for example, hair cell and nerve fiber loss, and the interpretation and integration of reduced information by the central auditory system. It is necessary to understand the relationships between specific physiological damage and their perceptual consequences. This information should provide guidelines for the design of processors that can be adjusted to meet individual needs. Electrical excitation produces auditory nerve action potentials that are more closely synchronized to the stimulus than are responses to acoustical stimulation. Whether the differences are critical to the improvement of speech encoding by electrical stimulation is not, as yet, clear.

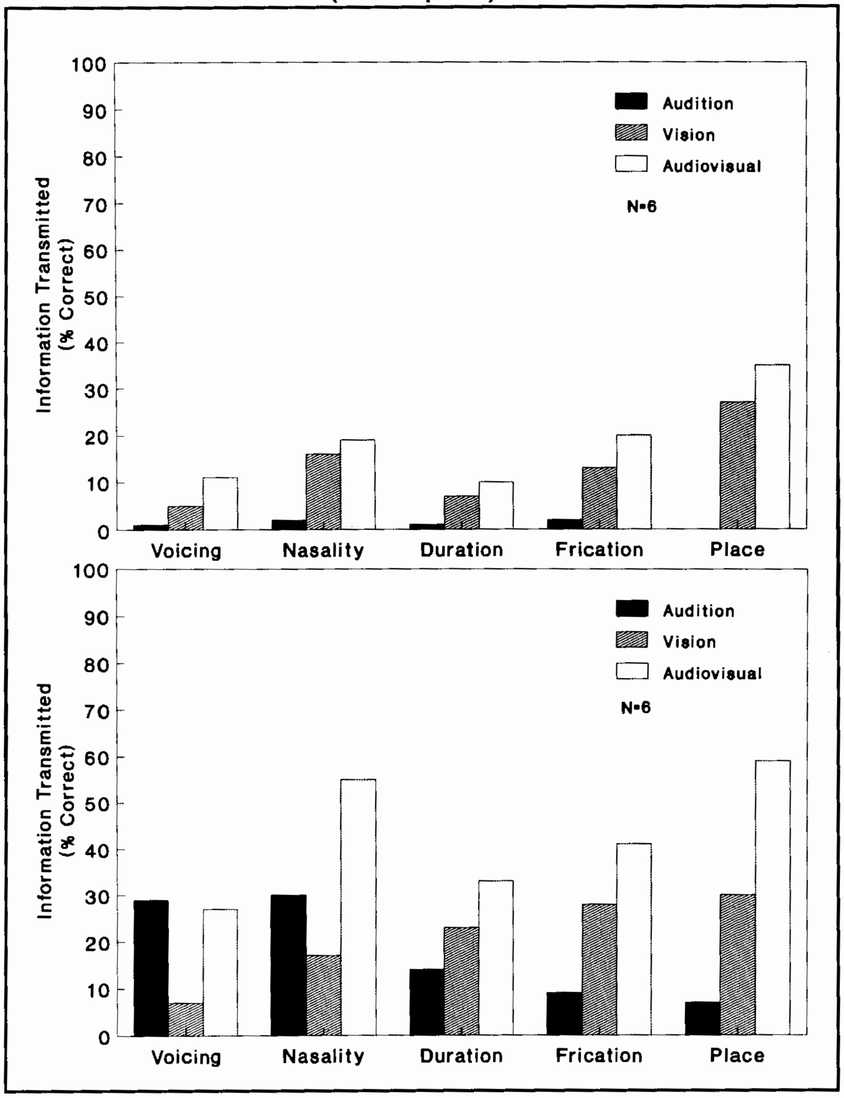
3. Design Cochlear Implants That Can Be Readily Modified

With the development of computer-based signal processing strategies, it should be easier to adjust the processor according to particular patient or environment needs. For example, situation specific processing might include a selection of frequency responses for several talkers, different automatic gain control circuits with different time constants, and/or noise reduction algorithms that adapt to the type of noise. These parameters could also be adjusted easily over time as the listening skills of the patient improve, for example, with rehabilitation, or are altered by perceptual changes brought about by aging.

4. Develop Optimal Fitting Strategies for Individual Patients

As the number of processing options increases, so will the need to develop new fitting strategies to assess the various parameters available (such as the frequency response, output limitation, number and frequency region of channels, number of electrodes, and noise suppression and amplitude compression circuits). The one-formula-fits-all approach is insuffi-

Figure 7. An information transfer analysis of the Audiovisual Feature Test from six children who did not score above chance in the audition-alone condition (top panel) and from six children who scored above chance on the audition-alone condition (bottom panel).



cient given the diversity of individual needs. Perhaps paradoxically, the increased number of parameters may mean that formulae may be an important first step to approximate the combination of parameters. However, additional fine tuning will be critical to optimize performance.

5. Increase the Number of Nerve Fibers Receiving Different Information

In the normal ear, approximately 40,000 auditory nerve fibers carry information to the central nervous system. Present cochlear implants stimulate with only 22 electrodes at most, and primarily nerve fibers originating from the basal region of cochlea are excited. More electrodes are needed in cochlear implants to stimulate different nerve fibers with different information.

There are several approaches that might be helpful in increasing the number of channels to 50 or 100. First, the electrodes could be made smaller so that more can be placed in the same area. Second, longer electrodes might be inserted into the round window compared to the 22-25 mm electrodes that are currently used, perhaps as the surgical approach or curvature or elasticity of the electrode carrier is changed. Third, electrodes could be placed in or adjacent to higher cochlear turns. Examples include stimulating from the medial wall of the middle ear cavity (Banfai et al., 1988) and drilling several holes through the medial wall at places adjacent to cochlear turns so that individual electrodes can be placed in each (Chouard, Fougain, Meyer, & Chabolle, 1986). Fourth, it is also possible to place an electrode into the auditory nerve directly (Simmons, 1966) or into the cochlear nucleus (Edgerton, House, & Hitselberger, 1982; Shannon, 1989). It may be that a combination of approaches will allow access to the widest range of nerve fibers, thereby more closely simulating normal excitation.

Patients with a bony obstruction of the cochlea represent a special challenge to provide electrical stimulation to additional nerve fibers. In these cases it is often difficult to place a complete electrode array. Balkany, Gantz, and Nadol (1988) and Gantz, McCabe, and Tyler (1988) have shown that multichannel implants can be inserted in obstructed and obliterated cochleas with careful surgical protocol. However, additional preoperative visual information about the degree and extent of ossification would be helpful. Perhaps improved resolution of magnetic resonance imaging will contribute to the development in this area.

6. Develop a Device That Is Completely Implantable

Behind-the-ear cochlear implants are feasible today, and in the future the entire speech processor hardware may be implanted. This may require a system to recharge the power supply, perhaps a headband worn during part of the day or night. It will also require surgical exploration for repairs or upgrades, but the cosmetic advantages will be very attractive to many patients.

7. Provide a Noninvasive Removable Implant

It could be very useful to provide a noninvasive cochlear implant for patients for whom the benefit obtained from a hearing aid is limited and cannot be determined precisely. Such situations arise, for example, with profoundly deaf children less than two years of age. If it is later determined that the child benefits more from the hearing aid than would be expected from the cochlear implant, then the implant could be removed easily. If the hearing aid later proves to be unsuccessful, then a more sophisticated intracochlear device could be considered. The child has benefited from auditory input during the early stage. A simple, removable cochlear prosthesis initially may have to be a single channel device. Although well designed multichannel implants typically provide more information than single channel ones, most patients benefit from single channel devices, and some patients achieve high levels of word recognition with single channel devices (Hochmair-Desoyer, Hochmair, & Stiglbrunner, 1985; Tyler 1988a, 1988b; Banfai, Karczag, Kubik, Luers, & Surth, 1986). The availability of a removable cochlear implant does not preclude the necessity of a preimplant trial with appropriate amplification and rehabilitation.

8. Implant Some Patients with More Residual Hearing

Some postlingually deafened adults using cochlear implants achieve scores in excess of 50% correct word recognition (Tyler, Moore, & Kuk, 1989; Tye-Murray & Tyler, 1989; Dorman, Hannley, Dankowski, Smith, & McCandless, 1989; Wilson et al., 1991). These scores are higher than those obtained by some severely to profoundly impaired hearing aid users. Therefore, it is likely that some of these patients will want cochlear implants.

The implantation of patients with useful hearing represents a challenge. Many of these patients are likely to have more hair cells and nerve fibers and therefore may obtain even higher speech perception scores. Therefore, some patients are likely to receive more benefit from a cochlear implant than from their hearing aid. Others, however, will likely be worse off after having received the implant, perhaps because their auditory system is more adept at coding acoustical than electrical stimulation. It will be necessary to compare preimplant hearing aid performance to the known performance of large numbers of implanted patients. Carefully controlled experiments will facilitate the identification of important predictor variables.

9. Design Synergistic Cochlear Implants, Hearing Aids, and Tactile Aids

Another critical challenge will be the synergistic fitting of two or more auditory prostheses. Many future cochlear implant patients may be using a hearing aid in the ear opposite to a cochlear implant. Other patients may receive additional benefit from the simultaneous use of tactile aids. Simply fitting each device independently may severely underestimate the potential of the combination of devices. However, coordinating the fitting of optimal parameters for the simultaneous signal processing for all these devices may be difficult.

One possible, systematic strategy might be to determine initially the speech features provided by each device separately. For example, a hearing aid worn by a profoundly hearing impaired patient might be able to provide low frequency voicing information, amplitude changes over time and, possibly, the location of the first formant frequency. In contrast, the cochlear implant might provide information about the second through fourth formant frequencies and about high frequency frication. It will also be necessary to determine which device settings will optimize performance when the two devices are used together. It should be appreciated that the evaluation should include the optimization of audiovisual, as well as auditory, speech perception.

10. Devise Measures of Auditory Skills for Children from Birth to 2 Years of Age

It is now possible to identify hearing loss within the first few months of life, often from birth. The cochlear implant could provide sound to profoundly or totally deaf children from this early stage of development. However, presently this cannot be accomplished because we cannot be certain how much benefit the newborn obtains from a hearing aid. This may represent the most formidable problem facing the future of cochlear implants in children.

One approach is to focus on establishing which newborns are totally deaf. If total deafness could be determined, then the expected benefit from a hearing aid would be minimal and a cochlear implant could be justified more easily. Auditory evoked potentials cannot yet measure low frequency hearing adequately but may offer a useful starting point.

11. Utilize Computer-Assisted Aural Rehabilitation

Aural rehabilitation includes training to use auditory-visual information. Efficient presentation of materials, via computer-based audiovisual training stations, and individualized aural rehabilitation strategies are two components that should change in the future.

The use of computer-based audiovisual training stations (Tye-Murray, Tyler, Bong, & Nares, 1989; Sims, Kopra, Dunlop, & Kopra, 1985) permits extremely efficient presentation of materials. These training stations are designed to function around a personal computer, using specially developed software and audiovisual presentation of stimuli. Individual training stations may be used either in the clinic or in the patient's home. Home use is particularly beneficial for patients who are limited in their ability to travel to aural rehabilitation therapy, either for physical reasons or because the patient is a young child. In addition, well controlled diagnostic tests may be administered that guide the appropriate type and duration of aural rehabilitation training. For example, diagnostic tests may determine the particular features of speech that an individual perceives poorly in auditory, visual, and audiovisual conditions. Specific training strategies could target problem areas. Currently, laser videodisc technology is used for audiovisual presentation. In the future, interactive compact disc technology may also be used.

Laser Videodisc Technology

Laser videodisc technology is an important part of computer-based aural rehabilitation training. Interactive laser videodisc programs permit auditory-visual materials to be presented to patients. Several interactive laser videodisc rehabilitative programs are currently under investigation (Tye-Murray et al., 1989; Boothroyd, personal communication). Interactive systems afford many advantages, including the following: (1) the speed and duration of the exercises may be programmed to reflect an individual's performance on earlier training sessions; (2) stimulus presentation is very efficient so that a large number of trials may be incorporated into a short training session; (3) programs can be linked with reinforcing animations and games so that interest and motivation in training is maintained; (4) the effect of various rehabilitation strategies on the patient's performance can be determined easily, using automated scoring; and (5) stimulus items may be accessed randomly by the computer so that there may be variation from training session to training session.

Compact Disc-Interactive Technology

Compact Disc-Interactive (CD-I) technology is an emerging medium that has the potential to provide many of the advantages that laser videodisc technology currently supplies in addition to several others. In the future, CD-I technology may become an important part of computer-based aural rehabilitation training. CD-I is expected to be a relatively inexpensive and easy to use interactive system. Because the unit is able to play standard audio compact discs and may be connected to most commercially distributed television sets, the CD-I unit should be an attractive addition to many home entertainment systems. These factors mean that CD-I players may become as common in the home as are video cassette recorders currently. In addition, a great deal of information may be stored on the disc, making it possible to store several training programs on a single disc. Although present CD-I systems do not supply the moving pictures necessary for presentation of auditory-visual training programs, it is expected that the capability will be available in the near future. When that occurs, CD-I technology should provide an important new tool for the aural rehabilitation of cochlear implant users and others with impaired auditory systems.

12. Develop Aural Rehabilitation Programs Tailored to the Fitting Characteristics of the Speech Processor

Another exciting future direction in aural rehabilitation is the development of training programs that are tailored to the type of speech processor worn by the patient. It is possible that the results of a training session could be used to automatically adjust the speech processor such that a particular (poorly perceived) speech feature could be emphasized. Computer-based aural rehabilitation could focus on the problem area and progress may be monitored. As perception of the feature improved, its coding could be gradually de-emphasized in the acoustic coding in the speech processor (Revoille, Holden-Pitt, Edward, & Picket, 1986).

13. Provide an Enriched Auditory Educational Program

Preliminary data regarding cochlear implant use by children suggest that the increased use of cochlear implants will alter the population profile of deaf students in two ways. First, by allowing virtually all totally and profoundly deaf children to detect some sound, the implant will change the population of hearing impaired children to include more children with some auditory capacity. Second, for some deaf children the implant will significantly improve their ability to perceive and produce speech. A greater portion of hearing impaired children will be able to communicate using primarily oral modalities. The education of these students should capitalize upon their increased perceptual abilities and emphasize the development of auditory and oral communication skills.

Special educators will continue to provide, or assist in providing, the optimal learning environment for young cochlear implant users. In addition to performing academic services and habilitative activities, they should be adept at managing all assistive devices and should understand the potential of each device to code acoustic information. The way in which educators implement educational services will have a great impact upon a child's success with an implant. Controversial issues in deaf education, such as educational placement, communication mode, and primary language system will need to be addressed to determine how to best serve the population. The resolution of these issues will require carefully designed and well controlled studies.

Much debate has centered around the optimal educational placement of deaf children. A child's ability to communicate with and to academically compete with hearing peers is often the basis for determining whether the child will be mainstreamed or segregated into a program for the hearing impaired, either within the community school or residentially. With increased access to auditory information, children with implants may have more opportunities to interact with hearing peers and family members. They may more readily integrate into the mainstream classroom and into the community. Children who remain at home and attend community schools will obtain more consistent exposure to spoken communication. However, to succeed in the mainstream classroom, implanted children may require a daily curriculum that includes auditory training and speech-language therapy to develop communication skills. This curriculum should be instituted early in elementary school and continue throughout a child's school career.

The purpose of providing an implant to a deaf child is to allow the child to perceive sound, most importantly speech. The mode of communication used with implanted children should, therefore, include oral speech. With increased auditory perception skills, more children may benefit from educational programs that advocate aural/oral communication. This is not to suggest that manual forms of communication should be eliminated in the educational programs of some implant users. Some children will be unable to rely upon spoken communication alone to develop language skills and to make academic progress. For these children, manual coding of speech should be used as an adjunct to oral communication to supplement the incomplete auditory signal. However, the difficulties in pairing oral and manual information accurately must be recognized.

The cochlear implant may make it possible for young children to acquire spoken English earlier and more proficiently because it affords increased exposure to conversational speech. American Sign Language (ASL) is recognized as the language of Deaf culture and may be appropriate for young children who, because of their hearing losses, cannot master the complexities of standard English. However, educational programs utilizing ASL do not emphasize the development of auditory and oral skills and may become less popular as the use of cochlear implants increases.

As the population of children using implants is extremely diverse, an important challenge for the future will be to design educational programs that suit the individual needs of children. The ability to perceive spectral information, not just amplitude and duration cues, may help determine the most appropriate and effective educational placement for a child (Moog & Geers, 1991). However, this alone cannot be the basis for a decision regarding a child's educational placement, communication mode, and language system. Other factors including the child's personality, previous experience with sound, and the family's involvement and their aspirations for the child's future will come into play as well.

14. Provide Cochlear Implants to Disadvantaged Populations

The high cost of obtaining a cochlear implant has restricted, to some degree, the population of users. In the United States, some insurance companies have become willing to cover the cost of implantation. This has permitted more individuals, for whom the device was formerly prohibitively expensive, to obtain an implant. In addition, it is possible that the cost of obtaining an implant may decrease. It may also be possible to design cochlear implants using simplified and, perhaps, less expensive circuitry. For example, new hearing aid signal processing uses single and multichannel technology that could be directly applied to cochlear implant technology. The single channel Vienna cochlear implant (Hochmair-Desoyer & Hochmair, 1985) has utilized hearing aid like processing with success in many patients. This sharing of research and development costs across the industry could result in less expensive implants. Thus, through increased insurance coverage and reduced cost, we may expect to see the cochlear implant become a viable alternative for a greater number of people.

It continues to be the case that cochlear implants are provided primarily to individuals living in industrialized nations. Several factors have contributed to this, such as the specialized training required of medical and allied health professionals, logistical and practical constraints, and the cost of implantation. As more is known of the benefits of implantation and as the process of obtaining and training to use a cochlear implant becomes more efficient, it may be more feasible to offer cochlear implantation in less industrialized nations.

Summary and Conclusions

The results that we have presented from adults and children with cochlear implants indicate that most are successful users. A justification for scoring lipreading enhancement as the percentage of maximum possible benefit was provided. This procedure is less influenced by vision-alone lipreading ability than other methods. A new audiovisual feature test for hearing impaired children was introduced, showing how speech feature transmission can be assessed in young children. Some children who do not score above chance on percent correct measures of word recognition may still benefit from their implant.

Future developments in cochlear implants should consider the entire rehabilitation process. More information is needed about typical speech and noise characteristics, surgical strategies, and signal processing. Rehabilitation and educational programs will also have an important role in the future development of cochlear implants.

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Address all Correspondence to: Richard S. Tyler, Ph.D., Department of Speech Pathology and Audiology, University of Iowa, Iowa City, Iowa 52242

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