Chapter 180: Cochlear Implants

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Cochlear implants are electronic devices that convert mechanical sound energy into electric signals that can be delivered to the cochlear nerve in profoundly deaf individuals. The devices seek to replace a nonfunctional inner ear hair cell transducer system.

The essential components of a cochlear implant system (Fig. 180-1) consist of (1) a microphone that picks up acoustic information and sends it to a processor worn external to the body, (2) a processor that serves as a transducer to convert the mechanical acoustic wave into an electric signal, and (3) an implanted electrode array placed near the auditory nerve (Fig. 180-2). The electric connection across the skin between the implanted electrode and the processor is accomplished via a system of induction coils in the majority of devices but may also be accomplished by a direct wire connection (percutaneous plug) (Eddington et al, 1983). The implanted electrodes differ accoring to the number of channels that are stimulated (single-channel or multichannel), their electric configuration (monopolar or bipolar), and their site of placement (extracochlear or intracochlear) (Banfai et al, 1987; Chouard et al, 1983; Clark, 1987; Eddington et al, 1983; Schindler and Kessler, 1987).

Several innovative strategies for electrically coding acoustic information are in current use. During analog transformation, the speech waveform or a derivative of it is presented to the cochlear nerve. This strategy, which is used by single-channel cochlear implants, provides primarily temporal and intensity information (Dobie and Dillier, 1985). Limited frequency information is provided in the lower frequency range (below 500 Hz) based on temporal information or "rate pitch". An example of this analog transformation scheme is the 3M/House device, which incorporates an amplitude-modulated 16 kHz carrier wave that is passed through a bandpass filter (200 to 4000 Hz) (Fretz and Fravel, 1985).

Multichannel cochlear implants attempt to produce tonal percepts by "place pitch" mechanisms by stimulating different locations in the cochlea and thus more discretely stimulating the central nervous system. The bandpass filter scheme separates the acoustic signal into discrete frequency bands, which are then delivered to multiple electrodes along the cochlear array (Eddington et al, 1983; Schindler and Kessler, 1987). This technique provides spectral information in addition to temporal and intensity cues. With this type of configuration simultaneous stimulation of two or more channels with continuous waveforms may result in summation of the electric fields from the different electrodes, which causes channel interaction. Channel interaction has been addressed by the use of nonsimultaneous stimuli using interleaved pulses that are delivered in sequence to the different channels in the implanted electrode array (Wilson et al, 1991).

The speech feature-extraction strategy by Nucleus 22-Channel Cochlear Implant (Cochlear Corp, Englewood, CO) selects only certain key features of speech to be presented to the central auditory system through the implanted electrode array (Clark, 1987). Incoming acoustic signals from the microphone are converted into a digital code that is presented to the feature extractor; a pattern of electric stimulation is developed and sent to the electrode array in the cochlea. The features encoded are the fundamental frequency F0 (which corresponds to the rate of vocal cord vibration) and the first and second formants, F1 and F2 (Blamey et al, 1987). The formants represent regions of greatest energy of sound within the vocal tract. The fundamental frequency provides voiced/voiceless information, and the formants are important for vowel identification. The F0 estimate is used to determine the frequency of the pulsatile stimulation sent to the electrodes and provides rate or voice pitch information to the patient. The location of stimulation along the electrode array is determined by the frequency estimates for F1 and F2. The processing scheme of the Nucleus device has been upgraded to include three high-frequency bands to provide added cues for consonant perception (Patrick and Clark, 1991). The stimulation level or amplitude of the signal determines the loudness of the perceived signal. The electric stimulation levels used clinically are determined by the patient's electric threshold and comfort levels.

Patient Selection

Adults

The selection criteria and procedures used to evaluate candidates for cochlear implants have evolved since the establishment of the first national clinical trial of single-channel cochlear implants by House in 1979 (Berliner, 1985). Cochlear implantation neither eliminates an underlying disease state nor restores normal function to the end organ of hearing. Therefore an objective view of risk/benefit ratios must serve to guide clinical decisions. Obviously, more risk can be accepted if more benefit is anticipated. With improved performance with multichannel cochlear implants, the strict criteria of the initial studies have been carefully broadened.

Cochlear implantation was initially limited to postlingually deafened adults who received no benefit from hearing aids and who had no residual hearing. Experience gained with this initial cochlear implant population served to establish expected performance limits that allowed expansion of the entry criteria to include selected patients with some residual hearing and measurable, although very limited, benefit from hearing aids (Osberger, 1990). Implantation of an ear with any residual, aidable hearing carries the risk that the implanted ear could be made worse than that ear with a hearing aid. Current investigations performed under US Food and Drug Administration (FDA) guidelines are testing the hypothesis that an ear with some residual hearing may have a better neuronal population, increasing the likelihood of superior performance with a cochlear implant, especially with more complex multichannel stimulation.

With an ever-expanding cochlear implant patient population it is now possible to compare speech perception performance of candidates (with hearing aids) to that of existing cochlear implant users. Test scores of the best current implant patients serve to establish upper performance limits. It is prudent to delay implantation of a patient who with a hearing aid is already performing at levels equal to those of the highest-performing implant subjects. As a general rule, average cochlear implant performance is used during counseling of prospective patients so as not to raise unattainable expectations. It is apparent that the audiologic criteria used to evaluate candidates constitute a complex and evolving process. With improved electronic equipment and coding schemes this process will continue.

The patient who becomes deaf as an adult (that is, postlinguistically deafened) has been the most readily identifiable beneficiary of cochlear implants to date. A period of auditory experience adequate to develop normal speech perception, speech production, and language skills before the onset of deafness is an advantage to understanding speech with an implant. Adult selection criteria include postlingual, profound bilateral sensorineural hearing loss in excess of 95 dB HL; little or no benefit from conventional hearing aids; and psychologic and motivational suitability. Prelinguistically deafened adults must be approached with considerable caution because performance benefits in this population are varied.

Medical assessment

The essential elements of the medical assessment include the otologic history, physical examination, and radiologic evaluation of the cochlea. Every effort is made to establish a precise etiologic diagnosis. However, experience with cochlear implants demonstrates that nearly all causes of deafness may be appropriate indications for cochlear implantation. With few exceptions, stimulatable auditory neural elements seem to be present regardless of cause of deafness (Hinojosa and Marion, 1983; Otte et al, 1978). Notable exceptions are the Michel deformity, in which there is a congenital agenesis of the cochlea and the small internal auditory canal syndrome where the cochlear nerve may be absent.

Routine assessment of the middle ear is performed. The ear proposed for cochlear implantation must be free of infection and the tympanic membrane must be intact. Medical treatment or surgical treatment or both before implantation are required if these conditions are not met. Chronic otitis media, with or without cholesteatoma, must be resolved before considering implantation. This is accomplished using conventional otologic treatments.

Prior ear surgery that has resulted in a mastoid cavity does not contraindicate cochlear implantation. However, this situation may require mastoid obliteration with closure of the external auditory canal or reconstruction of the posterior bony ear canal.

Radiologic examination of the cochlea is performed to determine if the cochlea is present and patent and to rule out a congenital deformity of the cochlea. High-resolution, thin-section CT scanning of the cochlea (Fig. 180-3) is the current imaging technique of choice (Yune et al, 1991). Intracochlear bone formation as a result of labyrinthitis ossificans can usually be demonstrated by CT scanning. However, sclerosing labyrinthitis with soft tissue obliteration may not be accurately imaged. In these cases magnetic resonance imaging (MRI); (Fig. 180-4) is an effective adjunctive procedure to provide additional information regarding cochlear patency. T-2 weighted MRI will demonstrate loss of the endolymp/perilymph signal in sclerosing labyrinthitis. Intracochlear ossification (labyrinthitis ossificans) is not a contraindication to cochlear implantation but can limit the type and length of the electrode array that can be introduced into the scala tympani of the cochlea (Jackler et al, 1987b). Congenital malformations of the cochlea, that is, Mondini deformity, are likewise not contraindications to cochlear implantation (Miyamoto et al, 1986a; Jackler et al, 1987). When temporal bone fracture has resulted in deafness, CT scanning may provide valuable information predicting the integrity of the cochlear nerve. This may be confirmed by electrophysiologic testing (Miyamoto, 1986; Miyamoto and Brown, 1988; Simmons and Smith, 1983).

No upper age limit is currently used in the selection process. Cochlear implantation is appropriate if other selection criteria are met and the patient's general health will permit an elective surgical procedure under general anesthesia. It is anatomically feasible to implant patients as young as 2 years of age or possibly even younger.

Audiologic assessment

Although the medical assessment may reveal information of special concern, exclusionary factors are rarely encountered. The audiologic evaluation is the primary means of determining suitability for cochlear implantation. Performance with an appropriate, high-power hearing aid is compared to expected performance with an implant. The basic tests include unaided and aided warble-tone and speech detection thresholds, environmental sound recognition, and speech perception measures on both open and closed set tasks (Pyman et al, 1990).

A period of training and experience with a properly fitted hearing aid is a requisite in the assessment. Performances in both the poorer and better ear are compared to the average level of performance and the range of performance demonstrated by patients using cochlear implants. Using the substantial data base now available, a judgment is made as to the likelihood that the patient will perform better with a cochlear implant than with a hearing aid or other assistive listening device such as a vibrotactile or electrotactile device. The crossover line is constantly evolving with improvements occurring in both hearing aid technology and cochlear implant design and signal processing.

As a general guideline, if a patient cannot attain an aided speech detection threshold of 70 dB SPL (approximately 53 dB HL) or better, performs very poorly on discrimination tests with a hearing aid, or both, a cochlear implant is likely to provide greater benefit. Other significant factors that may preclude effective hearing aid use such as recruitment or discomfort are considered. Patients with aidable hearing in the higher frequencies (above 1000 Hz) are very carefully assessed to determine if conventional amplification will have the potential of providing spectral information.

Psychologic assessment

Psychologic testing is performed for exclusionary reasons to identify subjects with organic brain dysfunction, mental retardation, undetected psychosis, or unrealistic expectations. Valuable information related to family dynamics and other factors in the patient's milieu that may affect implant acceptance and performance are assessed (Berliner and Eisenberg, 1985).

Children

The application of cochlear implant technology to the pediatric age group adds complexities to the already challenging management of the deaf child. General guidelines that apply to adults are applicable to children. Of paramount significance is a commitment of the child's family and educational setting toward providing an appropriate environment and training setting. An intact and functioning communication mode is invaluable in initiating the (re)habilitation process. As long as an auditory environment is provided, the cochlear implant can augment the child's auditory awareness whether an aural/oral approach, total communication, or cued speech is used (Miyamoto et al, 1986b).

The currently accepted minimum age limit of 2 years was initially chosen for anatomic reasons. The cochlea is adult size at birth, and by age 2 years the mastoid antrum and facial recess, which provide access to the middle ear for active electrode placement, are adequately developed. From a neurodevelopmental viewpoint an even younger age limit may be desirable. However, the difficulty in determining with certainty that a child in the 2- to 3-year age group is totally deaf and cannot benefit from a hearing aid is well known. For this reason, a prolonged hearing aid trial under close observation with appropriate aural rehabilitation is desirable for most children. Sufficient receptive and expressive abilities should be present to allow the child to learn stimulus/response associations to assist in accurate device setting and to permit the child to begin the extensive (re)habilitation program.

An otologically stable condition should be present before considering cochlear implantation in children. Because children are more prone to otitis media than adults, justifiable concern has been expressed that a middle ear infection could cause an implanted device to become an infected foreign body requiring its removal. Of even greater concern is that infection might extend along the electrode into the inner ear, resulting in a serious otogenic complication such as meningitis or further degeneration of the central auditory system. To date, although the incidence of otitis media in children who have received cochlear implants parallels that seen in the general pediatric population, no serious complications have been documented (Cohen et al, 1987).

The management of middle ear effusions in children either under consideration for cochlear implantation or who already have cochlear implants deserves special consideration. A noninfected middle ear is a preoperative prerequisite. Conventional antibiotic treatment will usually accomplish this goal. When it does not, treatment by myringotomy and insertion of tympanostomy tubes may be required. Removal of the tube several weeks before cochlear implantation will usually result in a healed, intact tympanic membrane before planned cochlear implantation. When an effusion occurs in an ear with a previously placed cochlear implant device, no treatment is required as long as the effusion remains uninfected.

Surgical Implantation

The most widely used surgical approach for cochlear implantation is through the facial recess or posterior tympanotomy. Skin incisions are designed to provide coverage of the external portion of the implant package while preserving the blood supply of the postauricular flap. Anterior- or inferior-based flaps are in common usage. Innovative modifications have improved flap viability and have allowed for special situations created by previous surgery.

The incision employed at the Indiana University Medical Center has eliminated the need to develop a large postauricular flap. The inferior extent of the incision is made well posterior to the mastoid tip to preserve branches of the postauricular artery. From here the incision is directed posterosuperiorly and then directed directly superior without a superior anterior limb. In children, the incision incorporates the temporalis muscle to give added thickness. A pocket is created for positioning the implant induction coil. Well anterior to the skin incision, the periosteum is incised from superior to inferior and a posterior periosteal flap is developed. At the completion of the procedure, the posterior periosteal flap is sutured to the skin flap, compartmentalizing the induction coil from the skin incision (Fig. 180-5).

Following the development of the skin incision, a complete mastoidectomy is performed. The horizontal semicircular canal is identified, and the short process of the incus is identified in the fossa incudis. The facial recess is exposed using the fossa incudis as an initial landmark. The facial recess is a triangular area bounded by (1) the fossa incudis superiorly, (2) the chorda tympani nerve laterally and anteriorly, and (3) the facial nerve medially and posteriorly. The facial nerve can usually be visualized through bone without exposing it completely. The round window niche is visualized through the facial recess approximately 2 mm inferior to the stapes. Occasionally, the round window niche is posteriorly positioned and is not well visualized through the facial recess or is obscured by ossification. Particularly in these situations it is important not to be misdirected by hypotympanic air cells. Entry into the scale tympani of the cochlea is best accomplished through a cochleostomy created anterior and inferior to the annulus of the round window membrane. A small fenestra slightly larger than the electrode to be implanted (usually 0.5 mm) is developed. A small diamond burr is used to "blue line" the endosteum of the scala tympani, and the endosteal membrane is removed with small picks. This approach bypasses the hook area of the scala tympani allowing direct insertion of the active electrode array. After insertion of the active electrode array, the round window area is sealed with small pieces of fascia.

Clinical Results

Adults

The single most important statement to be made about performance results is that a substantial percentage of postlingually deaf adults demonstrate some open-set speech recognition (that is, understanding words or sentences *without* a multiple-choice answer format and without lipreading) with a multichannel cochlear implant. The relative frequency of occurrence of open-set speech recognition among multichannel users is difficult to specify exactly because of differences in test materials and procedures among investigations and criteria used to determine open-set speech recognition. A reasonable estimate at this time is that roughly one half of the postlingually deafened adults who have received a multichannel implant have achieved some open-set speech recognition (on sentence or monosyllabic word tests) with their device. A finding of particular significance is that similar results have been obtained for users of the Nucleus and Ineraid implants even thous these two devices employ very different types of processing schemes and electrode arrays (Dorman et al, 1989; Gantz et al, 1987; Tyler et al, 1989). Additionally, it has been reported that approximately 25% to 50% of the patients with multichannel implants can understand speech to varying degrees on the telephone (Cohen et al, 1989).

With few exceptions, patients demonstrate better perception and recognition of environmental sounds and lip-reading performance with a multichannel cochlear implant than they did with conventional hearing aids. Even though not all patients are able to understand speech with an implant without lipreading, they still derive substantial benefit from the implant in terms of enhanced lipreading ability and environmental sound perception in everyday life. The clinical significance of this degree of benefit is varied by the patients' consistent use of an implant even though they cannot understand speech without lipreading with the device. It also is important to keep in mind that most of the everyday communicative interactions in which implant users are involved permit the use of visual as well as auditory cues.

The majority of adults who receive an implant are postlingually deafened. However, prelingually deafened adults who communicate orally and who have been consistent hearing aid users also benefit from a multichannel implant even though their level of performance is poorer than that demonstrated by persons who became deaf as adults.

Children

An important difference between the performance of adults and children with multichannel implants is the long time course over which learning takes place in the pediatric population (Miyamoto et al, 1991b). In fact, the upper limits of perception performance with a multichannel implant have not yet been determined in children. Two other findings with children also are noteworthy. First, improvement in speech perception skills may not be obvious until the devices have been used for 1 year or more. Second, children with the multichannel implant achieve significantly higher scores on nearly every type of speech perception test than do children who use a single-channel cochlear implant (that is, the 3M/House device) (Miyamoto et al, 1989; Osberger et al, 1991b, 1991c).

These trends are illustrated in data reported by Miyamoto et al (1991) as shown in Fig. 180-6. The data shown in this figure were collected from two groups of children who received either the 3M/House single-channel implant or the Nucleus 22-Channel Cochlear Implant System. All children had congenital hearing loss or ones that were acquired before 3 years of age. Word recognition scores on the Monosyllable-Trochee-Spondee Test (MTS) (Erber and Alencewicz, 1976) are plotted for each group of subjects over time in Fig. 180-6. On this test, the child was required to identify 12, one- or two-syllable words (for example, duck, popcorn, turtle) without lipreading. This is a closed-set test because the child had alternatives from which to choose the answer (chance performance = 8%). The test was not part of the evaluation protocol when the 3M/House users entered the study. The test was first administered when these subjects had used their devices for 1.5 years. On the average, the 3M/House users achieved scores only slightly higher than would be obtained by guessing (that is, chance level of performance) with negligible change in their test scores between the 1.5- and 2.5-year intervals after implant. In contrast, data from the Nucleus users showed no evidence of a plateau in performance over time. In fact, the upward trend in performance appeared to continue even 2.5 years after implantation. Note that, on the average, the Nucleus users did not demonstrate large changes in performance at the 6-month postimplant interval. The largest increase in performance occurred at the 1-year postimplant interval with steady improvement after that time.

Different auditory perceptual skills develop at different rates in children who use a multichannel cochlear implant. This point is illustrated in Fig. 180-7. The Nucleus users obtained substantially higher scores on the test that assessed recognition of words in a closed set than they did on the open-set test that assessed recognition of phrases. Recognition of phrases involves perceptual skills that tap linguistic abilities as well as auditory processing, thereby requiring years of implant use and special education before "open-set" sentence recognition appears.

Variables affecting performance

A number of investigators have explored the effect that communication mode has on children's perceptual skills with an implant. Berliner et al (1989) found that communication mode was one of the variables that accounted for differences in the open-set speech recognition abilities of children with the single-channel implant. This finding is consistent with that of Osberger et al (1991b), who showed that communication mode made a significant unique contribution to the variance in performance among subjects on an open-set word recognition test. However, Staller et al (1991) did not find communication mode to be a significant variable in accounting for the variance among the Nucleus users' perfomance on closed- and open-set speech-recognition tests. These findings taken as a whole suggest that communication mode predicts performance on some measures but not on others. Further research is needed on this issue.

Staller et al (1991) reported that age at onset of deafness and duration of deafness before implantation accounted for a relatively large percentage of variance among subjects' performance on open- and closed-set speech-recognition tests. These variables did not contribute uniquely to the variance in the word-recognition scores among subjects studied by Osberger et al (1991d). However, the range of difference among the subjects in the Osberger study in terms of age at onset of deafness and duration of deafness may have been more restricted than for the subjects in the study by Staller et al. The unique contribution of these variables might be affected with changing trends in implant candidacy. For example, as implant teams gain more experience with the pediatric population, there appears to be a trend toward implanting a larger number of children in the 2- to 4-year age range. Findings suggest comparable levels of speech perception performance in children with congenital or early acquired deafness (Osberger et al, 1991d). There also is a trend to implant children with hearing losses secondary to meningitis as soon as possible after the hearing loss is diagnosed (Firszt, 1991).

Finally, our experience has shown that children implanted in early or late adolescence (between 14 and 18 years of age) demonstrate (1) more limited improvements with a single-channel or multichannel implant and (2) a trend toward increased nonuse of the implant than do children who received their device during early childhood. There are, of course, exceptions to this trend illustrated by the consistent use of implants by some children who did not receive their device until adolescence.

Speech production skills

Although the primary role of a cochlear implant is that of an aid to speech *perception,* a secondary and vital role is that of an aid to speech *production.* A longitudinal study of speech development in children with Nucleus implants suggests that these children acquired consonant and vowel features that are difficult for children with profound hearing losses to produce (that is, high vowels, diphthongs, alveolar consonants, and fricatives) (Osberger et al, 1991a). Large improvements in speech production in children who received the Nucleus implant also have been documented by Tobey et al (1991a, 1991b).

Children who are implanted in early childhood generally show large improvements in speech (Osberger et al, 1991a). In contrast, children who were not implanted until adolescence show limited improvements in their speech production performance (Osberger et al, 1992). These children also demonstrated the smallest changes in their perception skills over time. These findings do not mean that children who are adolescents should not receive an implant. Rather the child and family should be counseled carefully regarding realistic expectations in performance with the implant.

Candidacy

Determining implant candidacy is difficult with young profoundly hearing impaired children whose speech perception performance with a sensory aid is directly influenced by their linguistic abilities and prior experience and training with the device (Kessler, 1991). The children who have been the most obvious candidates for an implant are those who have demonstrated no response to warble tones in the sound field with appropriate hearing aids or responses suggestive of vibrotactile rather than auditory sensation (that is, aided responses at levels greater than 50 to 60 dB HL in the lower frequencies with no responses above 1000 Hz).

Not all children with profound hearing losses are implant candidates. Data collected in our laboratory have shown that most children with pure-tone thresholds between 90 and 105 dB HL with residual hearing through at least 2000 Hz demonstrated closed- and open-set speech-recognition skills that were superior to even the highest performing multichannel implant users (Miyamoto et al, 1991a). Given that children with profound hearing losses demonstrate disparate speech perception abilities (Boothroyd, 1984), it is crucial that children with a wide range of hearing levels be tested on the same measures used to evaluate implant performance to develop objective criteria for candidacy.

Other important considerations for implant candidacy are the child's communication skills, his or her ability to make a conditioned response to tactile or auditory stimuli, parental commitment, and availability of rehabilitation services (Pope, 1991). Adequate communication skills are particularly important for the taks required to optimize the fitting of a multichannel implant such as the Nucleus device. Psychosocial factors also affect implant candidacy and management (Quittner and Steck, 1991; Quittner et al, 1991). It is desirable for a psychologist, preferably one who has experience with children who are hearing impaired, to be a member of the implant team to assess candidacy decisions and participate in counseling the parents about issues related to management of the child (Miyamoto et al, 1986b).

Physician's role in counseling families regarding cochlear implants

The physician plays a vital role in helping families determine whether their family member is an appropriate candidate for a cochlear implant. Because the physician's input carries heavy weight in the family's decision-making process, this input should be as accurate and realistic as possible. Three important areas to be covered with families are (1) benefits, limitations, and risks of the cochlear implant; (2) realistic expectations for a given patient; and (3) long-term prospects for the implant, including device failure and device upgrade.

Benefits, limitations, and risks

Families of prospective implant patients vary widely in their understanding of the cochlear implant at the time of the initial assessment. Some families may have carefully researched the topic and spoken to knowledgeable individuals. Other families, with limited access to accurate information about the implant, may have incorrect notions regarding the device. These notions often include the assumption that the device is completely implantable, with no external hardware; a belief that the implant is appropriate for hard-of-hearing individuals, or those with unilateral hearing loss; and an assumption that the implant restores normal hearing to deaf patients. These notions may not be directly expressed by the family to the cochlear team so it is critical that the physician explicitly state the known benefits, limitations, and risks of the implant. In particular, the family must understand that even "star" performers with the implant will continue to function as hearing-impaired individuals who experience considerable difficulty in certain listening and communication situations.

The risks associated with cochlear implantation should also be covered with families in simple laypersons' terms. This is particularly important for the deaf patient, who will need information stated slowly and clearly, often with frequent repetition. In addition to mentioning possible surgical complications, patients should be made aware that any residual hearing in the ear to be implanted will most likely be destroyed as a result of electrode insertion, thereby prohibiting future use of a hearing aid in that ear.

Realistic expectations for a given patient

Although data regarding group performance with cochlear implants are helpful to families of prospective candidates, it is equally important that the implant team provide information regarding realistic expectations for a given patient. This is especially critical if a patient presents characteristics that might limit performance potential, including prelingual deafness in adults; postlingual deafness with many years of auditory deprivation; severe cochlear anomalies, such as Mondini malformation; and additional handicapping conditions. Although these characteristics should not exclude candidates from consideration, the presence of such characteristics necessitates frank discussion regarding the upper limits of performance that are predicted in these patients. It also is helpful for interested families to correspond with or meet implant patients who share similar characteristics.

Long-term prospects for implant

Patients should be counseled regarding the long-term maintenance of the implant, including the cost of parts and repairs and the possibility of device failure that could necessitate additional surgery. Families of young children, in particular, should be encouraged to investigate insurance coverage for the speech processor in the event that it is lost.

Families frequently inquire about the potential for upgrading the device to make use of future improvements in electrode design or speech processing schemes. Discussion of these possibilities is warranted.

Summary

Cochlear implants are an appropriate alternative for selected deaf adults and children. Multichannel systems that provide spectral information in addition to intensity and temporal cues have demonstrated performance advantages. Additional research is necessary to address a number of fundamental questions. Preoperative techniques that access auditory neuronal survival and central auditory processing abilities are needed. Detailed longitudinal studies documenting the influence of cochlear implants in children's abilities to improve speech perception, speech production, and language skills are in progress and will need to be continued for many years to determine the full impact of cochlear implantation. Improved signal coding and processing and the ability to better match these strategies to the deafened peripheral auditory system will provide fruitful research areas for many years to come.