Recent Advances in Cochlear Implants

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Cochlear implants have had a great impact on the procedures that are used to treat profound hearing loss in children and adults. Before the introduction of cochlear implants, profoundly deaf individuals relied on lipreading, sign language, and amplification systems that were often unable to make speech sounds audible for the profoundly deaf user. Today, most profoundly deaf individuals who use a cochlear implant are able to detect speech sounds within a normal range of hearing (i.e., 25 db HL). This has resulted in great improvements in the speech recognition and spoken language skills of profoundly deaf children and adults. This article will provide a brief overview of some of the changes and technological advances that have taken place in the field of cochlear implants since they were first introduced.

ABSTRACT: Over the years, numerous technological advances have taken place in regard to the internal and external components of cochlear implant systems. Such advances include improvements in receiver and electrode design and placement, improvements in external component technology that have brought about downsizing and increased efficiency of externally worn speech processors, and improvements in surgical techniques that have resulted in decreased damage to the cochlea following electrode insertion. These advances have resulted in changes in candidacy criteria over time and improved outcomes for adults and children who receive cochlear implants. This article will provide a brief overview of some of the changes and technological advances that have taken place in the field of cochlear implants since they were first introduced.

KEY WORDS: cochlear implant, electrode, electrode array, speech processor, map, telemetry

COCHLEAR IMPLANT DEVICES

There are currently three manufacturers who offer cochlear implant systems in the United States: Advanced Bionics (Advanced Bionics Corporation, Sylmar, CA; www.advancedbionics.com), Cochlear Americas (Cochlear Pty. Limited, Sydney, Australia; www.cochlear.com), and MED-EL GmBH (Innsbruck, Austria; www.medel.com). A detailed description of each system can be found at each manufacturer’s Web site.

Each cochlear implant system has two primary components: (a) a surgically implanted electrode array and receiver and (b) an externally worn speech processor. The internal and external components work together to provide the implant user with sound. A schematic diagram of how a cochlear implant works is provided in Figure 1.

Internal Components

Internal components of a cochlear implant include the receiving coil, magnet, internal processor/receiver, and electrodes, which are housed along a carrier that is referred to as the electrode array. The internal device receives sound information from the external components via transcutaneous transmission of the signal to the antenna of the internal receiver coil. The internal coil is aligned with the externally located transmitter coil and is held in place by external and internal magnets. The internal magnet can and should be removed if the recipient needs to be tested using magnetic resonance imaging (MRI).

Several technological advancements have taken place in regard to the structure and function of internal cochlear implant components. The early 3M cochlear implant system (House, 1976) used a single electrode and was referred to
Current cochlear implant systems use between 12 and 24 electrodes and are, therefore, referred to as multi-channel devices. Unlike single-channel technology, multi-channel electrodes take advantage of the tonotopic organization of the cochlea and present pitch information based on place of stimulation within the cochlea.

Early multichannel cochlear implant systems used straight yet flexible electrode arrays. Such arrays tended to lay against the lateral wall of the cochlea after insertion (Patrick, Busby, & Gibson, 2006). In contrast, current electrode arrays are precoiled, allowing the electrodes to be placed closer to the center of the modiolus where spiral ganglion cells are located. Additionally, contemporary arrays are specifically designed to be less traumatic to the delicate structures of the cochlea during surgical placement, thereby increasing the likelihood that residual hearing may be preserved. Contemporary arrays are also designed to provide a more focused delivery of electric current than earlier devices (Roland, Huang, & Fishman, 2006). This has resulted in a decrease in the amount of current needed for clients to hear with electrical stimulation as well as improved battery life for speech processors.

Current cochlear implant systems offer various lengths, sizes, and configurations of electrode arrays. Standard arrays are most often used with clients who present with a normal cochlea; shortened arrays may be used when deep insertion is not desired or is not possible due to anatomic restrictions, such as cochlear ossification or cochlear anomaly. Compressed arrays, which contain the same number of electrodes as a standard array, may also be used with cochlear anomalies that may prevent complete insertion of a longer, standard array. Split arrays are also available and consist of two separate electrode branches designed for insertion into different areas of the cochlea. Last, electrode arrays can be either straight or precoiled to more closely fit the curves of the cochlea (Roland et al., 2006).

Additional improvements in internal components that have taken place since cochlear implants were first introduced include the addition of magnets for retention of the external coil; development of more efficient, current-focusing electrodes and precoiled arrays; downsizing and technological improvements of the receiver–stimulator, allowing for faster rates of stimulation and new and improved speech processing strategies; introduction of telemetry (the ability to send information to the implant and to receive information back from the implant about the device and neural status); and introduction of the ability of the internal device to recognize and only communicate with a speech processor that is programmed for the individual recipient (implant identification). Improvements in surgical technique and implant design have decreased the amount of trauma associated with placement of the electrode array in the scala tympani (Roland et al., 2006). Such recent improvements include perimodiolar electrodes that place the electrodes closer to the modiolar wall, thereby providing enhanced stimulation of spiral ganglion cells, and the advance electrode stylet (AOS), which improves the coiling feature of the electrode on insertion, thereby avoiding contact with and damage to the outer wall (Roland et al., 2006).

**External Components**

The external components of cochlear implant systems collect, analyze, process, and transmit sound information to the internally implanted device. Components of external speech processors include a microphone, processing unit, connecting cables, and transmitter coil.

When cochlear implants were first introduced, only body-worn speech processors were available. These processors were rather large and bulky and were powered by as many as three AA batteries. Today, all cochlear implant systems offer ear-level processors as well as modular components that can convert into small pediatric-friendly body-worn

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**Figure 1.** Schematic diagram of how a cochlear implant works: Sounds are picked up by the microphone, which is located on the headset/speech processor. The speech processor converts the sound to an electrical signal coded for transmission to the internal device. The coded signal travels from the speech processor to the external transmitter via a connector cable. The externally worn transmitter is aligned with the internal receiving coil by external and internal magnets. The external transmitter sends the signal to the internal receiver, which receives the information, decodes the signal, and delivers electrical stimulation to the implanted electrodes. Photo courtesy of Advanced Bionics. Used with permission.
processors. Such systems include a battery pack that can be attached to the processor and worn behind the ear or one that can be attached to the processor via a cable and worn on the recipient’s clothing. Such detachment of the speech processor decreases the size of the unit placed behind the recipient’s ear as well as the chance that the processor will be lost or detached from the user. Such modularity helps decrease cost as recipients can easily move from a body-worn to an ear-level processor without needing to replace the entire speech processor.

Modern-day processors are powered by either zinc-air disposable or rechargeable batteries. Battery life varies and may be influenced by several factors, including battery size, size of the skin flap, speech processing strategy, and the client’s psychophysical requirements. For many clients, rechargeable batteries will last approximately 12 hr; disposable batteries will last approximately 3–5 days.

Currently available speech processors offer several common features including separate dials to control on/off, sensitivity, and volume; private and public alarms; a variety of different-sized earhooks; adjustable magnet strengths; light emitting diodes (LEDs) to signal status of the processor; and external input ports that enable recipients to connect and use various assistive listening devices, including handheld microphones, FM systems, and personal audio systems such as MP3 players.

When first introduced, speech processors held only a single program. Today, the number of memory locations for programs varies from two to nine. Having more than one memory is advantageous as it provides the user with the ability to try different programs or different speech processing strategies outside the clinic setting. In many cases, having more than one program location decreases the number of appointments needed to adjust the speech processor programs (Zwolan & Griffin, 2005).

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**DETERMINING CANDIDACY FOR A COCHLEAR IMPLANT**

When cochlear implants were first introduced, the U.S. Food and Drug Administration (FDA), which oversees the selling, distribution, labeling, and marketing of drugs and medical products in the United States, required implant manufacturers to conduct lengthy clinical trials to evaluate and demonstrate the safety and efficacy of cochlear implants before they could receive approval for widespread use. These clinical trials successfully demonstrated that cochlear implants are a safe and effective treatment for severe to profound hearing loss. Today, the FDA continues to monitor cochlear implant device use and outcomes, and determines if the specific wording used in device labeling, including indications for use, is appropriate.

The clinical trials used to evaluate various cochlear implant systems have been conducted at different times. Thus, the FDA-approved labeling of “indications for use” varies for the different cochlear implant devices. In general, candidacy criteria, or indications for use, for early devices were stricter than those for more recently approved devices. For example, in early clinical trials, only clients with a bilateral profound sensorineural hearing loss who demonstrated no benefit from amplification (i.e., scored 0% correct on open-set sentence recognition tests) were considered to be candidates for a cochlear implant. Today, adult clients should demonstrate at least a moderate hearing loss in the low frequencies and a profound hearing loss (unaided threshold ≥ 90 dB HL) in the mid to high speech frequencies bilaterally (Nucleus Freedom, 2008). The criteria wording regarding speech recognition skills have also changed over time; with present-day devices (i.e., the Nucleus Freedom), the FDA defines limited benefit from amplification for adults as “a score less than or equal to 50% correct in the ear to be implanted on taped sentence recognition tests and a score less than or equal to 60% correct in the best-aided listening condition.” For children, FDA indications for use include the following:

Little or no benefit from hearing aids. In young children, this is demonstrated by lack of progress in development of simple auditory skills in conjunction with appropriate amplification and participation in an intensive auditory habilitation program. This is also demonstrated by parental response to client-administered questionnaires such as the Meaningful Auditory Integration Scale (MAIS) (Robbins et al., 1991) or the Infant-Toddler MAIS (Zimmerman-Phillips et al., 1998). In older children, minimal benefit from amplification is demonstrated by scores less than or equal to 30% correct on open-set speech recognition measures such as the Lexical Neighborhood Test (LNT) (Kirk et al., 1995) or the Multisyllabic Lexical Neighborhood Test (MLNT) (Kirk et al., 1995). A three to six month hearing aid trial is recommended for children with no previous hearing aid experience. (Nucleus Freedom, 2008)

Reasons for such expansions in candidacy include an improved understanding of the safety and efficacy of cochlear implants as well as continued monitoring of outcomes, primarily through clinical trials. Such trials have demonstrated that speech recognition skills have improved as technological advances have taken place with internal and external components of cochlear implant systems.

**Preoperative Appointments to Determine Candidacy**

There are several appointments that recipients are required to attend before candidacy for a cochlear implant can be determined. These appointments are listed in Table 1. Audiologic testing determines the type and severity of the hearing loss and usually includes unaided air and bone conduction, speech reception or speech detection thresholds, word recognition testing, otoacoustic emissions, tympanometry, and acoustic reflex testing. A hearing aid evaluation (HAE) is performed to evaluate and determine the appropriateness of hearing aids for the client’s loss. Once appropriate hearing aids have been identified, aided testing, which includes aided detection thresholds for each ear separately and in a binaural condition at frequencies ranging from 250 Hz to 4000 Hz, aided speech detection threshold (SDT), speech reception threshold (SRT), most comfortable level (MCL), and uncomfortable level (UCL), is performed. Speech perception testing should also be performed for each ear separately and in a binaural aided condition.
cochlear hypoplasia, incomplete cochlear partition, receiving cochlear implants. Such anomalies may include reports of clients with less severe anomalies successfully aplasia, and cochlear nerve aplasia. There are several anomalies that will preclude implantation. Such anomalies (Eisenman, Ashbaugh, Zwolan, & Telian, 2001). On rare cochlear anomaly that may affect client outcome to order a special type of electrode array, or if there is a the surgery (Fishman & Holliday, 2006), if there is a need to determine if there are any findings that may complicate and structure of the mastoid and inner ear and helps testing enables the surgeon to evaluate the development and can help identify clients with auditory dysynchrony. Electric auditory brainstem response (EABR) testing is performed at some clinics and involves presentation of current pulses via a trans tympanically placed promontory electrode and reception and interpretation of the resulting ABR (Kileny, Zwolan, Zimmerman-Phillips, & Telian, 1994). Such testing is particularly useful when a client presents with a cochlear anomaly that may prevent transmission of the signal along the eighth nerve (such as cochlear nerve aplasia).

With children, a speech and language evaluation is an essential part of the preoperative evaluation as it provides information regarding the effect that the hearing loss has had on the ability of the child to develop spoken language skills. Such an evaluation is particularly helpful when evaluating the candidacy of borderline candidates (children who receive some benefit from hearing aids) and when determining if a child with auditory neuropathy should be considered for a cochlear implant. The preoperative speech and language evaluation often includes assessment of expressive and receptive language skills (including auditory comprehensibility), articulation, speech intelligibility, and reading.

Over the years, cochlear implant candidacy has expanded to include children with greater residual hearing (i.e., borderline candidates and children with auditory dys synchrony) and greater numbers of children with special needs, such as those with additional physical or mental handicaps. This has increased the need for preoperative psychological evaluations to determine if factors other than hearing impairment have hindered the child’s development of spoken language skills and to determine if the disability may affect the anticipated outcome if the child receives a cochlear implant (Zwolan, 2008). Such testing should include nonverbal assessment of the child’s cognitive, social, emotional, and adaptive abilities.

**COCHLEAR IMPLANT SURGERY**

Once preoperative testing has been completed, the client can be scheduled for surgery. In most cases, surgery will last approximately 2–3 hr and involves making a postauricular scalp incision, drilling to make a well in the mastoid bone for placement of the internal receiver, drilling through the mastoid air cells (mastoidectomy) to open the facial recess for visualization of the cochlea, and drilling an opening in the basal turn of the scala tympani for placement of the electrode array (cochleostomy). This is followed by placement of the receiver into the mastoid well, electrode insertion, packing of the cochleostomy, and closure of the skin flap (Cohen & Roland, 2006).

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<th>Table 1. Appointments commonly involved in the determination of candidacy for a cochlear implant.</th>
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<td>Audiologic evaluation</td>
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<td>Hearing aid evaluation (HAE)</td>
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<td>Cochlear imaging (computed tomography, CT, or magnetic resonance imaging, MRI)</td>
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<td>Speech and language evaluation</td>
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<td>Psychological evaluation</td>
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<td>Final consult with audiologist and surgeon</td>
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Whenever possible, recorded test materials should be used for speech perception testing. Most clinics use a presentation level of 60 dB SPL (Firszt et al., 2004) for speech recognition assessment.

With adults, commonly used speech perception materials include the Consonant-Nucleus-Consonant (CNC) Monosyllabic Words test (Peterson & Lehiste, 1962), the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994), Bamford-Kowal-Bench (BKB) Sentences (Bench, Kowal, & Bamford, 1979), and City University of New York (CUNY) Sentences (Boothroyd, Hanin, & Hnath, 1985). With children, commonly used tests include the Meaningful Auditory Integration Scale (MAIS; Robbins, Renshaw, & Berry, 1991), the Infant–Toddler MAIS (IT–MAIS; Zimmerman-Phillips, McConkey-Robbins, & Osberger, 1998), the Early Speech Perception (ESP) test (Moog & Geers, 1990), the MLNT (Kirk, Pisoni, & Osberger, 1995) or LNT (Kirk et al., 1995), the Word Intelligibility by Picture Identification (WIPI) test (Ross & Lerman, 1979), and the Phonetically Balanced Kindergarten (PBK) word list (Haskins, 1949).

Once it has been determined that a client meets audiologic criteria for a cochlear implant, he or she is scheduled for a medical evaluation with a surgeon. The surgeon determines if treatment options other than a cochlear implant are more suitable for the client and if the client is healthy enough to participate in cochlear implant surgery if one is recommended. The surgeon ensures that the client has been fully vaccinated against meningitis and places an order for either computed tomography (CT) or MRI of the temporal bone. Such testing enables the surgeon to evaluate the development and structure of the mastoid and inner ear and helps determine if there are any findings that may complicate the surgery (Fishman & Holliday, 2006), if there is a need to order a special type of electrode array, or if there is a cochlear anomaly that may affect client outcome (Eisenman, Ashbaugh, Zwolan, & Telian, 2001). On rare occasions, CT or MRI may reveal cochleovestibular anomalies that will preclude implantation. Such anomalies may include complete labyrinthine aplasia, cochlear aplasia, and cochlear nerve aplasia. There are several reports of clients with less severe anomalies successfully receiving cochlear implants. Such anomalies may include cochlear hypoplasia, incomplete cochlear partition, common cochlear cavity, lateral semicircular canal dysplasia, enlarged vestibular aqueduct, and narrow internal auditory canal (Fishman & Holliday, 2006).

Certain electrophysiologic tests may be included in the preoperative assessment battery. Auditory brainstem response (ABR) and otoacoustic emissions are objective measures that can be used to verify behavioral test results and can help identify clients with auditory dysynchrony.

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With children, a speech and language evaluation is an essential part of the preoperative evaluation as it provides information regarding the effect that the hearing loss has had on the ability of the child to develop spoken language skills. Such an evaluation is particularly helpful when evaluating the candidacy of borderline candidates (children who receive some benefit from hearing aids) and when determining if a child with auditory neuropathy should be considered for a cochlear implant. The preoperative speech and language evaluation often includes assessment of expressive and receptive language skills (including auditory comprehensibility), articulation, speech intelligibility, and reading.

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POSTOPERATIVE MANAGEMENT

Postoperative management of clients with cochlear implants has changed dramatically since cochlear implants were first developed. Technological advances in computers and software have decreased the amount of time needed to program clients’ speech processors, and technological advances in hardware and software have made it possible for audiologists to evaluate the function of the internal device by the use of telemetry. Each of these advances will be described in the following section, and three primary components of postoperative management will be discussed: (a) mapping of the speech processor to fit the individual needs of the client, (b) monitoring performance using speech perception and speech/language measures, and (c) continued medical and audiologic monitoring and management of the implanted device.

Mapping the Speech Processor

All of the currently available cochlear implant systems use a setup for programming that involves a computer, specialized programming software, and a specialized box that enables the client’s speech processor to interface with the programming software. During programming, the speech processor, which is connected to the interface box via a cable, is placed on the client’s head. The programming software indicates if the internal and external devices are appropriately coupled to the programming system and also provides information regarding programs in the attached speech processor. This feature enables the clinician to upload programs that may have been created at a different facility.

Once the speech processor is connected, the first step in programming is the determination of electrode impedances. Impedance testing is automatically performed with the Advanced Bionics 90K device whenever a client file is initially opened. With Nucleus, MedEl, and earlier versions of the Advanced Bionics device, impedance testing is manually performed by the audiologist at the beginning of the test session. Such testing enables the identification of problem electrodes, such as those that are shorted or have an abnormally high impedance value. Such electrodes should be removed from the client’s program as their inclusion may result in distorted or intermittent sound. Impedance testing also provides information regarding voltage compliance—the ability of the electrode to deliver sufficient voltage to generate the requested current level. Voltage compliance levels are visible on the programming screens of Nucleus devices (Nucleus 24 and beyond) and with all Med El devices. With the Advanced Bionics devices (90K and beyond), the software automatically adjusts the pulse width of the signal in order to remain within voltage compliance. Early versions of Nucleus and Advanced Bionics devices (such as the Nucleus 22 and the Clarion CI) do not have telemetry capabilities.

Once the audiologist has determined which electrodes should be included in the client’s map, psychophysical testing can begin. First, the clinician should determine the parameters that will be used to create the initial program for the speech processor, including determination of speech processor strategy, mode of stimulation, rate of stimulation, and pulse width, to name a few. The specific map parameters selected for the client will depend on the type and model of the internal device and will be influenced by the make and model of the client’s speech processor.

The specific tasks that will be performed during the programming appointment will depend on the type of internal and external device used by the client. Psychophysical measures used to program speech processors may include determination of threshold (the softest level of sound that can be heard), C level (a level of sound that is loud but comfortable), or M level (a level of sound that is considered to be “most” comfortable). Such measurements can be obtained using either behavioral or objective test procedures or a combination of the two.

Once psychophysical measurements have been obtained for each of the electrodes, the clinician is ready to evaluate the suitability of the measurements using live speech. Testing for both children and adults should begin with the volume and sensitivity controls of the speech processor set to a minimum level. These settings can then be increased gradually as the client’s response to sound is monitored. Ideally, the client should be comfortable when listening to speech presented at an average conversation level when the sensitivity or volume is set to a recommended use setting (such as a volume of 5 and a sensitivity of 10–12 for a Nucleus device). If the client is not comfortable when using the device at this setting, C or M levels can be globally increased or decreased until sound is clear and comfortable.

Once it has been determined that the program is comfortable, the audibility of various speech signals should be evaluated using the Ling 6 Sound test (Ling, 1976, 1989). This test consists of presentation of six different phonemes that broadly represent the speech spectrum from 250 Hz to 8000 Hz: [m], [ah], [oo], [ee], [sh] and [s]. Ability to detect, recognize, or repeat the sounds when using hearing alone indicates good access to sound across the frequency range that is important for understanding speech. Depending on the speech recognition skills of the recipient, informal testing of the program may also include closed-set identification of stimuli such as numbers or colors and may progress to assessment of open-set recognition of words or sentences.

It is important for the client to return regularly for mapping of the speech processor. In most clinics, clients are required to attend numerous programming appointments the first year following device activation. During this year, appointments for children often occur 2, 4, 8, and 12 weeks postactivation and 6 and 12 months postactivation. Adults are usually seen less often; their appointments usually take place 1, 3, 6, and 12 months postactivation. During these appointments, the audiologist continues to obtain threshold information for some or all of the electrodes and refines the settings for the upper level of stimulation (C or M levels).

During the postoperative appointments, the client’s response to sound-field stimuli should be tested regularly to
ensure adequate detection of narrow-band or warbled pure tones, particularly those that fall within the speech spectrum. Most clients will demonstrate sound-field detection thresholds ranging from 15 dB HL to 40 dB HL for the frequencies 250 Hz–4000 Hz.

One of the greatest advances in speech processor technology is the ability to provide clients with more than one program. Early cochlear implant devices contained a single program location. Thus, clients were required to come back to the clinic any time their program needed adjustment. Most of the current speech processors provide recipients with three to four program slots. Early on in the mapping process, clinicians typically provide the recipient with programs with subsequent increases in C or M levels. This enables a gradual increase in the amount of sound being provided to the client without having to return to the implant center. Later on in the mapping process, clients can be provided with the flexibility to try different programs for different listening situations (i.e., a noise, music, or FM program) or to evaluate different speech processing strategies outside of the clinic setting.

An additional advancement in programming came with the introduction of objective programming procedures. All programming software has the ability to deliver a signal to a single electrode and to measure the resulting neural response via telemetry. This procedure is referred to as neural response telemetry (NRT) in the Nucleus device (Battmer et al., 2004; Brown, Abbas, & Gantz, 1990), as neural response imaging (NRI) in the Advanced Bionics device (Caner, Olgun, Gültekin, & Balaban, 2007), and as auditory response telemetry (ART) in the MedEl device (Hochmair et al., 2006). In all three systems, neural response testing can be used to obtain a general indication of program levels, to confirm neural function in a particular area of the electrode array, and to aid in the assessment of device function (Advanced Bionics, 2007).

Monitoring Performance Using Speech Perception and Speech/Language Measures

The second essential component of postoperative care includes monitoring performance using speech perception and speech/language measures. As stated previously, such monitoring of performance has led to the expansion of cochlear implant candidacy. Such monitoring is also important as it provides information regarding the adequacy of the speech processor mapping, the need for and/or effectiveness of rehabilitative procedures used with the client, and the integrity of the internal and external components of the cochlear implant system.

The specific test measures used to monitor performance will vary depending on the age of the client. Measures commonly used with adults are similar to those listed previously for preoperative determination of candidacy. Over the past several years, however, procedures used to evaluate postoperative performance with a cochlear implant also include materials with increased complexity and difficulty. Because the speech perception skills of clients with early devices were limited, materials were usually presented using loud listening levels (i.e., 70 dB SPL) and were only presented in quiet. Today, most clients demonstrate greatly improved speech recognition skills. Thus, most clinics present test materials at a softer listening level that more closely approximates the level of everyday speech (60 dB SPL; Firszt et al., 2004), and most clinics use more difficult sentences and words presented in background noise such as the Bamford-Kowal-Bench Speech in Noise Test (BKB-SIN), which uses Bamford-Kowal-Bench sentences (Bench et al., 1979) recorded in a background of four talker babble.

With children, the tests used to evaluate postoperative performance are greatly dependent on the child’s age and vocabulary level. Thus, the tests that a child is able to participate in usually will change with time. The materials used to evaluate the postoperative performance of children have increased in complexity over time, and the presentation level used to deliver stimuli is softer than what was used with early cochlear implant devices.

An important difference with children is that postoperative assessment should also include an evaluation of the child’s speech and language skills. Such a battery should include tests of articulation, speech intelligibility, receptive and expressive language, vocabulary, reading, and other speech and language skills.

Advances in Outcomes

When cochlear implants were first introduced, clinicians were uncertain of the types of outcomes that would be obtained by cochlear implant recipients, particularly young children. With single-channel devices, most clients demonstrated improvements in lipreading, and very few were able to demonstrate open-set speech recognition skills. The speech recognition results obtained with multichannel devices have been much more promising. For example, in 1982, clients who used the first speech coding strategy available with the Nucleus device (F0F2) obtained mean open-set CNC word recognition scores of approximately 2% correct (Patrick et al., 2006). In contrast, in 2007, users of the Nucleus Freedom demonstrated mean CNC scores of 62% correct (Cochlear Americas, n.d.). Such advances in speech recognition are likely the result of several factors, including technological advances in external and internal equipment as well as changes in cochlear implant candidacy (i.e., implantation of younger children and expansion of candidacy to include clients with more residual hearing).

A great deal of literature supports the finding that several different factors contribute to performance with a cochlear implant. These factors include age at onset of deafness, length of deafness before receiving a cochlear implant, etiology, status of the cochlea, and communication methodology (Waltzman, 2006), to name a few. With adults, the factor that seems to have the greatest impact on performance is the age at which the client experienced profound deafness. Adults who lost their hearing before the acquisition of spoken language skills (prelingually deafened adults) tend to demonstrate poorer speech recognition skills than do postlingually deafened adults (Skinner et al., 1992; Waltzman & Cohen, 1999; Zwolan, Kilényi, & Telian, 1996).
There are several common themes in the literature regarding the speech perception skills of postlingually deafened adults. The first common theme is the wide range in performance that is demonstrated by cochlear implant recipients. Recent reports indicate that some of the “better” clients demonstrate mean word recognition scores of 80%, whereas some of the more “average” clients demonstrate mean word recognition scores of 58% correct (Dorman & Spahr, 2006). Although Dorman found that the “better” clients tended to be younger and had been deaf for shorter periods of time, it is still not clear what role various factors will play for specific clients in regard to their outcomes with a cochlear implant.

With children, factors that contribute to performance are even more complicated and variable than those for adults. This is likely due to the fact that children have received implants at various stages of auditory development and they receive a variety of educational and rehabilitative instruction. One of the most strongly supported themes is that the age at which a child receives a cochlear implant plays a large role in outcome. Many researchers report that profoundly deaf children who receive an implant at a young age (before the age of 2 years) attain better speech perception and oral language skills than do children who receive a device after the age of 2 (Geers, Brenner, & Davidson, 2003; Geers, Nicholas, & Sedey, 2003; Kirk et al., 2002; Svirsky, Teoh, & Neuberger, 2004; Waltzman & Cohen, 1998; Zwolan et al., 2004).

Several other factors have been found to affect children’s performance with a cochlear implant. For example, children with cochlear anomalies tend to demonstrate higher psychophysical responses (Zwolan et al., 2008) and poorer speech recognition skills (Eisenman et al., 2001; Tucci, Telian, Zimmerman-Phillips, Zwolan, & Kileny, 1995) than children with normal cochleae. Children with additional handicaps, such as autism and cognitive delays, have also been found to demonstrate poorer outcomes than children who do not present with such delays (Donaldson, Heavner, & Zwolan, 2004; Fukuda et al., 2003; Waltzman, Scalchunes, & Cohen, 2000). Finally, several studies report that implanted children who are educated in an oral communication setting demonstrate higher levels of spoken language than children who are educated in a setting that uses total or manual communication (Geers et al., 2002; Geers, Brenner, & Davidson, 2003; Geers, Nicholas, & Sedey, 2003; Hodges, Dolan Ash, Balkany, Schloffman, & Butts, 1999).

Medical and Audiologic Management to Monitor Device Integrity and Function

As stated previously, one of the greatest technological advancements to take place in the field of cochlear implants relates to improvements in telemetry—our ability to send information to the implant and to receive information back about the device status. This has improved our ability to evaluate function of the internal device over time. In addition, telemetry can be used to perform detailed integrity testing, which traditionally has been performed by the device manufacturer.

Unfortunately, telemetry and integrity testing may not identify all potential problems with an internal device. In some cases, the intuition of the clinician may differ from the manufacturer’s test results, causing some investigators to question whether manufacturer’s integrity systems are sensitive enough to assess complete device function (Waltzman et al., 2004). Questions may also arise about device function based on assessments of client performance. Some clients present with a decrement in performance that cannot be explained by integrity testing or by other factors that may affect performance (i.e., change in educational setting, problems with external equipment, etc.). Such “soft failures” occur when clinicians believe that the reduction in performance may be due to a problem with the internal device, despite a normal result on an integrity test. In many instances, this may result in explantation of the device in question and replacement with a new device. The presence of such “soft failures” demonstrates the need for annual speech perception and speech/language evaluations, as such testing can provide insight into performance that traditional integrity tests cannot provide.

Clients should also be seen regularly by medical personnel, particularly when medical problems arise. Such problems may include otitis media, less than optimal electrode placement, skin flap complications, need for technological upgrade, or intratemporal pathologic conditions (Donatelli, Zwolan, & Telian, 2005).

CURRENT AND FUTURE TRENDS

There are several trends that have taken place in recent years in regard to cochlear implants. One strong trend has been the provision of bilateral cochlear implants. Such implants may be provided in the same surgical setting (simultaneous bilateral implants) or in sequential surgical settings. Advantages cited for persons with bilateral cochlear implants are similar to those cited for persons with normal hearing and for hearing aid users and include improved localization of sound and enhanced ability to hear in the presence of background noise (Hochmair et al., 2006). The number of bilateral implants being provided to clients has grown greatly in recent years. In the year 2006, Cochlear Americas reported that 15% of their U.S. sales were for bilateral implants (Ahmed, 2007), and MedEl reported that as of June 1, 2006, there were more than 1,000 bilateral MedEl users worldwide, two thirds of which were children (Hochmair et al., 2006). It is anticipated that this number will grow in future years as the benefits of bilateral implants become more well known.

Deterrents to clients receiving a bilateral cochlear implant include cost (some insurers will not pay for a second cochlear implant), lack of services available for bilateral implants, and the belief that placement of a cochlear implant in each ear will prevent the client from receiving benefit from future technological advances, such as hair cell regeneration.

Two cochlear implant manufacturers are presently working on the development of totally implantable cochlear
implant systems. One of these systems, the TIKI, which is being developed by Cochlear Limited and the Co-operative Research Centre for Cochlear Implant and Hearing Aid Innovation, is an internally implanted device that has a lithium ion rechargeable battery, a package-mounted internal microphone, and sound-processing electronics that provide the recipient with sound with or without (referred to as “invisible hearing”) the use of an external device (Briggs et al., 2008). Some problems reported with this technology include body noise interference and reduced sensitivity of the implanted microphone when in the invisible hearing mode.

Anticipated future developments include increased use of hybrid technology, which enables a cochlear implant recipient to use acoustic and electric stimulation in the same ear (Gantz, Turner, & Gfeller, 2006; Hochmaier et al., 2006); drug delivery to the inner ear via the cochlear implant (Hochmaier et al., 2006); improved music and speech perception with the introduction of new and improved coding strategies (Wilson & Dorman, 2008); continued improvements in surgical technique to allow even greater preservation of residual hearing; and continued improvements in external and internal components of cochlear implant systems.

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