Cochlear Implants

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Background and Introduction

Only in the past 35 years or so have physicians been able to adequately treat profound sensorineural hearing loss. Cochlear implants are computerized prostheses that partially replace the functions of the cochlea. Interest in electrical stimulation of the auditory system dates back to the eighteenth century. Djourno and Eyries (1953) provided the first detailed account of the effects of direct stimulation of the auditory nerve in deafness. In a patient undergoing surgery for facial nerve paralysis prior to cholesteatoma surgery they placed a monopole on the eighth nerve. The patient described hearing high frequency sounds. By using a 1000 Hz signal generator, the patient could recognize common words and improved their speech reading capabilities. This provided the early beginnings for cochlear implant development.

In 1961, House and Doyle and others separately described approaching the auditory nerve via the scala tympani. Simmons, three years later, placed an electrode directly into the modiolar segment of the auditory nerve through the promontory and vestibule and demonstrated that some tonality could be achieved. House and Michelson refined the clinical applications of electrical stimulation of the auditory nerve via the scala tympani implantation of electrodes. In 1972, the first commercially available device was developed. It consisted of a wearable speech processor that interfaced with the House 3M single-electrode implant.

In 1984, multiple channel devices were introduced and became the approach of choice based on enhanced spectral perception and open-set speech understanding. In the 1990s, improvements in both the technical and clinical approaches have developed from further basic science and clinical investigation. Now there is a trend for earlier implantation of cochlear implants based on the findings from research. As of early 1997 almost 20,000 people had cochlear implants placed.

Basic Science – Technology

Cochlear implants consist of implantable circuitry and information processing systems. Because much of the central auditory pathway remains vital in deafness, and processing capabilities are retained, cochlear implants are capable of restoring physiologically meaningful activity in that pathway. Rather than introducing a processed acoustic signal, implants receive, process, and transmit acoustic information via electrical stimulation. Electrode contacts implanted within the cochlea serve to bypass nonfunctional cochlear transducers and directly depolarize auditory nerve fibers. Implant systems employ an
The cochlear implant is fundamentally an electrical device. Most systems consist of internal and external components. The internal component acts as the control tower that directs the signal from the external component to the central nervous system. This receiver-stimulator accepts, decodes, and transmits signals. The signals are transmitted by way of a connecting lead down to an array of electrodes implanted within the scala tympani. The target of the electrical stimulus is the cell bodies of the auditory nerve. The external component is a speech processor that converts microphonic input into a distinct code of electric stimuli for each electrode. The processed signal is amplified and compressed to match the narrow electrical dynamic range of the ear. An external antenna enables radiofrequency transmission transcutaneously to the internal system. Batteries housed within the processor drive the system.

The cochlear implant is a transducer, which changes acoustic signals into electrical signals used to stimulate the auditory nerve. The electric signals are always processed to amplify the signal level, compress the signal to limit stimulation levels, filter the signal to shape or divide the acoustic frequency spectrum to match neural requirements, and encode the information in the signal for transmission to the implanted receiver. Each of these processes will be identified separately for clarity of discussion.

Amplification of the signal occurs within the processor. The signal from the microphone is usually several millivolts. This is generally too small to be directly used in the electrical circuits. Amplifiers are used to increase signal levels. The exact amount of increase is determined by the gain of the amplifier which is defined as the ratio of output signal level to input signal level. Amplifiers are used throughout the signal processing path to increase or decrease the signal level.

Compression is the second basic processing step performed by the cochlear implant electronics. The normal ear responds over a pressure range of nearly 120dB SPL. In general, as hearing becomes more impaired, the dynamic range from threshold to maximum loudness decreases. For the totally deaf subject with a cochlear implant, the acoustical dynamic range is generally limited to 10 to 25dB and it is not unusual to see acoustical dynamic ranges of 5dB at frequencies above 3000Hz. The acoustical signal must be compressed into the narrow electrical dynamic range suitable for stimulation because of the large difference between the acoustic and electric dynamic ranges. Without compression, the amplifiers typically act in a linear fashion. Linear and non-linear compression act in different ways, but the end objective is the same – to reduce the output to input ratio. There are numerous means of accomplishing compression. One way is by automatic gain control. This is an electronic method of automatically changing the gain of an amplifier so that the output to input ratio changes. These circuits operated by sensing the amplifier output voltage and changing the gain of the amplifier as needed to keep the output voltage in a certain range. Currently, there are a wide range of compressor types and operating characteristics in use today with little evidence to support one over another.
The third basic signal processing operation is filtering the input signal on the basis of frequency. The acoustic frequency spectrum of interest ranges from 100Hz to possibly over 4000Hz. Three basic types of filters are used to alter the frequency characteristics of the incoming signals: low pass, high pass, and bandpass filters. The low pass filter passes a frequency below a specified cutoff frequency. For example, a 100Hz low pass filter passes frequencies below 100Hz and stops frequencies above 100Hz. A 100Hz high pass filter would have the opposite action. A bandpass filter passes frequencies within a band specified by two cutoff frequencies. There are two principle reasons for filtering. The frequencies that provide no useful information can be removed and the frequency spectrum can be divided into separate bands so that these bands of information can be processed independently.

Filters can be used to extract certain frequency dependant features of speech. Auditory nerve sensitivity to electrical stimulation varies depending on the stimulation frequency. Therefore, it is desirable to divide the acoustic frequency spectrum into different channels that can be processed independently and be closely adjusted to the needs of the auditory nerve. Feature extraction systems are signal processors that use a specific filtering technique. They use bandpass filters to filter or extract frequency information from three fundamental spectral peaks. The three peaks that are of interest are the fundamental frequency (F0) and the first and second formant frequencies (F1 and F2). The fundamental frequency is typically between 100Hz and 200Hz. F1 ranges from 200Hz to 1200Hz, and F2 ranges from 550Hz and 3500Hz. Multichannel processing as described above is unrelated to the electrode system used to deliver the stimuli. It is more accurate to describe cochlear implant systems in terms of the signal processing as well as electrode configurations.

The signals that have been processed so far must be encoded in some manner for transmission to the implant receiver. Encoding preserves the information that has been processed to this point and provides a means of getting this information to the electrodes for stimulation of the auditory nerve. The signal that first enters the processor is an analog signal. The first general class of encoding preserves the analog nature of the signal and uses it to modulate a radio-frequency signal, which is transmitted to the receiver. Multiple radio-frequency signals can be used if independent channels of information are to be encoded. At the receiver, the information signal is removed from the radio-frequency signal and supplied to the electrode.

Another form of encoding involves converting the analog signals or information contained in them into digital signals. This is done by sampling the waveform at a very high rate and assigning digits to the measured values. The measurements are converted into digital bits by an analog to digital converter. The data bits can then be transferred to the receiver by way of a radio-frequency signal. The receiver to preserve the identity of the transmitted information must decode the bits of information.

The objective of the above steps is to condition the input signal so that the maximal amount of information can be transferred to the acoustic nerve. Charge is simply the
flow of current for a period of time. Cochlear implants typically transfer less than one microcoulomb of charge during each phase of stimulation current. Charge density is defined as microcoulombs per cm² of electrode surface area. Charge density is thought to be related to the safety of the electrode. Initiating an action potential in a neuron requires that the normally charged cell membrane be depolarized. Stimulation current supplied by two electrodes establishes an electric field between the electrodes, which induces a current flow in nearby nerve fibers and initiates an action potential.

There are two general configurations of electrodes; monopolar and bipolar. Monopolar electrode designs place one or more active electrodes adjacent to the neural target and a ground electrode external to the cochlea. Conversely, bipolar electrode designs place both active and ground electrodes within the cochlea. They provide a more restrictive field of current and the potential for more discrete patterns of neural stimulation with less channel interaction. The stimulation current depends upon the voltage and resistance between the electrode pair. Multiple electrodes are used for discrete and non-overlapping stimulation of nerve populations along the length of the basilar membrane. Unless the stimulator has been carefully designed so that each pair of electrodes is isolated from every other pair, then the current can flow between all pairs. How the current divides between the electrodes depends on the resistance between them. Another factor which limits the ability to stimulate discrete areas of the nerve is current spread within the highly conductive fluid of the cochlea. Since their first design cochlear implants continue to be revise and improved based on further research and clinical situations.

There are different speech processing strategies for the different types of cochlear implants. The Nucleus 22-channel implant utilizes the Spectral Peak (SPEAK) strategy implemented in the Spectra 22 processor. This uses a vocoder in which a filterband consisting of 20 filters cover the center frequencies from 200 to 10,000Hz. Each filter is allocated to an active electrode in the array. The filter outputs are scanned and the electrodes that are stimulated represent filters that contain speech components with the highest amplitude. The Clarion multichannel cochlear implant offers two types of speech processing strategies: compressed analog and continuous interleaved sampling. The compressed analog strategy first compresses the analog signal into the restricted range for electrically evoked hearing and then filters the signal into a maximum of eight channels for presentation to the corresponding electrodes. The continuous interleaved sampling strategy filters the incoming speech into eight bands and then obtains the speech envelope and compresses the signal for each channel. More than 90% of Clarion multichannel implant recipients use the continuous interleaved sampling strategy for speech processing. The MED-EL Combi 40-Cochlear Implant system utilizes the continuous interleaved sampling strategy for its speech processor.

Patient Selection

Original FDA guidelines for cochlear implantation contained narrow specifications of audiologic, medical, radiologic, psychologic, and cognitive criteria for implant
candidacy. Indications have now been broadened in each of these categories as more has been learned regarding the benefits provided by cochlear implants. Cochlear implants were originally limited to postlingually deafened adults who received no benefit from hearing aids and had no possibility of worsening hearing. This population has been the most readily identifiable beneficiary of cochlear implants. No upper age limit is used in the selection process. Cochlear implantation is appropriate if other selection criteria are met and the patient’s general health status will allow a general anesthetic.

The entry criteria have been expanded to include some patients with residual hearing. Adult selection criteria include postlingual, profound bilateral sensorineural hearing loss in excess of 95dB pure tone average (90dB for the Nucleus implant), little or no benefit from conventional hearing aids, and psychological, and motivational suitability. In the best-aided condition, the candidate should not have word discrimination scores better than 30% or speech detection threshold of 70dB sound pressure level. FDA guidelines hold that candidates should generally have at least 6 months experience with high-powered binaural amplification and should undergo aided speech audiometry. Each implant has its own FDA approval criteria typically specified in the product labeling or in the training manuals.

Pediatric cochlear implant candidate selection is a complex process that requires careful consideration of many factors. Criteria require the presence of bilateral, severe to profound sensorineural hearing loss with pure tone averages of 90dB or greater in the better ear. The child must be 2 years of age or greater, have received no appreciable benefit from hearing aids, and have no medical contraindications to surgery. Prior to implantation, a significant trial with appropriately fitted binaural amplification (3 to 6 month trial) and intensive auditory training must be completed to determine that even with adequate experience and training, a hearing aid cannot provide the same level of auditory benefit as expected from an implant. The parents and family must be highly motivated. Appropriate expectations in outcome should be explained and understood by all parties involved in the decision to implant a child. The child should be enrolled in a program that emphasizes the development of auditory skills and continue in this program postoperatively for rehabilitation. The minimum age of 2 years was initially chosen for anatomical reasons. The mastoid antrum and facial recess are adequately developed by the age of 2 years. Earlier implantation would be advantageous if profound deafness can be substantiated and the inability to benefit from conventional hearing aids is demonstrated.

The audiologic evaluation is the primary means of determining suitability for cochlear implantation. Thresholds for both aided and unaided using conventional amplification are determined for the candidate. Hearing aid performance is compared with normative cochlear implant performance. Not all patients with profound sensorineural hearing loss are implant candidates. Many with pure tone thresholds between 90dB and 100dB HL with residual hearing through 2000 Hz demonstrate speech recognition skills with conventional hearing aids that are superior to multichannel implant users.
The medical evaluation includes a complete history and physical examination to detect problems that might interfere with the patient’s ability to complete either the surgical or rehabilitative measures of implantation. Laboratory studies should be ordered only to eliminate any suspected medical disorder. The precise etiology of the deafness cannot always be determined, but is identified whenever possible; however, stimulable auditory neural elements are nearly always present regardless of the deafness.

In the physical examination it is important to identify preoperatively any external or middle ear disease that must be treated prior to cochlear implantation. The ear proposed for cochlear implantation must be free of infection and the tympanic membrane must be intact. If these conditions are not met then medical or surgical treatment to correct them should be employed prior to cochlear implant placement. Radiologic evaluation of the cochlea is performed to determine whether the cochlea is present and patent and to identify congenital deformities of the cochlea. This is accomplished through high resolution computed tomography of the temporal bone. Many kinds of congenital deafness are caused by osseous deformities of the inner ear, which can be visualized by CT. Abnormal anatomy of the cochlea may result in surgical problems or complications. Congenital malformations of the cochlea are not contraindications to cochlear implantation. Two exceptions are the Michel deformity, in which there is a congenital agenesis of the cochlea, and the small internal auditory canal syndrome, in which the cochlear nerve may be congenitally absent. During the medical evaluation, exclusionary factors are rarely found.

Psychological testing is performed for exclusionary reasons to identify patients who have organic brain dysfunction, mental retardation, undetected psychosis, or unrealistic expectations. A cochlear implant will provide the most benefit to individuals who possess sufficient motivation and support to complete a program of postimplantation device activation and rehabilitation. Psychological testing screens for any conditions that can severely complicate the implantation process. Counseling is often provided to families who have misconceptions and unrealistic expectations regarding the benefits and limitations of cochlear implants. Support from the family and friends is an important part of the rehabilitative process. During the psychological assessment there are occasionally exclusionary factors found.

**Surgical Implantation**

Once a candidate has been selected, the next question is which side to place the implant. If there is no difference acoustically, then the implant goes on the side of the better surgical ear as determined by CT evaluation. If the patient has had different durations of profound hearing impairment in each ear, better results are achieved by placing the implant in the ear that has the shortest duration of deafness. In the candidate who has the same etiology for the deafness and a similar duration of deafness in both ears but has used a hearing aid in only one ear, placing the implant in the ear that used the hearing aid should be discussed with the patient. Potential candidates who have residual hearing in the ear to receive the implant must be told that following implantation they will likely lose the residual hearing in that ear.
Cochlear implantation requires meticulous attention to the delicate tissues and small dimensions. Only qualified surgeons specifically trained to perform the procedure should implant the cochlear implant. The details of implantation differ from prosthesis to prosthesis. The patient is placed in the supine position with the surgeon and surgical nurse at the head of the bed. The electrodes for monitoring the facial nerve are placed prior to prepping the patient. The hair is shaved based on the design of the incision to be used; most frequently shaving four fingerbreadths above and four fingerbreadths behind the ear is sufficient. The patient is then prepped and draped similar to other ear surgeries.

The position of the internal component of the implant about 1 cm behind the auricle is then determined and marked on the external surface using a dummy coil. Once the location of the implant is determined, a skin flap is designed. A variety of skin flaps have been used in the past, but it is important to maintain a 1 to 2 cm distance from the edge of the implant and the incision. The flap must have a good blood supply. An alternative incision to the classic wide c-shaped incision is an extension of a postauricular incision near the postauricular crease, extending superiorly over the temporal squama and middle fossa, curving slightly posteriorly at the most superior aspect of the incision. The skin is incised with a knife and the subcutaneous tissue is incised with electrocautery. The temporalis muscle and fascia is preserved and the mastoid musculoperiosteal tissue is divided to expose the mastoid cortex. The site for the internal receiver in the skull is created at the position previously determined. A circular depression is created using drilling burrs for the internal device. Again a dummy device is used to correctly mark out the dimensions of the receiver so that an accurate sink may be created. Suture tunnel holes created on either side of the seat with a burr will be used to help hold the receiver-stimulator in place.

A complete mastoidectomy is performed creating a mastoid cavity with a minimal amount of saucerization of its edges. A shelf of mastoid cortex is created posteroinferiorly for securing the electrode array. The facial recess is opened in the usual fashion by first identifying the horizontal semicircular canal and incus. A thin layer of one can be preserve over the facial nerve to minimize surgical trauma. Once exposure through the facial recess is completed, the round window membrane is inspected. The basal turn of the cochlea is opened near the anteroinferior aspect of the round window membrane. A small fenestra slightly larger than the electrode to be implanted is developed. A small diamond burr is used to blue-line the endosteum of the scala tympani, and the endosteal membrane is removed by small picks. At this point the surgical site has been prepared for electrode insertion. The monopolar electrocautery devices are disconnected and not used once the implant is in place. Bipolar cautery should be used for hemostasis as necessary.

The implant may be inserted one of two ways. The electrode array may be inserted first, followed by securing of the internal coil. Alternatively, the internal coil is secured, after which the electrode array is inserted into the cochlea. The internal coil is secured by placing it within its bony well and secured with sutures placed across the internal receiver. With microclaws, the electrode array is inserted into the cochlea. It is
important to prevent kinking of the electrode, which may cause breakage of the wires leading to the electrode. Force must not be used in inserting the electrode as this may cause buckling of the electrode within the cochlea. This buckling of the electrode may disrupt the basilar membrane and result in additional degeneration of ganglion cells and degradation of the electrical signal. Deep insertion of the electrode array is desirable in order to reach the area of high density of ganglion cells near the upper basal turn. The cochlear multichannel device has 32 metal bands along the stimulating electrode, of which the distal 22 are active electrodes and the proximal 10 are inactive stiffening rings. Once inserted, one can count the remaining rings to determine depth of insertion of the electrode array. Once the electrode array is in place within the cochlea, connective tissue is used to obliterate the cochleostomy site and fill the facial recess. The surgical site is closed in multiple layers without a drain and a large bulky mastoid dressing is applied.

In approximately 50% of cases, the round window niche and membrane are replaced with new bone growth. This condition is more common in patients who have had meningitis. In these cases, the surgeon must drill forward along the basal coil for as much as 4 to 5mm. Usually the new bone is white and looks different than the surrounding otic capsule. If new bone growth completely obliterates the scala tympani, the electrode may be placed into a patent scala vestibuli. With complete ossification of the cochlea, a channel is drilled following the anatomic location of the scala tympani. Care must be taken to not injure the internal carotid artery in its location anterior to the cochlea. In cases of cochlear dysplasia, there is significant risk of encountering a gusher on fenestrating the cochlea while creating a cochleostomy. A gusher is managed by allowing the CSF reservoir to drain off and inserting the electrode array into the cochlea. A connective tissue plug is placed around the active electrode array at the cochleostomy site, sealing the leak. The external processor and antennae are fit 3 weeks after implantation of the internal device. This allows time for the incision to heal. The internal device and external processor contact one another via a small antenna that is retained magnetically behind the ear.

The overall surgical complication rate for cochlear implantation has been reduced in the last 5 years from 11% to 5%. Among the most commonly encountered problems are those associated with the incision and postauricular flap. Problems involving the skin flap include wound infection, wound breakdown with possible extrusion, and poor percutaneous transmission. The complications related to mastoidectomy and cochleostomy include facial nerve paralysis, bleeding from a dural sinus, CSF leak, and meningitis. Device related complications include breakage of electrode array or wires during insertion, excessive intracochlear damage from traumatic insertion, slippage of electrode out of the cochlea, and improper electrode placement. Eliminating specific electrodes when the array is mapped during postoperative programming of the device can usually control undesirable vestibular or facial nerve stimulation.

Rehabilitation

Rehabilitative needs differ in implant recipients based on their auditory experience prior to onset of deafness. For the prelinguistically deafened implant recipient, auditory and
speech training are critical in facilitating communication change. For the postlinguistically deafened implant recipient, auditory training often focuses on the more complex listening skills.

Success with cochlear implants in children requires a rehabilitation team’s significant skill and a family’s commitment to optimizing the use of the device. Cochlear implant rehabilitation must address the development of receptive language skills and expressive language skills. The rehabilitation of a cochlear implant user depends on a team approach. The goal of pediatric cochlear implant rehabilitation is to enable the early deafened child to learn incidentally from their environment at home and at school. In order to accomplish this there must be structured intervention. In order to maximize the effectiveness of the implant in children, the rehabilitative program must be committed to the development of auditory and speech training.

Results

Cochlear implantation has become a standard rehabilitative procedure for profoundly deaf patients who do not benefit significantly from hearing aids. Although many different cochlear implant devices are currently in use, none can provide normal hearing. The definition of success is different from patient to patient and family to family. Several factors, including age at time of deafness, age at implant surgery, duration of deafness, status of remaining auditory nerve fibers, training, educational setting, and type of implant, affect the benefit a patient receives from an implant. The variability in outcomes with cochlear implants is thought to be due primarily to patient factors. Improved speech perception is the primary goal of cochlear implantation.

The age of onset of deafness does have important implications as people who learn speech and language prior to becoming deaf adapt to cochlear implants more quickly and achieve open-set speech discrimination earlier than those who have not developed speech and language. Therefore, postlinguistically deafened patients do better than prelinguistically deafened patient with cochlear implants. Children who have not previously learned language, however, continue to improve over a period of 2 to 5 years, and during that time, their scores become closer to those achieved by postlinguistically deafened children. There have been several well documented studies that clearly demonstrate that prelinguistically deafened children who receive cochlear implants at an early age and are educated in aural-oral settings achieve open-set word recognition. Miyamoto and associates at Indiana University reported on 55 children who were born deaf or acquired hearing loss prior to age 3. The average child in this group had 63% open-set speech understanding. Likewise, Gantz and colleagues at Iowa University, in a study of 54 implanted children, reported that after 4 years of use, 82% of prelinguistically deafened children achieved open-set word understanding. At Washington University, Lusk and associates reported on 25 congenitally deaf children, all of who showed improvement with cochlear implants. Within 36 months of surgery, all of the children implanted under the age of 5 showed open-set speech understanding. This reveals that the earlier a child is identified with profound hearing loss and given an implant, the better the results.
Waltzman and associates at New York University reported on 14 children who were prelinguistically deafened, receive cochlear implants prior to age 3, and had been followed for 2 to 5 years. Improvement in perception was found in all aspects of hearing. All of these children had open-set speech discrimination, used oral language as their primary method of communication, and attended regular school. Current studies indicate that early implantation, before 6 years of age, is important for maximal auditory performance. These findings are consistent with the generally accepted notion that the shorter the period of auditory deprivation, the better the performance with any type of sensory aid. It has been shown that speech intelligibility following implantation is twice that typically reported for children with hearing impairments and continues to improve over time. It is also clear that speech produced by children with implants is more accurate than children using vibrotactile devices or hearing aids.

Conclusions

Cochlear implants are not experimental. Cochlear implants are valuable sensory aids for selected deaf adults and children. They are cost effective auditory prostheses that safely provide a high quality sensation of hearing to severely and profoundly deaf children and adults. There continues to be research to develop newer and better speech processors to help with development of better cochlear implants. This research will lead to improved signal coding and processing and the ability to better match these strategies to the deafened peripheral auditory system.

References


