CLINICAL THERAPEUTICS

Cochlear Implants for Children with Severe-to-Profound Hearing Loss

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This Journal *feature begins with a case vignette that includes a therapeutic recommendation. A discussion of the clinical problem and the mechanism of benefit of this form of therapy follows. Major clinical studies, the clinical use of this therapy, and potential adverse effects are reviewed. Relevant formal guidelines, if they exist, are presented. The article ends with the authors' clinical recommendations.*

A 4-month-old baby girl whose parents and 6-year-old brother have severe-to-profound sensorineural hearing loss is referred for consideration for cochlear implantation. Each of the baby's parents had previously received a cochlear implant in adulthood, and her older brother had received a cochlear implant at 18 months of age. The family uses oral communication in the English language. The baby had been diagnosed with sensorineural hearing loss during newborn screening, and she was fitted with bilateral hearing aids without clinically significant benefit. Bilateral profound sensorineural hearing loss, with pure-tone thresholds of 100 dB or higher, is confirmed and a homozygous mutation in the connexin 26 gene (*GJB2*) is identified. It is recommended that the child undergo auditory-verbal therapy followed by implantation of a unilateral cochlear implant at 12 months of age.

THE CLINICAL PROBLEM

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Sensorineural hearing loss affects 1 to 3 of every 1000 children born in the United States and other developed countries[1,2]; the rate is probably higher in the developing world.[3] In most cases, the hearing loss is nonsyndromic (i.e., it is not associated with other congenital features) and the child is otherwise healthy. The lack of auditory input during the child's development has a minimal effect on his or her motor and social development during infancy. Thus, if infant hearing screening is not performed, the deafness is often unnoticed during this period, resulting in a late diagnosis (at ≥1 year of age).[4]

The deaf child receives little or no access to environmental sounds and speech; this lack of access arrests or disrupts normal auditory development.[5-9] As the child grows older, auditory deprivation results in cortical reorganization, including an expansion of visually driven inputs into the secondary areas of the auditory cortex.[10] The duration of deafness before diagnosis and intervention is negatively correlated with the child's ability to perceive and use spoken language after being fitted for an auditory prosthesis.[11-13] Universal newborn hearing screening, which is now available in some countries, has markedly improved the early diagnosis of sensorineural hearing loss,[14] although the magnitude of the resulting benefit in terms of language outcome has been debated.[15]

PATHOPHYSIOLOGY AND EFFECT OF THERAPY

The causes of congenital sensorineural hearing loss include both environmental and genetic conditions. One third to one half of cases detected in infancy have an environmental cause,[2,14] with the most common cause being congenital cytomegalovirus

infection.[16] Congenital rubella syndrome, pharmacologic ototoxicity, neonatal asphyxia, and prematurity are other common causes. Among the genetic causes, by far the most frequent are mutations in *GJB2*, which may account for as much as 30 to 50% of profound nonsyndromic hearing loss in many populations.[17-24] Other genetic causes include syndromic disorders such as Pendred's syndrome and Waardenburg's syndrome, as well as nonsyndromic genetic conditions. More than 45 genes have been associated with nonsyndromic hearing impairment.[25]

Normal hearing requires that all the elements of the auditory pathway have intact structure and function. Sound vibrations cause movement of the tympanic membrane and the middle-ear ossicles, creating fluid waves in the cochlea that stimulate the inner hair cells (Fig. 1). The hair cells transduce these movements into electrical signals that are transmitted by the cochlear nerves to the spiral ganglia and the auditory nerve. Low-frequency sounds (<100 Hz) stimulate the most apical portion of the cochlea, whereas high-frequency sounds (>15,000 Hz) stimulate the most basal portion of the cochlea. The various causes of sensorineural hearing loss disrupt the structure, function, or both of one or more components of the inner ear.

Hearing aids amplify sound and can be effective in the management of sensorineural hearing loss if the deficit is mild to moderately severe (pure-tone average hearing threshold, <85 dB), but they are less effective or ineffective when hearing loss is severe to profound (pure-tone average hearing threshold, ≥85 dB). In contrast, cochlear implants bypass the inner ear to directly stimulate the auditory nerve (Fig. 1), and thus they can be effective even if hair cells are not functional or have been lost. Electrodes are inserted into the scala tympani, and cochleotopic organization of frequency is mimicked by assigning high-to-low-frequency bands to electrodes in a basal-to-apical direction. Sound is received by an external microphone and sent to a speech processor, which analyzes the spectral cues and sends instructions to the internal device regarding stimulation settings for each electrode. Electrical pulses, now representing the acoustic input, stimulate the auditory nerve.

CLINICAL EVIDENCE

The initial clinical testing of cochlear implants during the 1960s and 1970s provided sufficient confirmation of their efficacy and safety that the Food and Drug Administration (FDA) approved the devices for clinical use in adults in 1984 and in children in 1990. FDA approval was based for the most part on small, nonrandomized studies comparing patients before and after device implantation or comparing cochlear-implant recipients with hearing-aid users. To our knowledge, large, randomized trials comparing cochlear implants with other forms of hearing assistance have not been performed.

Nonetheless, the efficacy of cochlear implants has been shown systematically. Electrical pulses delivered by implants are highly effective in stimulating the auditory system; the majority of children have clear evoked responses from the auditory nerve and brainstem immediately after insertion of the device,[26,27] with access to a broad range of speech frequencies and a wide intensity range. Input from a cochlear implant can lead to improved speech perception and production over time.[28-31] In one series involving 82 children with 10 years of follow-up after implantation, 40% had speech that was intelligible to the average listener and 79% could use the telephone, although 76% had vocabulary scores below the median of those of their normally hearing peers.[29] In another report involving 181 children 8 to 9 years of age who had received cochlear implants by 5 years of age, the majority had language skills similar to those of hearing children who were 8 to 9 years of age.[31]

Several nonrandomized studies have compared the benefit of cochlear implants with that of hearing aids.[32,33] In one study, 13 children who had used cochlear implants for 3 years were compared with 13 age-matched hearing-aid users with a hearing threshold of more than 100 dB and with 13 age-matched hearing-aid users with a hearing threshold of 90 to 100 dB. The performance of cochlear-implant users on tests of spoken language was significantly better than that of hearing-aid users with a hearing threshold of more than 100 dB, but it was not different from that of children with a hearing threshold of 90 to 100 dB.[33]

CLINICAL USE

Treatment options for children with severe-to-profound hearing loss include training that emphasizes audition enhanced by technological approaches for the development of spoken language (e.g., auditory–verbal or auditory–aural therapy), the use of manual forms of communication (e.g., sign lan-

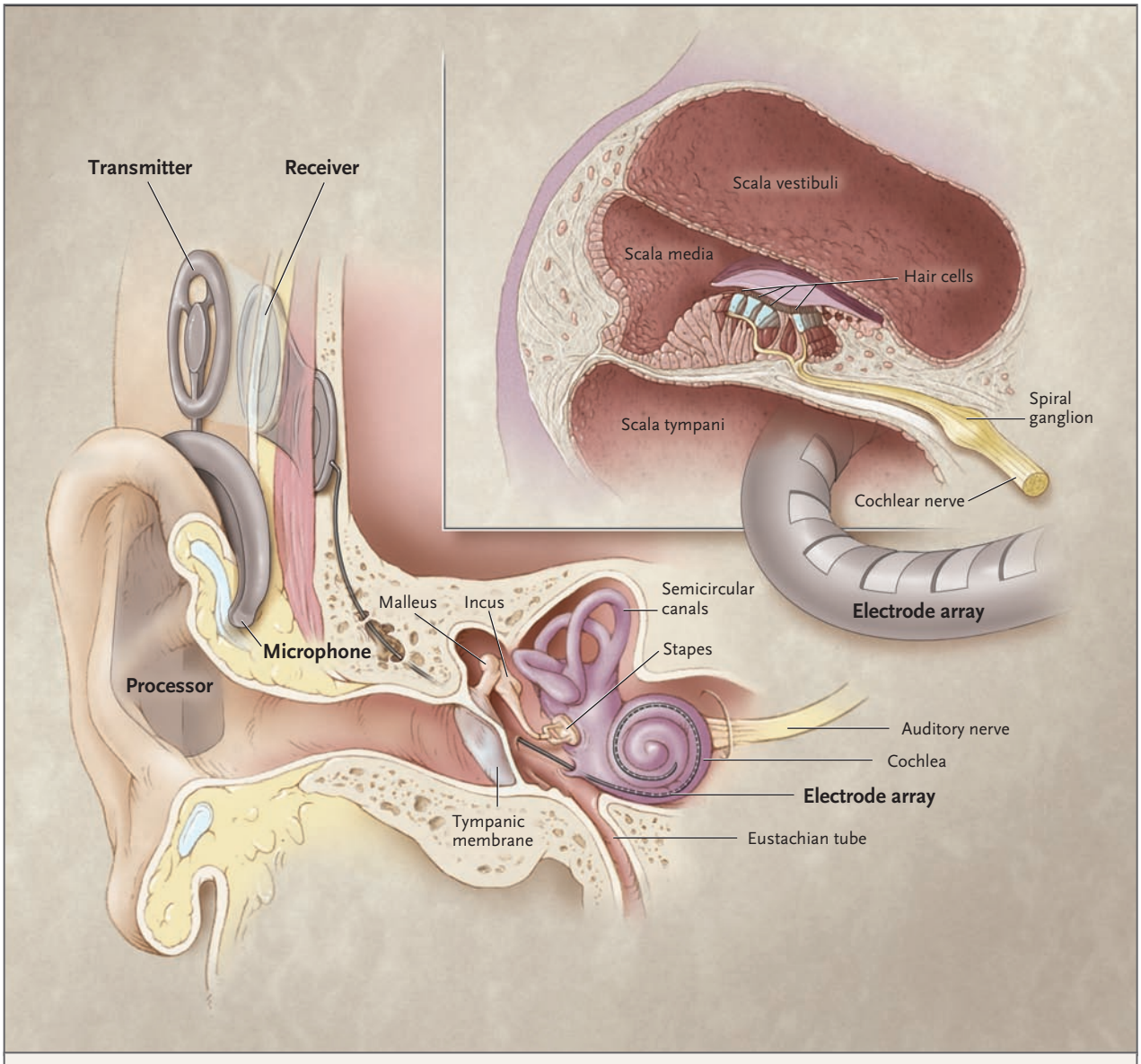

Figure 1. The Internal and External Components of a Cochlear Implant.

The cross section of the cochlea shows the electrode array surgically placed in the scala tympani. The implant converts acoustic sound to electrical pulses that stimulate the auditory nerve. Acoustic input enters the microphone, which is worn on the ear, and is sent to the speech processor for analysis of intensity in a number of set frequency bands. The resulting information is sent from the externally worn transmitting coil to the subcutaneous receiver–stimulator through FM waves. These components are held together by a pair of magnets so that they are separated only by the thickness of the skin flap. Each frequency band is assigned to a particular electrode along the implanted array (mimicking the normal basal-to-apical organization of high to low frequencies in the cochlea). If instructed, this array will provide a biphasic electrical pulse to stimulate the auditory nerve. The magnitude of the pulse provided by any one electrode will depend on the acoustic intensity within the assigned frequency band and the dynamic range of current (minimum to maximum) programmed for that electrode.

guage), or both (e.g., total communication and cued speech). All approaches are professionally directed by auditory–verbal therapists, speech-language pathologists, special-education teachers, or audiologists, but they require committed follow-up by parents and caregivers. The decision of parents and caregivers to choose oral communication for their child at the time the hearing loss is identified may be based on a variety of factors, including the severity of the child's hearing loss, attitudes about

deafness, professional recommendations, and costs.[34-36] Given that speech sounds must be audible for the development of oral speech and language, parents and caregivers who have chosen this approach will typically investigate whether their child might progress more easily or more rapidly by hearing with a cochlear implant. Parents should be informed that therapy that focuses on the development of auditory skills in children using cochlear implants leads to better spoken-language skills than approaches that incorporate manual forms of communication.[31,37]

Most implant centers conduct a multidisciplinary assessment of patients to determine whether they are candidates for cochlear implantation. The evaluation typically includes a medical and psychosocial evaluation with assessment of the family's commitment to structured therapy, an audiologic examination with and without amplification, and a computed tomographic scan or magnetic resonance imaging (MRI) of the temporal bones to evaluate the anatomy of the cochlea and auditory nerve. This process is intended to identify issues that would either exclude a child from receiving a cochlear implant or affect outcomes after implantation (Table 1). Bilateral implantation is not standard practice, although there is increasing interest in this approach (see the Areas of Uncertainty section).

The implantation procedure is performed while the patient is under general anesthesia. An incision of 2 to 3 cm is made behind the patient's ear, a skin flap is raised, and a mastoidectomy is performed. A depression is created posterosuperiorly to the mastoidectomy site in the parietal bone in order to hold the implanted receiver. Next, a passage is made from the mastoidectomy site into the middle ear to obtain access to the cochlea. A cochleostomy is then created in order to enter the scala tympani (Fig. 1). The electrode array is advanced as far as possible into the scala tympani, with caution to avoid injury to the surrounding structures. The flap is closed over the wound, which is given several weeks to heal.

The device is not activated until 3 to 4 weeks after implantation. The transmitter is positioned externally over the site of the receiver and is held in place magnetically. The microphone is positioned over the ear.

The stimulation settings of each implant electrode must be customized for each child. At a minimum, the stimulation levels must be high enough to be detectable and low enough to be comfortable. Although older children can provide reliable behavioral responses to the new input, young children with very limited auditory experience often do not. Physiological measures of central auditory activity (e.g., evoked-potential responses and the stapedius reflex) are useful to establish the integrity of each implanted electrode, estimate required stimulus levels, and identify unwanted nonauditory stimulation of the facial nerve.[38] Threshold measures correlate with subsequent behavioral responses, although not strongly enough to make accurate individual predictions.[27,39]

Stimulation levels do shift over time, and the implant itself must be monitored. Many adjustments may be required over the first months of implant use, and follow-up tends to be one to two times annually thereafter. This monitoring will continue throughout the child's life.

Children with cochlear implants are at increased risk for meningitis (see the Adverse Effects section), and they should receive pneumococcal vaccination.[40] MRI is contraindicated for patients with cochlear implants unless the magnet in the receiver–stimulator is removed. Monopolar cautery is also contraindicated anywhere on the body.

Table 1. Factors Involved in the Decision to Provide a Cochlear Implant and Factors Affecting Outcomes after Transplantation.

Exclusionary criteria
Successful use of hearing aids given sufficient residual hearing
Abnormal cochlear-nerve or auditory-nerve anatomy likely to preclude electrical stimulation
Medical illness precluding the use of a safe 2-to-4-hr general anesthetic
Lack of informed consent from a child who is capable of providing consent
Patient characteristics affecting outcome
Duration of deafness
Age at receipt of cochlear implant
Educational setting
Form of communication
Cognitive, motor, and social development
Speech–language development
Access to and participation in therapy and education providing support for oral speech–language development
Family structure and support
IQ*
Socioeconomic status*

* This factor is not assessed to determine the patient's candidacy for cochlear implants.

The total cost of cochlear implantation is typically $40,000 to $60,000. This figure includes the cost of the device itself, which may range from $20,000 to $35,000, as well as the costs of preoperative assessment and testing, the surgeon's fee, hospital costs, and follow-up.

ADVERSE EFFECTS

Perioperative complications of cochlear implantation include perilymphatic fistula or cerebrospinal fluid leak, tinnitus, vertigo, facial-nerve weakness or paralysis, epidural hematoma, and cellulitis of the surgical flap. Most of these complications are minor and resolve with appropriate management. Reported rates of perioperative complications vary, but complications typically occur among 15 to 20% of patients who receive cochlear implants.[41,42]

More serious complications, which tend to occur later, include flap necrosis, otitis media, cholesteatoma formation, nonauditory stimulation of the facial nerve, and electrode extrusion; each of these complications occurs at a rate of about 1%. The overall rates of major complications requiring surgical intervention range from 2% to 5% in large series.[41-45]

In 2002, the FDA received a series of reports of bacterial meningitis in children with cochlear implants. Subsequent investigation of this issue by the FDA, the Centers for Disease Control and Prevention, and several health departments identified 41 cases of bacterial meningitis, the majority due to *Streptococcus pneumoniae*, among 4264 children with cochlear implants, or an incidence of 189 cases per 100,000 person-years.[46,47] The development of meningitis was strongly associated with the use of a positioner, a small silicone rubber wedge inserted next to the implanted electrode to improve transmission. As a consequence, positioners are no longer used in cochlear implantation.

The most frequent complication in the long term is device failure requiring reimplantation in 3 to 6% of patients.[48-50] Device malfunction can occur because of "hard failure" of the internal components, traumatic failure (more often in children than in adults),[48] or "soft failure" characterized by a decrement in the auditory performance of a child or adult and thought to result from a poorly functioning device.[51] The long-term ability to reimplant cochleae after long-standing use or repeated reimplantation is not yet fully known. It is clear, however, that intracochlear changes result from implantation, potentially altering the underlying anatomy irrevocably, so that the implanted cochlea is unlikely to be usable for some future techniques.[52]

AREAS OF UNCERTAINTY

Numerous studies have confirmed that the successful development of language in children with early-onset deafness is strongly correlated with cochlear implantation between 12 and 24 months of age.[11-13,53,54] These findings reflect the importance of minimizing the interval between the onset of bilateral deafness and cochlear implantation, given that auditory development can proceed before the onset of acquired deafness and that the central auditory system is known to undergo reorganization during the period of bilateral auditory deprivation.[4,55] To further minimize this interval, implantation in infants with early-onset or congenital deafness before 12 months of age has been performed with good results.[56-58] Implantation in babies as young as 3 months of age has been reported[59]; however, the reliability of the audiometric results at this early stage of development remains questionable, and surgical safety must be viewed in the context of the uncertain, theoretical, physiological advantage.[60] Moreover, there is a risk that unrecognized developmental delays will emerge with age. Nonetheless, interest in early implantation is increasing.

Additional input through bilateral cochlear implants provides further benefits for adults who had bilateral hearing before their deafness; these benefits include improved hearing in noisy situations and sound localization with the use of intensity cues.[61,62] Relatively little has been reported regarding the outcomes of bilateral implantation in children with congenital deafness, although early data indicate better hearing in noisy situations with two implants rather than one,[63,64] an ability to discriminate between sounds at different locations,[65] and electrophysiological evidence of binaural processing in the brainstem.[26,66] Just as the interval between the onset of bilateral deafness and cochlear implantation has implications for the development of oral speech and language, the interval between the implantation in the first and the second ear may affect the development of binaural processing in children[66]; thus, there may be at least two sensitive periods in auditory development.

Risks are taken twice for bilateral implantation, with an additional theoretical risk of ves-

tibular or balance dysfunction, or both.[67] Bilateral implantation is also associated with a substantially increased cost, since two devices must be purchased and, when not done simultaneously, two procedures must be performed. However, simultaneous bilateral implantation requires less than double the surgical time and eliminates the need for two separate anesthetics, recoveries, and device activations.

It may be possible to promote binaural hearing by adding a hearing aid in the ear without the implant, provided that there is sufficient residual hearing. This "bimodal" hearing can successfully supply bilateral auditory cues[68] and access to fine-frequency information that is lost by the constant (and comparatively slow) rate of electrical-pulse presentation from the cochlear implant.

The decision by the FDA to approve cochlear implants for children in 1990 aroused controversy in the deaf community, with some persons asserting that deaf persons should be considered to be members of a distinct culture rather than patients with a disability, and arguing that parental approval of implants in their children is unethical.[69] More recently, however, this view has undergone some evolution. In 2000, a position paper of the National Association of the Deaf (NAD)[70] stated that "cochlear implantation is a technology that represents a tool to be used in some forms of communication, and not a cure for deafness." The paper added that "the NAD recognizes the rights of parents to make informed choices for their deaf and hard of hearing children."

GUIDELINES

The FDA has approved cochlear implants for children with severe-to-profound bilateral sensorineural hearing loss (hearing threshold, ≥90 dB in the better ear) who are at least 1 year of age and who have not benefited from an adequate trial (typically 4 to 6 months) of hearing-aid amplification. A similar position was taken in 2000 in a statement of the Joint Committee on Infant Hearing,[71] which noted that "cochlear implants may be an option for certain children age 12 months and older with profound hearing loss who show limited benefit from conventional amplification." As noted in the Areas of Uncertainty section, clinical practice in recent years has expanded beyond these criteria.

RECOMMENDATIONS

The infant described in the vignette is an appropriate candidate for cochlear implantation. With profound hearing loss, she is unlikely to benefit from hearing aids, and an initial trial of this approach has not been helpful. Although her other family members are deaf, they have all received cochlear implants and use oral communication at home. We would not favor waiting until the patient is 1 year of age to perform the operation, but we would recommend that surgery be undertaken when the child is 8 months of age, given the evidence suggesting that a greater benefit may be achieved when the duration of deafness is further restricted. Furthermore, we would favor simultaneous bilateral implantation to provide the advantages of binaural hearing outlined above. The devices should be activated 4 weeks after implantation, and a vigorous program of auditory and speech therapy should be implemented with the active participation of the family. The patient should receive the pneumococcal vaccine.

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