REVIEW ARTICLE

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Cochlear Implantation in Adults

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Hearing loss is one of the most prevalent and undertreated disabilities worldwide.[1,2] Often simply considered one of the stigmata of senescence, hearing loss has become increasingly recognized as an important health issue that may lead to increased risks of social isolation,[3,4] depression,[5] loss of autonomy,[6] reduced employability,[7] and neurocognitive dysfunction,[3,4,8] in addition to its association with many pragmatic safety concerns.[9-11] In view of these consequences, a growing emphasis has been placed on the prevention, early detection, and treatment of hearing loss.[12]

Although hearing aids suffice for many persons with hearing loss, a subset of the population with greater hearing impairment may benefit from cochlear implantation, a relatively low-risk outpatient procedure that generally leads to improvements in speech understanding and quality of life.[13] Yet it is estimated that less than 10% of adults in the United States and other developed countries who meet the current criteria for cochlear implantation actually receive this treatment.[14,15] Multiple factors contribute to the widespread underuse of cochlear implants, including limited awareness of the benefits and risks of cochlear implantation and lack of awareness of the current criteria approved by the Food and Drug Administration (FDA).[14,16] This review addresses the clinical features of hearing loss, current criteria for cochlear implantation in adults, modern cochlear-implant surgery, and anticipated surgical and audiologic outcomes.

Classification, Epidemiology, and Therapeutic Options

The type and degree of hearing loss are currently classified with the use of pure-tone and speech audiometry. Pure-tone audiometry is a standardized behavioral test that ascertains the quietest decibel threshold a person seated in a sound-attenuating booth can perceive through each ear across a range of frequencies. In contrast, word-recognition testing, which is a primary component of speech audiometry, evaluates a person's ability to recognize a list of monosyllabic words (e.g., car or boat) presented to each ear at a comfortably audible level; the resulting score is reported as the percentage of correct answers.

At least 1.2 million adults in the United States and 50 million adults worldwide are living with severe or profound hearing loss — a level of impairment that is not sufficiently corrected with hearing aids — and might benefit from cochlear implantation.[14,16-18] The prevalence of hearing loss increases with age, and approximately two thirds of people 70 years of age or older in the United States have hearing loss.[19,20] The proportion of the population that is older than 65 years of age is projected to double within the next three decades, and a proportional increase in the prevalence of hearing loss is likely.[21]

In the United States, advanced age, recreational or occupational noise exposure, hereditary factors, and exposure to ototoxic medications collectively are the most

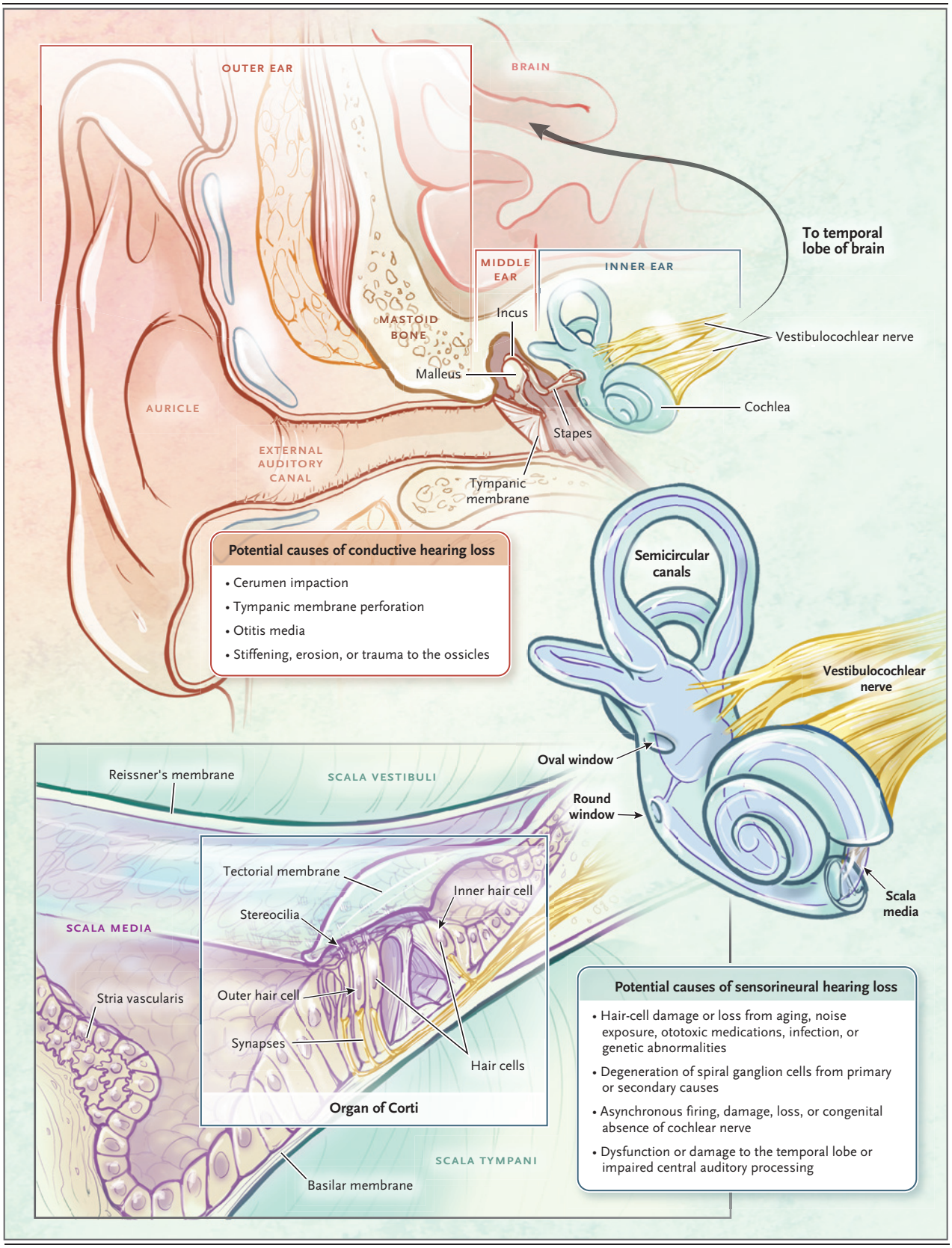

Figure 1 (facing page). Classification and Pathogenesis of Hearing Loss.

Hearing loss is broadly categorized as conductive or sensorineural. Conductive hearing loss results primarily from any condition that impedes the transmission of acoustic energy through the external or middle ear to the cochlea (e.g., tympanic-membrane perforation, middle-ear effusion, or ossicular-chain erosion). Conductive hearing loss rarely causes substantial deterioration in word recognition and is almost exclusively managed by surgical reconstruction or conventional hearing aids, not by cochlear implantation. In contrast, sensorineural hearing loss predominantly develops from disorders resulting in cochlear hair-cell injury (e.g., noise exposure or older age) and much less frequently from conditions involving the cochlear nerve or central nervous system.

common causes of sensorineural hearing loss that develops in adulthood (Fig. 1).[2,12,22] Numerous conditions lead to the development of sensorineural hearing loss, and most share a common pathway whereby damaged or missing sensory hair cells in the cochlea no longer transduce acoustic energy into neural action potentials that are processed by the central nervous system and perceived as understandable speech.

In the search to identify a cure for sensorineural hearing loss, regeneration of cochlear hair cells has become a focus of gene therapy and stem-cell research. Fish, birds, and amphibians are able to regenerate damaged hair cells, but cochlear hair-cell loss in mammals is currently largely irreversible.[23] The two leading strategies under investigation for mammalian regeneration of inner-ear hair cells are the identification of existing progenitor-like cells that might be used to repopulate cochlear hair cells, a technique that has been approached in mouse models that are transgenic for *Nestin*[24] and *Lgr5*,[25] and the transplantation and engraftment of murine pluripotent stem cells in mouse,[26] rat,[27] and guinea pig[28] models.

Currently, there are no FDA-approved pharmacologic or surgical treatments that reverse sensorineural hearing loss and reinstate normal acoustic hearing. Thus, current clinical management revolves around prevention of hearing loss (e.g., workplace hearing-conservation programs) and rehabilitation through the use of hearing aids or cochlear implants.

The decision to recommend treatment with a cochlear implant is driven by the results of audiometric testing, as well as the demands of the everyday listening environment. A person with limited unilateral hearing loss or mild bilateral high-frequency hearing loss may function reasonably well in a quiet environment. However, people with greater degrees of hearing loss frequently struggle with everyday communication, particularly in the presence of background noise. Fitted hearing aids provide sufficient benefit for most patients who have relatively good speech recognition (a score ≥60% on word-recognition testing) and less than severe-to-profound hearing loss (i.e., ≤70 dB hearing level [HL] at low frequencies and ≤90 dB HL at high frequencies). However, for patients with poor speech recognition and more advanced bilateral sensorineural hearing loss, cochlear implantation provides the only effective means of auditory rehabilitation currently available. Whereas hearing aids function by amplifying sound, cochlear implants bypass nonfunctional or missing cochlear hair cells and directly stimulate surviving spiral ganglion cells of the distal cochlear nerve, enhancing both audibility and speech recognition (Fig. 2).

ASSESSMENT AND CURRENT CRITERIA FOR COCHLEAR IMPLANTATION

Evaluation of an adult for cochlear implantation entails a detailed hearing assessment by an audiologist and a medical assessment by a cochlear-implant surgeon. The chief objective of the audiologic assessment is to determine whether the patient will receive more benefit from a cochlear implant than from properly fitted hearing aids, whereas the primary goal of the medical assessment is to determine whether surgery is sufficiently safe and feasible for the patient.

During unilateral cochlear-implant surgery in an adult, the typical time under anesthesia is less than 2 hours and limited blood loss occurs; therefore, the perioperative anesthetic risks are relatively low. Most centers now routinely perform cochlear-implant surgery in patients ranging from infants to nonagenarians.[29,30] In contrast to a subgroup of children with congenital sensorineural hearing loss, adults with postlingual hearing loss generally do not have severe cochlear dysplasia, cochlear-nerve hypoplasia, or a central process that precludes cochlear implantation.[31] The one notable exception is patients with profound hearing loss after bacterial men-

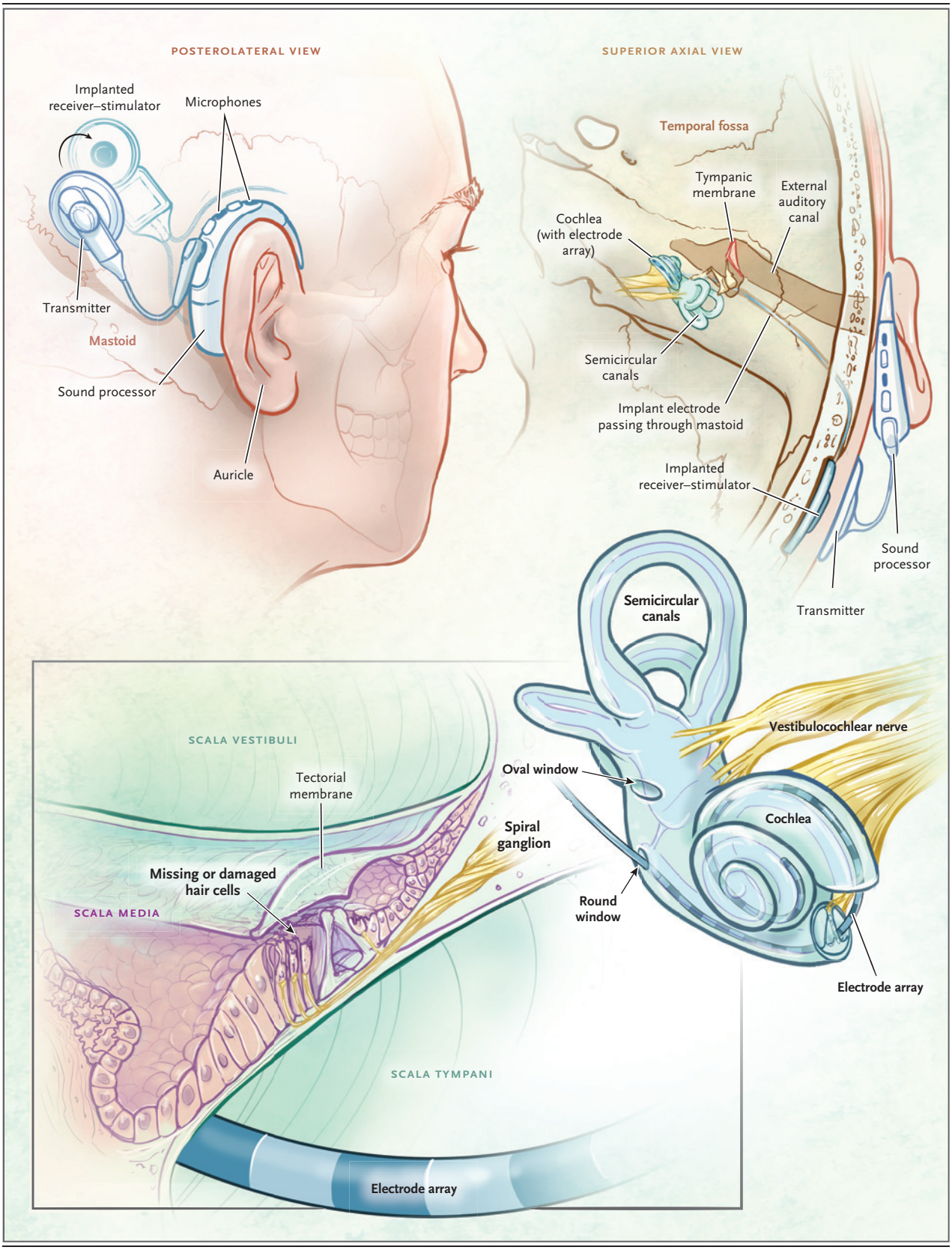

Figure 2 (facing page). Components and Mechanism of a Cochlear Implant.

The external sound processor converts acoustic sound to a coded electrical signal that is transmitted to the internal device through transcutaneous radiofrequency coupling. The internal device, in turn, relays the signal to the electrode array of the cochlear implant, bypassing damaged sensory hair cells in the cochlea and directly stimulating spiral ganglion cells of the cochlear nerve. Stimulation is delivered in a rapid, sequential, interleaved pattern through which neighboring electrode signals are temporally separated by milliseconds to avoid current summation of adjacent electrodes. This strategy improves sound quality and speech recognition by maximizing channel independence and spectral resolution.

ingitis. Labyrinthitis ossificans develops concomitantly in up to 35% of such patients, causing irreversible scarring within the cochlea.[32] If cochlear implantation is being considered in a patient with profound hearing loss due to bacterial meningitis, surgery is generally best performed soon after the onset of hearing loss so that the electrode can be inserted before prohibitive ossification ensues.

Currently, most insurance programs in the United States specify that to qualify for coverage, an adult must have bilateral sensorineural hearing loss that is moderate or more severe at low frequencies and profound at high frequencies, with no more than 50% of sentences understood correctly in the ear that will receive the implant or no more than 60% of sentences understood correctly when both ears are fitted with hearing aids (Fig. 3; and Table S1 in the Supplementary Appendix, available with the full text of this article at NEJM.org).[14,16] In most cases, the ear with the greater degree of hearing loss is chosen for implantation so that the patient can continue to use a hearing aid in the contralateral ear while adjusting to the new implant. Since the cochlear implant is not typically activated until 2 to 4 weeks after implantation, this strategy also allows most people to resume work and other social activities within 5 to 10 days after surgery. Depending on how well the patient is functioning with the cochlear implant and how much residual hearing is present in the ear without the implant, implantation in the second ear may be performed at a later date if the patient wishes.

There is a common misconception that patients must have bilateral profound sensorineural hearing loss to meet current criteria for cochlear implantation in adults. FDA device labeling has been broadened and currently encompasses device implantation in patients with varying degrees of preoperative residual acoustic hearing. In 2014, a hybrid cochlear-implant system with a short electrode was approved for use in adults with normal hearing to moderate hearing loss at low frequencies, severe to profound hearing loss at middle-to-high frequencies, and poor word recognition (www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfPMA/pma.cfm?id=P130016). The use of this specialized short electrode reduces apical cochlear trauma and allows for preservation of preoperative low-frequency acoustic hearing in 66% of cases (Fig. 3).[33] When functional acoustic hearing is preserved after surgery, patients can use a hearing aid in the ear with the cochlear implant, a strategy called hybrid stimulation, which may confer enhanced speech perception and music appreciation.[34] In July 2019, cochlear implantation was approved by the FDA for patients, 5 years of age or older, who have profound hearing loss in one ear and a range from normal hearing to moderate hearing loss in the other ear (www.fda.gov/medical-devices/recently-approved-devices/med-el-cochlear-implant-system-p000025s104).

There is no screening questionnaire or finding on clinical examination that can reliably predict whether a patient will benefit from cochlear implantation or will meet current FDA labeling criteria for implantation in adults. Furthermore, the degree of hearing loss is commonly underestimated during a typical face-to-face clinic visit. Outpatient encounters typically occur in a quiet room, where patients can compensate with lip reading and other visual cues or discreetly rely on an accompanying friend or family member to communicate. As a general rule, people who are struggling to understand speech during routine everyday activities, despite using hearings aids, may benefit from cochlear implantation (Table 1).[15,35,36] Ultimately, a comprehensive hearing assessment can be considered when more advanced hearing loss is suspected.

COCHLEAR-IMPLANT TECHNOLOGY

Currently, three device companies manufacture FDA-approved cochlear implants. Notwithstand-

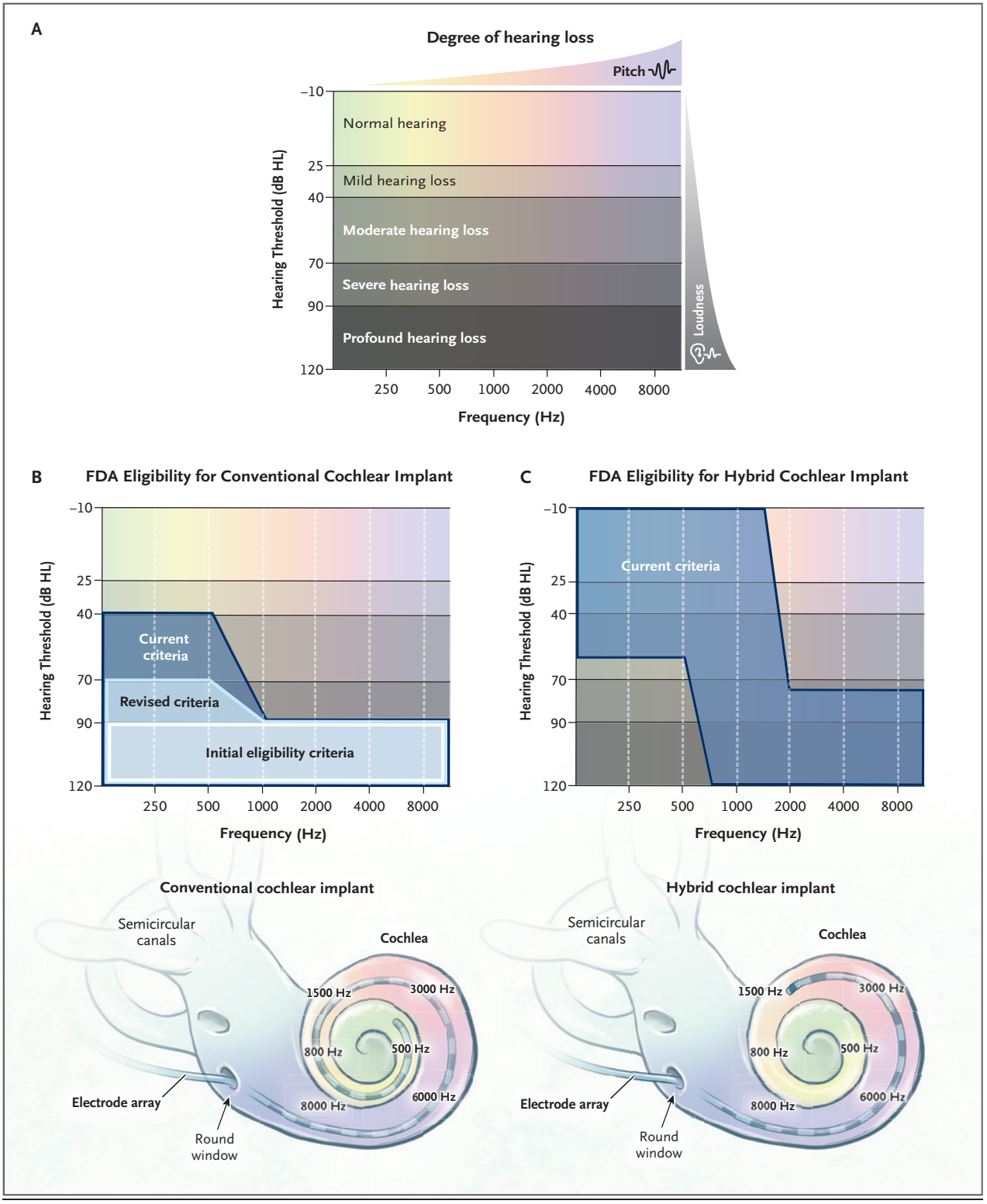

Figure 3 (facing page). Degree of Hearing Loss and Criteria for Cochlear Implantation in Adults.

Panel A shows the various degrees of hearing loss. Panel B shows that historically, only adults with bilateral, profound hearing loss underwent cochlear implantation (initial Food and Drug Administration [FDA] eligibility criteria), whereas currently, adults with moderate or more severe low-frequency hearing loss and profound high-frequency hearing loss meet the criteria for receipt of a conventional cochlear implant. Both the degree of hearing loss and word- or sentence-recognition scores are used to assess audiometric performance before cochlear implantation (see Table S1 in the Supplementary Appendix). Neurosensory cells that collect low frequencies aggregate in the apex of the cochlea, and those that collect high frequencies aggregate in the base. This serendipitous arrangement permits a cochlear-implant electrode to selectively activate different regions of the cochlea in order to precisely control pitch. Panel C shows that the tonotopic organization of the cochlea also allows specialized shorter-length electrodes, used in hybrid cochlear-implants, to treat mid- and high-frequency hearing loss through preferential electrical stimulation of the basal cochlea while simultaneously preserving preoperative low-frequency acoustic hearing by limiting trauma to the more apical regions of the cochlea.

Table 1. Clinical Screening Questions to Help Identify Adults Who May Benefit from Cochlear Implantation.

When using your hearing aid (or aids), are you able to carry on a conversation with another person when you cannot directly see his or her face?
Are you able to use the telephone without using visual aids such as caption or video?
Do you struggle when communicating with others at large gatherings such as dinner parties, even when you are using hearing aids?
Do you avoid social gatherings, meetings, and other events at which there is background noise, because you are unable to hear conversations well, even when you are using hearing aids?

ing small variations, virtually all commercially available devices share a similar design: the external component contains a microphone, battery, sound processor, and transmitting coil, and the internal component includes a radiofrequency receiver coil, microprocessor-based stimulator, and multichannel electrode (Fig. 2). The intracochlear electrode contains 12 to 22 active contacts, depending on the model, that independently stimulate different regions of the cochlea. Cochlear-implant technology takes advantage of the tonotopic anatomy of the cochlea, with neurons that collect low-frequency signals aggregating in the apical regions of the cochlea, and high-frequency signals collected in the basal regions. Precise pitch control is achieved through altering the stimulation rate and spatial location of stimulation along the tonotopic axis of the cochlea. Sound intensity is controlled by modifying the current amplitude and pulse duration at each individual electrode contact. The fact that many implant recipients can decipher complex speech with as few as 8 to 10 independent stimulating electrodes suggests that central nervous system processing and neuroplasticity play pivotal roles in speech perception.[13,37,38]

External cochlear-implant components have become increasingly miniaturized, and most current designs can be concealed relatively well under medium-length or long hair (Fig. S1). Virtually all current sound processors integrate smartphone and wireless Bluetooth technology, offer specific programs for various listening environments, and incorporate water-resistant encasements. As of June 2019, all manufacturers of FDA-approved cochlear implants integrate internal magnets that are "MRI conditional" (i.e., safe for a patient to undergo magnetic resonance imaging [MRI] under very specific conditions provided in the labeling) in a field strength of up to 3 Tesla (www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpma/pma.cfm?start_search=1&PMANumber=P970051&SupplementNumber=S183). This development is particularly important, since at least half of all cochlear-implant recipients will have a clinical indication for at least one MRI study during their lifetime.[39,40] Currently, several commercial implant manufacturers are evaluating the safety and feasibility of a totally implantable cochlear-implant system.[41,42] A totally implantable system not only would render the device virtually invisible but also would support full-time use. With current devices, the external component is typically removed while the patient is swimming, showering, and sleeping.

RISKS, BENEFITS, AND OUTCOMES OF COCHLEAR IMPLANTATION

SURGICAL AND DEVICE-RELATED COMPLICATIONS

As noted above, cochlear-implant surgery has evolved into a relatively low-risk outpatient surgical procedure performed while the patient is

A video showing cochlear-implant surgery is available at NEJM.org

under general anesthesia. A narrated video of cochlear-implant surgery in adults can be viewed at NEJM.org. Data on the estimated prevalence of complications associated with cochlear implantation, compiled from 10 large studies, are presented in Table S2 and summarized here.[43-52] The overall prevalence of complications is 12.8% (reported in 964 of 7513 patients),[43-49,51,52] and the prevalence of major complications is 2.7% (207 of 7542).[43,44,46-52] The prevalence of specific complications includes wound infection in 1.9% of patients (104 of 5556),[43,44,46-48,51,52] hematoma in 1.1% (85 of 7513),[43-49,51,52] chronic surgical-site pain in 1.7% (49 of 2889),[44,46,47,49,51,52] persistent vestibular symptoms in 2.2% (102 of 4664),[44,46,47,49,51,52] and permanent facial-nerve paralysis in 0.1% (7 of 8779).[43-52] The risk of postoperative meningitis has been strongly associated with an age of less than 6 years (when recurrent otitis media is most prevalent), with the presence of inner-ear malformations, and with the use of a specific cochlear-implant electrode positioner that was removed from the market in July 2002.[53] With the use of recent device models, the prevalence of postoperative meningitis was less than 0.1% (5 of 7167).[44-47,49-52] This risk might be further attenuated by adhering to Centers for Disease Control and Prevention guidelines for pneumococcal vaccine prophylaxis.[54] Total device failure requiring reimplantation has been reported in 1.9% of cases (125 of 6461).[44-46,48,49,51,52]

Until relatively recently, the loss of preoperative acoustic hearing in the ear that received the implant was considered an unavoidable consequence of cochlear-implant surgery.[55] However, in the late 1990s, several reports documented the feasibility of hearing preservation after cochlear implantation.[56,57] As FDA labeling criteria have expanded to include patients with better residual hearing, the ability to preserve functional preoperative hearing has become a priority. A meta-analysis by Santa Maria et al. showed that among adults who received cochlear implants with a conventional-length electrode (186 patients in 13 studies), preoperative low-frequency (≤1000 Hz) hearing was fully preserved (i.e., <10 dB loss) in 27.4% of patients and partially preserved (i.e., between 10 and 20 dB loss) in 25.3% but was not preserved (i.e., >20 dB loss) in 47.3%.[58] Thus, it appears that although most patients today benefit from the electrical stimulation provided by the cochlear implant, approximately half of adults who have functional preoperative acoustic hearing lose this residual hearing as a complication of surgery. Beyond modifying surgical techniques and electrode designs, research efforts have focused on advances that include automated electrode insertion,[59] glucocorticoid-eluting electrodes,[60] and real-time intraoperative electrophysiological feedback[61] to mitigate the risk of early or delayed acoustic hearing loss after cochlear-implant surgery.

SPEECH PERCEPTION AND SOUND QUALITY

Refinements in surgery, device design, programming strategy, and FDA labeling criteria have resulted in substantial improvements in multichannel cochlear-implant performance since the early devices were first approved for commercial use in 1985.[41] After cochlear implantation, there is a variable period of acclimatization to the new electrical input. Many recipients initially report that voices sound high-pitched and mechanical, though sound quality generally improves during the following 3 to 6 months. Sound clips are available as examples of what a cochlear-implant recipient hears (https://asha.figshare.com/articles/single-sides_deaf_ci_voice_quality_dorman_et_el_2019_/9341651).[62,63] For the first year after surgery, cochlear-implant recipients need to attend several device-programming sessions at which the sound quality and loudness of the implant are adjusted to improve speech recognition. During this time, patients are also encouraged to use their implant consistently throughout the day while watching television, listening to familiar music or audiobooks, or reading aloud in order to train the central nervous system to reconcile what is heard with known words.[64] At most centers, there is a routine delay of 2 to 4 weeks after surgery before the device is turned on. Recently, device activation within 24 hours after surgery was successfully implemented at several centers to expedite rehabilitation and potentially reduce the number of early postoperative return visits.[65,66]

Although the rate at which speech perception improves after cochlear implantation is variable, increases are usually steepest within the first 6 months of use. However, continued progress can be seen up to 3 years after surgery.[67,68] Data from an unselected, consecutive series of 259 adults (277 ears) who recently received implants at the Mayo Clinic provide information regarding

the audiometric profile and anticipated outcomes with the use of current device models (unpublished data). The median preoperative scores on tests of monosyllabic-word and sentence recognition were 8% (interquartile range [IQR], 0 to 24) and 7% (IQR, 0 to 29), respectively. Within the first 12 months after cochlear implantation, the median postoperative scores for word and sentence recognition were 58% (IQR, 36 to 72) and 75% (IQR, 53 to 91), respectively (Table S3 and Fig. S2).

ENVIRONMENTAL SOUND PERCEPTION

In addition to improving speech perception, cochlear implants have the capacity to restore sound thresholds to normal or near-normal levels. Although this benefit of implants is commonly underappreciated in the medical literature, patients frequently reflect positively on their newfound ability to hear many quiet or high-pitched environmental sounds, such as the faucet dripping, the click of a car's turn signal, or birds chirping. Beyond such perceptual benefits, enhanced environmental sound awareness improves personal safety, increases autonomy, and alleviates possible fears of not hearing a fire alarm, oncoming traffic, a doorbell, or other "directing" sounds.[10,11,69]

QUALITY OF LIFE AND COST-EFFECTIVENESS

Although scores for word and sentence recognition are the primary benchmarks used to assess outcome, these traditional metrics do not adequately capture the complex and multifaceted benefits that many implant recipients report, particularly with regard to social and emotional domains. A substantial body of literature elucidates consistent improvements in quality of life after implantation that appear to be independent of audiometric testing performance.[70,71] In a recent pooled analysis, Crowson et al. reported that the average improvement in quality of life for adult recipients of unilateral implants was 44.3% with the use of generic measures (among 954 patients in 15 studies) and 89.1% with the use of disease-specific instruments (among 360 patients in 11 studies).[71] Moreover, 6 studies (with a total of 674 patients) that assessed cost-effectiveness with the use of the Health Utilities Index showed a weighted mean cost (in U.S. dollars) per quality-adjusted life-year (QALY) gained of $23,310 (range, $9,426 to $33,656).[72-77] For context, a ratio of less than $50,000 per QALY has long served as the accepted benchmark for value in the United States.[78]

KEY ISSUES MOVING FORWARD

INDIVIDUAL VARIATION IN OUTCOMES

Although most implant recipients have significant gains in speech perception, a subgroup of recipients have poor outcomes, even after extended use of the implant and supplemental rehabilitation.[38,67,79] A recent analysis showed that up to 16% of adult cochlear-implant recipients had poor long-term outcomes (defined as a word- or sentence-recognition score of less than 30% at 12 months) (unpublished data; Table S3 and Fig. S2). Rumeau et al. reported that 9 of 26 experienced adult implant recipients (35%) were unable to routinely use the telephone.[80] The duration of deafness before implantation and the preoperative speech-perception scores have the highest predictive value for the speech-perception outcome among adults who have received cochlear implants, whereas age at the time of implantation and the cause of sensorineural hearing loss do not appreciably influence the outcome in most studies.[81-83] Nevertheless, even the most robust predictive models cannot fully account for the observed range in speech-perception scores.[67,84] Understanding the complex mechanisms underlying outcome variation and the development of new interventions to successfully remediate poor test performance remain two critical objectives in the field today.

ASSOCIATION BETWEEN COCHLEAR IMPLANTATION AND COGNITIVE FUNCTION

Growing evidence links hearing loss with cognitive impairment and dementia.[8,85] In the 2017 report from the Lancet Commission on Dementia Prevention, Intervention, and Care, Livingston et al. estimated that up to 35% of dementia cases are potentially preventable, with hearing loss considered the largest modifiable risk factor.[8] As a natural extension, whether rehabilitation with hearing aids or cochlear implants can successfully mitigate the risk of cognitive impairment or dementia has become an area of active research.[86] Five prospective longitudinal studies involving a total of 259 patients have identified improvements in attention, processing speed, and working memory after cochlear implantation.[86-90]

SUMMARY

Hearing loss is often viewed as an inconsequential process or an accepted part of aging rather than an important health risk that warrants treatment. Patients who struggle to understand speech in typical everyday listening environments despite using hearings aids may benefit from cochlear implantation. Age and coexisting medical conditions generally do not preclude cochlear-implant surgery and have a limited effect on performance outcomes. Although most adult cochlear-implant recipients gain clinically significant improvements in speech recognition and quality of life, a subgroup of patients do not have such benefits. The variation in outcomes, the ability to reliably preserve natural hearing after surgery, and the potential role of hearing aids and cochlear implants in mitigating the risk of late-life dementia represent three important areas of active research.

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Disclosure forms provided by the author are available with the full text of this article at NEJM.org.

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