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The Importance of the Electrode-Neural Interface in Supporting Long-Term Outcomes in Cochlear Implantation: Expert Opinion

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Abstract

Background: Since first introduced in the mid-1980s, cochlear implant (CI) technology has significantly evolved to reach the current state of the art. Commencing with straight, lateral wall electrode arrays, advances in the last decade led to the development of slim perimodiolar arrays that lie closer to the electrically targeted spiral ganglion. Over the years, as a consequence of improving hearing benefits, CI indications have been steadily expanded. Today, individuals with moderately severe-to-profound sensorineural hearing loss, many with residual hearing in the low-frequency range, may receive a CI in one or both ears. ***Summary:*** Before implantation, individual recipient characteristics, such as years of auditory deprivation, hearing thresholds, and speech understanding ability with conventional amplification, can have an effect on CI hearing outcomes. Also individuals with normal hearing/mild hearing loss in the low frequencies can also qualify for CI. Surgical procedures such as careful, soft surgery techniques are imperative to reduce cochlear trauma and optimize outcomes and can be supported by surgical guidance tools and drug therapies to help preserve the delicate intracochlear structures and also for patients with single-side deafness. Histopathological investigations provide evidence that support the design concept of slim perimodiolar electrode arrays. Modiolar proximity and scalar tympani location permit energy-efficient, focused electrical stimulation of the targeted neural interface, while minimizing injury to the fine structures of the intracochlear lateral wall and its blood supply. ***Key Messages:*** Modiolar electrode arrays may provide highly consistent scala tympani placement and modiolar proximity which may improve functional hearing outcomes, compared to lateral wall electrode array results. Modiolar proximity can

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result in narrower spread of excitation, reduced channel interaction, lower electrical stimulation thresholds and may improve speech understanding. Reservation of functional residual low-frequency hearing is possible with both straight and perimodiolar electrode arrays.

Introduction

The World Health Organization (WHO) has indicated that about 1.5 billion people have some degree of hearing loss (HL) which will have negative effects on most aspects of life when not treated. Approximately 430 million people require rehabilitation for their disabling hearing (functional deficits for HLs between 25 and 35 dB HL) [1].

Cochlear implant (CI) indications have changed significantly over the past 30 years. Initially, postlinguistically deafened adults with bilateral profound sensorineural hearing loss (SNHL) and no speech understanding were implanted. When technology and outcomes improved, expanding criteria allowed more individuals with less HL to benefit, including bilateral cochlear implantation. Currently, criteria have broadened to include individuals with normal hearing in one ear and severe-to-profound SNHL in the other ear (i.e., single-sided deafness).

Methods

An international group of CI surgeons each with more than 30,000 patients in their care provide a collective expert opinion narrative summarizing the identified influencing factors upon long-term CI outcomes. A non-systematic literature review led by the lead author enabled selection of relevant, recently published research papers providing evidence of patient characteristics, surgical aspects, and contemporary electrode design as influencing factors on CI outcomes. Researches published in the last 10 years, reporting on at least 20 subjects, treated with contemporary electrode designs were given priority for review and summary over older research describing legacy technology. An exception was made for researches published more than 10 years ago, or including smaller sample sizes, when reporting newly identified factors affecting performance. Selected papers were reviewed, summarized, and included in the narrative based on their clinical relevance, study design, and findings. All authors provided expert critical review of the summarized evidence shared in addition to providing supplementary articles for review and inclusion as appropriate and further review until all were aligned.

Factors Impacting Performance

Hearing outcomes following cochlear implantation vary across adult CI recipients and usually plateau after 1 year of experience [2]; by 12 months postimplantation, approximately 60% of patients exhibited single-syllable word understanding at a level (≥50%) that did not necessitate regular audiological follow-up. Hearing outcomes may be influenced by a number of factors, some acting independently and some interrelated. These may include patient-related factors, surgical factors, and device-related factors. Preimplant patient factors include age, duration of HL, residual hearing for speech recognition in quiet and pure-tone thresholds [3, 4]. Holden et al. [5] prospectively investigated biographical and audiological information, electrode position in the cochlea and cognitive capabilities in 114 recently implanted adults. They determined that older age at implant, longer duration of HL, length of hearing aid (HA) use, and length of severe-to-profound hearing loss (SPHL) had a significant negative relationship to performance, while lower implant sound field thresholds were positively correlated with outcomes.

Surgical and device-related factors may include surgical methods and outcomes, array placement in scala tympani (ST), insertion angle, array proximity to the modiolus, electrode type, number of electrode channels, and subsequent changes in the cochlear environment. These factors may individually influence performance outcomes; however, there are also synergistic effects where individual factors may be influenced by preceding factors which in turn may influence subsequent factors. Understanding and managing the relationship between the factors can impact the patient outcome both short and long terms. For example, cochlear anatomy, surgical approach, and electrode array design are interrelated and can influence ST placement and insertion angle. Proximity of the electrodes to the modiolus has been shown to improve speech outcomes, but only if the electrode array remains in ST. ST placement and insertion angle support intracochlear structural preservation, helping reduce immediate and delayed changes in the intracochlear environment and support cochlear health longer term. In summary, these factors in addition to an individual's peripheral and central processing attributes may influence hearing abilities over a CI recipient's life.

Preoperative Patient-Related Factors

There are a number of preoperative patient-related factors that have been shown to be correlated to postoperative outcomes with CI. The most commonly reported factors relevant to performance include duration of SPHL, age at SPHL, duration of HL, HA use, residual hearing, age at CI, preoperative speech recognition as well as postoperative implant experience. Genetics is also another factor affecting CI outcomes. There is also some evidence that intraoperative measures of hair cell/neural responses have an impact on CNC outcomes [6, 7].

Duration of HL (See Preimplant Speech Recognition Performance below)

One of the most commonly examined influencing patient factors is duration of significant HL, especially when in both ears, prior to implant. It is important that adults with moderate-to-profound HL are implanted as soon as possible in order to reduce sensory deprivation. Lazard et al. [8] found that speech perception declined with moderate HL and continued to decline as HL became more significant.

Bernhard et al. [9] conducted a systematic literature review and two meta-analyses of studies evaluating the relationship between duration of deafness and speech understanding following CI implantation. They found a negative correlation between duration of auditory deprivation (large period of deprivation, more than 15 years) and speech recognition and that "duration of deafness is one of the most important factors to predict speech perception after CI in postlingually deaf patients."

Kim et al. [3] found that patients with moderate and profound HL <10 years demonstrated better and more consistent speech understanding than those with longer durations. In addition, Budenz et al. [10], Sladen and Zappler [11], and Wong et al. [12] demonstrated that while older individuals gain important CI benefits, they do not perform as well as younger adults, which could potentially be influenced by age at implantation and cognitive capabilities. It is recommended that adults, regardless of age, with bilateral SNHL and inadequate HA benefit are implanted as soon as possible.

Preimplant Speech Recognition Performance

Various investigations have determined that better preimplant speech understanding is positively associated with better postimplant outcomes [5, 8, 13]. Huinck et al. [14] also showed that lower preimplant audiometric thresholds and better speech perception resulted in better CI, >70% word understanding on CNCs. Outcomes from their study indicated that more relaxed CI indications had a positive effect on speech perception abilities for individuals with severe HL.

Other researchers [6, 8, 15, 16] have assessed relationships between CI speech recognition performance and patient-related factors; many of the same factors are seen across studies; however, the strength of these associations varies and often is low or not significant which may be due to single center and/or small cohorts. Using univariate and multivariate analyses, Goudey et al. [15] conducted the largest retrospective investigation to date to examine the association between 21 preoperative factors and speech understanding approximately 1 year postimplant in 2,735 CI recipients from three CI clinics. The outcome measure used was monosyllabic word understanding scores at 12 months postimplant.

They found 17 significant relationships using univariate or multivariate analyses. Age at implantation and word recognition results were mixed; lower age was associated with better word understanding at some clinics, but older age was positively associated with better word understanding in the clinics' combined analyses. Multivariate analysis suggested results could be due to differences regarding varying etiologies in different age groups across clinics. Preimplant-aided word understanding in the implanted ear was related to better CI word understanding; poorer PTA in that ear was associated with poorer CI word understanding, consistent with the perception that poorer starting conditions deleteriously affect performance. Prelinguistic HL was strongly associated with poor outcomes; duration of any loss prior to CI was negatively associated with CI outcomes in the ear to be implanted and contralaterally, as well as years of severe-profound loss in ear to be implanted. The relationship between pre-implanted aided word recognition with HAs and CI word understanding has a positive relationship. Using multivariate analysis, investigators observed that longer time with HL before CI resulted in a strong, consistent negative effect on outcomes across clinics.

Perioperative Hearing Thresholds

The expansion of CI candidacy indications suggests that more adults indicated for CI will have some preoperative levels of residual hearing. Although electrode designs and surgical techniques have improved with the goal of residual hearing preservation (HP), outcomes postoperatively are still varied with many recipients experiencing postoperative delayed or progressive loss [17, 18]. As a result, nearly all recipients will rely on electrical stimulation alone for audibility, if not postoperatively, then likely within 1 year postimplant and very likely within 5 years.

Woodson et al. [18], Shew et al. [19], and Sharma et al. [20] have highlighted that a 20–25 dB postoperative loss is common. As a result, patients with a preimplant low-frequency pure-tone average (LFPTA) of ≤60 dB HL should be considered as possible candidates for electroacoustic stimulation (EAS) postoperatively considering their postoperative residual hearing thresholds will likely remain within the functionally aidable range of <80 dB HL [21]. (It should be noted that while <80 dB HL is considered structural preservation, from an audiology perspective, it actually really is not aidable by the HA component of current EAS sound processors.) Usually, 70 dB HL is the extreme end of what the HA component of current EAS sound processors can provide. As such, they should be counseled accordingly prior to implant. HP outcomes have been shown to be comparable for slim lateral wall (LW) and slim perimodiolar electrodes. Woodson et al. [18] conducted a retrospective review of 121 ears implanted with a slim LW ($n = 58$) or slim perimodiolar array ($n = 63$) with a subgroup of each candidate for HP (LFPTA <80 dB). Postimplant, the change in LFPTA between the electrode groups was similar. HP (<80 dB LFPTA) was almost identical, with 50% for the LW and 53% for the perimodiolar groups.

Studies comparing LW and modiolar electrodes are often subject to selection bias as electrode choice is driven by preoperative characteristics and often not specified. One recent study specifically looked at outcomes in those patients who meet US FDA Hybrid criteria implanted with a modiolar electrode and suggest some factors attributed to different arrays may in fact be related to patient factors [22].

Zhan et al. [23] retrospectively compared HP for patients implanted with a slim perimodiolar electrode ($N = 95$/72%) or with the slim LW array ($N = 37$/28%) and a preimplant LFPTA of ≤60 dB (125, 250, 500 Hz). They defined postimplant functional low-frequency HP as LFPTA ≤80 dB (125, 250, 500 Hz). HP rates at activation (precurved = 48/84 [57.1%], LW = 26/37 [70.3%]) and at 12 months postimplant (perimodiolar = 22/92 [23.9%], straight = 12/33 [36.4%]) were not statistically different.

Although residual hearing can be preserved in the long run (5–15 years post-CI) to allow for EAS, in many cases, residual hearing even if preserved may be degraded by underlying cochlear modifications (fibrosis, ossifications, etc.), limiting its functional benefit [24]. This remains an active topic of exploration, but it is clear that not all patients with preservation of acoustic hearing prefer to listen in that condition [25].

Adult Age

Although age may be a consideration when evaluating and counseling older adults, evidence suggests it does not generally result in poor outcomes; rather, CIs provide substantial benefits for speech understanding and quality of life regardless of age. Based upon published evidence, Boisvert, Reis, Au, Cowan, and Dowell [26] concluded "While advanced age and less residual hearing have been associated with poorer speech perception in some studies, neither factor has been shown to have strong predictive power."

Bourn et al. [27], Hammond-Kenny et al. [28], Wichova et al. [29], and Wong et al. [12] investigated postimplant outcomes in over 450 recipients in total who were 65 to 80+ years old. They observed improvements in words and/or sentences, including in dementia recipients. Elderly individuals, including 80- to 90-year-olds, obtain important hearing benefits and should be considered CI candidates.

CI Surgery-Related Factors

CI surgical procedures have evolved over the past 2 decades due to improved understanding of the interactions between the surgeon, the device, and cochlear anatomy. This was primarily the result of concepts of HP and soft surgery techniques leading to improved fundamental knowledge of their combined implications on preservation of cochlear structures, functional HP, which could lead to EAS and long-term health of the cochlea.

These in turn have led to expansion of CI candidacy indications resulting in more adults being indicated for CI and likelihood that these candidates will have some preoperative levels of residual hearing [30]. Although electrode designs and surgical techniques have improved with the goal of preserving residual hearing, postoperative levels of residual hearing are still varied with many recipients experiencing postoperative delayed or progressive loss post-CI. Successful HP may be achieved in more than 50% of the cases, and in many cases no significant difference was found between electrode designs. Also, it has been found that the EAS processors were fitted in 30% of the cases with residual hearing, meaning that the pre- and postoperative mean PTA thresholds were not absolutely predictive of EAS use [16, 17, 31].

Preservation of measurable low-frequency thresholds therefore is not the most important objective of implantation given the real possibility of delayed or progressive HL and reality that most CI patients will rely on electrical stimulation alone, but structure preservation may well be. Information gathered from research studies using measures such as the transimpedance matrix and cochlear microphonics with electrocochleography (ECochG) that can be found in several types of CI systems may provide important feedback to the surgeon and improve outcomes. Ramos et al. [32] investigated if intraoperative ECochG would be useful in preserving residual hearing during electrode insertion. Responses were recorded in 12/15 cases; they concluded ECochG was useful to evaluate residual hearing, but more studies were required. O'Leary et al. [33] reported that real-time ECochG CM monitoring can notify the surgeon if the cochlear microphonics drops so that immediate modifications can be made, during the insertion dynamics (modifications of angle of insertion, "pull back" actions), and potentially preserve residual acoustic hearing. Walia et al. [34] found that promontory ECochG correlated with extra- and intracochlear responses and partially explained CI performance variability.

In the future, minimally invasive robot-assisted surgery should enable high precision surgery and may improve HP [35]. Kaufmann et al. [36] showed that robotic electrode array insertions diminished trauma compared to human insertions.

CI Device-Related Factors

ST Location

Placement of the electrode within ST is the goal for all CI surgeries involving normal cochlear anatomies. Translocations from ST typically involve rupture of the basilar membrane (BM), potentially damaging Organ of Corti and osseous spiral lamina. Apart from leading to mixing of perilymph and endolymph and disrupting cochlear homeostasis, it also causes tissue trauma and bleeding which will result in not only a loss of any residual hearing, but also increased fibrosis and electrode impedances, which in combination with an unfavorable position of the electrodes compared to ST placement may negatively impact on electrical stimulation and hearing outcomes.

Additionally, ST placement is essential for modiolar proximity and subsequent benefits including reduced current requirements, reduced spread of excitation leading to improved electro-neural interface stimulation, and better hearing performance [5]. Modiolar proximity during electrode array insertion and in situ placement is enabled by slim, flexible perimodiolar electrode array designs. Modiolar proximity has been observed to help reduce damage to intracochlear structures, including the blood supply via the stria vascularis and the wider, softer structure of the BM compared to an LW location [37].

Higher rates of translocations have typically been associated with perimodiolar electrodes [38], with a recent meta-analysis [39] also finding a higher rate for PM (43%) versus LW (7%) arrays. This analysis does not differentiate between older generation stylet-based PM electrodes and newer generation slim perimodiolar electrodes and groups all generations of precurved electrodes as "PM."

In a similar review, Munhall et al. [40] found that the rates of translocation vary not only by electrode design (PM vs. LW) but also within PM designs, with translocation rates of LW electrodes ranging from 5 to 22% and 30–50% for PM electrodes with internal stylet, but rates of approximately 7% for PM electrodes with external sheath. Further analysis of Jwair et al. [39] by categorizing PM designs and "stylet" versus "sheath" highlights a rate of approximately 2% for PM electrodes with sheath versus 43% reported for PM in general.

Electrode position can be significant to CI outcomes; complete ST electrode array insertion without translocation has been related to improved hearing outcomes and more effective residual HP [38]. Shaul et al. [41] completed an observational study using an older and newer generation perimodiolar array. They found translocation independently resulted in a 10.5% decrease in phoneme scores. Shaul et al. [42] conducted a prospective observational study comparing ST placement for n = 120 and postoperative speech understanding for n = 98 postlinguistically deafened adults implanted with a sheath-based PM array to ST placement (n = 79) and speech understanding (n = 57) adults previously implanted with a stylet-based PM array from the same manufacturer, controlling for age, duration of deafness, and preoperative phoneme scores between the two groups. The sheath-based PM array had 0% translocation compared to 18% for the stylet-based PM array. Three- and 12-month postoperative scores were significantly better, p = 0.03 and p = 0.01, for recipients with slim modiolar electrodes compared to recipients with a previous perimodiolar device array.

Morrel et al. [43] retrospectively analyzed data from 177 ears with straight electrode arrays. Preoperatively, they measured LW ST height and postoperatively scalar location, angle of insertion depth (AID), and translocation depth, translocations = 39 (22%), median AID = 443°. There was a small, significant correlation between CNC word scores (n = 126 ears) and AID depth (not significant when including translocations). AID was significantly higher for translocated electrodes, and translocations generally occur around 380° (median translocation depth of 381°). Translocations were more frequent with deeper insertions due to decreasing LW ST height causing BM displacement; this risk increased substantially after 580°. Translocations may affect CNC scores. While straight electrode arrays sit far enough from the modiolar wall, their ability to stimulate spiral ganglion cells is significantly affected by translocation. In case of precurved electrodes [41], which sit closer to the modiolus use to stay completely in ST.

Ketterer et al. [44] completed a retrospective investigation of straight and perimodiolar arrays for radiological evidence of scalar dislocation (also known as translocation). They analyzed place of dislocation (considered as the initial trend of the insertion electrode dynamics) and correlated outcomes with postimplant speech perception. Four hundred ninety-five ears were implanted with straight or perimodiolar arrays from different companies (Cochlear or MED-EL). They compared speech recognition regarding array dislocation, scalar insertion, and angular insertion depth. Contour Advance (Cochlear) had the highest rate of SV insertions, and FlexSoft (MED-EL) had the highest rate of ST dislocations. Dislocation rates were not greater in cochleostomy-inserted arrays. Analysis indicated array dislocation, measured by radiological (CT scan), did not influence postoperative speech understanding. Deeper insertions resulted in significantly poorer speech understanding outcomes ($p < 0.0001$) in cases of straight electrode analysis. This investigation illustrates the importance of electrode array design on scalar location, dislocation, and site of dislocation.

Modiolar Proximity

Placing an electrode array close to the modiolus, nearer to the target spiral ganglia rather than at the LW, leads to narrower excitation spread, reduced channel interaction, and decreased electrical stimulation thresholds [45–48]. There is some evidence that these properties of perimodiolar electrodes can benefit the patient, as first demonstrated by Holden et al. [5]. This large prospective study investigated the relationship between wrapping factor, a measure of an electrode's modiolar proximity, and speech understanding in a subset of 59 patients with complete electrode insertions in ST. They found a significant correlation between CNC word scores and electrode position closer to the modiolar wall.

Several investigations have focused on speech perception outcomes in individuals using either LW or PM arrays. Sharma et al. [20] retrospectively compared postimplant speech recognition on words and sentences for 149 ears implanted with a slim LW array and 104 with a slim perimodiolar array. Speech recognition was assessed at 6 and 12 months; low-frequency hearing was evaluated pre- and postimplant. After controlling for numerous variables including preoperative hearing and duration of follow-up, recipients with perimodiolar arrays demonstrated significantly better performance on words and sentences than straight array recipients. HP was assessed for $N = 150$ of the original group who exhibited functional low-frequency hearing preoperatively ($n = 75$ straight and $n = 41$ perimodiolar array recipients). Pre- and postimplant LFPTAs were similar between the two groups.

Holder et al. [49] compared 29 CI recipients implanted with a slim LW array and 29 with a slim perimodiolar array. Recipients were matched for age and preimplant hearing thresholds. Investigators assessed HP, speech understanding, and programming parameters. Preoperative hearing was equivalent between the two groups. Postoperatively, the perimodiolar group exhibited significantly more HP (LFPTA), significantly higher CNC word scores, and lower impedances and pulse durations than the group with a straight array.

Recently, Vohra et al. [50] retrospectively evaluated the largest cohort of LW ($n = 176$) and PM ($n = 302$) patients to date ($n = 478$ ears) from the three main manufacturers. Their investigation spanned a 5-year period. They collected postimplant speech perception outcomes using CNC words and the Hearing in Noise Test. Participants had combined 4,968 postimplant CNC and HINT evaluations (average of 10 ± 9 appraisals per individual). Median CNC word and HINT sentence scores indicated a significantly greater improvement for the PM group from 6 months to 2 years ($p < 0.05$) and from 2 to 5 years ($p < 0.001$) compared to the LW group.

Heutink et al. [51] conducted a cross-sectional study with 129 experienced CI recipients who had a PM/with stylet ($n = 85$) or an LW array ($n = 44$) from one manufacturer. They reviewed their ultra-high-resolution computed tomography scans and measured speech perception. After correcting for various factors, including scalar location, they found a 12% better speech perception outcome for the PM array (95% confidence interval: 1.4–20.4%; $p = 0.03$).

Chakravorti et al. [52] developed generalized linear models to analyze the relationship between audiological outcomes and factors including age, duration of CI use, electrode type, and electrode position from a dataset of 220 CI ears. They found that when controlling for biographic, preoperative, and device usage factors, the most significant predictors of outcomes for precurved arrays were full ST insertion and modiolar proximity, whereas for LW electrodes the most significant predictor was insertion depth; however, they caution that insertions deeper than those found in these data (mean of 454.3°)

are more likely to cause trauma, negatively impacting outcomes. In addition, deep insertions may have occurred when resistance was not felt and there was minimal trauma; thus, better outcomes could be due to reduced trauma as opposed to increased insertion depth, as identified by both Ketterer, Aschendorff, Arndt and Beck [44] and Rivas et al. [53] who found deeper insertions either did not improve or negatively impacted outcomes.

Although previous studies that do not include slim modiolar electrodes, but previous perimodiolar electrodes (Contour Advance, Slim J, etc.), present no difference in audiological outcomes between perimodiolar or straight electrode arrays (51,52), this review provides evidence that perimodiolar proximity, as embodied by perimodiolar electrode arrays, may lead to patient benefit through improved speech perception. It should be noted however that a direct comparison of the electrode designs, in a prospective controlled study, has not yet been reported. This is required to ensure that these trends are maintained once all potential confounders are controlled.

Ramos-de-Miguel et al. [54, 55] investigated the effect of electrode array modiolar proximity on pitch discrimination to determine if electrode discrimination improved. Twenty-four postlingual adults were implanted with either a slim perimodiolar ($n = 12$) or an LW electrode ($n = 12$). All arrays were fully inserted into ST without SV translocations. Mean correct electrode discrimination was 41.6% for those with a straight array and 75% for perimodiolar participants ($p = 0.001$). Postimplant imaging showed a wrapping factor of 0.86 for LW and 0.57 for perimodiolar participants ($p < 0.001$). The mean homogeneity factor was 0.29 for participants with a straight and 0.06 for those with a precurved array ($p < 0.001$). The Intracochlear Position Index for straight array participants was 0.62 and 0.08 for those with a perimodiolar array ($p < 0.001$). Results indicated closer proximity to the modiolar wall provides better electrode discrimination as shown in perimodiolar vis-à-vis LW electrode discrimination outcomes. This provides a potential benefit of closer modiolar proximity that might underpin some of the trends toward better speech perception suggested in the literature reviewed here.

Cochlear Health

Cochlear health is best maintained by avoiding trauma to cochlear structures; this includes using the best surgical method given the individual's anatomy. Opening of the cochlea and placing an electrode in the cochlea result in numerous changes, either immediate, such as various types of insertion trauma and longer term, such as inflammation, fibrosis, osteogenesis, and foreign body reactions. The most common reported site of CI electrode insertion trauma is at the LW [56–60]. The LW structures often experience insertion trauma when the electrode tip contacts or meets resistance, potentially damaging the LW tissue or venous structures or contacting or perforating the BM. If LW contact can be avoided, then there is less likelihood of damaging the structures or rich blood supply which can lead to intracochlear bleeding and inflammation. In all cases however, foreign body reaction results in fibrosis around the electrode array, and even if the electrode does not contact, but is in close proximity to the BM, fibrous tissue that forms around the array over time may impede BM function. Avoiding contact with the BM and positioning the array near the modiolus (so far from the LW) help both conserve cochlear structures in the short term and more importantly support cochlear health in the longer term [61, 62].

Danielian et al. [63] evaluated 15 temporal bones to establish cochlear duct length, angular and linear distances of spiral ganglion neurons (SGNs), and the linear lengths of the first, second, and apical turns referenced to the round window. Outer LW linear distance from the round window to SGN end averaged 34.48 mm, and the inner modiolar wall distance averaged 17.87 mm. These data indicate that 90% coverage of SGNs would necessitate an LW length of about 31 mm compared to a modiolar wall length of about 16 mm, the approximate length of current perimodiolar arrays. LW electrode array trauma is related to greater insertion depth [43], especially >360°, emphasizing the difficult balance between reducing trauma risk and obtaining adequate SGN coverage when using LW electrodes. Perimodiolar arrays, due to close proximity to the modiolus, can achieve excellent coverage of the SGN and provide improved electrical stimulation properties while avoiding contact with the LW. As the linear length of a perimodiolar electrode to achieve a specified angular depth is also significantly shorter that is required for an LW electrode, the volume of electrode (or volume of foreign body) is also significantly reduced, therefore reducing the total volume of fibrosis.

Danielian et al. [64] studied 15 postmortem CI temporal bones to measure new cochlear tissue formation (fibrosis or bone) in ST, scala vestibuli, and media. Electrode insertion depth was measured for 12/15 specimens. They found that implant years predicted bone and total new tissue formation; as implant years increased, bone tissue included a greater amount of total tissue. They found that new tissue formation was localized to the length of the electrode and did not extend further apically.

Ishiyama et al. [65] in a postmortem temporal bone analysis, in long-term unilaterally implanted individuals for cochlear injury from surgery, found that "in seven temporal bones [lateral wall electrodes] demonstrated erosive changes to the lateral wall consistent with secondary degeneration due to long-term use of the electrode. The findings implicate that the perimodiolar electrode design may avoid secondary changes to the lateral wall for long-term use." Over time, despite expected fibrosis, perimodiolar positioning causes a much lower risk of disrupting LW structures, better preserving cochlear health. In addition, the array is near the auditory nerve supporting more efficient and effective long-term electrical stimulation.

Fujiwara et al. [66] conducted comprehensive ST height and cross-sectional area measurements in 10 temporal bones without middle or inner ear disease and correlated them with 10 different CI electrode dimensions. ST LW vertical height decreased from 1.28 to 0.88 mm going from 0 to 180°, and perimodiolar height decreased from 1.20 to 0.85 mm. The cross-sectional area decreased from 2.29 mm^2 to 1.38 mm^2 from 0 to 180°. After the basal turn, ST shape changed from ovoid to triangular, with significantly reduced lateral relative to perimodiolar height. CI electrode sizes varied considerably regarding the space occupied in ST and proximity of an electrode to the BM. These measurements are helpful to understand trauma locations during insertion, why translocations are more frequent at about 180° and 400°, and when designing electrodes.

Discussion

Although the vast majority of recipients will gain significant benefit from their CIs, variability in outcomes remains a challenge, especially in adults. The duration of HL and numerous other factors prior to CI have been identified as significant factors contributing to outcome variability [5, 7, 10], highlighting the role of cochlear health and integrity of the neural substrate for optimal CI hearing performance. As indications expand, however, the duration of HL in adult CI candidates can be reduced resulting in more patients with healthier neural substrate and better audiometric thresholds referred for CI [30]. Other outcome-related factors such as surgical and device factors [6, 67] may then play a larger role in helping patients reach their full hearing potential, as the role of both the electrode-neural interface and cochlear health becomes important consideration for both short- and longer term CI outcomes.

All CI patients, regardless of whether implanted as a pediatric patient or a senior, are expected to rely on their CI for functional hearing benefits over their lifetime [17, 18], so potentially anywhere from 10 to 80 years of CI benefit. The mechanism of hearing with a CI has not changed over the last 40 years, i.e., the fundamental principles of neural electrical stimulation, directly stimulating the SGNs and bypassing injured hair cells of the cochlea, in order to provide salient coded information for better speech perception in both quiet and noise.

There is a long-held belief that placing an electrode in close proximity to the SGN, via a precurved array, and minimizing trauma to cochlear structure are mutually exclusive endeavors and that straight arrays should be used for patients with residual hearing and precurved arrays for profoundly deaf patients [68]. This approach was supported by the evidence at the time which compared data from patients implanted with styleted precurved arrays and contemporary slim LW arrays, with the styleted precurved arrays demonstrating higher rates of translocation and HL with no significant performance benefit [39, 67]. The literature verified the additional performance benefits of a precurved array and higher number of electrodes, but that this was only significant when full ST placement of the array was achieved [5], as translocation of precurved arrays results in the electrodes being positioned further from the modiolus, in a more lateral position, and therefore negating the benefit of neural specificity provided by precurved arrays.

Similarly, earlier studies on the number of effective channels required for speech recognition have indicated an upper limit of only 8 electrodes. However, these earlier studies were based on LW electrode placement. More recent studies with precurved electrodes [69, 70] examined the correlation between speech recognition and number of electrode channels, from 4 to 22 electrodes, finding significant improvements in speech recognition, especially in noise, with precurved electrodes.

With the introduction of a new generation of slim perimodiolar arrays, rates of both translocation and residual HP have been shown to be significantly better than previous generation styleted precurved arrays and at least equivalent to that of contemporary slim LW arrays [19, 23]. Evidence supports that a slimmer precurved array that can be reliably and consistently placed in ST, avoiding the narrowing lateral ST structures while still placing the electrodes in close proximity to the SGN, can not only preserve residual hearing if present, but also better preserve cochlear health over a patient's lifetime. As superior hearing outcomes with precurved arrays have been demonstrated only when the electrodes remain in ST, this also provides the necessary prerequisite for ensuring patient hearing outcomes are optimized over their lifetime [52].

Conclusion

During the last 3 decades, there have been remarkable advancements in CI technology, allowing more individuals with unilateral or bilateral HL to benefit from CIs. Most patients will rely solely on electrical stimulation to hear; however, some patients presenting with preimplant functional hearing may be candidates for HP, thus choosing the best electrode array that not only supports preservation in the short term, but cochlear health and superior electrical stimulation outcomes in the long term are important. Thin LW and thin perimodiolar arrays are available that can preserve hearing, at least in the short term; however, perimodiolar positioning causes a much lower risk of disrupting LW structures, thus better preserving long-term cochlear health. The proximity of the electrode contacts to the auditory nerve seems to be beneficial in terms of resolution and ultimately CI performance.

Limitations of the Study

Papers were selected with a potential bias on paper selection given that it is a non-systematic review.

Conflict of Interest Statement

All authors declare no conflict of interest.

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Author Contributions

A.R.M.: design of the work, data analysis, drafting, writing the manuscript, and final approval of the version to be published. R.B., B.Y.C., D.F., A.I., T.L., E.M., S.O., J.T.R., and A.Z.: data analysis, drafting, writing the manuscript, and final approval of the version to be published.

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