Cochlear Implantation for Single-Sided Deafness: A New Treatment Paradigm

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Abstract

Keywords

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Unilateral severe-to-profound sensorineural hearing loss (SNHL), also known as single sided deafness (SSD), is a problem that affects both children and adults, and can have severe and detrimental effects on multiple aspects of life including music appreciation, speech understanding in noise, speech and language acquisition, performance in the classroom and/or the workplace, and quality of life. Additionally, the loss of binaural hearing in SSD patients affects those processes that rely on two functional ears including sound localization, binaural squelch and summation, and the head shadow effect. Over the last decade, there has been increasing interest in cochlear implantation for SSD to restore binaural hearing. Early data are promising that cochlear implantation for SSD can help to restore binaural functionality, improve quality of life, and may facilitate reversal of neuroplasticity related to auditory deprivation in the pediatric population. Additionally, this new patient population has allowed researchers the opportunity to investigate the age-old question “what does a cochlear implant (CI) sound like?”

Introduction

Unilateral severe-to-profound sensorineural hearing loss (SNHL), also known as single-sided deafness (SSD), has been estimated to affect between 12 and 27 per 100,000 adults among the general population. The etiology of the majority of these losses is sudden or idiopathic SNHL.¹ Similarly, in the pediatric and adolescent population, unilateral hearing loss has an incidence of 0.4 to 3.4 per 1,000 live births and continues to rise throughout childhood with a prevalence in school-aged children of 3 to 6% when hearing loss of any severity is included.^{2–4} Conservative estimates place the incidence of SSD between 2 and 5 per 1,000 school-aged children.⁵

The implications of SSD in the pediatric population are fairly well studied, especially in those children in whom the hearing loss is congenital or prelingual. As a consequence of congenital SSD and sound deprivation, there are often developmental

delays in speech and language acquisition.^{6–8} Unilateral sound deprivation during early development and the resultant cortical reorganization has been demonstrated in animals^{9,10} and human studies have also shown cortical auditory evoked potentials in children with SSD are significantly different than those obtained in normal-hearing controls.^{11,12} In addition, studies indicate impaired educational progress for the pediatric SSD population when compared with their normal-hearing peers, including higher rates of grade failure, a higher incidence of individualized education programming (IEP), and an increased need for educational resources and attention in the classroom.^{13–15} Additionally, many of these children are incorrectly classified on the attention deficit/hyperactivity spectrum or as having learning disabilities since SSD demands higher concentration for listening, leading to rapid fatigue, frustration, and easy distractibility.^{13,16–18}

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Auditory Effects of SSD

In addition to the early-life disadvantages demonstrated in children with SSD, the psychoacoustic literature has similarly demonstrated diminished auditory function and speech perception in both children and adults with SSD.¹⁹ Unilateral profound hearing loss causes its detrimental effects due to the loss of three functional advantages seen only with binaural hearing: the head shadow effect, binaural summation, and binaural squelch.²⁰ The head shadow effect occurs during every day listening conditions when speech and noise are spatially separated, and unlike summation and squelch, does not require higher level cortical processing. In the case of spatially separated speech and noise, the head creates an acoustic shadow resulting in an improved signal to noise ratio (SNR) in one ear allowing the listener to selectively attend to the ear with the better SNR. The head shadow attenuates high frequency sounds by approximately 20 dB and low frequency sounds by only 3 to 6 dB.²¹

Like the head shadow effect, binaural squelch occurs when speech and noise are spatially separated and the two ears receive different inputs. Unlike the head shadow effect, binaural squelch requires central auditory processing, integrating the signal from each ear alone at the level of the auditory cortex to improve audibility. Squelch helps differentiate meaningful sound from background noise and has been shown to reduce SNR by 2 to 3 dB.^{22,23} However, evidence of the objective benefits of binaural squelch are limited and are not as robust as the head shadow effect.¹⁹

Binaural summation is also a central auditory processing effect of binaural hearing but unlike squelch which relies on varying SNR between ears, summation occurs when both ears are presented with a similar signal. The higher order auditory processing of the combined signal creates a "doubling" of perceptual loudness by up to 3 dB leading to improvements in speech perception in quiet conditions and is particularly beneficial in background noise.²⁴

In addition to improvements in speech perception gained from binaural hearing as described above, sound localization also requires binaural hearing and is severely impaired in patients with SSD.^{17,22,25} Accurate sound localization relies on interaural timing differences (ITD) and interaural level (intensity) differences (ILD). For low frequency sounds (below 800 Hz), the binaural auditory system relies mainly on phase delays caused by ITDs (i.e., the difference in time of arrival of a sound at one ear versus the other ear). For frequencies greater than 1,600 Hz (high frequencies), the primary cue for localization comes from ILDs which arise mainly from the head shadow effect.^{19,26,27} Both ILD and ITD are used in the mid-frequencies between 800 and 1,600 Hz.

Rehabilitative Options for SSD

Historically, the sequelae of SSD have been grossly underestimated, and were not considered significant enough to warrant intervention, even in the form of noninvasive strategies, such as preferential classroom seating for children, contralateral routing of signal (CROS) hearing aids, or bone

conduction devices (BCD). The CROS aid system uses a microphone worn on the poorer ear which routes signals to a receiver worn on the better ear and is intended to overcome the loss of head shadow but importantly does not restore true binaural hearing. CROS aids are often poorly tolerated by the listener and demonstrate low user satisfaction.^{28,29} Similar to CROS aids, BCDs route signal to the better hearing ear using vibratory stimulation across the skull, and only activate a single auditory pathway preventing the use of binaural cues. BCDs yield variable improvements in speech perception in noise and demonstrate poor sound localization.^{30–32}

The restoration of binaural hearing is the standard of care in patients with bilateral hearing loss. Cochlear implantation in at least one ear is recommended for patients with bilateral severe-to-profound SNHL and poor speech recognition in the best-aided condition. Extensive clinical evidence unequivocally supports the advantages of binaural stimulation of the auditory system in any combination (bilateral cochlear implant [CI], normal acoustic hearing, binaural amplification, and binaural bimodal amplification in which acoustic hearing in one ear is combined with CI hearing in the contralateral ear). These advantages include but are not limited to improvements in sound localization, speech understanding in noise, improvement in music appreciation, improvement in pitch and melody recognition, and improvements in quality of life.^{23,24,33–41} Furthermore, multiple studies have demonstrated that in patients with binaural bimodal stimulation, the same binaural listening advantages are achieved as seen in those patients with bilateral acoustic hearing or bilateral electric hearing.^{42–44} Therefore, hearing loss even in one ear cannot only disrupt central auditory processing strategies and impair auditory function but can be severely detrimental to the listener's quality of life as well. Restoration of binaural hearing, even in patients using more than one modality, appears to be extremely effective.

Cochlear Implantation for SSD

For the past 30 years researchers, surgeons, and audiologists have posited, albeit on opinion alone that patients with SSD could not benefit from a CI as it would be impossible for central auditory processing to resolve the auditory discrepancy between acoustic and electric input. It was not until 2008 when van de Heyning et al studied a group of 22 adults with SSD and incapacitating tinnitus who underwent CI for tinnitus control. All patients reported decreased tinnitus burden post-operatively but unfortunately hearing-related outcomes were not assessed.⁴⁵ In 2009, Vermeire and van de Heyning studied a small group of patients with SSD and to investigate the effects CI had on binaural hearing. While binaural squelch and summation effects were not significantly improved, there was a significant improvement for the head shadow effect in the binaural condition using the CI. Additionally, results of the speech, spatial, and quality of hearing scale (SSQ) evaluating subjective improvements using the CI showed significant improvements with the CI over the SSD condition.⁴⁶

It was not long after these initial studies that investigators began to evaluate whether CI offered greater objective improvements in speech perception and binaural auditory

function when compared with alternative treatment options for SSD, namely, CROS aids and BCDs. Arndt et al studied a group of patients with SSD and compared objective outcomes between CROS aids, BCDs, and CIs. All subjects in all conditions showed improved outcomes for speech perception in noise compared with the unaided condition when the SNR favored the deafened ear. However, the key difference was that in the CI condition, the subjects performed significantly better on speech perception testing than in both the CROS and BCD conditions when the deafened ear received the poorer SNR.²² Similarly, Zeitler et al demonstrated that children and adults who underwent CI for SSD, not only showed improved speech understanding in the implanted ear but scores over the unaided SSD condition were significantly improved even in challenging listening conditions, such as roving speech in noise and multidirectional noise.^{47,48} Importantly this study and others showed no detrimental effect of the CI on the performance of the normal hearing ear, dispelling the theory that a normal acoustic ear, and a fully electrically stimulated ear could not function in tandem.^{22,47,49,50}

Since these early studies, numerous investigators have shown the benefits of cochlear implantation in postlingually deafened adults with SSD, and all studies show a significant benefit of the CI plus normal hearing ear condition over the SSD condition.^{51–60} The improvements in SNR are fairly modest when speech and noise are presented from in front of the subject, but this is expected as coincident speech and noise eliminates the need for restoration of the head shadow effect.^{22,46,54}

Additional studies have been done evaluating sound localization following CI for SSD. Arndt et al compared localization accuracy in patients with SSD between the unaided, CI, BCD, and CROS aid conditions. Patients who had received a CI showed significantly less localization error compared with the unaided condition, BCD condition, and CROS aid condition.²² Zeitler et al compared localization accuracy in SSD patients following CI to normal hearing listeners, bilateral CI patients, and the unaided SSD condition. Sound localization was significantly improved in all patients with the CI, and these patients were able to localize sound as well as bilateral CI patients. Interestingly, a small population of the patients were able to localize in the 95th percentile of normal hearing listeners.⁴⁷

The majority of these reports have been performed outside of the United States (U.S.). The first large study performed in the U.S. evaluating the benefits of CI for the treatment of SSD was published in 2013.⁵¹ Twenty-nine patients with SSD and normal or near-normal hearing in the contralateral ear underwent CI. Although there was some variability in objective outcomes, 13/19 (68%) demonstrated improved word recognition scores (mean improvement 28%) after CI and 14/19 (74%) demonstrated improvements in sentence recognition scores. Most subjects demonstrated significant benefit in sound localization ability, and this improvement was shown to be experience dependent with scores improving with increasing duration of CI use. The outcomes reported by Hansen et al were corroborated by Sladen et al in the second largest study performed in the U.S. which included both children and adults

undergoing CI for SSD. The mean improvement in word recognition score in quiet following CI was 37% by 3-month postoperatively and the mean improvement in sentence recognition score in quiet following CI was 47% by 3-month postoperatively. Interestingly the scores at the 6-month testing interval were not statistically different from those at the 3-month interval.^{50,51}

Another aspect related to the SSD population that has been well documented is tinnitus in the deafened ear which can often be severe and incapacitating. Conventional treatment options for SSD including CROS and BCD have been unsuccessful in effectively suppressing tinnitus. This is due to the fact that neither intervention is able to deliver acoustic input to the affected ear and therefore cannot affect the peripheral and/or central processes involved in the generation of tinnitus. While CI for SSD was originally performed to suppress tinnitus and achieved suppression or resolution in 95% of patients,⁴⁵ subsequent studies have shown similar effects of tinnitus suppression in patients undergoing CI for the treatment of SSD.^{59,61–63}

Much of the literature reporting on the utility and effectiveness of CI for SSD has examined adults and children with acquired, postlingual hearing loss. There is a lack of information on the benefit of CI for congenital SSD, specifically in children. It is well documented that congenital, bilateral severe-to-profound deafness results in sound deprivation during the sensitive period of cortical maturation and development of the central auditory pathways leading to irreversible changes to the auditory cortex. This period of maximal cortical plasticity, termed the critical period, during which sensory deprivation can lead to cross-modal plasticity and intervention can lead to reversal of these changes, is maximal until 3.5 years of life and appears to decrease dramatically after 7 years of life.^{11,12,64} It is also possible that auditory deprivation at an early age may have negative downstream effects on higher-level executive brain function.⁶⁵ Studies have consistently demonstrated that children with congenital bilateral deafness derive significantly greater benefit following CI if surgery is performed as early as possible and ideally before 12 months of age.^{66–68} These improved outcomes following early implantation are likely related to intervening during the critical period, reversal of existing cross-modal plasticity, and prevention of further cortical disruption.

To date, it is not known if the same critical period exists in children with congenital SSD or if the singly functional, normal hearing ear is able to sustain bilateral cortical maturation and prolong the critical period either temporarily or indefinitely. If this critical period is prolonged temporarily, cochlear implantation in children with congenital SSD should be successful even in childhood and early adolescence. However, the duration of prolongation is currently unknown. If the critical period is prolonged indefinitely, cochlear implantation in adults with congenital, unilateral profound hearing loss should also be beneficial. Sharma and colleagues demonstrated that despite undergoing CI for SSD after the conclusion of the predefined critical period of auditory cortical development, some children show reversal of cross-modal plasticity as demonstrated by high-density

Fig. 1 Current density reconstructions (CDR) for the P2 visual evoked potential (CVER) response to an apparent visual motion stimulus preimplantation (upper left panel) and 27-months post-CI (upper right panel). CDR for the P50 cortical somatosensory evoked potentials (CSSEP) in response to right finger stimulation preimplantation (lower left panel) and 27-month post-CI (lower right panel). (Reprinted with permission from Sharma et al¹⁰) CI, cochlear implant.

electroencephalogram (EEG) even after many years of unilateral deafness¹⁰ (► Fig. 1).

SSD Related to Vestibular Schwannoma: Implications for CI

In any discussion about SSD and CI, patients with SSD as a result of unilateral vestibular schwannoma (VS) must be mentioned. Unilateral deafness in these patients can occur secondary to progressive hearing loss in conservatively managed tumors or following treatment with either stereotactic radiation or microsurgical excision. Regardless, these individuals suffer from the same hearing disabilities as those patients with SSD from other causes including difficulties with sound localization, hearing in background noise, and the loss of head shadow. Previous work has demonstrated that a functional cochlear nerve can be maintained following VS resection, and therefore it is not unreasonable to predict that some patients undergoing microsurgical resection may subsequently be candidates for CI.⁶⁹

Cochlear implantation following VS resection has been described in small numbers of patients, the majority of whom have neurofibromatosis type 2 (NF2), but has also been reported in patients with sporadic VS.^{70,71} Of paramount importance is the presence of an anatomically and functionally intact cochlear nerve. Some authors have pro-

posed a waiting period after VS surgery with preservation of the cochlear nerve whereby postoperative audiometry can be performed to evaluate the functionality of the cochlear nerve. In cases with measurable (albeit nonserviceable) hearing thresholds, CI is a reasonable option to attempt to rehabilitate the sensory (cochlear) SSD. In cases with non-measurable thresholds and possible neural (cochlear nerve) hearing loss, promontory stimulation can be done to determine the functionality of the cochlear nerve.⁷² Interestingly, promontory stimulation has been shown to have relatively poor predictive value in assessing 8th nerve function following VS surgery.⁷⁰ Intraoperative electric auditory brainstem response testing (eABR) and/or cochlear nerve action potential (CNAP) can also be performed but similar to promontory stimulation have unproven accuracy. Perhaps in the future, intraoperative eABR will be widely available and accurately able to assess the function of the cochlear nerve to prognosticate success of CI following VS surgery.

One concern in patients undergoing translabyrinthine VS resection with delayed CI is the risk of intracochlear ossification precluding electrode insertion. Imaging studies examining cochlear patency after labyrinthectomy have shown up to one-third of patients develop ossification, and these patients if implanted successfully, tend to have poorer hearing outcomes compared with unaffected peers.^{73,74}

Hassepass et al described a technique in which an intracochlear spacer is placed during primary labyrinthectomy followed by delayed CI surgery 12 months later after complete tumor resection is confirmed with imaging and cochlear nerve integrity can be tested.⁷⁵ To further mitigate the risk of postoperative cochlear ossification, simultaneous translabyrinthine VS resection and CI was first described by Arriaga and Marks in 1995⁷⁶ and multiple reports in small groups of patients since that time undergoing simultaneous VS and CI surgery with preservation of the cochlear nerve have been extremely promising.^{70,71,77,78}

Although positive outcomes have been demonstrated for cochlear implantation at the time of VS resection, some argue the risk to the cochlear nerve can be eliminated if a CI is placed without tumor resection. For purely intracochlear schwannomas, Carlson et al described leaving the intracochlear tumor in situ to preserve cochlear anatomy and physiologic function, while using a styleted electrode with late deployment of the electrode off-stylet to aid in advancement of the electrode. Eighty percent of the affected ears achieved good open-set word recognition and all 10 cases showed adequate visualization of the ipsilateral internal auditory canal and inner ear on post-CI magnetic resonance imaging (MRI).⁷⁹ Additionally studies have confirmed that MRI scanning without CI magnet removal is not only safe and well tolerated in NF2 patients but allows for unobstructed views of the internal auditory canal and cerebellopontine angle in over 80% of cases.⁸⁰ It is unclear whether in situ tumor growth over time may affect CI performance in SSD patients with VS, with the limited data in the literature showing equivocal outcomes.^{72,81}

What does a CI “Sound” Like?

The SSD-CI patient population has provided researchers a window into answering the question asked by (almost) every CI patient—“What will my CI sound like?” An internet search for “cochlear implant simulation” most commonly returns descriptions of noise-excited vocoders (or voice coders). The similarity in signal processing for channel vocoders and for CIs has led many to use the noise vocoder as a surrogate for CI sound in many prior studies. However, because noise vocoders have a whispered sound quality (a product of the noise-band output), these studies have consistently asked questions about factors that influence speech intelligibility, while speech quality has never been evaluated.

Since SSD-CI patients have one normal hearing ear and one CI, in the laboratory, these patients can subjectively rate the similarity of a “clean” signal (a sentence) presented to the CI ear via direct connection into the speech processor to that of a “candidate” signal that can be altered using sound mixing software and presented to the normal hearing ear using an earphone. Because of the ubiquity of noise vocoders as simulations of CI signal processing, the first question to be answered is whether noise or sine vocoders capture the sound quality of a CI. The “candidate” signal in this case was a sentence altered to sound like that produced by either a noise vocoder or a sine vocoder. The answer was clearly no.

On a scale of 0 to 10 where 10 was a signal that sounded exactly like the CI, SSD-CI patients gave noise vocoders a mean score of 1.9 and sine vocoders a mean score of 2.9.⁸²

If CIs do not sound like vocoders, what do they sound like? To answer this question, it is important to consider two factors that could affect sound quality. The first factor is limited information available in the frequency domain. In a classic experiment, Fishman et al configured a CI with 20 active channels. When patients were tested in this condition, the speech understanding score was near 80%. The number of active channels was then reduced to 10, 7, 4, and 1, and interestingly the speech recognition scores were not significantly different between the 20, 10, 7, and 4 channel conditions.⁸³ Thus, CI listeners likely receive the necessary frequency information through a small number of independent channels. It is relatively easy to imagine that reduced information in the spectral domain would negatively impact speech understanding. But what about sound quality?

A second factor that could affect sound quality is the location of the electrical stimulation along the spiral ganglion within the cochlea. According to the Greenwood’s function, there is a correlation between the position of the hair cells in the inner ear to the frequencies that stimulate their corresponding auditory neurons within the spiral ganglion, thereby creating a place pitch map of the cochlea. It is reasonable to suppose that, in the best case, the energy in a given frequency range in the CI input signal would be delivered to the corresponding place frequencies in the spiral ganglion. For example, the energy of speech components near 500 Hz would be delivered to the 500 Hz region in the spiral ganglion. This best-case scenario is difficult to achieve. Kalkman et al showed that in the basal (proximal) turn of the cochlea, CI induced pitch can be predicted fairly well using the Greenwood’s function. However, beyond the first turn this pitch becomes increasingly unpredictable, dependent on stimulus level and cochlear neuronal health, among other factors. With even deeper electrodes near the end of the spiral ganglion, the pitch becomes incredibly unpredictable with broad frequency ranges.⁸⁴

Consider the data shown in ►Table 1 which was taken from a patient with a deep angular insertion (525 degrees). A digitized three-dimensional reconstruction of this patient’s CI electrode array in situ is shown in ►Fig. 2.⁸⁵ The last row of ►Table 1 shows the offset in Hertz (Hz) between the filter center frequency (i.e., the frequency of signals delivered to the electrode contact) and the place frequency of that area of the cochlea according to the cochlear frequency map described by Stakhovskaya et al.⁸⁶ Even with a relatively deep electrode insertion, the input signal is shifted up in frequency, with the magnitude of the shift differing between electrode contacts. The smallest shift (270 Hz) occurred at electrode 1 where energy near 125 Hz was directed to the 390 Hz place. At electrode 6, energy from the 1,175 Hz region was directed to the 1,980 Hz place, and at electrode 10 energy from the 4,000 Hz region was directed to the 7,191 Hz place. Therefore, the place of stimulation in most cases was significantly less than double the intended input frequency.

Table 1 Angular depth of electrode array in degrees, frequency of nearest tissue in the spiral ganglion, CI filter center frequency and offset in frequency between filter center frequency and nearest tissue

Electrode	1	2	3	4	5	6	7	8	9	10	11	12
Angular depth (degree)	525	434	382	337	281	244	210	161	119	81	42	18
Frequency at nearest tissue (Hz)	390	590	720	960	1,430	1,980	2,630	3,770	5,210	7,190	12,010	14,800
Filter center frequency (Hz)	120	235	384	579	836	1,175	1,624	2,222	3,014	4,084	5,507	7,410
Offset (Hz)	+ 270	+ 355	+ 336	+ 381	+ 594	+ 805	+ 1,006	+ 1,548	+ 2,196	+ 3,106	+ 6,503	+ 7,390

Fig. 2 Three-dimensional reconstruction of a cochlea the electrode described in ►Table 1 in situ (angular insertion depth = 525 degrees). Green = modiolus. (Image courtesy of Dr. Jack Noble, Vanderbilt University School of Medicine).

In ►Table 2, the same type of data are shown for a patient fit with an electrode array that reached an angular insertion depth of 419 degrees. A reconstruction of the electrode array in situ is shown in ►Fig. 3. With this angular depth, the most apical (distal) electrode was near the 620 Hz place (in contrast to the 390 Hz place for the more deeply inserted array). In this case, the place of stimulation is approximately double the intended input frequency at all locations, for example, 330 Hz is directed to 620 Hz place; 1278 Hz is directed to the 2730 Hz place; and 4,000 Hz is directed to the 11,000 Hz place.

In our patient series ($n = 18$), regardless of angular insertion depth, there has been no case where the energy at the input frequency is delivered to the corresponding place frequency in the spiral ganglion. If this patient sample is representative of the CI population as a whole, then for all (or most) CI patients, the cortex receives a signal that is upshifted in frequency. However, the consequences of an upshifted frequency spectrum as it relates to the speech quality of a CI is unknown.

When a stimulus signal for the patient shown in ►Table 1 was constructed for the normal hearing ear that matched the perceived sound quality of the CI, the match was not upshifted in pitch despite the significant pitch place-input frequency mismatch. Instead, the patient preferred to change the stimulus signal using bandpass filtering and spectral flattening resulting in a “muffled” percept. The data from this patient and others with deep electrode insertions indicates that cortical processing is able to normalize some degree of upshift in frequency.

The data shown in ►Table 2 are representative of the data we find for patients with shallower angular insertion depths whereby the pitch place in the cochlea is approximately double the input frequencies. In this case, the patient increased pitch by 10 Hz and upshifted the entire speech frequency spectrum by 800 Hz to match the sound quality of the CI.

To date, the matches in sound quality in SSD-CI patients vary as a function of the angular depth of electrode insertion. The

Table 2 Angular depth of electrode array in degrees, frequency of nearest tissue in the spiral ganglion, CI filter center frequency and offset in frequency between filter center frequency and nearest tissue

Electrode	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Angular depth	419	370	328	298	273	247	226	204	176	164	145	122	95	69	47	29
Nearest tissue	620	750	1,040	1,300	1,490	1,940	2300	2,730	3,240	3,700	4,310	5,110	5,950	8,700	11,350	13,460
Filter cf	333	455	540	642	762	906	1076	1,278	1,518	1,803	2,142	2,544	3,022	3,590	4,264	6,665
Offset	+ 287	+ 295	+ 500	+ 658	+ 728	+ 1,034	+ 1,224	+ 1,452	+ 1,722	+ 1,897	+ 2,168	+ 2,566	+ 2,928	+ 5,110	+ 7,086	+ 6,795

Abbreviation: cf = center frequency; CI, cochlear implant.

Fig. 3 Three-dimensional reconstruction of a cochlea the electrode described in ► **Table 2** in situ (angular insertion depth = 419 degrees). Green = modiolus. (Image courtesy of Dr. Jack Noble, Vanderbilt University School of Medicine).

sound quality for patients with longer insertions (e.g., ► **Table 1**) can be characterized as “muffled” to some degree. It is encouraging, and somewhat perplexing, that some matches are only very slightly muffled. The sound quality for patients with relatively shorter insertions (e.g., ► **Table 2**) can be characterized as upshifted in voice pitch, formant frequencies, or both. The cut-off value for angular insertion depth that leads to one voice quality or another remains to be determined. It also remains unknown whether these sound quality percepts will continue to change over time and/or with patient experience using the CI. Whatever the case, SSD-CI patients have provided a new window to study the perceptual consequences of electrical stimulation.

Note
This manuscript will discuss the off-label use of an Food and Drug Administration approved device.

Conflict of Interest
None declared.
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