Hearing Preservation Cochlear Implantation

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Abstract Electric-acoustic stimulation or hybrid cochlear implantation was originally developed for patients with residual low-frequency hearing detection and profound high-frequency hearing loss. Typically, these patients achieve limited benefit from conventional amplification but are often not considered cochlear implant candidates. However, thanks to modified electrodes and optimized surgical techniques, many patients featuring these audiometric configurations have successfully undergone cochlear implantation with preservation of residual hearing. The subsequent combination of electric and acoustic hearing has been demonstrated to provide a performance benefit especially in noise. This article will briefly summarize the key developments, clinical data and future developments.

Keywords Cochlear implantation · Hearing preservation · Bimodal hearing

Introduction

Since the first single channel devices were implanted in the 1960s, cochlear implant technology has advanced tremendously. As such, cochlear implants have evolved into a standard treatment for substantially hearing impaired children and adults. Initially, cochlear implants were provided to

profoundly deaf candidates only. Specifically, the presence of residual hearing was considered a contraindication, a notion mainly based on the fact that ipsilateral hearing is typically compromised during the implantation process. Furthermore, simultaneous central processing of both electric and acoustic modalities was thought to be impossible.

However, with evolving clinical algorithms and device technology, indication criteria have continued to expand and many patients with substantial hearing remnants are currently being considered candidates. While cochlear implants generally provide excellent speech perception performance, users often struggle with hearing in noise and music perception. One solution developed over a decade ago is the controlled utilization of residual hearing in conjunction with the cochlear implant. This algorithm has been inconsistently termed electric acoustic stimulation (EAS) [1], hybrid [2], or partial deafness cochlear implantation (PDCI) [3].

Obviously, candidacy for EAS includes patients with normal-to-moderate low-frequency pure-tone thresholds and severe-to-profound high-frequency hearing. A variety of etiologies result in this audiometric configuration, including congenital hearing loss, ototoxic medications, presbycusis and prolonged noise exposure. In these patients, the majority of hair cell damage occurs in the basal cochlear turn, while the cochlear architecture and function is mostly preserved in the more apical regions. After partially inserting a cochlear implant electrode array into the basal turn, patients may experience improved speech perception from electric stimulation of the high frequencies and simultaneous acoustic representation of the preserved low frequencies. As such, EAS relies on successful intra- and postoperative hearing preservation and various technical and device modifications have been proposed and subsequently implemented to enhance its

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Fig. 1 EAS principle. The audiogram of a typical EAS candidate and the principle of combined stimulation. Specifically, the hearing aid covers the residual low-frequency portion, which is located in the apical cochlear regions. The cochlear implant, on the other hand, covers the more basally located high-frequency regions of the inner ear

likelihood. Also, clinical studies and trials have been conducted that use somewhat different clinical protocols, surgical techniques, modified devices, and terminology.

The objective of this article is to review the pertinent history, recent advances, and future directions of hearing preservation cochlear implantation and subsequent combined EAS of the auditory system. For the purposes of this article, we will use the term EAS to describe the ipsilateral combination of both stimuli.

Hearing Preservation

Historical Remarks

Lehnhardt first described a soft surgical electrode insertion technique as early as 1993 [4]. Ever since, multiple potential benefits have been described from an atraumatic surgical technique with its primary use being preservation of low frequency hearing for hybrid or EAS candidates [5].

Additionally, minimizing intracochlear trauma may decrease intracochlear ossification, ease re-implantation in the future, and possibly allowing for future hearing regeneration technologies. Previously, it had also been theorized that nontraumatic implantation techniques would result in improved performance outcomes in traditional implant recipients [6•]. Specifically, it has also been hypothesized that insertional trauma may damage hair cells or spiral ganglion cells and result in suboptimal electric stimulation [7–9].

In order to minimize trauma, Kiefer et al. [6•] advocated several changes to the surgical technique in order to reduce intracochlear damage, including: (1) use of a small and slow rotating diamond drill to minimize acoustic trauma; (2) cochleostomies inferior to the mid-line of the round window to avoid basilar membrane damage; (3) cochleostomies instead of round window insertions, given the often poor RW membrane visibility further requiring unnecessary drilling of the RW overhang, and bending of the electrode with RW insertions that could increase the

Table 1 Summary of currently available clinical data on hearing preservation cochlear implantation and subsequent combined electric acoustic stimulation of the auditory system

Publication		Surgery		Percent HP			Clinical Data			Benefit from EAS		
No.	Studies	Device and electrode	Depth (mm)	Topical steroids	Approach	Subjects	Partial (%)	Complete (%)	Complete HP definition		Followup (months)	Test measure
1	Hodges et al. [32]	Cochlear Nucleus (33) Advanced Bionics Clarion (7)	16–22	No	Cochleostomy	40	52	40	<10 dB PTA shift at 500, 1 kHz, 2 kHz	1–41	NU6 words CID sentences	No
2	Frayse et al. [11]	Cochlear Nucleus 22 Cochlear Nucleus 24	19	No	Cochleostomy (17) RW (3)	16	50	25	No change in hearing thresholds	6	NA	NA
3	Skarzynski et al.[12]	MED-EL Combi 40 (9) MED-EL Combi 40+ (17)	26	No	Cochleostomy	26	81	62	<5 dB PTA shift at 125, 250, 500 Hz	1	NA	NA
4	Gstoettner et al. [52]	MED-EL Combi 40+ (10) MED-EL Combi 40+ M (11)	18–24	Yes	Cochleostomy	21	85	62	<10 dB PTA shift	4–60	Freiburg monosyllables HSM sentences (quiet and noise)	Yes (n = 1)
5	Kiefer et al. [6••]	MED-EL Combi 40+ (8) MED-EL Combi 40+ M (6)	19–24	Yes	Cochleostomy	14	86	64	<10 dB PTA shift at 125, 250, 500, 1 kHz	3	Freiburg monosyllables	Yes
6	James et al. [13]	Cochlear Nucleus 24 Contour Advance (12)	17–19	No	Cochleostomy	12	83	50	<80 dB HTL at 125 and 250 Hz or <90 dB HTL at 500 Hz	1	Speech reception thresholds in noise	Yes
7	Balkany et al. [34]	Cochlear Nucleus Contour Advance	19	No	Cochleostomy (21) RW (7)	28	57	32	<10 dB PTA shift at 250, 500, 1 kHz	9 (mean)	CNC words HINT sentences	No
8	James et al. [14]	Cochlear Nucleus 24 Contour Advance	17	No	Cochleostomy	10	70	10	<10 dB PTA shift at 125, 250, 500, 1 kHz	6–12	Sentences in MTB (SNR + 5)	Yes
9	Frayse et al. [15]	Cochlear Nucleus 24 Contour Advance	17	No	Cochleostomy	12	75	33–50	<20 dB PTA shift at 125–1 kHz	23	Monosyllables Sentences in noise	Yes
10	Di Nardo et al. [51]	Advanced Bionics Clarion 5100H (5) Advanced Bionics HiRes 90 K (2) MED-EL Combi 40+ (4) Cochlear Nucleus 24 (19) Cochlear CI22 M (4) Cochlear CI24 M (1) MXM Digisonic MX10/C (2)	19–24	No	Cochleostomy	37	78	38	No change in hearing thresholds at 125–1 kHz	3–13	NA	NA
11	Luetje et al. [16]	Cochlear Nucleus Hybrid 10	10	No	Cochleostomy	13	85	54	<10 dB PTA shift at 250–1 kHz	3–24	CNC words	Yes
12	Skarzynski et al. [17]	MED-EL Combi 40+	22–24	No	RW	10	90	50	<20 dB PTA at 250–2 kHz (author never defined this)	3–12	NA	NA
13	Gstoettner et al. [54]	MED-EL Combi 40+ M	18–22	Yes	Cochleostomy	18	83	66	<20 dB PTA shift at 125–1 kHz	12	Sentences in noise	Yes

Table 1 continued

Publication		Surgery		Percent HP			Clinical Data		Benefit from EAS			
No.	Studies	Device and electrode	Depth (mm)	Topical steroids	Approach	Subjects	Partial (%)	Complete (%)		Complete HP definition	Followup (months)	Test measure
14	Lorens et al. [18]	MED-EL Combi 40+ (6) MED-EL Combi 40+ M (5)	18–22	No	RW	17	88	NA	NA	12–53	Monosyllables (quiet and noise) HSM sentences (SNR + 10)	Yes
15	Berrettini et al. [19]	Cochlear Nucleus 24 M-K Cochlear Nucleus 24 Contour Cochlear Nucleus 24 Contour Advance	25 17–19	No	Cochleostomy	30	53	33	<10 dB PTA shift at 250, 500 and 1 kHz	6–48	NA	NA
16	Soda-Merhy et al. [20]	Cochlear Nucleus 24 K (16) Cochlear Nucleus 24 Contour (12) Cochlear Nucleus 24 Contour Advance (10) MED-EL Combi 40+ (6) Advanced Bionics Hi-Res 90 K 1 J (4)	17–31	No	Cochleostomy	48	86	51	<10 dB PTA shift at 125, 250, 500 Hz	1–56	NA	NA
17	Gantz et al. [5]	Cochlear Nucleus Hybrid 10	10	No	Cochleostomy	87	91	75	<30 dB PTA shift at 125–1 kHz	3–60	CNC words	Yes
18	Garcia-Ibanez et al. [21]	Cochlear Nucleus 24 Contour Advance	19	No	Cochleostomy	28	71–86	36	<10 dB PTA shift at 250–1 kHz	6	NA	NA
19	Gstoettner et al. [39]	MED-EL Flex EAS	18–22	Yes	Cochleostomy/ RW	9	100	44	<10 dB PTA shift at 125–750 Hz	6–15	Freiburg monosyllables HSM sentences (quiet and noise)	Yes
20	Lenarz et al. [22]	Cochlear Hybrid L 24	18	No	RW	32	100	68	<15 dB PTA shift	6–12	Freiburg monosyllables Oldenburg sentences in noise	Yes
21	Skarynski et al. [23]	MED-EL Combi 40+ (15) MED-EL Combi 40+ M (3) MED-EL Combi 40+ Flex (1) MED-EL Pulsar M (7) MED-EL Pulsar Flex (2)	20	No	RW	28	85	46	<10 dB PTA shift at 125–4 kHz	12–48	Monosyllables (quiet and noise)	Yes

Table 1 continued

Publication		Surgery		Percent HP			Clinical Data			Benefit from EAS		
No.	Studies	Device and electrode	Depth (mm)	Topical steroids	Approach	Subjects	Partial (%)	Complete (%)	Complete HP definition		Followup (months)	Test measure
22	Brown et al. [49]	Advanced Bionics 90 K Helix (6)	20–25	No	Cochleostomy	31	90	45	<10 dB PTA shift at 250, 500, 1 kHz	1–30	NA	NA
		Advanced Bionics 90 K I J (9)										
		Advanced Bionics 90 K (3)										
		Cochlear Nucleus 24 Contour Advance (12)										
23	Rajan et al. [24]	MED-EL Pulsar CI100 (1)										
		MED-EL Flex EAS (9)	24–31	Yes	RW	34	94	29	<10 dB BC PTA shift	8–60	NA	NA
		MED-EL Flex soft (25)										
24	Skarzynski et al. [25]	Cochlear Nucleus Straight Research Array (CI 422)	20–23	No	RW	23	100	NA	NA	1–13	Monosyllables (quiet and noise)	Yes

MTB multi-talker babble

MTB multi-talker babble

likelihood of electrode-driven intracochlear trauma; and (4) insertion depths limited to approximately 20 mm [6••]. Soon thereafter, however, histologic evidence from cadaveric temporal bone insertions demonstrated that the round window might in fact be a less traumatic avenue for electrode insertion; despite the need to remove its bony overhang. Further experiments conducted controlled insertion maneuvers and confirmed the importance of the round window as an anatomic landmark for scala tympani access. In fact, clinicians advocated for either direct round window insertions or round window–related cochleostomies, depending on the anatomic configuration of this region. This notion was further supported by Roland et al., who further modified this technique by advocating that the cochleostomy be placed 0.5–1.0 mm anterior inferior to the round window, as this site allows for reliable entry into scala tympani with a low rate of damage to the basilar membrane or basal spiral lamina. In addition, this group reinforced the soft surgical principles previously described [10•]. Various electrode arrays were evaluated using the above mentioned insertion techniques and temporal bone experiments and clinical data essentially confirm the currently used surgical technique utilizing the round window as a landmark for cochlear opening (Table 1; Fig. 1).

Surgical Technique

Hearing preservation surgeries typically utilize a standard cochlear implant approach including a cortical mastoidectomy and facial recess. To gain proper access to the round window niche, a large approach should be drilled with identification of both the facial nerve and the chorda tympani within the recess. The bony overhang covering the round window membrane is subject to great anatomical variations. Furthermore, the membrane itself demonstrates marked size and positional variations [26]. As such, the round window can be easily accessed with minimal drilling of the overhang in some cases, whereas it remains mostly hidden in other situations. The surgeon should also remove all loose tissue within the round window niche that covers the round window membrane. In rare cases, however, the round window remains hidden, despite the surgeon's best efforts to maximize the facial recess approach. One group advocates an additional transcanal view via a tympanomeatal flap in these cases [27].

Once the round window membrane can be seen, its position and size should be assessed. With a predominately posterior facing round window, electrode insertions through the membrane are typically easy and nontraumatic. With a predominately inferior facing membrane, however, a round window related cochleostomy has been shown to be least traumatic [28]. For this approach, drilling should start directly inferior to the round window. The drilling can

then continue in a slightly anterior direction to identify the endosteum of the scala tympani. This approach allows a relatively straight trajectory while directing the electrode away from the basilar membrane and osseous spiral lamina. The implant can be gently inserted along the lateral scala tympani wall. Care must be taken to avoid perilymph suctioning. Also, the electrode should be slowly advanced and the surgeon should watch for electrode buckling or other signs indicating mechanical trauma. Once the insertion process has been completed, the round window niche is sealed using a free tissue (fascia) graft. Topical (intratympanic dexamethasone) and systemic steroids should be utilized to protect the inner ear. Also, postoperative antibiotics are typically used for infectious prophylaxis.

Despite the well-documented morphologic benefits of the round window insertion technique described above, it is not without detractors. One group, for example, has hypothesized that round window insertions may interfere with the physiologic functions of the round window, including immune defense and molecular secretion [29]. It also appears that despite the evidence of decreased intracochlear damage, many surgeons still prefer cochleosotomies for hearing preservation surgery in order to avoid insertional difficulties associated with the hook region of the cochlea [30]. However, current and future educational efforts underline the importance of a detailed knowledge of the surgical anatomy in this region [31•].

Internal Array Technology

Postoperative hearing preservation has been reported in a number of studies in conventional cochlear implant recipients with standard electrode arrays [32–34]. With growing interest in successful hearing preservation, cochlear implant manufacturers began to modify electrode design to be thinner, shorter, and more flexible with the goal to reduce intracochlear trauma.

One of the first modified electrode arrays designed for a limited insertion depth into the basal region was the Iowa/Cochlear Nucleus CI24 with either a 6- or 10-mm intended insertion depth, otherwise known as the Hybrid S [2]. This electrode array featured a smaller diameter than previous generations of Cochlear Corporation (Sydney, Australia) arrays and 6 channels of stimulation. Additionally, Cochlear Corporation has more recently introduced the Hybrid L24, which offered the standard number of 22 electrode contacts and a 16-mm electrode array [35].

Likewise, MED-EL (Innsbruck, Austria) has developed modified electrode arrays with the aim of preserving residual hearing. The standard electrode features 12 paired electrode contacts mounted in a silastic carrier of 31.5-mm length. This insertion depth is markedly greater when

compared to the ones used by other manufacturers and should provide access to more apical cochlear regions. However, temporal bone histology recently confirmed the more traumatic nature of such long insertions. Therefore, shorter electrode carriers specifically for hearing preservation were developed. As such, the MED-EL Medium array features slightly shorter contact spacing and thus an overall shorter insertion depth of about 26 mm when inserted fully [36]. Mostly, however, insertions of 20 mm have been advocated and a more recent revision reflects this. MED-EL has also developed electrodes featuring a smaller tip diameter (Flex_{EAS}, Flex_{Soft}) to further reduce insertion forces and intracochlear damage [37]. This was subsequently documented in temporal bone studies and clinical trials [38, 39]. Despite these advances, electrode design continues to evolve and recent concepts incorporate even thinner and more flexible arrays as well as drug delivery solutions and steerable devices.

Pharmacological Therapy

Prevention of hearing loss after cochlear implantation using adjuvant pharmacological therapy has been an area of great interest. Glucocorticosteroids have long been hypothesized to assist in preservation of residual hearing in both partial and full insertion cochlear implants given their efficacy in treatment of noise induced and sudden sensorineural hearing loss [40]. Prior animal studies have shown that glucocorticoids act as transcription factors protecting hair cells from apoptosis [41, 42]. Initially, intravenous application of steroids peri-operatively was considered, but both animal and human studies demonstrated that the dosage of intravenous steroids necessary to obtain measurable intracochlear levels was very high, especially given concern for steroid induced side effects [43, 44]. Using local delivery via an intratympanic route, on the other hand, experimental data confirmed markedly greater perilymphatic concentrations than systemic application [45]. Yet animal experiments have shown a decreasing intracochlear steroid concentration gradient, with greatest concentrations measured basally [46]. Further animal studies utilizing MRI to evaluate the distribution of gadolinium weighted steroid administration demonstrated that round window application via a gelatin-sponge may achieve appropriate apical drug levels [47]. Given these results, a prospective study using the MED-EL Flex_{soft} electrode was undertaken and demonstrated superior hearing preservation rates with perioperative transtympanic methylprednisone application [48]. Although the study was not randomized and the study size was relatively small, these are promising results for pharmacological therapy to assist in increasing hearing preservation rates.

Postoperative Outcomes

Hearing Preservation Rates

One challenge when reviewing current reports on hearing preservation rates is the lack of universal terminology. Some report successful hearing preservation to be within 10 dB of the preoperative thresholds [6•, 34, 49], while others define it as functional hearing or a level of hearing that is within the output limits of acoustic amplification [50]. The reader is advised to be critical of the various reports on hearing preservation.

As discussed previously, hearing preservation surgical procedures were initially conducted with electrode arrays designed for conventional cochlear implantation. Despite use of these longer, more rigid arrays, there were reports of postoperative preserved residual hearing in conventional cochlear implant adult and pediatric recipients [32–34, 49, 51].

Hearing preservation has also been reported in subjects with substantial preoperative residual hearing who were implanted with conventional electrode arrays [6•, 50, 52, 53]. Kiefer et al. [6•] reported on attempts to preserve low-frequency hearing with a limited insertion depth (19–24 mm) of the MED-EL standard array ($n = 8$) and a modified version of the array where the electrode contacts were closer together ($n = 6$). Reducing the distance between contacts offered more stimulation sites within the cochlea. Three months postoperatively, nine patients had complete hearing preservation, three had partial hearing preservation, and two suffered a total loss of residual hearing. Similarly, Gstöettner et al. [52] implanted subjects with MED-EL's standard and medium electrode arrays, with insertion depths of 18–24 mm. Postoperatively, 13 experienced complete hearing preservation, 5 had partial hearing preservation, and 3 had a total loss of residual hearing. More recently, Carlson et al. [50] reviewed hearing preservation rates in subjects with substantial preoperative hearing at 250 Hz who received a conventional array from Advanced Bionics, MED-EL, or Cochlear Corporation. Of the 126 implantations, 69 had preserved residual hearing and 57 had a total loss of hearing at 250 Hz. Further, Prentiss et al. [53] found postoperative hearing preservation in patients with 20–28 mm insertion depths with either the MED-EL standard or medium electrode arrays.

Additionally, hearing preservation rates have been reported in subjects who were implanted with the shorter, more flexible electrode arrays [2, 5, 37, 39, 54]. Gantz and Turner [2] reported postoperative hearing preservation within 10–15 dB of preoperative findings in 6 subjects who were implanted with Cochlear's Hybrid S (6- or 10-mm insertion depths). In 2009, Gantz et al. [5] reported outcomes

from the US clinical trial using the Cochlear Hybrid 10-mm electrode array. Of the 87 adults reviewed, 79 had residual low-frequency hearing postoperatively after long-term listening experience. With the FlexEAS electrode array, Helbig et al. [37] found a significant decrease in mean low-frequency thresholds between the preoperative and initial activation evaluations. They reported a further significant decrement in the mean thresholds at 500 Hz between the 3- and 6-month follow-up intervals.

Speech Perception Outcomes

When hearing preservation is achieved postoperatively, patients may utilize electric and acoustic stimulation in an ipsilateral listening condition. Earlier, this was presented with a cochlear implant external speech processor and a separate in-the-ear hearing aid in the same ear. Today, cochlear implant manufacturers offer these two technologies in a single unit, such as the DUET speech processor (MED-EL Corporation) and the Hybrid sound processor (Cochlear Corporation).

Listening with combined electric and acoustic stimulation modalities in the same ear has been shown to offer recipients improved speech perception abilities over electric stimulation alone [37, 39, 55]. Further, the addition of low-frequency acoustic information offers improved speech perception abilities in challenging, multi-talker background noise [56], which is a known challenge for conventional cochlear implant recipients. Gantz et al. [57] reported a nonsignificant relationship between the amount of residual hearing lost post-implantation and speech perception scores in quiet, yet found a significant relationship between postoperative residual thresholds and speech recognition thresholds in noise. It is suspected the superior speech perception abilities with ipsilateral combined stimulation results from access to acoustic low-frequency cues [58], which current electric signal coding strategies cannot effectively replicate. Gantz et al. [57] proposed that the improved speech perception abilities over conventional cochlear implantation rely on preservation of residual hearing. If residual hearing thresholds decrease to profound levels then the benefit may be lost.

EAS recipients experience an additional gain in speech perception in noise and localization abilities with the inclusion of the contralateral hearing aid [59–61]. On a speech perception in a multi-source noise task, bimodal EAS recipients (EAS plus a contralateral hearing aid) achieved significantly lower speech reception thresholds as compared to bilateral conventional cochlear implant recipients [59]. Again, this improvement noted over electric stimulation alone is suspected to result from utilization of acoustic low-frequency cues, including the fundamental frequency.

Music Perception

When compared to normal-hearing peers, conventional cochlear implant recipients experience poorer performance on pitch perception, melody recognition, and timbre discrimination tasks [62]. With the inclusion of low-frequency acoustic information, EAS recipients have shown improved pitch perception abilities as compared to conventional cochlear implant recipients [58]. Despite the improvements with music perception abilities with the inclusion of acoustic information, EAS recipients do not reach the performance levels of normal listeners [63].

Future Directions

Although current results with EAS are promising, clinicians and researchers continue to search for methods to consistently achieve complete hearing preservation while providing optimal electric stimulation. One such method is an intracochlear trauma warning system during implantation. Prior studies have demonstrated the feasibility of evaluating and monitoring cochlear health using electrocochleography in the animal model in order to assess pre-implantation, intra-operative and post-implantation cochlear health using both the cochlear microphonic (CM) and the compound action potential (CAP) [64–67]. Recent studies have translated this methodology into the operating suite and utilized it in human implantations [68]. In 2009, Oghalai et al. [69] used auditory steady-state responses (ASSR) in 16 patients and determined that intraoperative monitoring of the cochlea led to improved hearing preservation outcomes [69]. Choudhury et al. [70] demonstrated that in cochlear implant recipients, electrocochleography (ECoG) measurements were feasible even in profoundly deaf patients with little to no pure tone detection [70]. An Italian group used ECoG measurements to monitor the CAP threshold and latency data intraoperatively in 15 cochlear implant recipients. This group concluded that intraoperative monitoring using ECoG led to slower, step-wise electrode insertions and decreased postoperative pure tone averages (PTA) [71]. A German group used CM thresholds to monitor intracochlear health during implantation in six patients undergoing full or partial insertion of the electrode array. In this group, CMs were reliably recorded in all patients and able to detect imminent trauma when the electrode kinked in the basal turn during insertion [72]. While the ability to detect areas of residual hearing and monitor for intracochlear trauma may ultimately lead to improved postoperative hearing preservation rates, surgeons continue to work to improve the surgical implantation process.

While both implant technology and surgical approaches have continued to evolve, investigators continue to search

for implantation methods to reduce intracochlear trauma and insertion forces. With traditional straight electrodes, the electrode begins to experience increased frictional forces when it encounters the lateral wall of the cochlea at approximately 180°. In order to overcome these frictional forces, a high cumulative load is placed on the electrode, causing it to buckle and increase the chance for intracochlear trauma [38, 73, 74]. Although pre-curved, perimodiolar electrodes have decreased lateral wall insertional forces, intracochlear trauma and tip rollovers continue to occur [75]. Given the importance of intracochlear trauma despite changes in electrode design, a robotic surgical assistance device utilizing a steerable electrode array was proposed and utilized to decrease insertional forces up to 70 % [76]. In 2010, the same group developed a novel steerable electrode with an robotic surgical assist device and developed a surgical assist robot with force sensing capabilities meant for clinical use [77]. Their results showed that increased ability to adjust the trajectory of insertion decreased insertion forces with straight and perimodiolar electrodes. In addition, they created a surgical assist device that can detect insertional forces as small as 0.1 G and grants the surgeon micromanipulation similar to the da Vinci assist device. Ultimately, the authors conclude that surgical assist devices may enable surgeons to reliably prevent intracochlear trauma and preserve residual hearing [77]. In order to ensure proper alignment of the electrode insertion in the basal turn, a recently study revisited the idea of intracochlear microendoscopy using chip tip fiberoptic technology and demonstrated the feasibility of inserting the smallest chip tip camera up to 270° into a human cochlea while maintaining the ability to identify intracochlear anatomy. In the future, intracochlear visualization using microendoscopy intraoperatively could provide the surgeon with real time visualization during implantation [78, 79].

Conclusions

Advances in both surgical procedures and cochlear implant technology have allowed for continued increase in hearing preservation rates. Many different electrode lengths and insertion depths have been proposed to optimize both residual hearing preservation and electrical stimulation outcomes, but ultimately the depth of insertion will likely be individualized for each patient's level of residual hearing. Strides have been made in areas of intraoperative near field recordings but have not been implemented clinically. Steroids continue to show promise in preserving hearing post-implantation, but an ideal dosage and delivery system has yet to be determined. In order to avoid cochlear trauma, the debate continues over round window insertion versus cochleostomy, but surgical assist devices may be the

key to slow insertion speeds with force feedback to avoid intracochlear shearing.

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- Of importance
- Of major importance

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