Electroacoustic Stimulation

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KEYWORDS

- Electroacoustic stimulation • EAS • Hybrid cochlear implantation
- Hearing preservation

KEY POINTS

- Electric acoustic stimulation (EAS) is indicated for individuals with good low-frequency hearing and profound high-frequency hearing loss.
- EAS uses the cochlear electrode array to convey high-frequency stimuli and a hearing aid to convey low-frequency stimuli to the same ear.
- EAS shows improvement in word and sentence recognition as well as speech in noise.
- Complications associated with EAS are consistent with known risks for cochlear implantation, including loss of residual hearing.
- Progressive advancements in electrode design and atraumatic surgical techniques have resulted in improved hearing preservation and a valuable resource in the appropriate patient population.

INTRODUCTION

Electric acoustic stimulation (EAS), also known as hybrid stimulation or partial deafness cochlear implantation (CI), is indicated for individuals with intact low-frequency hearing and profound high-frequency hearing loss. Although low frequencies contribute information to aid in speech perception, speech production, environmental sound awareness, music, and emotion recognition,[1] these individuals are usually able to detect vowels, but few or no consonants, and thus have difficulty with word understanding and hearing in noise. Continuing innovations in CI have led to increased success in the preservation of residual acoustic hearing, thus allowing for the expansion of CI candidacy and the development of combined technologies in which both electric and acoustic stimulation are delivered to the implanted ear. Von Ilberg and colleagues[2] reported encouraging outcomes from the first clinical patient experience using EAS in 1999. In the EAS model, a CI electrode array (**Fig. 1**) conveys high-frequency stimuli to the implanted ear, whereas the coupled hearing aid conveys

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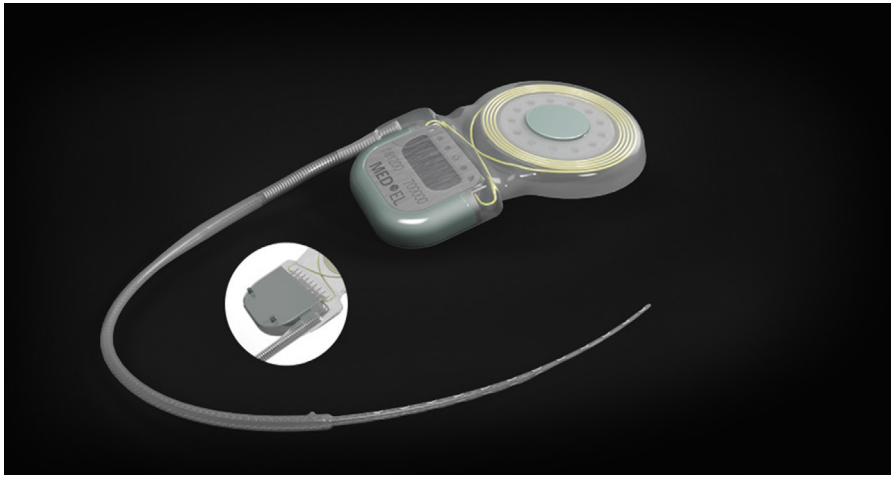

Fig. 1. Lateral wall electrode. (*Courtesy of* MED-EL Co, Durham, NC; with permission.)

low-frequency stimuli to the same ear (Fig. 2). Traditionally, the electrode insertion depth is confined to the basal turn of the cochlea, avoiding damage to the apical cochlear region.[3] Advances in electrode design and surgical technique have contributed to promising audiologic outcomes in clinical studies using EAS over the past

Fig. 2. EAS processor coupled with a hearing aid. (*Courtesy of* MED-EL Co, Durham, NC; with permission.)

couple of decades. This article aims to review current audiometric criteria, electrode design concepts, surgical considerations for hearing preservation, and audiologic outcomes for EAS.

AUDIOMETRIC CRITERIA FOR ELECTRIC ACOUSTIC STIMULATION

Currently, there are 2 companies that offer EAS/Hybrid options:

Cochlear America Hybrid System

Cochlear America's Hybrid system was Food and Drug Administration (FDA) approved in the United States in March 2014. FDA approved candidacy for the ear to be implanted with the Cochlear Hybrid System (Cochlear Corporation, Sydney, Australia) is summarized below and audiometric profile shown in **Fig. 3**. In brief,

- Normal hearing up to 60-dB threshold hearing loss through to 500 Hz
- Severe to profound sensorineural hearing loss in the mid to high frequencies using the average of 2 K, 3 K, and 4 K Hz, which needs to be greater than 75 dB
- Word score of 10% to 60%
- The word score of the contralateral ear should be equal or better than the ear being considered for the hybrid; however, no greater than 80%

MED-EL Electric Acoustic Stimulation System

MED-EL's EAS system (MedEl, Innsbruck, Austria) was approved in September 2016 for those meeting the following audiometric criteria (**Fig. 4**):

- Normal to moderate sensorineural hearing loss up to the mid frequencies, sloping to a severe to profound sensorineural hearing loss thereafter

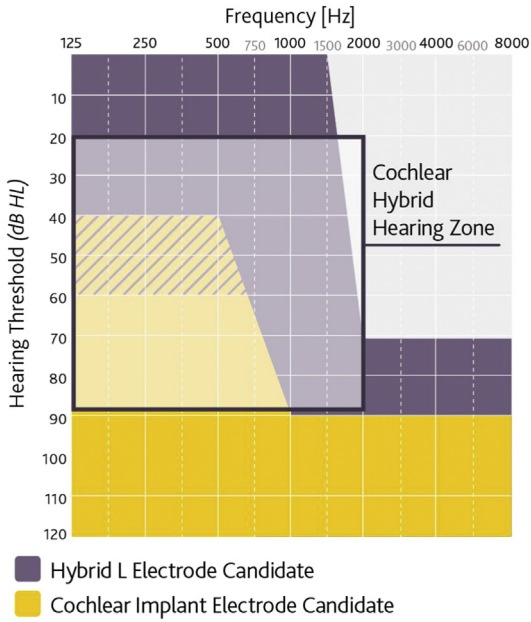

Fig. 3. Audiometric criteria with EAS indication in purple compared with traditional cochlear implant candidacy in yellow. (*Courtesy of* Cochlear Limited, Sydney, Australia; with permission.)

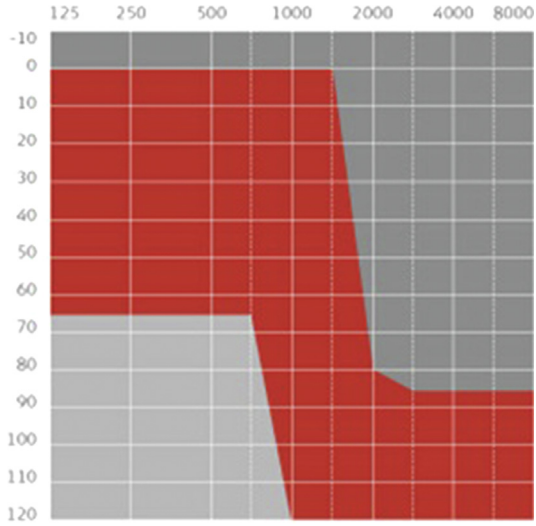

Fig. 4. MED-EL EAS audiometric profile shown in red. (*Courtesy of* MED-EL Co, Durham, NC; with permission.)

- Word score of 60% or less in the ear to be implanted

Although this criterion is inclusive of more hearing than traditional candidacy, there are considerations such as progressive hearing loss and cochlear abnormalities that need to be determined along with the audiologic criteria when considering EAS versus cochlear implant long term.

SPECIAL DEVICE DESIGN FOR ELECTRIC ACOUSTIC STIMULATION

EAS uses electrode arrays that minimize trauma during insertion and thus maximize hearing preservation. Several characteristics, such as electrode length, diameter, and degree of flexibility, contribute to atraumatic insertion. Histologic temporal bone insertion studies using flexible electrodes have demonstrated that insertion up to 1 full turn is atraumatic in the setting of correct cochleostomy techniques.[4–6] Beyond this limit, it may impart significantly increased trauma. Studies have shown that lateral wall electrodes (see **Fig. 1**) are less traumatic than precurved, perimodiolar hugging electrodes (**Fig. 5**)[7,8] because insertion occurs along the lateral wall of the scala tympani, thereby preventing trauma to the modiolus and spiral lamina.

The first application of shallow insertion electrode was reported by Gantz and Turner in 2003.[9] This Nucleus CI implant was shortened from the standard 22 mm to 6 mm and subsequently 10 mm, and the number of channels was reduced from 24 to 6. Subsequent generations of electrode design include the Flex^{EAS} electrode (MED-EL). This electrode consists of 12 contacts and measures 20.9 mm between first and last contact. Its cross-sectional diameters vary from 0.33 $\times$ 0.49 mm at the apex to 0.8 mm at the cochleostomy site. Zigzagging of the platinum iridium wires within the silicone carrier contributes to electrode flexibility. Furthermore, the small volume and flat shape contribute to extra flexibility at the tip of the electrode. Later generations of specialized hybrid stimulation electrodes include the Flex24 (MED-EL) electrode array, measuring 24 mm in length, and the Hybrid-L electrode (Cochlear),[7,10] which has 16-mm functional length with dimensions ranging from 0.55 $\times$ 0.4 mm at the base

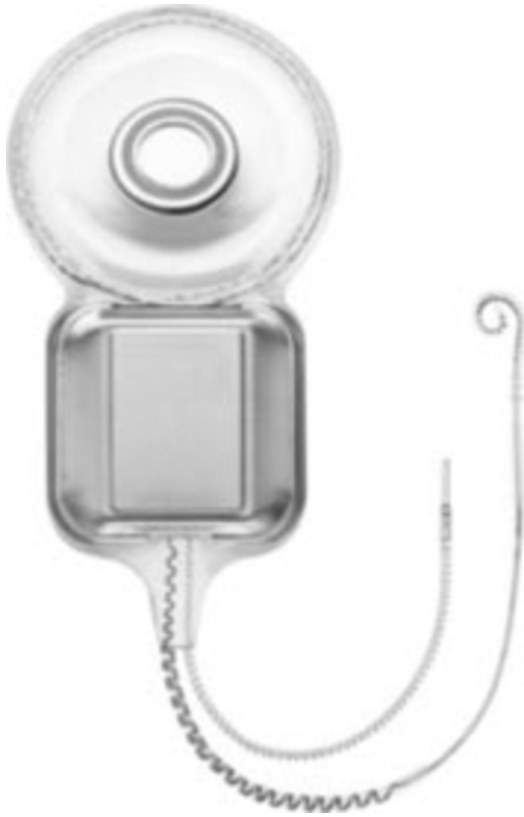

Fig. 5. Perimodiolar electrode. (*Courtesy of* Cochlear Corporation, Sydney, Australia; with permission)

to 0.35 × 0.25 mm at the apical end. More recently, Advanced Bionics have introduced their version of lateral wall electrode, Slim J, with the hope of also preserving the cochlear architecture and thereby preserving residual hearing (Table 1).

PRESERVATION OF RESIDUAL HEARING

Electrode Design

Many experts have examined the influence of electrode design on hearing preservation during implantation. Electrode arrays can be classified into straight and

Table 1
Summary of electrodes designed for hearing preservation

EAS Electrode	Year	Length (mm)	Diameter (mm)
Cochlear nucleus	2003	6 or 10	0.2 × 0.4
MED-EL Flex^{EAS} (now known as FLEX[25])	2004	20.9	0.33 × 0.49–0.8
Cochlear Hybrid-L	2006	18	0.35 × 0.25
Advanced Bionics HiFocus Slim J	2017	15	0.5–0.7

perimodiolar.[11] The first hearing preservation electrodes were straight and thus adopted a lateral wall position in lieu of the perimodiolar electrodes that were designed to lie adjacent to the modiolar wall, allowing for more spatially focused stimulation of the spiral ganglion cells. Both types of electrodes have a role depending on the patient indications. Straight electrodes are useful in patients with a variety of anatomic variations where the structure of the cochlear is not suitable for a perimodiolar electrode, such as in the case of common cavity cochlear deformity. Straight or lateral wall electrodes, such as the Slim Straight electrode (Cochlear), have demonstrated long-term low-frequency hearing preservation within 20 dB of preoperative levels in patients with usable acoustic hearing.[12] There was also significant improvement in speech understanding in quiet/noise in subjects using this electrode along with the hybrid sound processor to provide acoustic stimulation.[13] Perimodiolar electrodes aim to bring the electrode contacts closer to the neural elements of the cochlea. Studies have demonstrated a narrower spread of excitation, reduced behavioral and electrically evoked compound action potential thresholds, and wide dynamic range.[14] Perimodiolar electrodes are also applicable in a range of anatomic variations/conditions.[15] In summary, individuals with specific anatomic/medical conditions should be considered on a case-by-case basis.

Mady and colleagues[16] in 2017 compared hearing preservation outcomes using lateral wall versus perimodiolar full-length electrodes in 45 patients. At short-term follow-up, straight or lateral wall electrodes were associated with significantly better hearing preservation than perimodiolar electrodes. In multivariate regression, straight electrode use was a significant predictor of better hearing preservation. At long-term follow-up, however, electrode type was not associated with improved hearing preservation, and younger patient age was the only significant predictor of long-term hearing preservation on multivariate analysis. However, a recent meta-analysis by Santa Maria and colleagues[17] showed no disadvantage of longer electrode array length and no difference for low-frequency hearing preservation between straight versus contoured electrode arrays and electrode array type, including Cochlear's Nucleus 24-K, 24-Contour, Contour Advance, Iowa Nucleus; MED-EL's FlexEAS, FlexSoft, Combi 40+, Standard, and Custom; Advanced Bionics HiFocus Helix and Hifocus.

Perioperative Pharmacologic Interventions

Inflammation is a frequently reported reason for posttraumatic hearing loss.[18] Because of their anti-inflammatory properties, glucocorticosteroids have been and continue to be extensively examined for their effect on hearing preservation in the setting of CI. There are several animal studies supporting the use of steroids for hearing preservation.[19–22] Various preoperative, intraoperative, and postoperative regimens with topical/intravenous/oral forms have been investigated.[23–28] It is particularly difficult to penetrate the apical region of the cochlea, and it has been shown that the parenteral route is the best for covering the apical region, whereas round and/or oval window applications are best for covering the basal region.[29] Low-frequency hearing preservation has been demonstrated with the use of perioperative oral corticosteroid regimen (2-week oral corticosteroid taper beginning 3 days before surgery) in patients implanted with standard length electrodes on their first postoperative audiogram.[30] Although various studies suggest hearing preservation benefit imparted by glucocorticoids, there is no standard regimen to minimize inflammation and maximize desired outcome. The effects of steroids on wound healing in the postoperative period should also be a consideration.

Hyaluronic acid has been used as a lubricant to reduce friction trauma during electrode insertion as well as to serve as a seal around the cochleostomy to prevent

perilymph leak. Antibiotic prophylaxis has also been suggested to prevent formation of bacterial biofilms at the surface of the electrode, which may lead to acute or chronic labyrinthitis.[3] The aforementioned meta-analysis by Santa Maria and colleagues in 2014[17] reported that a soft tissue seal for cochleostomy was found to be better than fibrin glue-only seal for hearing preservation. The investigators also found no benefit to postoperative oral steroids, intraoperative parenteral steroids, or preincision transtympanic steroids. They did demonstrate a beneficial effect with intraoperative topical steroids, specifically for hearing preservation at 2 kHz.

Surgical Technique

Soft surgery principles, as first described by Lehnhardt[31] in 1993, for hearing preservation during CI include avoidance of perilymph suctioning, careful manipulation around the cochleostomy, slow and delicate electrode insertion, and cochleostomy sealing. He also described a minimal cochleostomy approach, inferior and anterior to the round window. In general, there are multiple factors to consider in drilling a cochleostomy, such as acoustic trauma, presence of bone dust, and inconsistent landmarks. The round window insertion avoids these shortcomings and sets a safe morphologic landmark for the scala tympani. Kang and Kim[32] in 2013 found that patients with favorable RW anatomy who underwent round window CI electrode insertion demonstrated comparable speech perception compared with the traditional cochleostomy insertion group. Adunka and colleagues[33] in 2014 also performed a retrospective review comparing the 2 approaches in 20 patients enrolled in the EAS clinical trial. They found no statistically significant differences in postoperative outcomes for both preservation of residual hearing and unaided and aided speech perception between the 2 approaches. The true safety of approach may depend on RW orientation. Specifically, a vertical orientation may permit a fairly straight trajectory through the scala tympani, whereas a horizontal orientation makes insertion more traumatic due to deflection of the electrode by the bony cochlear hook.[33] A systematic review comparing cochleostomy versus RW approach by Havenith and colleagues[34] showed no difference in mean postoperative pure tone audiometry threshold shifts comparing both insertion techniques as well as type of electrode used (MED-EL Standard/Medium and Flex^{EAS} electrode arrays). Complete low-frequency hearing preservation (defined as mean pure tone average shift at lower frequencies at 125, 250, 500, and 750 Hz, of 10 dB or less) was reported to be 0% to 40% with cochleostomy and 13% to 59% with RW approach. Complete loss of residual hearing occurred in 0% to 26% with cochleostomy and 3% to 20% with RW approach. Thus, there was no clear benefit of a specific surgical approach in this meta-analysis, but the literature is limited because there are no randomized studies with direct comparisons. Results to date suggest there might be an advantage regarding fewer patients with complete hearing loss after RW insertion. Conversely, the meta-analysis by Santa Maria and colleagues[17] report that cochleostomy is better than RW insertion in that it is more likely to yield higher rates of complete hearing preservation and trends to lower rates of partial hearing preservation. This review was different from that performed by Havenith and colleagues because they used pure tone audiometry of 250, 500, 750, 1000 $\pm$ 2000 Hz. If 2000-Hz frequency is taken into account, the cochleostomy approach has a trend toward more favorable rates of complete and partial hearing preservation.

Santa Maria and colleagues also found that mastoidectomy with posterior tympanotomy approach trended toward higher rates of complete hearing preservation compared with the suprameatal approach. Other studies found no difference.[35] Slow insertion speed showed a trend toward higher rates of hearing preservation compared with insertion speeds of less than 30 seconds because slow insertion

reduces fluid forces within the cochlea.[36] Indeed, it has been shown that the slower the insertion speed, the better preservation of hearing.[37]

Systemic Inflammation

Ongoing studies are in process to define the role of inflammation in hearing preservation following CI.[38] One study in guinea pigs showed that systemic immune activation at the time of CI broadened the range of frequencies experiencing elevated thresholds after implantation. The immune activation had no significant detrimental effect on thresholds without implantation. In immune activated animals, dexamethasone treatment (20% dexamethasone phosphate adsorbed onto gelfoam and applied to the round window for 30 minutes before electrode insertion) significantly reduced threshold shifts at 2 and 8 kHz.

To date, existing literature lacks clinical evidence regarding the contribution of systemic inflammation to hearing loss or preservation after CI. There is evidence, in 2 separate longitudinal aging cohorts, that systemic inflammation is independently associated with age-related hearing loss. Using the population within the Epidemiology of Hearing Loss Study, a longitudinal cohort study of more than 1000 adults aged 48 to 92 years in Beaver Dam, Wisconsin, Nash and colleagues[39] measured markers of systemic inflammation, including serum C-reactive protein, interleukin-6, and tumor necrosis factor-α at 3 time points over a period of 22 years. The same individuals underwent audiometric testing at 2 time points to calculate a 10-year cumulative incidence of hearing impairment. Individuals less than 60 years old with high or increasing levels of serum C-reactive protein over a period of 10 years were almost 2 times more likely to develop hearing impairment. Furthermore, individuals less than 60 years of age with a higher-risk C-reactive protein profile had significantly higher pure tone averages and were more likely to experience a greater than or equal to 10-dB pure tone average progression over a period of 10 years in multivariate analyses.

ELECTRIC ACOUSTIC STIMULATION AUDIOLOGIC OUTCOMES

EAS and Hybrid systems show improvement in monosyllabic words, sentences, and speech in noise. Adunka and colleagues 2018[33] report on speech perception outcome data in the American and European trials for MED-EL EAS system, indicating that most recipients demonstrate significant improvement compared with preoperative scores on words and sentence tests.[40] Usami and colleagues[41] report improvement in monosyllabic word recognition scores from 24.1% preoperatively to 67.4% postoperatively at 1 year. Studies from Iowa University looking at the Cochlear Hybrid system indicate not only an improvement with monosyllabic words postoperatively but also overall improvement with speech understanding in noise and subjective improvement in quality of life.[42] Although the best performers used both the acoustic and the electric portions of the device, there was also improvement seen even with the electric portion alone compared with preoperative testing in all these studies.

The greatest challenges that one may face while programming EAS patients are extended appointment times due to additional counseling and testing, and integrating the acoustic and electric signals. It is recommended that one measure the unaided hearing in the audio booth before every programming session to ensure that the residual hearing has not changed. The addition of a quick threshold check will contribute to a longer appointment and greater booth utilization. The programming audiologist has to work to integrate the 2 signals for the best sound quality. More time will be spent programming to find the best crossover of acoustic signal to create the best sound

quality for the patient. In addition to testing and programming, there is more counseling involved to manage the acoustic portion of the processor (ie, changing wax traps, ear mold impressions), which again contribute to longer appointment times.

Options with Loss of Residual Hearing

A small percentage of patients will lose residual acoustic hearing following EAS surgery. Gstoettner and colleagues[43] reported that 2 out of 23 patients experienced complete hearing loss immediately after surgery, and additional 5 patients experienced delayed hearing loss 7 to 17 months after surgery. Gantz and colleagues[44] reported complete hearing loss in 6 out of 87 patients over 3 to 24 months during the Hybrid 10 Clinical Trial. Similarly, Luetje and colleagues[45] described a delayed hearing loss at 2 and 24 months in 2 out of 13 patients. In these cases where residual hearing in the low frequencies is lost immediately or diminishes over time, individuals fall into the same scenario as conventional CI candidates with some residual hearing before surgery. Therefore, a minimum length of 18 mm is recommended for EAS in order to ensure a fully functional implant and allow for reprogramming for more electric stimulation for recipients who lose acoustic hearing over time.[46]

COMPLICATIONS

Complications or adverse events associated with EAS are consistent with known risks for CI. One of the most commonly reported complications is loss of residual hearing. In one multicenter clinical trial for the MED-EL EAS System, using the FLEX[25] electrode arrays, profound to total residual hearing loss occurred in 8 (11.0%) out of 73 patients.[40] In long-term studies, with up to 11 years of follow-up time, Helbig and colleagues[47] reported 22 (21.4%) cases of total hearing loss out of 103 ears implanted with different electrodes, including the MED-EL Standard, Medium, and Flex 24, and Cochlear Slim Straight. Eight of the 22 cases occurred postoperatively, whereas the other 14 cases occurred at a mean of 26 months after surgery. There were no associations found between total hearing loss and electrode design or surgical approach. Other complications reported in EAS patients include type B or type C tympanogram, conductive hearing loss, and pain at the surgical site.

Although not specifically a complication, multiple studies report the discontinuation of acoustic amplification by some EAS recipients. Some of these individuals exhibited severe to profound hearing loss in the implanted ear without sufficient hearing for the combined stimulation. Indeed, Helbig and Baumann[48] observed that acceptance of acoustic amplification occurred when individuals had residual hearing less than 75 dB in the 500-Hz frequency or below. On the other end of the spectrum, there were also individuals who rejected acoustic amplification because they retained significant amounts of residual low-frequency hearing and could combine this natural acoustic hearing with the electric stimulation.[10,49] There were also individuals who rejected acoustic stimulation due to the discomfort or inconvenience of wearing the supplementary acoustic instrument and/or external ear canal issues, such as acute external otitis media.[50]

SUMMARY

EAS was first introduced over a decade ago and has proven to be a valuable resource in the appropriate patient population. Progressive advancements in electrode design and atraumatic surgical techniques result in improved hearing preservation and consequently a demand for combined acoustic and electric stimulation.

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