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Benefits and Limitations of Cochlear Implantation for Single-Sided Deafness

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Unilateral, severe-to-profound sensorineural hearing loss (SNHL), otherwise known as single-sided deafness (SSD), is estimated to occur in 2 – 5 per 1,000 school-age children (Lee et al., 1998) and 0.11–0.14% of all adults (Kay?Rivest et al., 2021). Those affected have a loss of hearing acuity on the affected side and impaired binaural hearing which negatively impacts sound source localization (Firszt et al., 2012; Wie et al., 2010), understanding speech in noise (SIN) (Johnstone & Litovsky, 2006; Rothpletz et al., 2012; Sargent et al., 2001) and overall quality of life (QoL) (Wie et al., 2010). The mechanisms of binaural hearing include the head shadow effect, binaural squelch, and binaural summation. The head shadow affect is not a true binaural process but rather a function of hearing on both sides of the head. This allows listeners to use a greater signal-to-noise ratio (SNR) when speech is directed to either ear. The head shadow effect has a negative impact on speech understanding in noise for those with SSD when speech is directed to the affected side. Binaural summation occurs when sounds are processed from either side of the head, leading to a perceived signal enhancement. Binaural squelch refers to reducing competing noise because the ears have combined the amplitude and phase differences from each ear (Carhart, 1965).

Historically, treatments for SSD were limited to devices for re-routing sound from the affected ear to the typical hearing ear, such as bone-conduction devices (BCDs) or contralateral routing of signal (CROS) hearing aids. A CROS device can be prohibitive since it requires using a device in the normal hearing ear, which can disrupt the natural acoustics delivered to that side. (Pedley and Kitterick, 2017).

A BCD avoids this problem since it relies on transmitting the signal from the affected side using transcranial conduction. Both devices are effective for improving speech understanding in noise when speech is directed towards the affected side (Picou et al., 2020; Young et al., 2023), though neither are sufficient for restoring the binaural system needed for spatial hearing (Peters et al., 2021).

A cochlear implant (CI), first developed for those with bilateral hearing loss, was suggested as a possible treatment for SSD as early as 2008, partly to manage incapacitating tinnitus (Van De Heyning et al., 2008). Since then, over 400 scholarly papers have been published exploring post-implantation outcomes. In 2019 the US Food and Drug Administration (FDA) approved cochlear implantation as a treatment option for adults and children over age 5 with SSD or asymmetric SNHL. Overall, current research demonstrates that once implanted, adult and pediatric SSD patients have improved speech understanding on the implanted side and overall speech understanding in noise, improved localization, and overall QoL. The current paper describes the benefits and limitations of a CI for SSD, which are important to consider when counseling patients.

Speech Recognition on the Implanted Side

Those with SSD are often seeking improved hearing on the ear with hearing loss, in addition to improved binaural hearing. To date, studies of speech perception on the implanted side show significant improvement between pre- and post-operative test intervals (Buss et al., 2018; Holder, 2017; Sladen, Carlson, et al., 2017; Sladen, Frisch, et al., 2017; Zeitler et al., 2019). However, research is conflicted on the degree of improvement following implantation. For example, some researchers report 6-month post-activation monosyllabic word scores in the range of 40% and 45% (Holder, 2017; Sladen, Carlson, et al., 2017), whereas others have reported scores in the range of 50% to 55% (Buss et al., 2018; Friedmann et al., 2016) which is more similar to scores of patients with bilateral SNHL (Holden et al., 2013). We found the disparity in word scores of interest. We wanted to determine if specific speech features drove the differences between adults with SSD and adults with bilateral sensorineural hearing loss (BSNHL). To explore this disparity, Sladen & Zeitler (2022) examined word and sentence scores among adults with SSD + CI and compared them to those with BSNHL + CI. A total of 12 adults with BSNHL and 12 adults with SSD were included; all had received a unilateral CI. Participants completed consonant recognition testing using the iCast system and conventional CNC word testing and AzBio sentence testing. Feature analysis of the consonant recognition scores showed that SSD + CI participants had a lower perception of voicing and manner of articulation cues compared to the BSNHL + CI participants, yet pace of articulation scores were similar between the two groups. The results suggest that despite the benefits of implantation for SSD, additional aural rehabilitation may be needed to assist them in taking advantage of voicing and manner cues. There is likely little room for improvement in perceiving the place of articulation cues due to the device's limited spectral resolution.

Speech Recognition in Noise

Patients with SSD are also seeking improved SIN recognition. Overall, studies show that following implantation for SSD, SIN in noise is improved in children (Benchetrit et al., 2021; Ehrmann-Mueller et al., 2020; Sladen, Frisch, et al., 2017; Thomas et al., 2017) and adults (Arndt et al., 2011; Buss et al., 2018; Deep et al., 2021; Dirks et al., 2019; Sladen, Carlson, et al., 2017; Sladen, Frisch, et al., 2017). Additional work suggests that benefits for SIN come primarily from the listener being able to take advantage of the head shadow effect such that improvement occurs when speech is directed towards the affected side (Arndt et al., 2015; Bernstein et al., 2017; Dirks et al., 2019; Sullivan et al., 2020). However, several studies have shown small, yet significant improvements when listening in diffuse noise (Firszt et al., 2012; Sladen, Carlson, et al., 2017). For example, Sladen and colleagues measured speech in noise using HINT sentences in an R-SPACE test environment. The R-SPACE presented multi-talker babble from eight speakers arranged in a 360° pattern. Speech was presented from directly in front and was roved up and down in an adaptive fashion to find the SNR for 50% correct. Performance with the CI on improved scores by ~2dB compared to the CI off condition.

Sound Source Localization

Sound source localization is also known to improve following implantation for SSD for both adults (Arndt et al., 2011; Bernstein et al., 2022; Dirks et al., 2019; Dorman et al., 2015; Ludwig et al.,

2021) and children (Arndt et al., 2015; Benchetrit et al., 2021; Ehrmann-Mueller et al., 2020). Overall the degree of benefit varies across studies with reported improvements in root-mean-square (RMS) error falling between 15 and 30^{o}. Improvement in localization has been reported to occur as early as 3-months post-activation (Dorman et al., 2015) and, according to some, continue improving as long as 5-years post-implantation (Thompson et al., 2022). Of interest, researchers have found that adults with SSD + CI can use interaural level difference (ILD) cues but not interaural timing difference (ITD) cues for sound source localization (Dirks et al., 2019; Dorman et al., 2015). This is not surprising, given CIs extract amplitude-envelope cues and do not preserve ITD cues (Grantham et al., 2008).

Tinnitus Suppression

As noted above, CIs were initially used among SSD patients for tinnitus suppression. Since then, partial hearing restoration has become the primary objective, though tinnitus relief remains a likely, welcome by-product. Overall, researchers agree that SSD patients may experience tinnitus relief with the device on. In fact, a recent systematic review of the literature indicated a high probability of tinnitus relief (>75 to 100%) when listening with the device (Dillon et al., 2022). Some also show that tinnitus relief is possible when the device is removed (Sladen, Carlson, et al., 2017).

Health-Related Quality of Life

The World Health Organization defines QoL as a broad multi-dimensional concept that includes subjective evaluations of both positive and negative aspects of life (The World of Health Organizational Quality of Life Assessment, 1988). However, health-related quality of life (HRQoL) is specific to aspects of quality of life clearly related to physical or mental health (Center for Disease Control and Prevention, 2000). For this reason, HRQoL measures are useful to researchers when measuring the impact of health on quality of life. Several possible HRQoL scales have been used in this domain: the child and adult versions of the Speech, Qualities of Hearing Questionnaire (SSQ), Abbreviated Profile for Hearing Aid Benefit (APHAB), Health Utilities Index (HUI), and the Cochlear Implant Quality of Life (CIQOL 35 or CIQOL 10). Overall, investigators agree that HRQoL is improved following cochlear implantation for SSD for adults (Galvin et al., 2018; Sladen, Carlson, et al., 2017; Tolisano et al., 2023) and children (Zeitler et al., 2019).

Auditory Deprivation

Timing and length of auditory deprivation are known to influence outcomes among patients with BSNHL negatively (Holden et al., 2013; Niparko et al., 2010). For example, children with congenital BSNHL implanted after age three years of age are known to have poorer spoken language outcomes compared to children implanted earlier (Niparko et al., 2010). Researchers generally agree that children with congenital losses should receive a CI as early as possible to take advantage of a “critical period” for development. That is not to say older children should not receive CI, but rather the topic should be included in conversations surrounding post-operative outcomes.

Studies examining the impact of auditory deprivation on outcomes among patients with SSD + CI generally agree that a shorter duration of deafness leads to improved outcomes. In fact, a recent systematic review and meta-analysis using the available research concluded that children with a shorter duration of deafness had greater improvement in speech perception in quiet, speech perception in noise, and sound source localization compared to children who were implanted at older ages (Benchetrit et al., 2021). In adults, however, there are conflicting reports such that some researchers found that adults with long duration of deafness showed little to no benefit from a CI (Arndt et al., 2011; Cohen & Svirsky, 2019; Rahne & Plontke, 2016) especially for those with congenital losses. In contrast, others have shown no difference in speech recognition performance between adults with long vs. short duration of deafness (Nassiri et al., 2022). It is worth noting that small sample sizes limit our understanding of this issue, and continued research is needed. Regardless, counseling prospective patients with SSD should include a conversation over possible limits with long duration of auditory deprivation.

Daily Device Use

In addition to the length and timing of auditory deprivation, daily device use has been shown to predict post-activation outcomes among those with SSD + CI. In short, longer wear time positively impacts speech recognition performance for both adults (Lindquist et al., 2023) and children (Park et al., 2023) with SSD + CI. Again, prospective patients should receive extensive pre-operative counseling on daily use to understand how to clearly maximize their post-operative outcomes.

Summary

In summary, cochlear implantation is largely successful in overcoming many of the complaints of patients with SSD. Specifically, post-implantation for SSD, most patients experience improved speech understanding on the implanted side, overall improved SIN when using both ears together, improved localization, increased HRQoL, and decreased perceived tinnitus. Though improvements are generally positive, there is variability across studies, and patients and their families should have access to this information when considering implantation. Furthermore, patients whose hearing history includes a long duration of auditory deprivation, especially when it is congenital, should temper expectations. Patients can maximize their outcomes when they use the device full-time.

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