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Improving Sound Localization After Cochlear Implantation and Auditory Training for the Management of Single-Sided Deafness

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Objective: To report a successful case of cochlear implantation and auditory training for the improvement of sound localization in a patient with single-sided deafness.
Study Design: Case report and literature review.
Setting: Tertiary referral otology practice.
Patient: Fifty-seven-year-old man receiving cochlear implantation after 8 years of unilateral sensorineural hearing loss.
Intervention: Initially, CROS hearing aid, then osseointegrated bone conduction system and finally cochlear implantation and auditory training.
Main Outcome Measures: Sound localization tests.
Result: Sound localization tests after CI and auditory training showed improvement when compared with testing performed after fitting of an osseointegrated bone conduction system.
Conclusion: Cochlear implantation followed by 3 months of auditory training may have improved sound localization in this patient with single-sided deafness. Further case-controlled studies need to be undertaken to ascertain whether CI alone without formal auditory training will promote the same results.
Key Words: Auditory training—Bone-Anchored Hearing Aid—Cochlear implant—Osseointegrated bone conduction system—Single-sided deafness—Sound localization.

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Since its development, cochlear implants (CI) have become the treatment of choice for profound hearing loss (1). As technology has improved and surgical experience increased, attention has begun to focus on the use of CI in the treatment of single-sided deafness (SSD) to improve both speech discrimination and sound localization.

We report a case of a postlingually single-sided deaf adult patient who was managed with a counter routing of signal (CROS) hearing aid, then an osseointegrated bone conduction system (OBCS) and finally a CI, as previous methods did not improve his chief complaint of difficulties with sound localization.

SSD has been estimated to affect approximately 9% of the adult population (2,3). It confers difficulty with sound localization and recognition of speech in noise. This is because these functions require binaural hearing, that is, sound stimulation from both ears (4).

The head shadow effect occurs when sound is presented from one direction; the head acts as a barrier, reducing the sound intensity reaching the contralateral ear. In those with SSD, if sound is presented to the deaf ear, the head shadow effect can make hearing more difficult. In those with binaural hearing, this acoustic shadow results in an intra-aural intensity difference (IID). This, in combination with the intra-aural time difference (ITD), the temporal difference between sounds reaching either ear because of its location, confer the benefits of binaural hearing. Stimuli from both cochleae travel to the ipsilateral cochlear nucleus via the cochlear nerve. From here, the bilateral stimuli are conducted into the central processing systems (4).

Processing of the ITD and IID helps in sound localization. These spatial and temporal separations also assist in the recognition of speech in noise by means of the squelch effect, that is, the suppression of unwanted sounds through use of the signal to noise ratio. It is also assisted by binaural summation, where stimuli from both ears are consolidated, affectively resulting in better signal-to-noise ratio when compared with unilateral hearing (4).

SSD is usually managed by routing sound signals to the hearing ear, either by air conduction using a CROS hearing aid or via bone conduction using a bone conduction hearing aid such as an OBCS. Studies have shown

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FIG. 1. Pure tone audiometry.

that these treatments can help improve signal-to-noise ratio and can help detect sounds presented to the deaf ear; however, they have not been shown to improve sound localization abilities (5–17). Additionally, they are beneficial in only limited circumstances, for example, speech recognition is better when it is presented to the OBCS ear or noise to the hearing ear; however, it is detrimental if noise is presented to the deaf ear (8–22).

More recently, cochlear implants have been used in those with SSD. Studies have shown a benefit in sound localization and speech recognition using this approach (23–33). However, CI does not result in synchronization of stimuli from both cochleae, resulting in unreliable ITDs (4,34). This may afford a role for auditory training to help improve hearing in noise and sound localization. Several animal and human studies have demonstrated the plasticity of the auditory cortex, affirming the role of auditory training for the improvement in sound localization in induced unilateral hearing loss (35–39).

This case study reports the history of a patient with a sudden sensorineural hearing loss in the left ear who first received a CROS hearing aid, then an OBCS and subsequently a cochlear implant with auditory training in the pursuit of improving his ability to localize sounds. A variety of detailed audiologic tests were conducted to assess dichotic hearing.

CASE REPORT

In 2004, an otherwise fit and healthy 49-year-old man developed sudden, left-sided sensorineural hearing loss (SNHL) of unknown etiology. MRI scan was normal, but pure tone audiometry revealed profound left-sided SNHL (Fig. 1).

The patient was referred to the audiology clinic with the chief complaint of difficulties in localizing sounds. This ability was particularly important to this patient as he is a road engineer, working in an environment with proximity to fast moving motor vehicles. In this scenario, poor sound localization poses a significant safety risk as he could not determine the direction of the traveling vehicles. Initial management with a CROS hearing aid (Unitron Tandem) was unsuccessful and an OBCS (Cochlear Nucleus BAHA Divino) was implanted in 2009. As expected, this improved detection of sound presented to the deaf ear; however, the patient was dissatisfied with the inability to recognize it as sounds coming from the direction of the deaf ear, and he continued to complain of suboptimal sound localization.

Sound localization tests were performed with the BAHA. The procedure was conducted in an anechoic chamber using a circular array of loudspeakers each at 18-degree intervals in the horizontal plane. The patient sat in the center with loudspeakers at the interaural axis 90- and 270-degree azimuth and on the sagittal axis with the loudspeakers at 0- and 180-degree azimuth. The patient's task was to identify as accurately as possible the angle of which the sound source had come from, with reference to the hand-held diagram of their location in the 360-degree layout.

The patient was required to keep his head stationary during each trial, while fixating on a point at 0 degrees. A second speech signal was used in groups of 40 trials, with random presentations (each loudspeaker activated twice). Pink noise was set at 65 dB Leq with ±3 dB random jitter. Testing was assessed under conditions of both aided and unaided listening. The OBCS was set at the omnidirectional microphone mode. The results show no improvement in localization despite the OBCS, as he perceived all stimuli to be from the right side (Table 1, Fig. 2).

Because of ongoing safety concerns related to this patient's employment situation and poor sound localization, cochlear implantation in the deafened ear was considered. After a full discussion of potential risks and benefits, cochlear implantation was performed in March 2012 using Nucleus CI24(RE) The surgery was performed in such a way that the BAHA abutment was preserved, in case the cochlear implantation was not successful. The implant was switched on to a Cochlear Nucleus CP 810 speech processor 4 weeks after surgery. The CI was mapped by measuring patient's subjective comfortable (C) and threshold (T) levels at each of the 22 electrodes. Only 1

TABLE 1. *Patient's sound localization test results with osseointegrated bone conduction system in the left ear*

Condition	Total REM	L/R RMS	L/R mean	F/B RMS	F/B mean
Unaided	94.2	73	44.6	58	29
OBCS	89.5	57	0.8	72	14.3

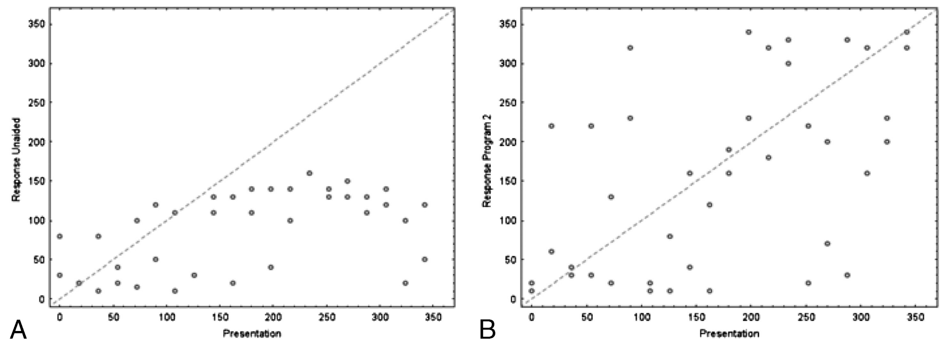

FIG. 2. *A*, Sound localization test results in the unaided condition. Most responses localized to the right side. (The *y* axis represents responses in degrees azimuth, and the *x* axis shows the stimuli presentation in degree azimuth; the *diagonal line* represents what would be a perfect score). *B*, Sound localization test results with the BAHA on the left mastoid set at omnidirectional microphone. The results show no consistency of responses with a few random left/right reversals, inaccurate left/right localization and random front/back reversals.

program with omnidirectional microphone was set in the speech processor. Patient was reviewed 2, 4, and 6 weeks after switch-on and then on a monthly basis until 12 months. Formal auditory training to promote binaural interaction started at the 4-week appointment.

The hardware used for the auditory training included an iPod plugged to a custom-made 2 channels attenuation box with a 15-dB attenuation range in each channel. This was connected to the left ear via the cochlear implant speech processor CP810 using a direct audio input cable and to the right ear using an earphone.

Sound tracks downloaded to the iPod included a prerecorded split track BKB-SIN (Bramford-Kowel-Bench Speech-in-Noise) sentence test with babble background noise from the National Acoustic Laboratory (NAL) and background noise and dichotic digits test material (40).

The aim of training was to stimulate both ears simultaneously to promote binaural interaction. To improve left ear performance, the stimuli were presented at a comfortable level to the implanted ear and reducing the volume in the right ear to obtain maximum perception on the opposite ear. The volume of the right ear was then gradually increased as training progressed with the aim to achieve equal volume and performance in both ears. This training was provided in the clinic with the audiologist and practiced at home on a daily basis. The patient reported practicing 1 hour a day 5 days a week while driving to and from work. After 3 months, the patient was able to relearn how to lateralize sounds on the horizontal plane, as demonstrated by dichotic digit and sound localization testing. The patient also reported a subjective improvement in his ability to localize sounds on the vertical plane, but his was not clinically tested (Table 2; Fig. 3) (41).

DISCUSSION

The world's first multichannel cochlear implantation took place in the late 1970s (35). Since then, there has been expanding indication for their use. Whereas the focus was initially on the treatment of bilateral severe-to-profound hearing loss, as technology has improved, attention has begun turning to broader indications such as the treatment of SSD (42–46).

Traditionally, SSD has been managed through the use of CROS aids and, more recently, OBCS. As expected, these methods have not shown benefits in sound localization (5–17). OBCSs have been shown to improve the signal-to-noise ratio and the detection of sound presented to deaf ear; however, they do not improve sound localization (17). Additionally, they can be detrimental in certain scenarios, for example, when noise is presented to the deaf ear (8–22).

More recently, cochlear implantation has been performed in the search for better assistance with sound localization in unilateral deafness. Studies have suggested a benefit in hearing, speech recognition, reduction in tinnitus, and improved sound localization using this approach (23–32).

In their 2008 study, Van de Heyning et al. (23) demonstrated the positive effects of CI in a series of 21 participants with SSD and severe unilateral tinnitus. This study showed a reduction in tinnitus loudness perception promoted by a CI in the affected ear. These results were supported by Kleinjung et al. (24). In contrast, Buechner et al. (25) studied 5 subjects with SSD and CI who did not receive consistent benefit for their tinnitus but showed significant improvement in speech recognition threshold in noise.

Vermiere and Van de Heyning (26) investigated the results of CI on the speech recognition of 20 subjects with SSD and tinnitus, 9 of whom wore hearing aids on the contralateral side. This study showed that CI improved speech understanding in difficult conditions. This positive effect was more pronounced in the hearing aid group. However, although squelch effect was improved in the

TABLE 2. *Dichotic digits testing performed at equal volume bilaterally*

Dichotic Digits	Pretraining	Posttraining	Normative data
Right ear	100%	92.5%	94.3%
Left ear	0%	85%	94.2%

The table shows results before and 3 months after training with CI in the left ear.

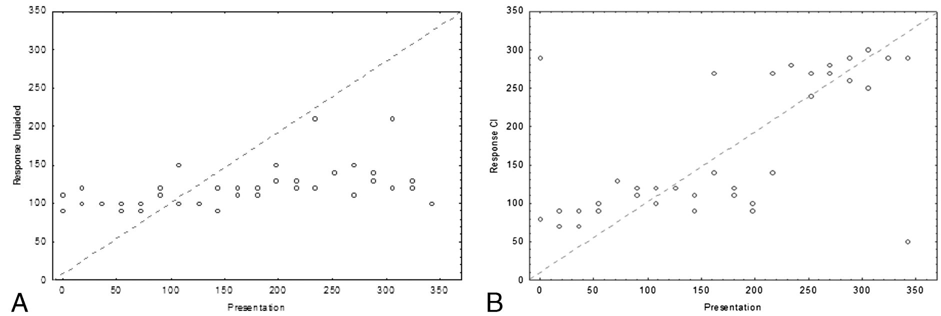

FIG. 3. *A*, Sound localization test results in the unaided condition 3 months after CI in the left ear. Most responses localized to the right with a few back to front reversals. *B*, Sound localization test results after auditory training with CI in the left set at omnidirectional microphone with no other sound processing. The responses seen in the graph are closer to the *diagonal line* as compared with the unaided condition, indicating improved lateralization.

hearing aid group when noise was presented to the CI side, it worsened speech recognition threshold (SRT) for those with contralateral normal hearing. SRT improved significantly in both groups when speech was presented to the CI ear. Subjective improvements in hearing was tested using the SSQ questionnaire, which revealed significant improvement in all 3 areas for those with normal hearing and significant improvement in speech and qualities for the hearing aid group. This is supported by Stelzig's case series demonstrating the benefits in speech recognition of 4 individuals with acquired unilateral hearing loss (27).

In 2011, Arndt et al. (28) published a prospective study assessing sound localization, speech recognition, and tinnitus distress of 11 subjects who had failed to improve sufficiently with CROS or OBCS. This study demonstrated improved speech recognition when the signal was presented to the CI and noise to the normal hearing side, as compared with the unaided condition and with CROS or OBCS. Subjective assessment using the SSQ showed that CI conferred a significant benefit in the speech and spatial components of the questionnaire; however, improvement was not significant for quality of hearing. Five of their 10 subjects with preimplant tinnitus had complete suppression with activated CI, 3 had significant reduction, and 1 had no change, whereas the other had increased tinnitus when the CI speech processor was deactivated. Localization error was significantly reduced when CI was used, as compared with CROS or OBCS.

Two 2011 German studies by Jacob and Arndt, with 13 and 28 subjects, respectively, also found that speech comprehension and localization were improved in those with CI for SSD (29,30) Hassepasse et al. (31) reproduced similar findings in 3 children with acquired unilateral hearing loss in his 2013 study. Firzt et al. (32) published a study on 5 prelingual and 5 postlingually deaf individuals with asymmetrical hearing loss who received unilateral CIs. Their study found that speech recognition was improved in all participants and that sound localization was significantly improved for those who were prelingually deaf.

Our case report is adding to the available body of literature supporting the use of CI for the improvement of sound localization in SSD. Search of the literature revealed approximately 55 subjects tested for sound localization after CI in SSD.

It is known that using CI for hearing restoration does not provide synchronized stimulus from both cochleae affecting ITD (4,34). Theoretically, this would result in suboptimal binaural hearing also affecting localization of sounds. We hypothesize, however, that auditory training and brain plasticity contribute to minimize the lack of synchronized signal provided by a CI and therefore allowing for sound localization to be relearned in cases of postlingually unilateral deafness.

There are several studies, which demonstrate brain plasticity and ability to learn sound localization. A 1984 study on barn owls show that animals are able to regain sound localization abilities after bilateral hearing was regained at a young age, but older animals did not exhibit this improvement (35). Plasticity in the adult animal was demonstrated by the study by Kacelnk et al. on adult ferrets, where they simulated unilateral deafness by occluding 1 ear. The ferrets then received auditory training using behaviorally relevant tasks and showed improvement in sound localization abilities (36). These abilities may be explained by increased reliance on spectral cues, which help sound localization in the vertical plane as a result of filtration of high-frequency sounds by the external ear. Further studies on ferrets have shown that this increased reliance on monaural spectral cues is also accompanied by neuronal changes (37).

Similar studies have been performed in humans. A 2010 study on 20 adults with prolonged unilateral ear plugging had participants divided into 3 groups who received variable quantity and duration of training. The first group received all training in 1 day, the second group received 125 trials per day for 7 to 8 days, whereas the third group received 250 trials a day for 8 days. Interval sound localization tests showed continuous improvements in the both groups who were daily trained in contrast to the first group (38).

Similar results were seen in the 2011 study Irving and Moore on 12 adults who were split into 2 groups: one with ear plugs and another control group. Their study showed that there were improvements in sound localization up to the fifth day in those without ear plugs. Significant improvements were seen with training in those with unilateral ear plugging, especially in the first 4 days after plugging (39).

Kuhn-Inackers (47) advocated the use auditory rehabilitation after bilateral CI in children. They demonstrated the benefit of auditory verbal training to help improve speech discrimination in noise.

To the best of our knowledge, there are no published studies demonstrating the effects of auditory training to improve binaural hearing after cochlear implantation in SSD. According to the available research, the auditory system is capable of adaptation. We found in this study that our patient's localization abilities improved significantly 3 months after implantation and auditory training.

CONCLUSION

Our study has demonstrated that in our patient, cochlear implantation provided superior improvements on sound localization when compared with the OBCS. Additionally, the 3 months of auditory training may have allowed further improvements in sound localization, although not to the same accuracy as in people with normal binaural hearing.

We acknowledge that this is a single case; however, we aim to contribute to the available literature to expand the evidence base in favor of CI for SSD, as well as auditory training. Further controlled studies are required to ascertain whether CI alone would provide the same end result as compared with CI with the intervention of formal auditory training.

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