The binaural cues in the single-sided deafness rehabilitation with cochlear implant

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Abstract
The aim of the study was to investigate speech perception in noise in patients with Single-Sided Deafness (SSD) who received cochlear implant (CI). A cross-sectional, experimental, retrospective study was conducted involving 15 patients with SSD (8 males and 7 females, mean age 41.1 years). The SSD in the studied sample had different etiologies including cases with poor prognosis. All subjects underwent the Matrix test in Italian language in three different spatial configurations: speech and noise both from the front, speech from the front and noise on SSD side, speech on SSD side and noise on normal hearing side. Each condition was measured with the deaf side aided by cochlear implant or unaided. The patients were then invited to complete The Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004). Speech perception thresholds via Italian Matrix Sentence Test were measured initially in 15 patients and subsequently in 12 patients, given the exclusion of three participants as they were non users. With the use of cochlear implant were observed improvements in the head shadow effect in the sample of 15 patients and also in the squelch effect in the sample of 12 patients. No statistically significant results emerged from the SSQ questionnaire. Patients who have received CI as treatment for SSD may experience benefits in speech recognition in noise, even in challenging cases.

Keywords: Single-Sided Deafness, Cochlear implant, Binaural hearing, Matrix Sentence Test.

Introduction

Single-Sided Deafness (SSD) refers to a condition in which there is severe-to-profound hearing loss in the worse ear, with a pure-tone average (PTA) > 70 dB HL, and normal hearing (NH) threshold in the better ear, with PTA ≤ 25 dB HL (Morelli et al., 2023). SSD prevents binaural acoustic stimulation. Specifically, binaural hearing consists of processing the information that arrives from both ears, which is then integrated by the brain to create a three-dimensional acoustic landscape that helps with the segregation of sound objects and their localization (Avan et al. 2015, 3-6). Patients with SSD cannot benefit from three functional advantages of binaural hearing: head shadow effect, squelch effect and binaural summation. In the head shadow effect the head acts as an acoustic barrier and attenuates signals from the contralateral side: when noise comes from a specific direction, the ear farthest from the noise perceives a better signal-to-noise ratio due to the attenuation of the noise by the head; the ear closest to the noise, on the other hand, will have a lower ratio (Avan et al. 2015, 3-6). Binaural squelch is a neurophysiological process occurring in the brainstem that leverages the differences in the acoustic signals received by each ear to improve the understanding of a target sound, especially in noisy environments; the head shadow effect contributes to this discrimination as noise coming from one side can be attenuated by the opposite ear. The binaural summation effect describes a phenomenon in which the signal coming from both ears combines, creating a sensation of greater sound intensity (Zeitler & Dorman, 2019). As a result of the loss of binaural advantages, patients with SSD experience greater difficulty in speech perception in noise and sound localization, with various functional limitations. These include safety risks, such as not hearing an approaching vehicle from the deaf side, as well as a high cognitive load required to process auditory information. Furthermore SSD has been associated with increased levels of anxiety and communication difficulties in the presence of background noise and decrease in self-esteem (Kobosko et al., 2018). The difficulty in communicating with multiple parties leads patients with SSD to withdraw from social situations, impacting both personal and professional relationships. To manage SSD, treatment options such as CROS hearing aids, bone-conduction devices (BCDs) and cochlear implants (CI) are available (Bruschini et al., 2024), but only the cochlear implant allows direct stimulation of the deaf side. Systematic reviews of the available literature (Cabral et al., 2016); (Katiri et al., 2021) generally report that cochlear implantation is the solution capable of providing adults with SSD not only with improved speech perception in noisy environments, but also with more precise sound localization abilities and a reduced severity and incidence of tinnitus (Arndt et al., 2011); (Tokita et al., 2014); (Vlastarakos et al., 2014) compared to an air-conduction CROS system, a BAHA (Bone-Anchored Hearing Aid) or no treatment. CROS devices and bone-conduction implantable systems are only able to overcome the deficits caused by the head shadow effect (an exclusively physical mechanism that does not involve binaural fusion), as they place a sensor on the side of the deaf ear and transmit the acoustic signal to the cochlea of the better ear; this implies a constant effort with postural adjustments in an attempt to become aware of the sound coming from the deaf side, with a nearly constant sense of confusion, especially in noisy environments. Although it is widely proven that the cochlear implant is a well-established, safe, and effective treatment for adult and pediatric patients who do not receive sufficient benefit from traditional acoustic amplification (Grounds et al., 2021); (Hermann et al., 2019); (Brown et al., 2022); (Culbertson et al., 2022), the evidence from studies remains limited due to the use of different methodologies, making the results difficult to compare with one another. The guidelines currently available primarily focus on national rather than international contexts, and they have an undefined structure that is not universally shared. The latest available Italian guidelines on cochlear implantation suggest cochlear implantation for adult patients with SSD and a hearing threshold in the better ear PTA ≤30 dB (strength of the recommendation conditional in favor), although the evidence is very weak (ISS, online source). Given this, the study was born from the desire to provide a small scientific contribution to the literature aimed at documenting the outcomes achieved with the use of the cochlear implantation in patients with SSD and to standardize the methodology for conducting instrumental assessments carried out for this purpose, so that the results obtained can be considered uniform and therefore comparable.

The aim of the study was to evaluate the outcomes of remediation with cochlear implantation in patients with severe or profound unilateral hearing loss and preserved hearing in the contralateral ear, both in objective terms through the execution of the Matrix Sentence test (MST), and in subjective terms by completing the Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004).

Materials and Methods

Study design and participants

This is a cross-sectional, retrospective, bicentric study conducted on 15 patients with SSD treated with CI (8 males and 7 females, mean age 41.1 years); 8 patients were followed-up at the Audiology Service of the “Molinette” Hospital - AOU City of Health and Science of Turin, and the other 7 patients were followed-up at the Simple Structure of Audiology and Cochlear Implants of the “Martini” Hospital- ASL City of Turin. Inclusion criteria were age over 10 years and use of CI in worst ear. Subjects with syndromes or associated pathologies, unable to complete the adult version of the Italian Matrix Sentence Test (Puglisi et al., 2021) were excluded from the study. The SSD in the studied sample had different etiologies: congenital left sensorineural hearing loss, Ski-slope type, suddenly worsened due to delayed ipsilateral endolymphatic hydrops, with significant deterioration in speech recognition (n 1), acquired right unilateral sensorineural hearing loss with rapidly evolving partial cochlear ossification, as a result of otogenic labyrinthitis (n 1) sudden unilateral sensorineural hearing loss (n 8), 4 of whom resulting from head trauma, unilateral Meniere's disease (n 1), progressive unilateral sensorineural hearing loss (n 4). In our study, the duration of auditory deprivation did not exceed fifteen years for any of the subjects, except for one case: the patient with congenital left sensorineural hearing loss and delayed ipsilateral endolymphatic hydrops, for whom the deprivation period exceeded fifteen years, which is typically regarded as the threshold beyond which deprivation may become a negative prognostic factor (Sorrentino et al., 2020). Patients from the respective hospitals underwent cochlear implantation procedure by the same otosurgeon. None of them experienced significant postoperative complications. Subject with ossified cochlea only received partial electrode insertion due to the obstacle in the advancement of the array caused by medio-apical turn ossification. No surgical difficulties occurred in the other patients and the electrodes insertion was thus complete. All patients underwent imaging exams (CT and MRI) in the preparatory phase for the intervention in order to assess the anatomy of middle and inner ear. Speech therapy rehabilitation was conducted following implant insertion.

Study protocol

All patients underwent CI fitting, checks of the implant status and tested, speech-in-noise ability and the administration of a questionnaire.

Audiological assessment

Speech assessment in noise was performed using the Italian Matrix Sentence Test, an adaptive vocal audiometry. This test measures SRT (Speech Reception Threshold), i.e. the signal/noise ratio that allows the patient to recall 50% of the words. The listeners conducted the exam in three different spatial configurations of signal (S) and noise (N), both unaided and aided, for better evaluation of the main phenomena characterizing binaural hearing (summation, squelch, head shadow). The configurations used were those proposed by Paul Van de Heyning et al. (2016): S0N0 (signal and noise both from the front for the binaural summation effect); S0NSSD (signal from the front and noise from the SSD side for the squelch effect; SSSDNNH (signal from the SSD side and noise from the NH - normal hearing – side for the head shadow effect. Initially, the data analyzed included all the enrolled patients; subsequently, since three patients were found to be non-users at the datalogging, we decided to exclude them from the study and to run a new statistical analysis.

Questionnaire

The Italian version of the Speech, Spatial and Qualities of Hearing Scale questionnaire (Noble & Gatehouse, 2004) was administered before and after cochlear implantation. The SSQ is a commonly used questionnaire that measures the impact of hearing loss in different daily-life listening circumstances, e.g. speech hearing in the presence or absence of background noise in different spatial auditory situations, as well as the ability to localize sounds and evaluate the perceived quality of speech in terms of naturalness, clarity, ability to differentiate interlocutors and perception of music. The Italian translation that we used consists of three sections (Speech, Spatial, Other Qualities) for a total of 50 items; however, a question was removed from the Other Qualities section as it was not applicable to this patient group. Therefore the items administered totaled 49. The scoring method used for each item consists of a "ruler" representation, with scores ranging from 0 to 10: a lower score indicates greater auditory difficulty or disability, while a higher score reflects better auditory performance in the situations described by the scale. The final result is the average of the scores obtained in the three domains.

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics software, version 30.0. Since the analyzed sample consisted of a limited number of patients, the first step was to assess the possibility of analyzing the obtained data using parametric formulas. For this purpose, skewness and kurtosis were initially considered. Subsequently, since the values of skewness and kurtosis were within tolerable limits (set as accepted values up to or slightly beyond +1 and -1), the Kolmogorov-Smirnov test was performed, that is a non-parametric normality test that examines the shape of the sample distributions to provide greater certainty regarding the potential normality of the analyzed curves. Since the significance of the Kolmogorov-Smirnov test was found to be greater than 0.05 (which we set as the statistical significance level) for all the analyzed curves, it could be assumed that all the curves examined did not differ from a normal distribution. Student's t-test for paired samples was used to analyze the data from the MST, all tests were conducted with a two-tailed approach and the statistical significance level was set at the conventional value of $p<0.05$. To compare pre- and post-cochlear implant scores of SSQ we choose to apply the Wilcoxon signed-rank test as sample size was smaller (N=9) and normality of the distribution was not guaranteed.

Results

Initially, the study sample consists of 15 cochlear implant recipients with SSD. Table 1 summarizes the gender, age, etiology of the hearing loss, and characteristics of cochlear implant insertion in the study sample of 15 patients with SSD.

Table 1: Demographic and clinical characteristics of the study sample

Patients	Gender	Age (y)	Etiology of Hearing Loss	Cochlear Implant Insertion
1	F	34	Congenital hearing loss and ipsilateral delayed endolymphatic hydrops	Complete
2	M	54	Progressive hearing loss	Complete
3	F	30	Otogenic labyrinthitis	Partial (about half the array)
4	F	50	Sudden idiopathic hearing loss	Complete
5	F	53	Sudden idiopathic hearing loss	Complete
6	F	52	Meniere's disease	Complete
7	M	23	Progressive hearing loss	Complete
8	M	24	Sudden hearing loss in head trauma	Complete
9	M	22	Progressive hearing loss	Complete
10	F	62	Sudden idiopathic hearing loss	Complete
11	F	10	Progressive hearing loss	Complete
12	M	71	Sudden hearing loss in head trauma	Complete
13	M	66	Sudden hearing loss in head trauma	Complete
14	M	43	Sudden hearing loss in head trauma	Complete
15	M	50	Sudden idiopathic hearing loss	Complete

The overall results of the evaluation performed using the Matrix Sentence Test are shown in Table 2: the comparison between the values obtained in patients unaided or aided with cochlear implant indicates that there were no statistically significant improvements in speech intelligibility in noise neither when the signal (speech) and noise were presented both from the front (summation), nor when speech was presented from the front and noise from the SSD side (squelch). However, when speech was presented from the SSD side and noise from the normal hearing side (head shadow), the difference was found to be statistically significant.

Table 2 – Results of the Italian Matrix Sentence Test in the Configurations: Summation, Squelch, Head Shadow, with and without Cochlear Implant

Patients	Summation		Squelch		Head Shadow	
	Without CI	**With CI**	**Without CI**	**With CI**	**Without CI**	**With CI**
1	-4.80	-6.80	-6.70	-7.10	-2.20	-4.60
2	-1.00	.00	-3.90	-6.20	6.50	5.20
3	-4.00	-5.20	-6.50	-5.40	-0.70	-1.20
4	-3.60	-3.70	-9.70	-11.70	3.80	1.00
5	-2.40	-3.10	-5.80	-3.80	-1.10	-2.20
6	-2.30	-3.00	6.10	3.60	-2.30	0.10
7	-3.50	-3.70	-10.60	-9.20	-10.30	-11.70
8	-5.20	-4.70	-8.60	-9.70	-12.00	-12.70
9	-4.40	-4.50	-2.40	-7.30	-2.90	-4.70
10	-4.40	-4.70	-0.70	-3.80	-3.00	-7.00
11	-3.20	-3.60	-4.60	-4.40	-8.50	-8.80
12	-3.50	-3.40	-4.30	-5.00	-12.80	-11.70
13	-5.20	-5.80	-8.20	-8.70	0.40	-3.30
14	-1.60	-3.20	-6.90	-8.50	7.30	5.00
15	-6.10	-5.80	-6.90	-7.50	-3.70	-7.10
Mean	-3.68	-4.08	-5.31	-6.31	-2.77	-4.25
	Without vs with CI		Without vs with CI		Without vs with CI	
Paired Differences (Mean)	0.40		1.00		1.48	
Significance	.068		.052		.006	

In the analysis conducted excluding the three non-users (see patients n. 5, 7, and 8) the paired differences (mean) were found to be 0.47 for summation, 1.44 for squelch and 1.58 for head shadow configuration; the results obtained in the squelch and head shadow settings, in the comparison without and with CI, were statistically significant with p-values of 0.011 and 0.017, respectively (the significance level used was set at 0.05).

The participation rate in the SSQ questionnaire was 60% of the study participants, with only 9 out of 15 individuals providing feedback. The mean scores of the SSQ questionnaire sections, pre- and post-cochlear implantation, divided by individual patient, are shown in Table 3.

Table 3: Mean SSQ Scores of Each Patient Before and After Cochlear Implant, Divided by the Three Subscales (Speech, Spatial, Other Qualities)

Mean SSQ Scores						
Patients (N=9)	**Speech**		**Spatial**		**Other Qualities**	
	Pre-CI	**Post-CI**	**Pre-CI**	**Post-CI**	**Pre-CI**	**Post-CI**
1	6,00	8,78	4,82	7,47	7,22	7,94
3	7,28	6,92	4,35	5,88	8,94	8,33
4	7,28	6,64	5,11	6,29	6,83	6,83
6	2,43	5,57	1,82	4,88	1,88	5,22
7	7,00	7,92	3,29	4,82	9,50	8,50
8	7,35	7,50	6,00	6,47	8,94	7,77
10	7,28	7,28	8,80	8,82	9,16	9,05
12	8,50	5,35	7,94	5,00	8,83	6,27
15	6,07	6,50	3,70	5,17	7,83	7,16

In the Speech section, five participants showed improvement in their scores, three showed deterioration, and one showed no change; the differences between pre- and post-implant scores were not found to be statistically significant, as the *p*-value (0.5529) was well above the 0.05 threshold. For the Spatial section, eight participants showed improvement in their post-implant scores, while one showed a decline; although the *p*-value in this section also indicates a result that is not statistically significant (*p*-value of 0.0856), the results suggest that cochlear implantation may have a positive effect on spatial perception. Finally, for the Other qualities section, two participants showed better post-implant scores, six showed worse post-implant scores, and one showed no change; in this section as well, no statistically significant differences between pre- and post-cochlear implant scores emerged (*p*-value of 0.3424).

Discussion

The study aimed to investigate cochlear implantation outcomes and binaural benefits in patients with SSD. Paul Van de Heyning et al. (2016) formulated a Consensus Paper, suggesting guidance on how to detect the binaural benefits using adaptive speech audiometry in competitive conditions; we followed the guidelines provided by this Consensus Paper and used the configurations outlined in it for conducting the Matrix Sentence Test. With this observational methodology, we registered an SRT improvement in all settings, but the results were statistically significant only for SSSDNNH (head shadow) setup in the sample of 15 patients and for SSSDNNH (head shadow) and S0NSSD (squelch) setups when non-users were excluded. The SRT improvement measured in the particular scenario in which noise is closer to SSD side (squelch) could suggest that the use of CI can restore the brainstem ability to compare and integrate a dichotic sound presentation (i.e. different signals at each ear) enhancing the signal while reducing the noise. As well known for this effect to take place, neural integration from both sides is required. These findings support the idea that patients with SSD can experiment binaurality restoring. Even patient with partial electrode insertion and patient with long deprivation reported benefits and subjective satisfaction. In the partial insertion case the electrode array insertion was limited to the basal turn and it was not possible to reach the regions of the cochlea corresponding to the mid-to-low frequencies, which are precisely the frequencies where the squelch phenomenon mainly occurs. Therefore no improvement in the squelch effect was observed. Regarding the long deprivation, in our study only in two cases there was an interval of time (3 years in one patient and 27 years in another) between the onset of hearing loss and its remediation. As reported in several studies, there is a negative correlation between duration of deafness and cochlear implant performance in SSD individuals when the effect of monoaural hearing on the plasticity of the auditory pathways is prolonged (Ullah et al., 2023). However, monoaural and binaural auditory deprivation are not necessarily contraindications for cochlear implantation (Canale et al. 2016, 1905-1910). It seems that a constant use of the device led to good outcomes, even if this is not always demonstrable or true. In this regard the non-users of this study deserve a special note: it is, in fact, noteworthy to mention that two of three patients (n. 7 and n. 8) showed matrix values that were already very high at baseline (without CI) suggesting that their poor utilization could be due to a lack of need. However, it is important to be mindful of the fact that a lack of acceptance, as a consequence of the stigma associated with disability (Kobosko et al., 2018), is possible. Finally, the picture that emerges from the SSQ results reveals that more patients showed improvement in the speech and spatial sections after cochlear implantation, compared to those who did not. Although these differences were not statistically significant, they suggest a potential positive impact of cochlear implantation on specific auditory functions such as speech perception and sound localization. In contrast, most patients did not show significant improvement in the qualities section, highlighting the need for further adjustments to achieve optimal sound quality. In our study, the analysis of the SSQ results is likely influenced by the small sample size (N=9) and potential individual variability: therefore, caution is needed in the interpretation. Even though the results obtained in this study are consistent with what has been observed in the literature, the missing data highlight the importance of certain aspects of perception that should be further investigated to improve outcomes. The focus should be on raising the patient's awareness to share their experience and dedicating the appropriate time—preferably during audiometric testing or at clinical follow-up visits—to systematically and properly collect such information.

Conclusions

Our findings suggest that patients who received CI as treatment for SSD may experience benefits in speech recognition in noise, even in suboptimal conditions. Understanding more thoroughly the real objective and subjective benefits of cochlear implant application in this type of hearing loss is essential for providing stronger support for the recommendations that guide clinical decision-making. The need to continue conducting studies like the one we carried out is crucial in order to standardize and make the collected data more comparable.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Ethics permission

This study was conducted in accordance with the ethical principles of the World Medical Association Declaration of Helsinki.

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