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Factors Predictive of Binaural Hearing Restoration by Cochlear Implant in Single-Sided Deafness

Guillaume Gersdorff[a] Vincent Péan[b] Séverine Camby[a] Sébastien Barriat[a]
Philippe P. Lefebvre[c]

[a]Department of Oto-Rhino-Laryngology, Head and Neck Surgery, CHU Liège, Liège, Belgium; [b]MEDEL (Med El Care Center Paris), Paris, France; [c]Department of Oto-Rhino-Laryngology, Head and Neck Surgery, University of Liège, Liège, Belgium

Keywords
Binaural hearing · Single-sided deafness · Cochlear implant

Abstract
Introduction: Cochlear implants (CIs) can restore binaural hearing in cases of single-sided deafness (SSD). However, studies with a high level of evidence in support of this phenomenon are lacking. The aim of this study is to analyze the effectiveness of CIs using several spatialized speech-in-noise tests and to identify potential predictors of successful surgery. ***Methods:*** Ten cases underwent standard CI surgery (MEDEL-Flex24). The speech-in-noise test was used in three different spatial configurations. The noise was presented from the front (N0), toward the CI (NCI), and toward the ear (Near), while the speech was always from the front (S0). For each test, the speech-to-noise ratio at 50% intelligibility (SNR50) was evaluated. Seven different effects were assessed (summation, head shadow [HS], speech released of masking [SRM], and squelch for the CI and for the ear). ***Results:*** A significant summation effect of 1.5 dB was observed. Contralateral PTA was positively correlated with S0N0-B and S0NCI-B (CIon and unplugged ear). S0N0-B results were positively correlated with S0N0-CIoff ($p < 0.0001$) and with S0Near-CIoff results ($p = 0.004$). A significant positive correlation was found between delay post-activation and HS gain for the CI ($p = 0.005$). Finally, the HS was negatively correlated with the squelch effect for the ear. ***Conclusion:*** CI benefits patients with SSD in noise and can improve the threshold for detecting low-level noise. Contralateral PTA could predict good postoperative results. Simple tests performed preoperatively can predict the likelihood of surgical success in reversing SSD.

Introduction

Binaural perception is an important aspect of hearing function that allows the localization of sounds and understanding of speech in a noisy environment. This auditory ability helps listeners orient toward a sound of interest and to avoid interferences with background noise [1–3]. Unilateral hearing loss (UHL) or single-sided deafness (SSD) affects 3–6% of the general population [4]. Receiving unilateral sound negatively impacts binaural function, which leads to impairment. Affected patients have difficulty with localizing sounds, their capacity to understand speech in noise is decreased, and discriminating between words is harder. This situation

karger@karger.com
www.karger.com/aud

Correspondence to:
Philippe P. Lefebvre, pp.lefebvre@uliege.be

Karger

requires compensatory mechanisms and high concentration. Furthermore, patients' quality of life can be affected by social isolation [5–7].

tFew hearing-assistive devices have been developed to counteract SSD-related impairments. These devices re-route sounds that arrive at the impaired ear to the unimpaired ear. This can be achieved through the air with a contralateral routing of signal (CROS) device or through bone with a bone conduction hearing aid (BCHA). In the former case, sounds are received at the side of the impaired ear by a microphone connected to a hearing aid on the non-impaired side. Sounds are transmitted from the impaired to the unimpaired ear, which results in the unilateral input of sounds without restoration of true binaural function [8–10]. Consequently, those types of devices improve auditory capacity in some conditions but degrade them in others [8, 11].

Many binaural functions can be restored by a CI [12]. Unlike CROS and BCHA, CI acts by electrically stimulating auditory neurons that remain within the impaired ear. Acoustic parameters (e.g., number of electrodes, pulse rate, etc.) are adjusted to adapt electric stimulation of the impaired ear using acoustic stimulation of the unimpaired ear [13]. The implantation of a single CI was previously recommended in cases of bilateral hearing loss, but indications were extended. The first use of CI to treat SSD was reported in 2008 [14].

Many studies have assessed outcomes in patients affected by SSD treated by CI compared to BCHA and CROS. Studies showed that CI implantation in the deaf ear enables binaural function rehabilitation. Sound localization was restored, and speech understanding highly improved after implantation, while the severity of SSD-related tinnitus was reduced. Moreover, CI confers greater improvement in sound localization than BCHA or CROS [10, 14–18]. Localization also improves when a CI is implanted in the deaf ear and a hearing aid is used in the unimpaired ear [19, 20]. Improvement in speech understanding is higher in cases of CI implantation, but these results depend on sound orientation and the speech-to-noise ratio [19, 21]. Tinnitus symptoms can decrease or disappear entirely after CI, especially in cases of resistant tinnitus [14, 16, 17].

However, none of the previous studies provide a high level of evidence to consider CI a suitable treatment for patients with SSD. Criteria to recommend implantation and predictive factors have yet to be defined [16, 17].

Here, we present a series of 10 cases of unilaterally implanted patients affected by SSD. The aim of this study is to analyze the efficiency of CI through several spatialized speech-in-noise tests and examine any associated central effects. Finally, we identify potential factors predictive of a successful surgery.

Materials and Methods

This retrospective study includes 10 cases from one tertiary referral center (CHU Liège, Liège, Belgium) assessed between February 2018 and December 2019. All patients were listed in an Excel database (Excel, Microsoft, USA).

Inclusion and Exclusion Criteria

The inclusion criteria of the patients presenting with SSD or unilateral asymmetric hearing loss (UAHL) were as follows: Adults (>18 years of age) with a pure-tone average (PTA) (mean thresholds at 0.25, 0.5, 1, 2, 4 kHz) over 70 dB HL in the poorer ear and under 30 dB HL (for SSD) (interaural threshold gap ≥40 dB HL) or between 30 and 55 dB HL in the better ear (for UAHL) (interaural threshold gap ≥15 dB HL) [22]. They were all native French speakers. Based on preoperative CT scans and additional evaluation, patients were excluded if they presented middle ear pathology, cochlear ossification, retro-cochlear pathology, or documented severe central auditory processing disorder.

Methods of Research

The patients were seen at least twice in the 2 months preceding implantation surgery. All patients underwent standard CI surgery with a 12-channel Concerto system (MEDEL-Flex 24 electrodes, Innsbruck) and received standard audiology and speech therapy care. Rehabilitation was performed using an audio or audio-video source connected directly to the implant via a cable connector. Training sessions were performed once daily for at least 30 min. Patients were instructed to wear the implant all day.

Speech perception and binaural hearing were evaluated using a spatialized speech-in-noise perception test. The earliest point of testing was 4 months post-CI activation and the latest one was 65 months post-CI activation. Stimuli included French dissyllabic words (Fournier lists) with or without free-field stationary white noise.

The speech-in-noise test was carried out in three different spatial configurations, the speech always coming from the front (S0): with CI and ear (B), with CI off and unplugged ear (CIoff), and with the ear plugged and muffled and CI on (EARoff). The ear was plugged and muffled using an insert and a headset (PELTOR, 3M®). The resulting attenuation was 30 dB from 250 to 1,000 Hz and 40 dB from 1,000 to 8,000 Hz. Because we only had two channels (one for noise and one for speech), we were not able to carry out masking. Regarding contralateral masking mistakes, 4 patients were excluded from some analyses.

For each spatial configuration, the noise was presented from the front (N0), on the CI side (NCI), or on the ear side (Near).

The patient ran nine tests:

- Three with noise presented from the front (S0N0-B, S0N0-EARoff, and S0N0-CIoff). (Fig. 1)
- Three with noise presented on the CI side (S0NCI-B, S0NCI-EARoff, and S0NCI-CIoff). (Fig. 2)
- Three with noise presented on the ear side (S0Near-B, S0Near-EARoff, and S0Near-CIoff). (Fig. 3)

The CI side could be right or left. For each test, the speech-to-noise ratio for 50% intelligibility (SNR50) on dissyllabic words was evaluated. An adaptive procedure was used; the noise level was set at 60 dB SPL, and the speech level varied depending on the response of the patient. The first SNR was set at a level depending on the patient (defined by the audiologist): if the patient correctly

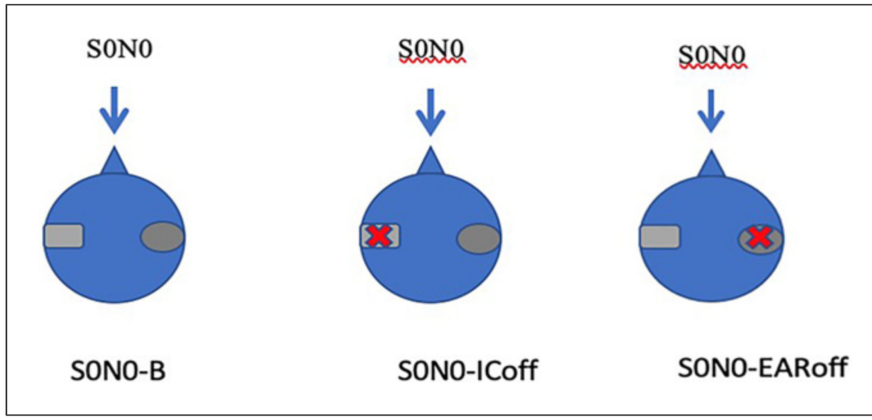

Fig. 1. Tests with noise presented from the front (S0N0-B, S0N0-EARoff, S0N0-CIoff).

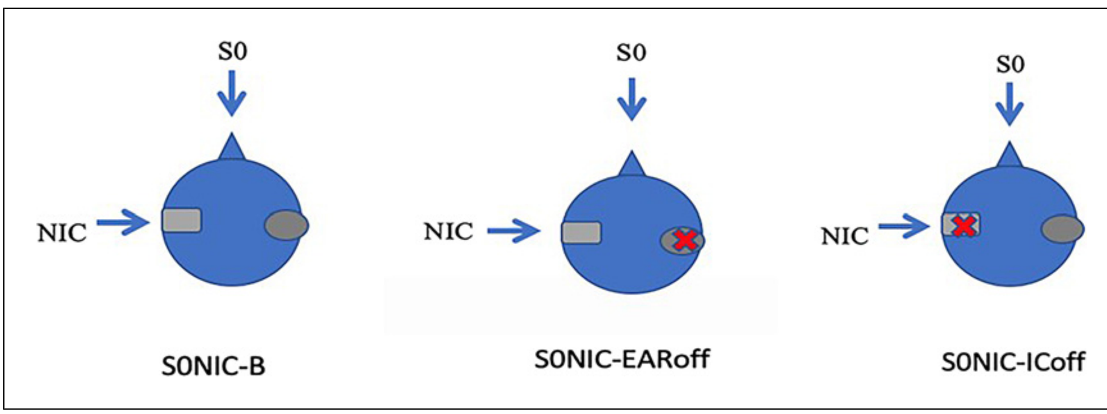

Fig. 2. Tests with noise presented on the CI side (S0NCI-B, S0NCI-EARoff, S0NCI-CIoff).

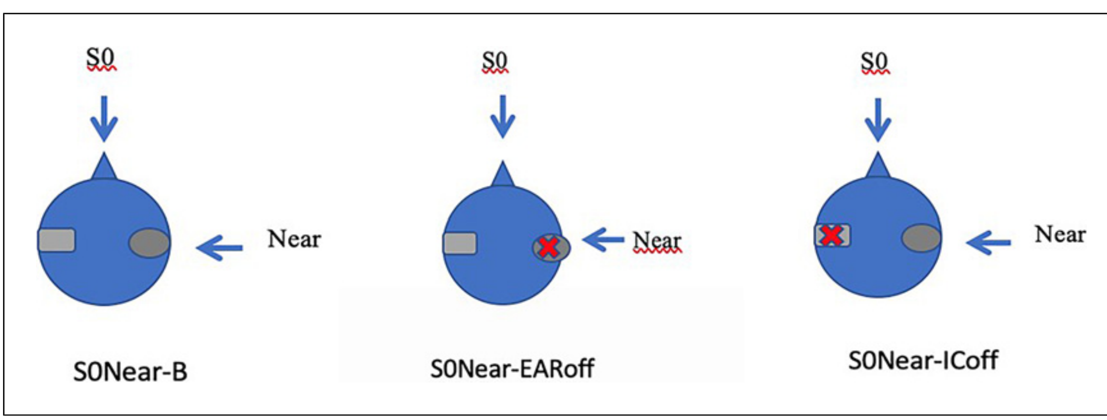

Fig. 3. Tests with noise presented on the ear side (S0Near-B, S0Near-EARoff, S0Near-CIoff).

repeated the word, the SNR was reduced; otherwise, the SNR was increased. The SNR variation step was 5 dB at first, then refined to 2 dB throughout the test.

For each patient, nine results were used to calculate different effects [23]: summation effect, head shadow (HS) effect for CI, and for the unaffected ear, speech released of masking (SRM) for CI;

and for the unaffected ear, squelch effect for CI and for the unaffected ear.

Seven effects were evaluated with the following gains:

1. Summation = SNR50 (S0N0-B) – SNR50 (S0N0-CIoff)
2. HS for CI = SNR50 (S0Near-EARoff) – SNR50 (S0NCI-EARoff)
3. HS for ear = SNR50 (S0NCI-CIoff) – SNR50 (S0Near-CIoff)
4. SRM for CI = SNR50 (S0Near-EARoff) – SNR50 (S0N0-EARoff)
5. SRM for ear = SNR50 (S0NCI-CIoff) – SNR50 (S0N0-CIoff)
6. Squelch for CI = SNR50 (S0Near-B) – SNR50 (S0Near-EARoff)
7. Squelch for ear = SNR50 (S0NCI-B) – SNR50 (S0NCI-CIoff)

Statistical Analysis

For each effect, mean and standard deviation (SD) were calculated. The mean of each effect was compared to 0 with the Wilcoxon signed-rank test, and the Holm-Bonferroni correction was applied with a significance level between 0.007 and 0.05 (seven comparisons).

Two groups of patients were compared: patients with unilateral sudden hearing loss (USHL) and patients with other etiologies. The Mann-Whitney U test with the Holm-Bonferroni correction was applied at a significance level between 0.007 and 0.05.

The correlations between the nine tests and age, time since activation, ipsilateral (implanted ear) 250 Hz hearing threshold, or contralateral PTA (non-implanted ear) were calculated with Pearson's correlation coefficient and Holm-Bonferroni correction was applied to set the significance level between 0.005 and 0.05. The same analysis was done with the gains obtained for the seven effects with a significance level between 0.007 and 0.05.

The correlation between the results of the nine tests (2-by-2) was evaluated with Pearson's correlation coefficient, and Holm-Bonferroni correction was applied with a significance level between 0.001 and 0.05. A 95% confidence interval (95% CI) for the correlation coefficient was given for the significant results. The same analysis was done with the gains obtained for the seven effects (2-by-2) with a significance level between 0.002 and 0.05.

Linear regression was calculated to express the result of each condition with the CI and the ear (B) as a linear combination of the other results. The best linear model was automatically selected by the stepwise method.

For all models, the normality of studentized residues was checked by the Q-Q plot and normality test (e.g., Shapiro-Wilk), and the prediction with respect to studentized residues was plotted to check the independence between the two [24]. Discriminant analysis (DA) was used to compare the group of patients with USHL sudden hearing loss from the others using the results of the nine tests. DA was used to compare the group of patients with a short duration of deafness (<5 months) to the group with a long duration of deafness before implantation (>1 year and 9 months).

Results

Ten patients were enrolled in the study, six of whom presented with unilateral sudden hearing loss (USHL). The mean age was 54.5 years (ranging from 22 to 75 years old). There were four men and six women. The duration of deafness before implantation varied between 4 months and 15 years. The patients with USHL were implanted with a short delay of 4–21 months (Table 1).

Nine patients presented a single side deafness (SSD), and one had a (slight) asymmetric hearing loss (AHL) with a contralateral ear with a PTA of 34 dB HL [22] (Table 2). The range of the ipsilateral 250 Hz hearing threshold was 45–120 dB HL (mean: 88.5; SD: 24.3).

Effects and Tests in Noise Results

The patients were tested in noise after cochlear implantation and fitting when they reached a plateau in their speech intelligibility after a period ranging from 7 to 65 months of CI use.

A significant mean summation effect of 1.5 dB (SD = 0.71; p = 0.007) was observed, and the mean head shadow effect was 1.3 dB (SD = 2.9; p = 0.396) for the cochlear implant (CI) and significant with 6.3 dB (SD = 2.8; p = 0.006) for the better hearing ear. The mean speech-masking release effect was 0.7 dB (SD = 2.7; p = 0.785) for the CI and significant with 5.5 dB (SD = 2.8; p = 0.006) for the better hearing ear. The mean squelch effect was 1.5 dB (SD = 2.6; p = 0.269) for CI and 0.40 (SD = 2.5; p = 0.607) for the better-hearing ear (Table 3).

Difference between Test Results with Etiology of Deafness

No significant difference was observed between the group of 6 patients with USHL and the group of 4 patients with other etiologies, including Meniere's disease, unilateral fluctuating, and slowly progressive hearing loss (Mann-Whitney U test: p between 0.01 and 0.46).

Correlation between Test Results with Age, Delay since Activation, Ipsilateral 250 Hz Hearing Threshold

Various correlations were tested to evaluate the potential effects of age or time since activation on the test results or ipsilateral 250 Hz hearing threshold. No significant correlations were found.

Correlation between Test Results and PTA

A significant positive correlation was found between PTA of the contralateral ear and results (SNR50) with "CI + ear" with noise from the front (S0N0-B; R = 0.799, 95% CI = [0.342; 0.951], p = 0.006), or on the CI (S0NCI-B; R = 0.863, 95% CI = [0.511; 0.967], p = 0.001) (Fig. 4). And significant positive correlation was found between PTA of the contralateral ear and results with CI off and noise from the front (S0N0-CIoff; R = 0.873, 95% CI = [0.289; 945], p = 0.008), or on the CI (S0NCI-CIoff; R = 0.873, 95% CI = [0.540; 0.970], p = 0.001).

Table 1. Patient characteristics

Subject	Sex	Age, years	Etiology	Duration of deafness before implantation	Delay between CI activation and tests (months)
S1	M	58	Fluctuating bilateral hearing loss	Some years	25
S2	F	50	USHL	8 months	65
S3	F	50	USHL	1 year and 9 months	23
S4	M	22	USHL	4 months	19
S5	F	47	USHL	4 months	13
S6	M	78	Ménière	A few years	15
S7	F	44	USHL	5 months	4
S8	F	58	Unilateral progressive deafness with slight contralateral hearing loss	15 years	6
S9	M	63	Ménière	3–4 years	8
S10	F	75	USHL	5 months	7

Table 2. Audiometric results

Subject	PTA 500–1,000–2,000–4,000 Hz		Average tone loss in dB	Degree of hearing loss (BIAP)
	affected ear	non-affected ear		
S1	109	28	52.3	MD1*
S2	120	10	43	MD1
S3	120	18	48.6	MD1
S4	110	10	40	MD1
S5	110	13	42.1	MD1
S6	120	27	54.9	MD1
S7	118	10	42.4	MD1
S8	98	34	53.2	MD1
S9	95	23	44.6	MD1
S10	114	22	49,6	MD1

BIAP, International Bureau for Audiophonology – In the event of asymmetric hearing loss of more than 15 dB, the average loss level, expressed in dB, was multiplied by 7 for the "good" ear and by 3 for the "bad" ear. The total was then divided by 10.

For each significant correlation, linear regression was applied and yielded the following models:

- S0N0-B = −9.4 + 0.29* PTA, explained 63.9% of the variability
- S0NCI-B = −13.5 + 0.27 PTA, explained 74.5% of the variability
- S0NCI-CIoff = −14.2 + 0.33 PTA, explained 76.2% of the variability
- S0N0-CIoff = −8.4 + 0.31* PTA, explained 60.4% of the variability

Correlation between the Test Results

The results with the CI off and noise from the front (S0N0-CIoff) strongly positively correlated with the results with "CI + ear" with noise from the front (S0N0-B; $p < 0.0001$; $R = 0.984$; 95% CI = [0.930; 0.996]), or on the CI (S0NCI-B; $p = 0.004$; $R = 0.816$; 95% CI = [0.383; 0.955]) (Fig. 5). The results with the CI off and noise on the ear (S0Near-CIoff) were strongly positively correlated with the results with "CI + ear" with noise from the front (S0N0-B; $p = 0.004$; $R = 0.817$; 95% CI = [0.386; 0.955]), on the CI (S0NCI-B; $p = 0.001$; $R = 0.874$; 95% CI = [0.542; 0.970]), or with "CI off" with noise from the front (S0N0-CIoff; $p = 0.003$; $R = 0.834$; 95% CI = [0.429; 0.960]).

Linear regressions were applied to express the results of the tests with the "CI + ear" with the results of the monaural tests with CI off. The best model was calculated using the stepwise method:

- S0N0-B = −1.78 + 0.88 * S0N0-CIoff explained 96.8% of the variability.
- S0Near-B = −1.55 + 0.70 * S0Near-CIoff explained 50.1% of the variability.

Table 3. Effects gains

Gain	Summation	HS_CI	HS_EAR	SRM_CI	SRM_EAR	SQUELCH_CI	SQUELCH_EAR
S1	2	3	7	−1	9	−1	1
S2	0		3		2		4
S3	2	6	3	4	6	6	2
S4	1		9		7		−3
S5	2	2	9	4	7	0	−1
S6	1		3		1		3
S7	2		9		6		−2
S8	2	−1	5	−2	5	1	−1
S9	1	−1	5	−1	3	0	3
S10	2	−1	10	0	9	3	−2
Mean	**1.5***	**1.3**	**6.3***	**0.67**	**5.5***	**1.5**	**0.40**
SD	**0.71**	**2.88**	**2.83**	**2.66**	**2.76**	**2.59**	**2.50**
Median	2	0.5	6	−0.5	6	0.5	0
p value	**0.007**	0.396	**0.006**	0.785	**0.006**	0.269	0.607

*Statistically significant.

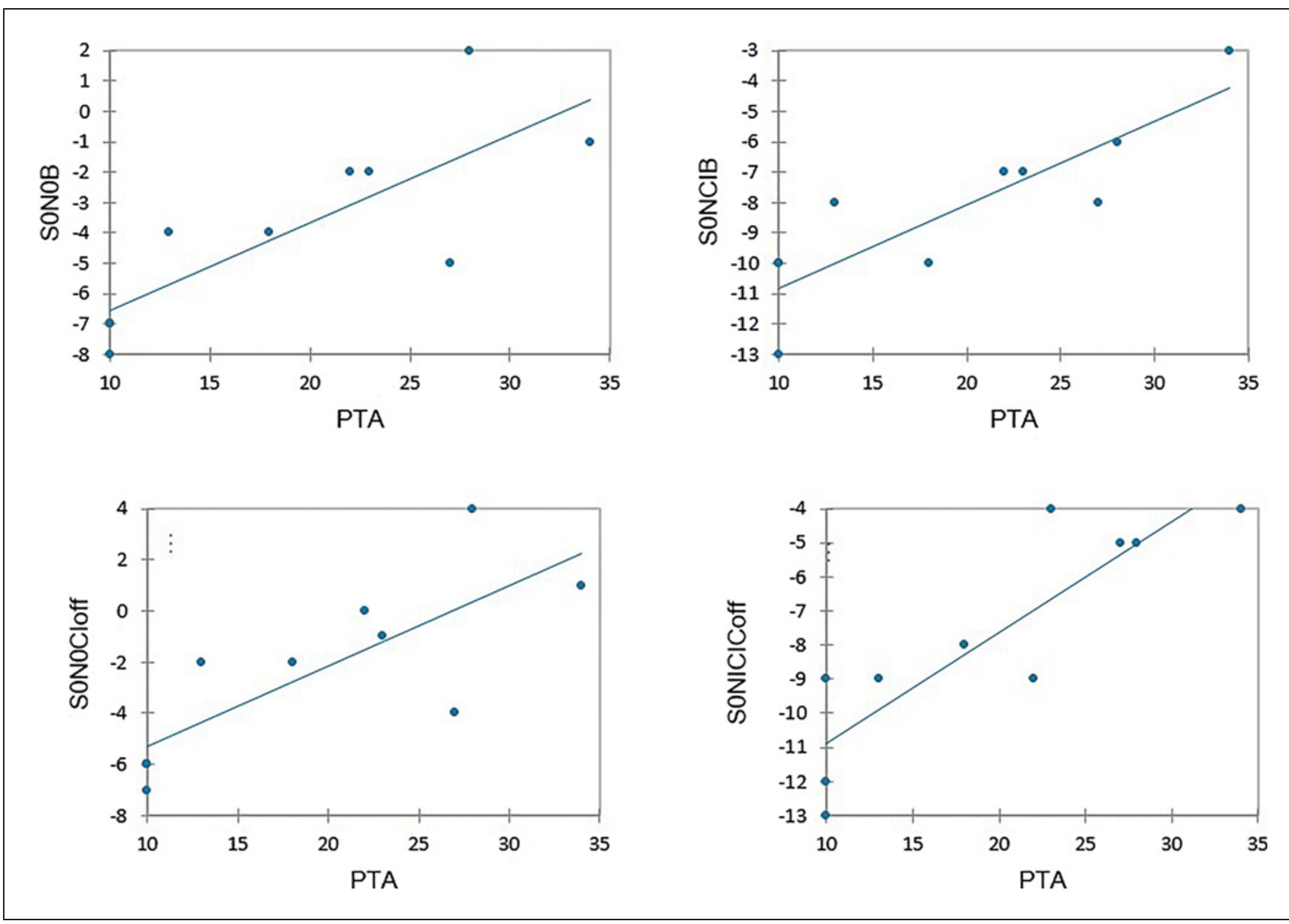

Fig. 4. Correlation between test results and PTA.

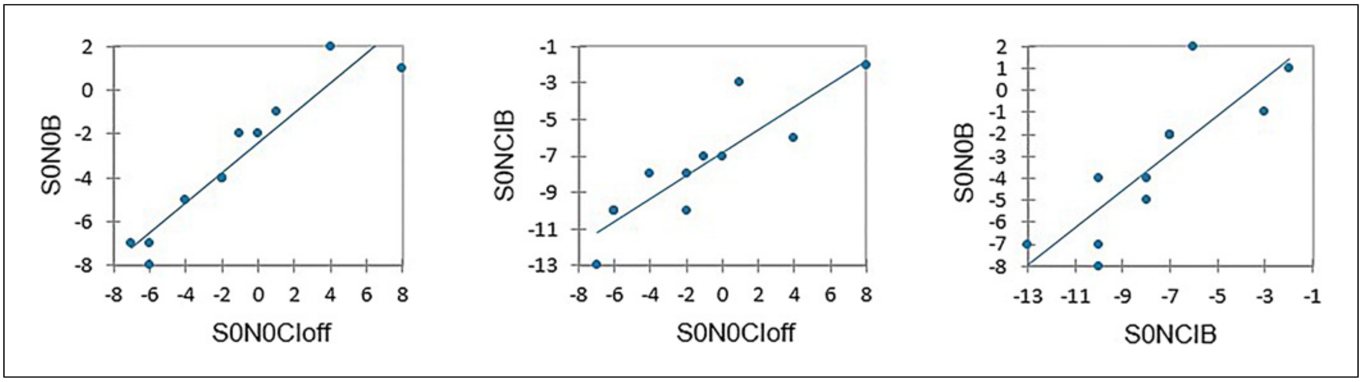

Fig. 5. Correlation between tests' results.

- S0NCI-B = −6.95 + 0.83 * S0Near-CIoff explained 76.3% of the variability.

Discriminant Analysis USHL and Others

Discriminant analysis (DA) was used to compare the group of patients with sudden hearing loss from the other using the results of the nine tests. The best model with selection showed that the results of the test with the CI off and noise on the CI (S0NCI-CIoff) could separate those with USHL from the other patients.

However, DA applied on the duration of deafness before implantation (short [<5 months] or long [>1 year and 9 months]) yielded the same classification result. Moreover, USHL had lower PTA, and PTA strongly correlated with the S0NCI-CIoff results.

Gains

Difference between Gain with Etiology of Deafness

No significant difference was observed between the group of 6 patients with USHL and the group of 4 patients with other etiologies (Mann-Whitney test: p between 0.05 and 0.9).

Correlation between Gain with Age, Delay since Activation, Ipsilateral 250 Hz Hearing Threshold

Various correlations were tested to evaluate the potential effects of age or time between activation and auditory gains. No significant correlation was found between gains and age.

A significant positive correlation was found between delay since activation and HS gain for the CI ($R = 0.902$; 95% CI = [0.464–0.986]; $p = 0.005$) (Fig. 6). Subsequently, the more they wore their CI, the better the HS effect was with the CI (S0Near-EARoff – S0NCI-EARoff) in terms of gain.

No significant correlation was found between gains and ipsilateral 250 Hz hearing threshold. However, the significance for the SQUELCH EAR effect was $p = 0.009$. The patients with negative squelch ear effects had lower ipsilateral hearing thresholds. As the test with CI off was done without plugging or masking the ipsilateral ear, their results were better with the CI off due to their residual hearing.

Correlation between Gain and PTA

No significant positive correlation was found between any gain and PTA in the contralateral ear.

Correlation between Gains

The Pearson correlation between the seven gains (2-by-2) was studied. A negative correlation between HS-EAR (head shadow for the ear: S0NCI-CIoff – S0Near-CIoff) and SQUELCH-EAR (squelch for the ear: S0NCI-B – S0NCI-CIoff) came out from this analysis. The greater the gain for HS, the less gain for the squelch effect and the less effect there will be to activate/deactivate the CI (in this context). The subjects who had a very high HS-EAR gain had no SQUELCH-EAR gain measured by this method.

Linear regression was applied to express the results of the squelch effect for the ear with the results of the head shadow effect for the ear. The best model was calculated using the stepwise method:

- SQUELCH-EAR = 5.22–0.77 * HS-EAR explained 74.9% of the variability.

Discriminant Analysis of USHL and Other Etiologies

No best model could be obtained with our criteria. There was no gain effect in some groups. As such, it was impossible to separate USHL from other etiologies.

Discussion

The effects of the cochlear implant in SSD or UAHL can be measured by several effects (summation, HS for CI, SRM for CI, and squelch for CI). Among these, our

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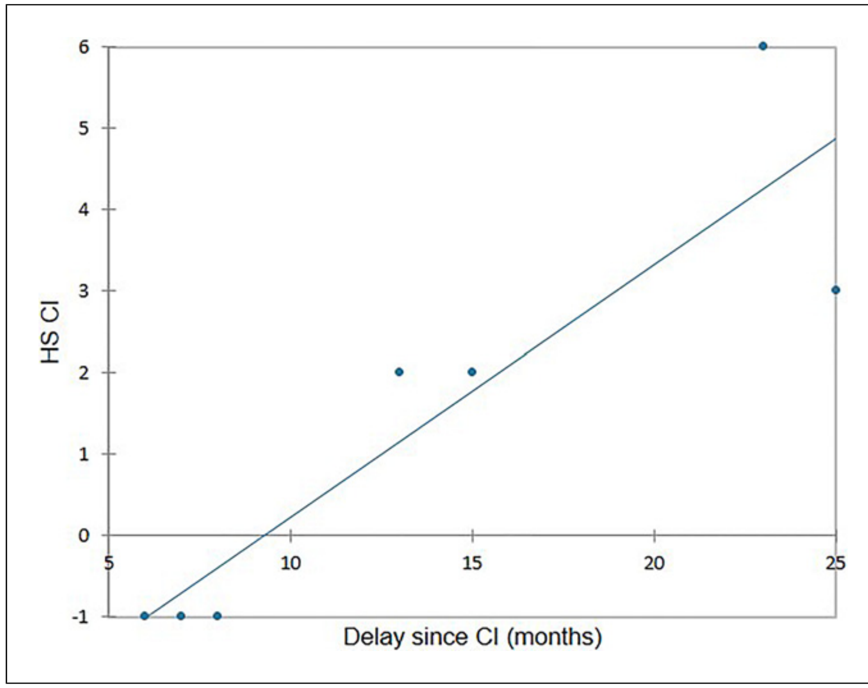

Fig. 6. Significant correlation between HS for the CI gain and the delay since activation ($n = 7$).

results were only significant for the summation effect. Subsequently, CI could also improve the threshold for detecting low-level noise. However, the effect from CI in SSD for listening in noise is rather limited.

This may be consistent with previous findings [25] which demonstrated that adding the worse ear to the better ear, in asymmetric hearing loss, has only a limited effect on the summation and speech understanding effect in noise, leading sometimes to difficulties with monaural hearing aids. Interestingly, our data also support these results, since we have shown that the preoperative state of the contralateral ear can explain and influence postoperative results to a large extent.

It is important to note that it was a small cohort. Subsequently, we had to use stringent statistical criteria, which led to individual results not being highlighted. However, large variability was observed in our data, as is usual in this type of study. For example, a study by Dorbeau et al. [26] did not find a summation effect but observed great inter-subject variability in CI benefit in the S0N0 condition from −4.4 to +6 dB. With such a small cohort, it is not advisable to generalize based on averages. If we look individually at those results, CI led to a clear positive HS and squelch effect for 4 patients and to a clear positive SRM effect for 2 patients. CI tended to produce a positive effect on noise for some SSD patients. However, the profile of subjects for whom this might occur remains unknown. Factors must exist to explain the difference in outcomes between individuals.

In our study, the test results could not be explained by age and time since activation. Moreover, on average, USHL subjects did not perform better than other subjects. A study by Bakhos et al. [27] (2018) observed a significant correlation between age (at testing) and test results in the S0N0 condition with CI on or off. This result could be due to the age repartition difference between the studies in Bakhos et al. [27]; 17% of subjects were younger than 50 years, 33% were between 50 and 60 years, and 50% were older. However, the older patients in our study (75 [S11] and 78 [S7] years old) did not have lower results in these test conditions.

There was a significant positive correlation between contralateral PTA and noise test results under certain conditions (S0N0-B, S0NCI-B, S0N0-CIoff, S0NCI-CIoff). The greater the contralateral hearing loss (PTA) was, the more disappointing the results in noise were. Thus, a better analysis of the signal-to-noise ratio would come from the contralateral ear, whose PTA could explain part of the results of certain tests. However, the PTA was in the normal range for all subjects. Moreover, USHL subjects had better PTA and shorter deafness duration. Thus, the better results in noise could also be due to these confounding factors. The study by Dorbeau et al. [26] separated the patients into two groups (unrestricted acoustic hearing [UNRES] and restricted acoustic hearing [RES]) according to their normal ear PTA thresholds (≤25 dB HL and >25 dB HL) and also found a PTA effect on the test results in the S0N0-B and S0N0-CIoff conditions. The performance was significantly better for the UNRES group than the RES group. When speech and noise were separated (S0NCI-B condition), they also observed better performance for the UNRES group than the RES group. They concluded that this could be due to the availability of high-frequency speech cues with acoustic hearing. When considering all subjects, they found a significant correlation between PTA and test results in S0N0 condition with CI on or off. However, they did not express the test results as a function of PTA. The preoperative tests could explain bilateral postoperative CI results. Thus, a better analysis of the signal-to-noise ratio would come from the contralateral ear, whose PTA could explain part of the results of certain tests. Indeed, our study shows that small PTA differences in the better-hearing ear can have a great effect on the outcome with the CI. Therefore, additional factors remain unknown. Regarding our results, it seems that high or low residual frequencies are not valuable. Plus, it turns out that etiology (e.g., USHL), duration of deafness, and age could play a role. Central plasticity could also be more important as expected (e.g., HS-ear and Squelsh ear correlation). Unfortunately, we are not able to confirm this hypothesis. Consequently, patients with USHL may be good candidates for CI due to their excellent contralateral PTA. A good preoperative contralateral PTA could, therefore, predict good postoperative outcomes, given the positive correlation between the test results and contralateral PTA. However, a prospective study on a larger cohort with central assessment could help to determine the real impact of contralateral PTA compared with other confounding factors.

Indeed, with a linear model, the results of the S0N0-CIoff test explained 97% of the variability of the results of the S0N0-B test. This model revealed that this postoperative test with CI on could be partially predicted by preoperative test results with CI off. The correlation was positive, meaning the better the results preoperatively, the better the results postoperatively. The difference between the postoperative and the preoperative test results, which was the summation effect here, was not dependent on the preoperative test results but was not sufficient to give good postoperative test results for the subjects with low preoperative test results. The same was true for the S0Near-CIoff test, which explained 76% of the variability in the postoperative results of the S0NCI-B test, and, to a lesser extent, for the S0Near-CIoff test, which explained 50% of the variability in the S0Near-B test. Finally, DA showed that the S0NCI-CIoff test could discriminate between subjects with USHL and other forms of HL. Patients with USHL had superior results on this test in addition to better PTA and shorter hearing-loss duration; all of these factors likely underlie the results.

The gain analyses did not reveal differences between patients with USHL and other subjects. In terms of gain, contralateral PTA does not presume an observable effect. The gain (effect) does not correlate with PTA. The study by Dorbeau et al. [26] also found that PTA did not affect summation The summation effect was the same in the UNRES and RES groups. When the speech and noise were separated, they found the CI benefit was greater for the RES group than the UNRES group. This contrasts with our findings, potentially because the PTA range in their study (5–63 dB HL) was larger than in our study. However, there was a significant positive correlation between HS gain for CI and time since activation. This confirms the importance of maintaining the CI over time. Finally, patients with a negative squelch ear effect had a lower ipsilateral hearing threshold. As the test with CI off was done without plugging or masking the ipsilateral ear, this could be due to the fact that their results were better with the CI off due to their residual hearing. This could mean that they had access to binaural cues when the CI was off and that the activation of the CI led to interference between these cues [28]. The correlation analyses between the effects showed a negative correlation between the HS-ear effect and the squelch-ear effect. The HS-ear effect explained 74.9% of the variability of the squelch-ear effect. However, the gain measures of the squelch-ear effect involve a similar condition to that of the HS-ear, namely S0NCI-CIoff. Some authors, such as Dieudonné and Francart, have questioned the method for measuring the squelch effect [29]. This issue should be considered further. Thus, in light of these correlation measures, the greater the HS-ear effect, the lower the squelch-ear effect, and the less effect there will be to activate/deactivate the CI. Interestingly, this suggests that if a subject has developed too much of an HS-ear effect before surgery, the exploitation of binaurality in the squelch-ear situation used here will be difficult to acquire after CI. The advantage is that HS can easily be assessed preoperatively and thus give more realistic expectations to the patient. The better the HS preoperatively, the lower the gain with CI in this context. There are certainly other factors that prevent the effect of CI activation from being accurately predicted. Larger cohort studies with long-term assessment may help us to better understand these measures.

A novel contribution of this paper to the field is the identification of 2 distinct groups of patients according to their preoperative test results. We have shown that the

S0N0-CIoff and S0Near-CIoff tests could predict the results of the other tests as well as the bilateral tests. Those who were good at the beginning will be good at the other tests and the bilateral tests postoperatively. These tests can again be easily performed preoperatively and would therefore predict the results of all other tests and bilateral tests postoperatively. Conversely, one should not have high expectations postoperatively if the preoperative tests are not good. Nevertheless, they may show an improvement in their gain. In addition, the perception of improvement may be less in those who were good than in those who were poor at the start. Subjective analyses of satisfaction are complex. They vary considerably from patient to patient and have, therefore, not been extensively researched. Our discriminant analyses showed that the S0NCI-CIoff test could separate patients with USHL from other etiologies. As far as gains are concerned, the discriminant analyses did not show such a separation. In our study, patients with USHL have the lowest contralateral PTA; however, S0NCI-CIoff correlates highly with PTA. Confounding factors, such as PTA and duration of deafness, do not allow any conclusions to be drawn from this analysis.

Conclusion

This study highlights the benefits of CI in patients with SSD, particularly in noise. The CI also improved the threshold for detecting low-level noise. However, the effect on the summation and speech understanding in noise is rather limited and could be limited to a high degree by the preoperative state of the contralateral ear.

This study revealed the importance of contralateral PTA. A good preoperative contralateral PTA seems to predict good postoperative results. Patients with USHL could be good candidates for CI due to their excellent contralateral PTA.

We demonstrated that preoperative tests can predict the postoperative results of other tests and bilateral tests with CI. Some simple tests can be done preoperatively to predict a tendency to obtain good postoperative results in bilateral tests with CI. This study also highlighted that if the preoperative HS-ear is too well developed, the exploitation of binaurality may be more difficult to acquire after CI. HS can easily be assessed preoperatively and, thus, provide more realistic expectations for the patient. The better the HS ear is preoperatively, the lower the gain is with CI. Even though the results may not be good initially, it is important to continue wearing the CI. There is a positive correlation between the gain in HS for CI and the duration of activation.

Finally, while some of the results are statistically significant, one should not draw generalized conclusions from them, given the small cohort size. This study has greater value as a case study. Other factors must exist to explain the difference in outcomes between individuals for the different effects and tests. These measures should be continued in a larger cohort to confirm the results described here.

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Statement of Ethics

This study was performed according to the regulation of the Ethics Committee of CHU Liège (Liège, Belgium) and the principles outlined in the World Medical Association Declaration of Helsinki. The study was approved by the local Ethics Committee of CHU Liège (ref: 2023/34). The need for informed consent was waived by the University Faculty Hospital Ethics Committee of CHU Liège (Ethics Committee Number 707; ref: 2023/34).

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

P.P. Lefebvre performed the surgeries. Clinical evaluation was assessed by S. Barriat and P.P. Lefebvre. G. Gersdorff reviewed the electronic medical records. Vincent Péan performed the statistical analyses. S. Camby performed the draft review and editing for final manuscript.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

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