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Audiology

Binaural hearing in monaural conductive or mixed hearing loss fitted with unilateral Bonebridge

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SUMMARY

Objective. To determine the benefits of binaural hearing rehabilitation in patients with monaural conductive or mixed hearing loss treated with a unilateral bone conduction implant (BCI).

Methods. This monocentric study includes 7 patients with monaural conductive or mixed hearing loss who underwent surgical implantation of a unilateral BCI (Bonebridge, Med-El). An ITA Matrix test was performed by each patient included in the study - without and with the BCI and in three different settings – to determine the summation effect, squelch effect and head shadow effect. Subjective hearing benefits were assessed using the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire.

Results. The difference in signal to noise ratio of patients without and with BCI was 0.79 dB in the summation setting ($p < 0.05$), 4.62 dB in the head shadow setting ($p < 0.05$) and 1.53 dB ($p = 0.063$) in the squelch setting. The APHAB questionnaire revealed a subjective discomfort in the presence of unexpected sounds in patients using a unilateral BCI (aversiveness score) compared to the same environmental situations without BCI, with a mean discomfort score of 69.00% (SD ± 21.24%) with monaural BCI *versus* 25.67% (SD ± 16.70%) without BCI (difference: -43.33%, $p < 0.05$). In terms of global score, patients wearing a unilateral Bonebridge implant did not show any significant differences compared to those without hearing aid (difference: -4.00%, $p = 0.310$).

Conclusions. Our study shows that the use of a unilateral BCI in patients affected by monaural conductive or mixed hearing loss can improve speech perception under noise conditions due to the summation effect and to the decrease of the head shadow effect. However, since monaural BCIs might lead to discomfort under noise conditions in some subjects, a pre-operative assessment of the possible individual benefit of a monaural BCI should be carried out in patients affected by unilateral conductive or mixed hearing loss in order to investigate the possible additional effect of the fitting of hearing aids.

KEY WORDS: monaural hearing loss, conductive hearing loss, unilateral bone conduction implant, binaural hearing

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Introduction

The benefits of binaural over monaural hearing in terms of sound localisation and speech understanding have been known for several years [1,2]. Some previous works showed how both air conduction (AC) and bone conduction (BC) hearing pathways activate the cochlear basilar membrane in a comparable way [3]. On the other hand, Stenfelt showed that, since there is more cross-hearing with BC than with AC, the binaural processing of sound delivered by BC is expected to be less than that achieved with AC transmission [4]. For this reason, AC hearing aids are generally the first choice for hearing stimulation, including in patients with conductive hearing loss. However, rehabilitation with bone conduction implant (BCI) hearing aids (e.g., bone-anchored hearing aids, BAHA implant systems, Bonebridge) represents the first choice for patients suffering from conductive or mixed hearing loss who cannot wear conventional AC hearing aids (e.g., patients with atresia auris, recurrent external otitis, chronic otitis media, cavities after radical mastoidectomy) [5].

Recent studies reported speech perception advantages in the binaural fitting of BC devices in bilateral conductive hearing loss [6,7]. In particular, some previous works in children showed that, due to the binaural unmasking, the bilateral application of a percutaneous BC implant in symmetric bilateral conductive hearing loss results in better sound localisation and speech perception under noise conditions [8,9]. The question remains whether unilateral BC devices can ensure an adequate hearing rehabilitation in patients affected by monaural conductive hearing loss who cannot be fitted with AC hearing aids [10].

The importance of hearing rehabilitation in patients affected by monaural conductive hearing loss was stressed by some authors who demonstrated how unilateral conductive hearing loss leads to deficits in the auditory skills that rely on binaural input, and results in damages of the neural coding of spatial information in the *inferior colliculus* neurons, which persists after the conductive hearing loss is resolved [11]. In addition, previous authors demonstrated that children with unilateral congenital conductive hearing loss might run into poor school performances and academic difficulties due to their hearing disability [10,12]. In the past, only a few authors have tried to demonstrate the binaural hearing restoration after fitting BCIs in such patients, and their results turned out to be conflicting [13,14].

Meanwhile, recent studies are evaluating and researching the benefits of treating unilateral conductive hearing loss (UCHL) in unilateral aural atresia. Brotto et al. reinforce the idea that using BCIs in UCHL might improve speech perception in noise thanks to the summation effect, but the setting of the study prevented the investigation of real binaural hearing [15]. Vogt et al., in a 2021 review, suggest instead that the benefits of BCIs might be related to bilateral hearing (2 "separate" inputs) rather than "binaural hearing" (a fused concept) [16].

For this reason, the use of unilateral BCIs in patients with monaural conductive hearing loss remains controversial. The aim of this study is to determine whether the use of a unilateral Bonebridge device in patients affected by monaural conductive or mixed hearing loss improves hearing and speech perception under noise conditions thanks to the advantages of binaural hearing.

Materials and methods

The cohort included 7 adult Italian mother tongue speakers (3 females and 4 males) who underwent surgery implantation of a monolateral bone conduction hearing aid (Bonebridge^{tM}, Med-El, Innsbruck, Austria) at the Otolaryngology Division of Molinette Hospital, Turin, between 2015 and 2021. The mean age at implantation was 48 years (SD ± 15.09). Participation in the study was voluntary. The following inclusion criteria were applied: patients older than 18 years affected by monaural conductive/mixed hearing loss and normal hearing capacity, or mild hearing loss in the contralateral ear. The International Organization for Standardization (ISO) 7029:2017 standard was adopted to assess the hearing threshold deviation for audiometric tones of subjects included in the study and prove that any observed hearing loss in the AC thresholds was associated with age and not with any cochlear injury. Exclusion criteria were: age under 18 years, bilateral hearing loss, learning disability and attention disorders. Information for each subject, including age at implantation, gender, aetiology of deafness (congenital or acquired, aural atresia or tympanoplasty), type of hearing loss (pure conductive or mixed), side of implantation and pre-implantation audiometric scores are summarised in Table I. In accordance with the indications provided by the manufacturer (Med-El), the retrosigmoid approach was used for all subjects in the study. All patients underwent pre-operative CT and MRI before surgery to evaluate the individual anatomy of the skull and to exclude any bone deformity that could interfere with the implantation of the aid.

Participants underwent pure tone audiometry (250-8000 Hz) to measure their bilateral hearing threshold in daily life 1 month before implantation, and speech intelligibility in noise without and with the BCI using the ITA Matrix test [17]. Results are expressed in decibels and represent the signal to noise ratio (SNR) at which a subject understands 50% of the words given during the test. Audiological evaluations after implantation of all patients were conducted in October 2022, after at least one week of continuous use of the BCI. We thus obtained an average post-operative ITA-Matrix Test time interval of 55 months (minimum of 12 months for P3 and maximum of 84 months for P6).

For this study, the ITA Matrix test was performed using two loudspeakers in three different settings to determine speech intelligibility in three noise situations, and to evaluate the benefits of binaural hearing with a monolateral bone conduction aid. The scores of all three settings were registered without and with the aid:

- summation setting: speech and noise were both presented from the front of the patient (S_0N_0);
- head shadow effect: speech was presented on the side affected by conductive or mixed hearing loss and noise on the better ear ($S_{90}N_{-90}$);

Table I. Anamnestic and baseline audiometric data of the sample.

Patient	Age (yrs)	Sex	Congenital/ acquired	Type of hearing impairment	Year of surgery (months between surgery and ITA-Matrix-Test after surgery)	Side	Ear	AC (BC) thresholds (dBHL) at frequency			
								0.5	1	2	4 kHz
P1	68	M	Acquired	Mixed (tympanoplasty)	2018 (46)	Left	Normal	25	30	30	35
							Impaired	70 (30)	70 (35)	85 (45)	85 (55)
P2	24	M	Congenital	Conductive (aural atresia)	2017 (58)	Left	Normal	10	15	10	10
							Impaired	80 (15)	70 (15)	65 (20)	60 (25)
P3	61	M	Congenital	Mixed (aural atresia)	2021 (12)	Right	Normal	15	15	20	40
							Impaired	85 (15)	60 (15)	75 (15)	65 (25)
P4	54	F	Acquired	Mixed (tympanoplasty)	2015 (82)	Right	Normal	10	10	15	10
							Impaired	65 (30)	60 (20)	50 (35)	75 (35)
P5	43	F	Congenital	Mixed (aural atresia)	2018 (51)	Right	Normal	10	10	10	10
							Impaired	80 (15)	75 (20)	60 (30)	55 (20)
P6	30	M	Acquired	Conductive (tympanoplasty)	2015 (84)	Left	Normal	10	10	10	10
							Impaired	50 (15)	45 (10)	40 (15)	60 (15)
P7	56	F	Acquired	Conductive (tympanoplasty)	2018 (54)	Left	Normal	25	30	20	40
							Impaired	55 (15)	65 (20)	70 (35)	50 (30)

AC: air conduction; BC: bone conduction; dBHL: decibel hearing loss; kHz: kilohertz; M: male; F: female.

- squelch setting: speech was presented from the front and noise on the side affected by conductive or mixed hearing loss (S_0N_{90});
- tests were conducted in a sound-attenuated room with the speakers placed one meter away from the patient. Subjects were asked not to move their head during the test. We performed a calibration of the perceived signals using a sound level meter (Volcraft, Schallpegelmessgerät 332 Datalogger).

In addition, each patient was administered a 24-question self-assessment questionnaire (Abbreviated Profile of Hearing Aid Benefit questionnaire, APHAB) to assess the perceived satisfaction of the subject with the BCI. The scores obtained provided the surgeon and audioprothesist with information on:

- ease of communication (EC), defined as communication under quiet conditions;
- reverberation (RV), defined as communication under reverb conditions;
- background noise (BN), defined as communication in places with different noise levels;
- aversiveness (AV), defined as the discomfort deriving from ambient sounds.

The subjects involved in the study were asked not to wear the BCI for one week and to fill in the questionnaire. Subsequently, they filled in the same questionnaire after at least one week of continuous use of the hearing aid. A global score (GS) calculated from the average scores of the four parameters for the two listening modes (without and with BCI) was calculated for each patient. The difference between the GS obtained without BCI and the GS obtained with BCI resulted in the global benefit obtained by each patient from the implantation of the BCI. All scores of the APHAB questionnaire were expressed as percentages. All surveys on the APHAB questionnaire were carried out 2 months after BCI implantation for every subject of the study; all subjects used the implant correctly throughout the day until our evaluation.

Statistical analysis

Categorical variables are reported as frequency and percentage; continuous variables are reported as mean ± standard deviation (SD). Due to the small sample size of the study, the statistical analysis was performed using the Wilcoxon Signed Ranks test, a non-parametric test used to compare the means between two groups. The test allowed us to evaluate the significance of the difference between test results at t2 (Matrix test performed with BCI) and t1 (Matrix test performed without BCI). The statistical significance was set at $p < 0.05$.

As for the APHAB questionnaire, results were analysed using the Wilcoxon Signed Ranks non-parametric test to highlight differences in subjective hearing and quality of life without and with BCI for all four categories (EC, RV, BN, AV). Statistical analysis was performed using the IBM SPSS Statistics for Macintosh software, Version 28.0.

Results

The hearing profile of each subject was obtained by testing pure tone thresholds, showing a mean air conduction pure tone average (PTA) of 63.31 dB (SD ± 13.05) without BCI for frequencies between 250 to 8000 Hz. Table II shows the results of the Italian Matrix test in all settings.

In the summation setting, the mean SNR without BCI is -2.11 dB (SD ± 1.90 dB), compared to an average SNR of -2.90 dB (SD ± 1.56 dB) with unilateral BCI. The difference between the scores obtained in these settings (0.79 dB) was statistically significant ($p < 0.05$). In the head shadow configuration, we obtained a mean SNR of 0.63 dB (SD ± 2.58) without unilateral BCI and a mean SNR of -3.99 dB (SD ± 3.76 dB) with unilateral BCI, resulting in a statistically significant decrease between the two scores (4.62 dB, $p < 0.05$). The squelch setting showed an average SNR of -3.06 dB (SD ± 3.53 dB) without unilateral BCI, compared to an average SNR of -4.59 (SD ± 3.89) with a monaural Bonebridge. The difference was not statistically significant (1.53 dB, $p = 0.063$).

As for the APHAB questionnaire, in terms of GS, patients with a unilateral Bonebridge implant did not show significant differences compared to those without BCI (difference: -4.01%, $p = 0.310$). However, looking at the individual items of the APHAB questionnaire, AV score averages revealed a significant difference (-43.33%) between the two patterns (without and with BCI), resulting in a subjective discomfort of 69.00% (SD ± 21.24%) in the presence of unexpected sounds in patients with BCI *versus* 25.67% (SD ± 16.70%) of discomfort without BCI ($p < 0.05$).

Table III shows the individual results of the APHAB questionnaire.

Discussion

Binaural hearing in the rehabilitation of patients affected by monaural conductive hearing loss using a unilateral hearing device has been investigated over the years, but the question whether monaural conductive hearing loss should be amplified with a unilateral BCI remains unclear [13,14].

Some previous studies reported improved speech perception in patients with monaural hearing loss after fitting a BCI, but they did not investigate speech intelligibility in different settings under noise conditions. For example, Danhauer et al. showed that patients affected by congenital monolateral aural atresia perceived benefits with the implantation of unilateral BAHA devices and reported a re-

Table II. Results of Matrix Test in the three settings.

	Summation effect (dB)		Squelch effect (dB)		Head shadow effect (dB)	
	Without BCHA (t1)	With unilateral BCHA (t2)	Without BCHA (t1)	With unilateral BCHA (t2)	Without BCHA (t1)	With unilateral BCHA (t2)
P1	-1.3	-3	-2.5	-1.9	3.4	-9
P2	-3.7	-4.7	-2.4	-6.2	-0.9	-5.9
P3	-0.6	-1.4	-4.6	-6.1	4.7	3.2
P4	-2.6	-2.8	-0.8	-3.1	-1.6	-3.1
P5	-1.8	-2.1	-3.3	-2.1	1.4	-5.6
P6	-5.2	-5.2	-9.6	-12	-1.7	-3.1
P7	0.4	-1.1	1.8	-0.7	-0.9	-4.4

dB: decibel; BCHA: bone conduction hearing aid.

Table III. Individual results of the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire.

	Without BCHA (%)					With BCHA (%)				
	EC scale	BN scale	RV scale	AV scale	GS	EC scale	BN scale	RV scale	AV scale	GS
P1	41.67	45.83	49.83	24.50	40.46	6.5	47.67	43.33	83	45.13
P2	6.83	45.67	14.50	31	24.50	8.33	58.33	20.83	72.50	40
P3	82.83	51.67	56.17	60.17	62.71	83	49.67	58.17	64.17	63.75
P4	31.17	84.67	55.83	21	48.17	14.50	71.83	54	48	47.08
P5	6.50	29	15.75	18.50	17.44	37.50	29.00	22	87	43.88
P6	37.67	49.67	56.17	9.17	38.17	29	20.83	37.17	93	45
P7	23.33	70.50	82.67	15.33	47.96	1	28.83	25.17	35.33	22.58

BCHA: bone conduction hearing aid; EC: ease of communication; RV: reverberation; BN: background noise; AV: aversiveness; GS: global score.

duction in activity limitations when using it. In their work, both speech and noise were presented at the frontal speaker (S_0N_0), and no further settings were analysed [18]. Priwin et al. investigated the benefits of using both bilateral BAHAs in children with bilateral conductive hearing impairment and unilateral BAHAs in children affected by unilateral conductive hearing loss, and concluded that – contrary to those implanted with bilateral BAHA, who experimented benefits in terms of better sound localisation and speech recognition in noise – children affected by monaural conductive hearing loss benefited from the fitting of a unilateral BAHA in terms of better speech recognition. However, no advantages were noticed regarding sound localisation under noise conditions [14]. These results were observed with adhesive bone conduction hearing aids (Adhear); these devices provide a similar hearing gain compared to BCIs in conductive hearing loss in the summation context [19] and may have a role in assessing the individual hearing outcome with BCI. However – in line with the above results – they were shown to be unable to obtain real binaural hearing in monaural conductive hearing loss [20].

We now know that one must consider two further aspects that can affect the benefits of treatment. On one hand, the impaired-deprived neural processing in subjects with congenital UCHL who did not experience binaural hearing and, therefore, might not have a normally developed neural auditory system, and the possibility that patients with congenital UCHL might be "forced" to develop a unilateral hemispheric dominance if an atretic ear is not stimulated in the first years of life [21]. On the other, a different transcranial attenuation (TA) was measured in human subjects by Nolan and Lyon in 1981 (mean TA: close to 10 dB, SD ± 5-10 dB) [22] and by Stenfelt in 2012 (range from 3 to 10 dB, with intersubject variability around 40 dB) [23].

Despite the limitation of the small sample size of the study, our data suggest that unilateral BCIs in patients affected by monaural conductive hearing loss improve loudness by stimulating both ears (summation effect) and improve speech intelligibility by eliminating the physical reduction of speech due to the head shadow effect, but do not show advantages in terms of improving SNR when the existing conditions cause a squelch effect (the difference appeared not to be statistically significant ($p = 0.063$)). By analysing the individual results of the subjects included in the study, we noticed that patient P2 – who was fitted with unilateral Bonebridge because of a left monaural atresia and had never used AC hearing aids – showed the highest reduction of SNR in the squelch setting, while the worst result in this setting was achieved by patient P5, also suffering from congenital unilateral conductive hearing loss due to right monaural atresia, and for whom the cause of a congenital neural deprivation was excluded (Tab. II). This divergence could be explained by the different TA of the patients in the study, which might lead to various outcomes in the squelch setting regardless of the type of hearing impairment (congenital or acquired). The role of TA in determining different results in patients affected by congenital or acquired hearing loss fitted with unilateral BCIs was also stressed by Snik et al. who noticed, partially in contrast to our results, that patients with congenital unilateral conductive hearing loss did not benefit from a monaural BCI in terms of sound localisation, while patients affected by acquired conductive hearing loss showed an improved sound localisation ability under noise conditions [13], calling into question the impact that altered neural processing might have in individuals with congenital UCHL.

Our audiometric results find some correspondence in the APHAB questionnaire, which revealed a subjective discomfort in the presence of unexpected sounds (e. g., smoke detectors and alarms) and evidenced annoying hearing sensations in noisy environments such as busy streets and construction sites while using the hearing device. The global dissatisfaction of patients using a BCI for unilateral BC is also confirmed in previous studies, which showed that patients with monaural hearing impairment seemed not to use the BAHA all day and that they were not overly impressed by BC sound quality [24]. Furthermore, Priwin et al. found that some children with unilateral hearing loss used the BCI only in the classroom, thus revealing that unilateral BC hearing might show benefits in the school environment due to the better speech perception with the device, but did not seem to represent a subjective fundamental tool for patients in their everyday hearing life [14].

The APHAB questionnaire was also used by Ratuszniak et al. to assess the benefits of the Bonebridge system in patients affected by unilateral or bilateral conductive hearing loss: they noticed a significant improvement in the satisfaction of subjects with the hearing aid, resulting in a mean reduction of problems with hearing from 45% before implantation to 22% after implantation [25]. However, they did not differentiate patients affected by bilateral conductive hearing loss from those who suffered from unilateral hearing loss, both fitted with unilateral BCIs. It follows that, due to the huge improvement of speech intelligibility through the use of a BCI in patients with bilateral conductive hearing impairment, the mean level of satisfaction may result in an overestimation of the subjective benefits of patients affected by unilateral conductive hearing loss fitted with monaural Bonebridge. According to a recent work by Irmer et al. who highlighted the benefits of BC implantation in terms of subjective hearing [26], our results account for the better speech perception of patients implanted with monaural Bonebridge.

To the best of our knowledge, this is the first study on speech recognition in three different setting under noise conditions after fitting a unilateral Bonebridge aid system in monaural conductive or mixed hearing loss, and the first on a new model of BC rehabilitation which aims to investigate the benefits of binaural hearing in unilateral conductive hearing impairment. The limitations of our work are represented by the small sample size and the heterogeneity of subjects affected by both congenital and acquired hearing loss. In particular, subjects with congenital hearing impairment who have never been fitted with a BCI before are expected not to have developed neuronal binaural processing. The outcomes of some (e. g., patient P2 and patient P3, Table II) – which turned out to be better than those obtained by subjects with acquired hearing loss – may be explained by the different individual TA of the subjects in the study, even if this phenomenon has not yet been fully clarified.

Conclusions

Our study shows that the use of unilateral Bonebridge devices in patients affected by monaural conductive or mixed hearing loss improves speech perception in noise due to the summation effect and to the decrease of the head shadow effect. However, since in some subjects monaural BCIs might lead to discomfort under noise conditions, in order to investigate the possible supplementary effect of the fitting of hearing aids, a pre-operative trial with Softband or adhesive devices may be of value in patients affected by unilateral conductive or mixed hearing loss. Further studies are required to investigate the neural mechanism of the squelch effect in determining various outcomes of patients with different TA.

Conflict of interest statement

The authors declare no conflict of interest.

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Author contributions

AC: substantial contribution to the conception and design of the work, final approval of the version to be published; AU: substantial contribution to the design and writing of the work, final approval of the version to be published; RA: substantial contribution to the selection of patients eligible for the study; MG: execution of audiometric test; VB: substantial contribution to the statistical analysis and interpretation of the data; GR: substantial contribution to the assessment and evaluation of APHAB questionnaires; ESB: substantial contribution to the design and writing of the work; AA: substantial contribution to the design of the work, final approval of the version to be published.

Ethical consideration

This retrospective study has been performed in accordance with the ethics standards laid down in the 1964 Declaration of Helsinki. Committee approval was obtained from “Città della Salute e della Scienza” University Hospital Ethics Committee (March 13, 2018, Protocol Number: 0026286; CS2/622). Informed consent was obtained from all subjects involved in the study.

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