Instant Auditory Benefit of an Adhesive BCHD on Children with Bilateral Congenital Microtia

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Abstract

Purposes: To evaluate the instant auditory benefit of an adhesive bone conduction hearing aid (ADHEAR) on children with bilateral congenital microtia, especially the sound localization ability under unilateral and bilateral fitting. Methods: Twelve patients with bilateral congenital microtia aged from 6 to 17 were included in this study. Pure tone threshold under sound field, speech recognition threshold in quiet and sound localization abilities were tested and compared before and after wearing the device. The pure tone threshold test was additionally repeated for two different wearing method – adhesive or fixed with softband; the sound localization test was repeated for both unilateral and bilateral fitting. Correlation analysis was then conducted to find the influencing factors of sound localization improvement. Results: Significant auditory improvement were found: the average pure tone threshold (PTA) reduced by 24.8 (adhesive) and 27.3 dB HL (softband), with no significant difference between the two wearing methods. The speech recognition threshold also improved by 29.0 dB. As for sound localization abilities, no significant improvement was found under unilateral fitting; but half (6 of 12) of the patients were notably benefited from bilateral fitting. The improvement was found to be strong correlated with the patients' unaided sound localization ability – those with poorer localization abilities tends to benefit more. Moreover, it was found that the sound localization improvement was also negatively related with the malformation degrees of the patients' head. Summary: ADHEAR affords significant auditory benefits for children with bilateral congenital microtia, in terms of sound and speech perception. The sound localization abilities could be partly improved instantly by bilateral fitting, and the improvement is related with factors such as adaption and skull malformations.

Key points:

1. The adhesive bone conduction hearing device (BCHD) – ADHEAR offers significant auditory gain to children with bilateral congenital microtia.
2. The adhesive wearing method of ADHEAR performs as well as the conventional softband, which sufficiently releases the static pressure and offers more comfort.
3. For bilateral congenital microtia, unilateral fitting of ADHEAR does not improvement the sound localization ability, while bilateral fitting demonstrates instant improvement in half of the patients.
4. The improvement of sound localization ability under bilateral fitting is strongly correlated with the unaided sound localization ability – patients who performs worse when unaided tend to benefit more.
5. The skull malformation also disturbs the sound localization after bilateral fitting. Therefore, a detailed fitting procedure may be in need.

1. Introduction

Bilateral congenital microtia is commonly accompanied with mild-to-severe conductive hearing loss (CHL), which, if untreated, greatly affect the patients' daily communication, causing developmental retardation of speech, poor learning achievement and mental diseases [1]. Bone conduction hearing devices (BCHDs) are widely used to improve the hearing ability of congenital microtia [2]. Wearable BCHD is proven to be an effective temporary or life-time solution for young patients not suitable for, or adults refusing implantable devices [3]. Most wearable BCHDs are attached to the patient's skin (usually on the mastoid or forehead) with a softband, steel-spring headband or other types of fixation, which causes a pressure on the skin. This pressure, reported optimal to be about 3˜5 Newtons for good fixation and auditory performance [4-6], smaller than the un-tolerable pain limit, however, leads to discomfort, skin reactions and/or pains for long-time use. Skin pressure is also involved in implantable bone conduction systems (e.g. BAHA attract, Sophono and BoneBridge) and the pressure-induced skin reaction problem, although greatly reduced compared to the bone-anchored system, should still be cautiously taken care of [7,8].

To overcome the above pressure and pressure-induced issues, a pressure-free, wearable bone conduction hearing device named ADHEAR was designed, with an adhesive adapter to ensure attachment onto the skin. Auditory benefit of this device has already been estimated for bilateral or unilateral CHL such as otosclerosis, otitis media and congenital macrotia in both adults [9] and children [10,11]. But the data for children with congenital microtia are still limited. Therefore, one purpose of this study is to gain an instant evaluation of the auditory benefit of bilateral congenital microtia children using ADHEAR.

Another issue considered in this study is the sound localization under bilateral fitting. Bilateral fitting provides better hearing performance, for example, the threshold decreases by about 3˜6 dB, called the "summation effect" [12]. The speech recognition in quiet and noise environment also improves, so as the sound localization [13,14].

Sound localization, especially for hearing impaired people and under bone conduction, is an old talk but not fully clarified [15]. There are still dispute on the sound localization benefit for unilateral hearing loss (either conductive or sensorineural) fitted with BCHD [16-18], which seems to be strongly related with factors such as whether the hearing loss is congenital or acquired [19,20]. Unlikely, it is commonly accepted that a bilateral fitting of BCHDs would be advantageous in sound localization for bilateral CHL [21-23]. Above all, the other aim of the study is to give an overview of sound localization benefits of bilateral congenital microtia with unilateral or bilateral fitting of BCHDs. Moreover, the possible influencing factors are studies.

2. Subjects and Methods

2.1. Subjects

Twelve children (age: 11.1±3.0 years) with mild-to-severe bilateral conductive hearing loss due to congenital microtia were included in this study. Pure tone threshold was previously conducted to ensure that the average threshold (PTA, averaged of 0.5, 1, 2 and 4 kHz) satisfies the following criteria: PTA for air conduction [?] 45 dB HL and the air-bone gap (ABG) [?] 25 dB HL. Most subjects suffered from bilateral conductive hearing loss, the only exception is a patient (No.10) with bilateral mixed hearing loss. All patients' characteristics are presented in Table 1.

Clinical CT data of the 12 patients were also included in this study. Two doctors majored in plastic surgery, who were not aware of the study purpose, help to evaluate the level of facial malformation according to the skull CT as well as the photos of the patients. Pruzansky-Kaban classification for hemifacial microsomia was adopted, with five different types, 0, I, IIa, IIb and III for increasing severity [24,25].

For comparative purposes, a group of 6 control listeners, aged 7-18 (mean 12.0 years), without hearing loss, were also included in the study. These listeners had pure tone thresholds (both air and bone conduction) below 20 dB HL, with the range of 0.5-8 kHz in both ears. All the control listeners were not informed about the purpose and details of the study. Sound localization test, with the same setups for the patients (which will be presented later), was conducted. The average performance of the control listeners was adopted as the sound localization response for normal hearing people under air conduction.

2.2. Setup and test procedures

Sound field pure tone threshold, speech recognition threshold in quiet were tested. All tests were carried out in a sound-treated room. The background noise was below 30 dBA, measured by a calibrated sound level meter. The tests were conducted for all patients, before and after fitting with one ADHEAR device. The aided side is chosen randomly if the patient had never used a bone conduction device according to the patient's preference. Or else, if the patient was using a BCHD, the ADHEAR devices was fitted onto the mastoid of the patient's "usual" side. During the test, the patient was seated in front of a speaker, approximately 1 meter away. For sound field threshold test, wobble sound of six frequencies (0.25, 0.5, 1, 2, 4 and 8 kHz) were used. For speech recognition test, a short sentence of 7 Chinese characters were used.

2.3. Sound localization test

Twelve speakers were mounted at head level, forming a semi-circle, ranging from -82.5deg to 82.5deg with 15deg intervals. The subject (a patient or a control listener) was seated in the center of the semi-circle, approximately 1 meter from the speakers and turned his/her back to the speakers, see Fig.1. During the test, a recorded gunshot sound (65 dB SPL) was presented by a random speaker, and the subject was then asked to recognize the sound direction by picking out the right speaker. Randomized trials of 24 presentations were given, each speaker presented 2 times. During the presentation, the subject was not permitted to turn his/her head. No training or feedback were given. The test was carried out in three cases, before the patient was fitted by the ADHEAR device (unaided case), fitted with one device (unilateral fitting) to two devices (bilateral fitting). During bilateral fitting, the output gains of two devices were kept the same. The aided side in the unilateral fitting case was defined as 90deg, and its opposite side was accordingly -90deg.

Root mean square error (RMSE) was adopted to evaluate the localization results, defined as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\theta_i^{\text{stimulus}} - \theta_i^{\text{response}}\right)^2}$$

where $n = 24$ is the number of presentations,$\theta_i^{\text{stimulus}}$ and $\theta_i^{\text{response}}$are the stimulus and response angles of the i -th presentation, respectively. The chance level of RMSE in our setup is about 73.2°, according to a Monte Carlo simulation. And in the case of good lateralization but poor localization, the chance level of RMSE is about 36.4°.

2.4. Data analysis

Primary statistical methods were used, paired Student's T-tests were adopted to evaluate differences between groups, where $P < 0.05$ was considered significant difference. For evaluation of the influencing factors of sound localization improvement, the Pearson correlation coefficient r (ranging from -1 to 1) was adopted,

$$r = \frac{\sum\left(X - X\right)\left(Y - Y\right)}{\sqrt{\sum\left(X - X\right)^2} \times \sqrt{\sum\left(Y - Y\right)^2}} = \frac{\operatorname{cov}\left(X, Y\right)}{S_X S_Y}$$

where X, Y are two pared sets of data, $\bar{X}$ and $\bar{Y}$ are their mean values, $cov(X,Y)$ is covariance of X and Y,S_X and S_Y are variances of X and Y, respectively. All data analysis was conducted using the mathematical software MATLAB (version 2020a, MathWorks).

3. Results

3.1. Pure tone threshold under sound field

Figure 2(A) presents the frequency-related sound field pure tone threshold, in the unaided, adhesive and softband cases. The average threshold (PTA) are 52.1±5.8 dB HL in the unaided case, 27.3±3.4 dB HL in the adhesive case and 24.8±3.1 dB HL in the softband case, as shown in Fig.2(B). Significant improvements are found ($P < 0.0001$). The average benefit was 24.8±7.8 dB HL and 27.3±7.0 dB HL for the adhesive and softband cases, respectively. Although softband seems to be a little bit better than adhesive case, their difference in auditory benefit is statistically not significant ($P = 0.054$).

3.2. Speech recognition in quite

Figure 2(C) shows the speech recognition thresholds in the unaided and adhesive cases. The mean recognition thresholds are 68.5±6.2 dB when unaided, and significantly improves to 39.4±9.2 dB after aided ($P < 0.0001$), with an improvement of 29.0±5.2 dB.

3.3. Sound localization in azimuth

Figure 3 gives two typical trials of sound localization test in the unaided, unilateral fitting and bilateral fitting cases. One (patient No. 8, Fig.3(A1-A3)) demonstrates obvious improvement after bilateral fitting, with stimulus-response relations closer to the diagonal regression line $y = x$. The RMSE values are 68.1° (unaided,$\mathrm{RMSE_{unaid}}$), 69.8° (unilateral,$\mathrm{RMSE_{uni}}$) and 38.0° (bilateral,$\mathrm{RMSE_{bi}}$). The other (patient No. 7, Fig.3(B1-B3)), however, shows no improvement.

Unilateral fitting generally shows no improvement, and usually the laterization bias to the aiding side. In contrast, bilateral fitting gives bipolar results, either with great improvement, or with no improvement and even deterioration. Therefore, the patients could be classified into two groups, i.e., improvement and non-improvement groups under bilateral fitting, each group contains 6 patients. In the improvement group, the RMSE values decrease by at least 20 degrees, showing great improvement in sound localization. Table 2 presents the sound localization results in terms of RMSE values for individual patients. The patients are reorders for better interpolation of the two groups.

The RMSE decreases from 67.9±10.9° (unaided) to 33.7±4.9° (bilateral fitting) in the improvement group ($n = 6$), with a significant difference of $\Delta\mathrm{RMSE_{bi}}$=33.3±8.1° ($P < 0.001$); while the RMSEs in the non-improvement group are 49.7±15.0° (unaided) and 57.7±15.1° (bilateral fitting), with no statistical difference. As for unilateral fitting, no significant improvement could be found, for both groups or for all patients together. Figure 4 presents the stimulus-response relation for the two groups separately for an intuitive view. Subfigure (A1-A3) put together the results of the improvement group ($n = 6$). After bilateral fitting, the stimulus-response dots distribution obvious get closer to the diagonal line, as shown in subfigure (A3), indicating the significant improvement. Such improvement is not demonstrated in the non-development group, as shown in Fig.4(B1-B3). However, the improved$\mathrm{RMSE_{bi}}$ for the improvement group is 33.7±4.9°, which is still obviously worse than the average score of the control listeners under air conduction (14.9±2.3°, see Fig.4(C)). Additionally, as shown in Fig.4(A2 and B2), the response angles are mostly distributed between 0 to 90°, i.e. the aided side.

3.4. Influencing factors of sound localization

The dots in Fig.5(A) gives the correlation between the unaided RMSE ($\mathrm{RMSE_{unaid}}$, x -axis) and its improvement after bilateral fitting (y -axis), namely,$\Delta\mathrm{RMSE_{bi}} = \mathrm{RMSE_{unaid}} - \mathrm{RMS}E_{\mathrm{bi}}$. A strong positive correlation is shown between$\mathrm{RMSE_{unaid}}$ and $\Delta\mathrm{RMSE_{bi}}$, with a Pearson's r of +0.74. The dashed line in Fig.5(A) gives a linear fitting of their relation, and the solid line show the chance level.

Figure 5(B) gives the relation between the malformation degree and$\Delta\mathrm{RMSE_{bi}}$. Different stages of P-K malformations (0, I, IIa, IIb, III) were quantized into integers 0, 1, 2, 3 and 4, see Table 2. In this study, no patients were classified as stage III. A slightly negative correlation exists ($r = -0.22$). However, as along as one patient (No.9) get excluded, the negative correlation become clearer with $r = -0.49$. The excluded patient had an impressively good localization performance in the unaided case, and the aided performance got even worse, indicating that the malformation degree is a less important factor for him.

No correlation can be found between $\mathrm{RMSE_{unaid}}$ and the malformation degree, see Figure 5(C), indicating that the malformation degree is an independent factor.

4. Discussions

4.1. Auditory gain of the device

ADHEAR gives instant auditory gain for all the patients included in this study. The sound field pure tone threshold and speech recognition threshold were both significantly decreased in our test. The auditory gain is about 25 dB in this study (Fig.2(A-B)), which is similar with other published results [26]. The speech recognition threshold was also greatly improved by about 29 dB, see Fig.2(C).

One may concern that the absence of pressure may affect the performance of a BCHD. According to our study, the auditory gain of ADHEAR is only slightly reduced when using the adhesive pad instead of the conventional softband or headband. The adhesive design enables ADHEAR free from the required static pressure [4-6] for other BCHDs. The pressure is required mainly because a close and tight attachment is needed for effective vibration transmission. Huber et al. (2011) found that BC threshold between 2-4kHz would be lower by at a static pressure of 5N, than that of 2N [27]. The difference between adhesive or softband attachment of different static pressures may result from the change of skin impedance, which affect the performance of the device [28,29]. Most patients in our study were satisfied with the ADHEAR device, especially due to its small size, concealment and press-free design.

4.2. Sound localization under unilateral fitting

Unilateral aid for bilateral CHL is unable to form a reliable interaural level difference (ILD) and time difference (ITD), which are essential to horizontal sound localization [15]. Therefore, it is not surprising that the sound localization performance of most patients in this study did not benefit from unilateral fitting. In fact, some even performed worse, see Table 2. Usually, their localization bias to the aided side, see Fig.4(A2 and B2).

The exception is patient No. 2, an eleven-year-old boy who also benefits from unilateral fitting. The reason is unknown yet. Since this patient has been fitted with a BCHD unliterally for more than 9 years, it is possible that this patient has develop monoaural sound localization ability [30].

4.3. Sound localization under bilateral fitting

The concept that bilateral bone conduction enables direction hearing, has been generally accepted. However, most children with bilateral CHL was usually treated using unilateral fitting, because of cost-effective considerations. In our study, half of the patients gain significant benefit in sound localization instantly after bilateral fitting of ADHEAR devices, but still not to the normal people level (see Fig.4(A3 and C)). Their improved RMSE score is closed to the results of good lateralization with poor localization (36.4°, see Table 2). According to Agterberg et al. (2011)[19], the long-term performance tends to be better, but still not reaching the normal people level. They used the mean absolute error (MAE) as an assessment instead. The MAE was 66° for patients with bilateral conductive/mixed hearing loss, and improved to about 25° (compared with a good lateralization, poor localization score of 35°) at least ten weeks after bilateral fitting of BCHDs, while for the control group of normal listeners, the MAE was as good as 8°. This may be caused by the mechanism of bone conduction, e.g. cross hearing between the two cochleae [12,14].

4.4. Influencing factors of sound localization

Half of the patients did not benefit from bilateral fitting instantly, or even perform worse, according to this study. The instant sound localization improvement is strongly correlated with the unaided performance, see Fig.5(A). Since training and adaption are crucial in the forming of sound localization. Patient with bilateral hearing loss, who get good sound localization score in the unaided, have already been well adapted. An alteration of their hearing preformation (typically, by wearing BCHDs), will worsen their sound localization ability in the short term.

Another influencing factor is the skull malformation degrees, according to our results. Bone conduction pathways are much more complicated than air conduction, these pathways are often categorized according to the anatomical divisions that bone conduction sound affects – the outer ear component, the middle ear component and the inner ear component, respectively [12]. Malformations of the head will cause the asymmetry of the skull bones as well as other essential structures that are involved in the bone conduction pathways. Although the skull anatomy is drastically individually different, the asymmetry of skull is not as significant, therefore, the vibration transmission of bone conduction shows good symmetry in normal people [31]. However, this may not be true for patients with congenital microtia, who are usually accompanied with different kinds of facial malformations, such as hemifacial microsomia. A potential solution for those patients is a more careful fitting process to balance their bone conduction hearing of the two ears.

Symmetric hearing loss may also be an influencing factor of sound localization ability under bilateral fitting of BCHDs [32]. In this work, all patients had symmetric or slight asymmetric conductive hearing loss component, and the sensorineural component was also symmetric (the BC thresholds of both the ears were symmetric). Age is also an influencing factor, although statistically no obvious correlation between the sound localization improvement and age were found in this study. The sound localization ability for normal hearing people is developed before the age of 8 [15]. Most subjects in our study is above the age of 8, except Patient No. 7, who did not benefit from binaural fitting.

4.5. Limitation and future work

Currently, patients with bilateral congenital microtia, who wear, or implanted with BCHDs, are mostly unilaterally aided. Therefore, long-term outcomes of bilateral fitting for these patients are very limited. However, bilateral fitting is beneficial for directional hearing, which is getting more concerns for these patients and their families. The main limitation of this study is the lack of long-term results, which need future work.

5. Summary

In this study, instant auditory outcome of children with bilateral congenital microtia fitted with BCHDs (ADHEAR) were given. The adhesive ADHEAR device offers a good solution for hearing reconstruction of these children, demonstrating good auditory benefits in the pure-tone sound field threshold as well as speech recognition. Bilateral fitting of ADHEAR will also improve the sound localization ability. But some patients may not get benefited in short term because of adaption problems, those who get benefited somehow did not reach the level of normal hearing people. Moreover, for children with moderate to several facial malformations, the sound localization recovery would require more efforts, and maybe a personalized and careful fitting procedure is needed.

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Table 1 Characteristics of 12 children in this study

Subject Number	**Age (years) at time of tests**	**Gender**	**Age (years) of wearing BCHDs**	**BCHD type**	**PTA (0.5, 1, 2 and 4 kHz) in dB HL**	**PTA (0.5, 1, 2 and 4 kHz) in dB HL**	**PTA (0.5, 1, 2 and 4 kHz) in dB HL**	**PTA (0.5, 1, 2 and 4 kHz) in dB HL**	**PTA (0.5, 1, 2 and 4 kHz) in dB HL**
					Left side AC	**Left side BC**	**Left side ABG**	**Right side AC**	**Right side BC**
1	13	F	3	P	66.25	21.25	45.00	67.50	21.25
2	11	M	2	B	51.25	22.50	28.75	57.50	22.50
3	10	F	NA	-	72.50	32.50	40.00	61.25	22.50
4	17	M	NA	-	61.25	16.25	45.00	62.50	12.50
5	13	F	NA	-	75.00	27.50	47.50	71.25	26.25
6	15	M	NA	-	57.50	26.25	31.25	67.50	32.50
7	6	M	NA	-	61.25	32.50	28.75	70.00	27.50
8	9	F	NA	-	75.00	16.25	58.75	77.50	16.25

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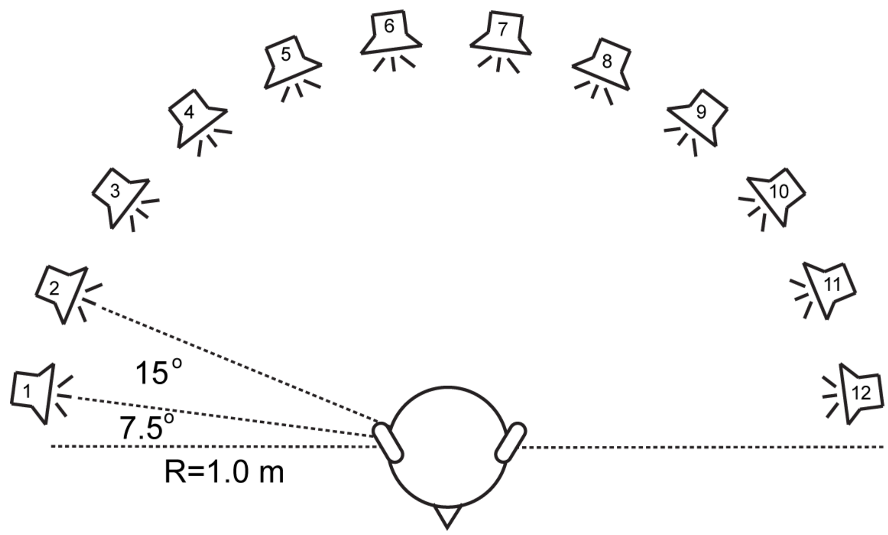
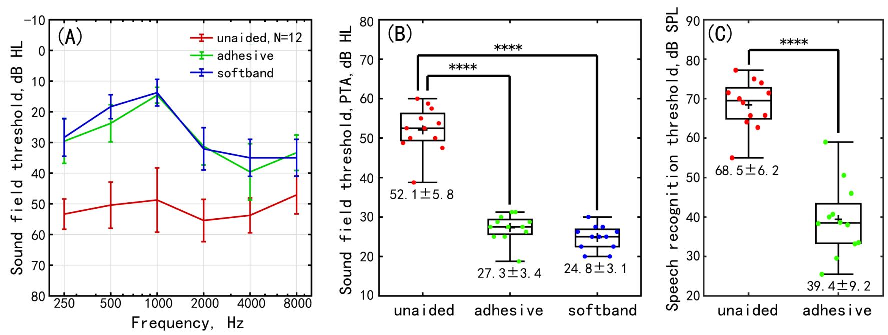
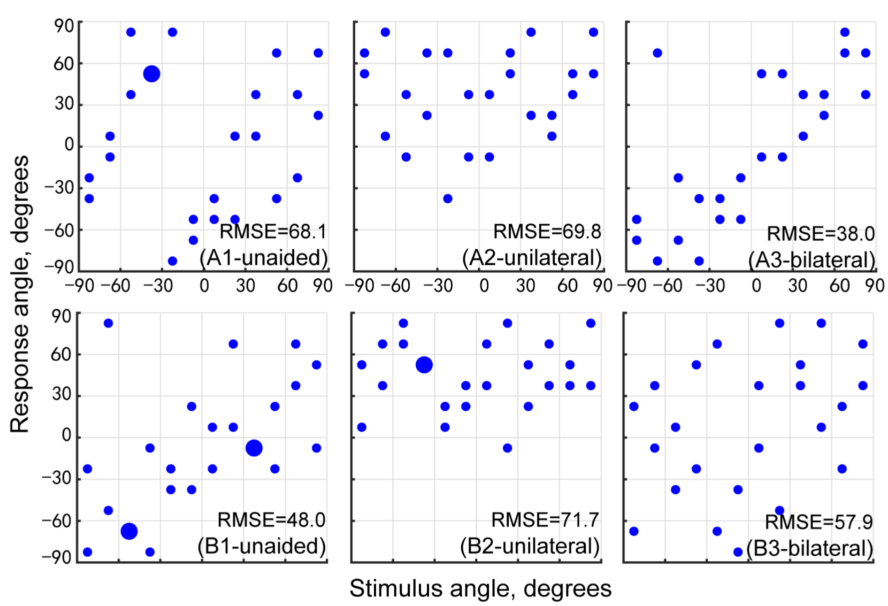
9	11	M	3	B	61.25	17.50	43.75	61.25	17.50
10	8	M	NA	-	72.50	42.50	30.00	76.25	51.25
11	10	M	4	B	66.25	21.25	45.00	67.50	21.25
12	10	M	6	-	70.00	27.50	42.50	67.50	27.50
Mean±SD	11.1±3.0	-	-	-	65.8±7.5	25.3±7.8	40.5±9.2	67.3±6.0	24.8±10.0
NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap	NA – the patient has not used BCHDs before; P – Ponto headband; B – Baha softband; PTA – pure tone average; AC – air conduction; BC – bone conduction; ABG – air-bone gap

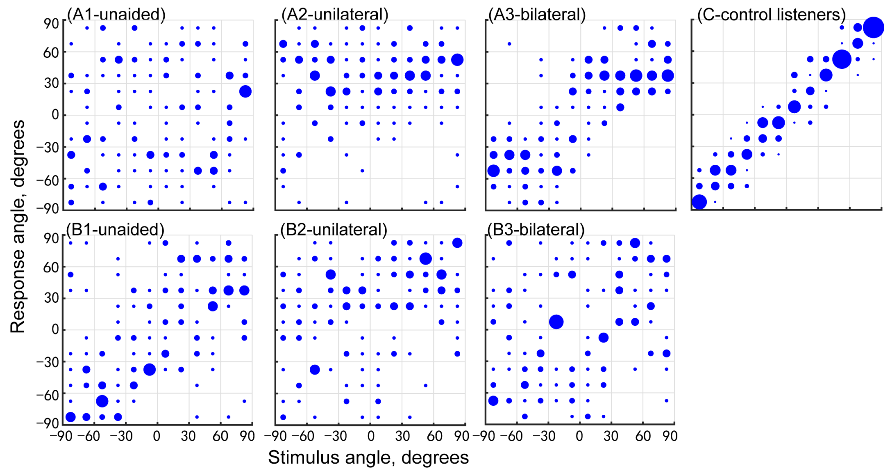
Table 2 Sound localization results of the 12 subjects

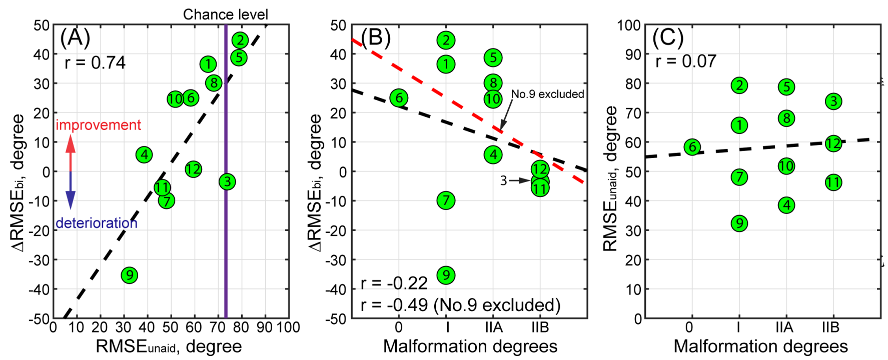
Groups	**Subject number**	**Subject number**	**unaided** $RMSE_{unaid}$	**unilateral fitting** $RMSE_{uni}$	**bilateral fitting** $RMSE_{bi}$	$\Delta RMSE_{uni}$	$\Delta RMSE_{uni}$	$\Delta RMSE_{bi}$	$\Delta RMSE_{bi}$	**Pruzansk Kaban classification / score**
Non-Improvement Group	9		32.3	48.2	67.6	-15.9		-35.3		I / 1
	7		48.0	71.7	57.9	-23.7		-9.9		I / 1
	11		46.2	60.9	51.8	-14.7		-5.6		IIb / 3
	3		73.8	71.7	77.3	2.1		-3.5		IIb / 3
	12		59.5	59.1	58.7	0.4		0.8		IIb / 3
	4		38.5	42.1	32.8	-3.6		5.7		IIa / 2
Improvement Group	10		51.8	73.9	27.2	-22.1		24.6		IIa / 2
	6		58.3	61.8	33.3	-3.5		25.0		0 / 0
	8		68.1	69.3	38.0	-1.2		30.1		IIa / 2
	1		65.7	76.2	29.2	-10.5		36.5		I / 1
	5		78.7	74.3	40.0	4.4		38.7		IIa / 2
	2		79.3	39.9	34.6	39.4		44.7		I / 1
Mean±SD										
Non-improv.	-	-	49.7±15.0	59.0±12.0	57.7±15.1	-9.0±10.4	-9.0±10.4	-8.0±14.4	-8.0±14.4	-
Improvement	-	-	67.0±10.9	65.9±12.7	33.7± 4.9	1.1±20.9	1.1±20.9	33.3±8.1*	33.3±8.1*	-
Total	-	-	58.4±15.4	62.4±12.9	45.7±16.5	-4.1±16.6	-4.1±16.6	12.7±24.2	12.7±24.2	-
$\Delta RMSE_{uni}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.	* Significant improved, $P <$ 0.001.


1
2
3
4
5
6
7
8
9
10
11
12
15°
7.5°
R=1.0 m


(A)
unaided, N=12
adhesive
softband
Sound field threshold, dB HL
Frequency, Hz
(B)
Sound field threshold, PTA, dB HL
****
52.1±5.8
27.3±3.4
24.8±3.1
unaided
adhesive
softband
(C)
Speech recognition threshold, dB SPL
68.5±6.2
39.4±9.2


RMSE=68.1
(A1-unaided)
RMSE=69.8
(A2-unilateral)
RMSE=38.0
(A3-bilateral)
RMSE=48.0
(B1-unaided)
RMSE=71.7
(B2-unilateral)
RMSE=57.9
(B3-bilateral)
Response angle, degrees
Stimulus angle, degrees


(A1-unaided)
(A2-unilateral)
(A3-bilateral)
(C-control listeners)
(B1-unaided)
(B2-unilateral)
(B3-bilateral)
Response angle, degrees
Stimulus angle, degrees


(A)
r = 0.74
Chance level
improvement
deterioration
ΔRMSEbi, degree
RMSEunaid, degree
(B)
No.9 excluded
r = -0.22
r = -0.49 (No.9 excluded)
ΔRMSEbi, degree
Malformation degrees
(C)
r = 0.07
RMSEunaid, degree
Malformation degrees