Sound Localization in Unilateral Deafness With the Baha or TransEar Device

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Objective: To evaluate the sound localization capabilities of patients with unilateral, profound sensorineural hearing loss who had been treated with either a bone-anchored hearing device (Baha BP100) or a TransEar 380-HF bone-conduction hearing device.

Study Design: Nonrandomized, prospective study.

Setting: Tertiary referral private practice.

Patients: Patients with unilateral, profound sensorineural hearing loss treated with a BP100 (n=10) or a TransEar (n=10) device. Patients wore the hearing device for at least 1 month and had normal hearing in the contralateral ear. Ten patients with normal, bilateral hearing were used for control.

Interventions: Sound localization of a 3-second recorded sound with and without a TransEar or Baha device was assessed using an array of 7 speakers at head level separated by approximately 45 degrees. The recorded sounds were that of a barking dog or a police siren. Randomized trials of 4 presentations per speaker were given for each hearing condition.

Main Outcome Measures: Sound localization was assessed by the accuracy in response and the generalized laterality of response.

Results: The mean accuracy of speaker localization was 24% and 26% for the aided condition using the BP100 and TransEar devices, respectively. The mean accuracy of laterality judgment was 59% and 69% for the aided condition using the BP100 and TransEar devices, respectively. These results were only slightly better than chance. There was no statistical difference in localization accuracy or laterality judgment between the BP100 and TransEar groups.

Conclusion: Neither the BP100 nor the TransEar device improved sound localization accuracy or laterality judgment ability in patients with unilateral, profound sensorineural hearing loss compared with performance in the unaided condition.


IN THE UNITED STATES, THERE ARE approximately 50,000 to 60,000 new cases per year of unilateral, profound sensorineural hearing loss (UPSNL).1 This results in a number of significant auditory perceptual difficulties relative to binaural hearing. The most prominent of these difficulties include (1) difficulty understanding speech in background noise or in reverberation, (2) poor understanding of the person talking on the deaf side, and (3) poor sound localization capabilities. Because of these difficulties, monaural listening often results in decreased communication ability and reduced psychosocial function in everyday listening situations.2-4 Since 2000, the bone-anchored hearing device (Baha) has become a popular choice in the treatment of UPSNL.5 The Baha device, when used as treatment for UPSNL, acts as a transcranial contralateral routing of off-side signal.

Several studies6-10 have demonstrated the benefit of Baha amplification to improve speech intelligibility in noise and the quality of life in patients with UPSNL. Studies6,7,11,12 evaluating the effectiveness of sound localization using the Baha device, however, have shown little to no benefit.

The US Food and Drug Administration first approved the Baha device for use in UPSNL in 2002. Since that time, the device has undergone gradual design improvements. Since 2002, the device has evolved from the Baha Compact to the Baha Divino and now, the current device, the BP100 (all manufactured by Cochlear Americas). The Baha Compact or Divino device was used in most studies that evaluated the effectiveness of the
Baha device for sound localization in UPSNHL. The BP100 (Figure 1) is a significant improvement compared with previous models. Some of these improvements relative to previous models are, first, an improved directional microphone system with 2 microphones rather than 1 microphone; second, digital feedback reduction; third, improved noise reduction; and fourth, microphone position compensation, which is an attempt to compensate for the postauricular placement of the microphone rather than anteriorly in the ear canal. Position compensation equalizes sounds between the 2 microphones by calibrating loudness, which is designed to mimic the directivity of natural hearing. Fifth, there has been an improvement in the software used for BP100 fitting. The software, BC Direct, allows measurement of bone conduction through the abutment, thus bypassing the skin and soft tissue. The BC Direct bone conduction is more accurate than preoperative bone conduction, which is performed over the skin and soft tissue with a resulting attenuation of sound. Using the BC Direct software, BP100 fitting prescriptions require less gain and ultimately have less distortion and a clearer signal compared with previous generations of Baha fitting prescriptions.

Some of these improvements could plausibly improve sound localization capabilities in patients with UPSNHL. Specifically, position compensation is designed to correct and rebalance the soundscape by compensating for the posterior location of the BP100 while preserving the natural head shadow effects for different frequencies. The head shadow effect has been found to be useful for sound localization in UPSNHL patients. Improved noise reduction and BC Direct fitting lead to less sound distortion, with possible improvement in sound localization ability in noise.

The TransEar 380-HF (Ear Technology Corporation) is another bone-conduction hearing device designed to treat UPSNHL as a transcranial contralateral routing of off-side signal (Figure 2). The TransEar device consists of a behind-the-ear digital hearing aid with a flexible wire connected to a custom molded acrylic half-shell. The shell houses an oscillator that vibrates the bony portion of the ear canal on the deaf side. When sound is processed on the deaf side, the sound is converted to mechanical energy that drives the oscillator. The TransEar processor includes digital feedback reduction and adaptive noise reduction. The main benefit of the BP100 and TransEar device is to reduce the acoustic head shadow and to provide improved signal-to-noise ratios, depending on the spatial distribution of the signal and noise sources.

Several UPSNHL patients have reported to members of our practice that their sound localization capabilities were improved when using the BP100 or TransEar 380-HF device. To our knowledge, no previous study has evaluated the sound localization capabilities of UPSNHL patients using the BP100 or TransEar 380-HF device. Because of this, we sought to objectively evaluate the sound localization capabilities in the horizontal plane of UPSNHL patients using these 2 devices.

## METHODS

### PATIENTS

Patients included in the study were identified in 2011 from the Ear Institute of Chicago database of UPSNHL patients. From this database, a subgroup of patients was identified who met the following criteria: (1) use of the BP100 or the TransEar 380-HF device for at least 30 days, (2) age greater than 18 years, (3) no previous experience using contralateral routing of off-side signal amplification, and (4) normal hearing in the contralateral ear. Normal hearing was defined as a pure-tone average (0.5, 1, 2, and 4 kHz) of 25 dB or less and a word recognition score of 90% or better in the only hearing ear. A letter of invitation to be included in the study was sent to this subgroup of patients. Enrollment in the study was stopped when 10 patients each using a BP100 and a TransEar device completed the study.

A group of 10 age-matched adults with bilateral, normal hearing were used as a control group. Thus, there were 3 groups in the study: BP100, TransEar, and control.

Approval for conducting this study was obtained from the Hinsdale Hospital Institutional Review Board, with all patients signing the informed consent form.

Table 1 displays patient characteristics of the BP100 group. In this group, the mean (range) age was 49.8 (26.0-66.0) years. The mean (range) duration of UPSNHL was 11.8 (0.8-32.0) years in the BP100 group. The mean (range) duration of device use
was 10.4 (3.0–14.0) months. All patients had the titanium fixture placed 55 mm posterior and superior to the ipsilateral external auditory canal. This position has been shown to be the ideal placement for bone-conduction sound transmission of the Baha device.15

Table 2 displays patient characteristics of the TransEar group. The mean (range) age was 62.8 (42.0–68.0) years. The mean (range) duration of UPSNHL was 5.1 (1.5–15.0) years and of device use was 17.4 (6.0–25.0) months.

LOCALIZATION TESTING

Localization testing was performed in a sound-treated room with internal dimensions of 6 ft × 6 ft 4 in. The patient was seated in the center of the room, approximately 3 ft from the speakers in any direction. Seven speakers were mounted at head level, labeled 1 through 7 (Figure 3). Patients were asked not to move their heads during sound presentation. Patients were free to move their heads after sound presentation to identify the speaker.

The BP100 and TransEar groups were tested in 2 different conditions: unaided and BP100- or TransEar-aided hearing conditions. In the aided condition, patients were tested in an omnidirectional listening program, which amplifies sounds all around the patient (360 degrees). The omnidirectional was chosen to give patients the best opportunity to localize sound.

Sound localization was performed using 2 recorded sounds, which were that of a barking dog or a police siren. The presentations were divided equally between these 2 recorded sounds. Randomized trials of 4 presentations per speaker were given for each hearing condition for a total of 28 presentations (14 presentations each of the barking dog and police siren) for each of the unaided and aided conditions. The duration of sound presentation was 3 seconds, with an approximate 3-second interstimulus interval. The presentation level was the 60-dB hearing level. Patients identified the sound source by the number of the speaker.

STATISTICAL ANALYSIS

Each of the patients’ responses was recorded and compared with the correct response. Localization accuracy and laterality judgments were determined for each of the 3 groups. Localization accuracy was calculated as the proportion of correct responses.

Laterality judgments were evaluated by combining the responses for speakers on the patient’s right (speakers 1, 2, and 3) and those on his or her left (speakers 5, 6, and 7). Trials from speaker 4 were excluded from analysis of laterality judgment. The percent correct identification was then calculated as the number of correct identifications per hemifield divided by the total number of presentations per hemifield.

A paired-sample t test was used for analyses within the same group (eg, unaided vs aided in the same group of patients). A 2-group t test was used when analyzing data across groups (eg, BP100 vs TransEar). 𝑃 < .05 was considered significant.

Initially, the proportions of correct responses for the dog and siren stimuli were analyzed separately. There were no significant differences in performance using the dog or siren sounds, when examined separately, either in terms of localization (𝑇29 = 0.48; 𝑃 = .64) or localization (𝑇29 = 1.01; 𝑃 = .32) accuracy. For this reason, the following results are for the combined results of dog and siren stimuli.

Table 1. Characteristics of Patients Treated With Baha BP100

<table>
<thead>
<tr>
<th>Patient No./Sex/Age, y</th>
<th>Side</th>
<th>Cause of Hearing Loss</th>
<th>Duration of Hearing Loss, y</th>
<th>Duration of Device Use, mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/M/26</td>
<td>Right</td>
<td>Head trauma</td>
<td>3.0</td>
<td>13</td>
</tr>
<tr>
<td>2/F/34</td>
<td>Right</td>
<td>AN</td>
<td>1.3</td>
<td>4</td>
</tr>
<tr>
<td>3/F/42</td>
<td>Right</td>
<td>AN</td>
<td>1.5</td>
<td>8</td>
</tr>
<tr>
<td>4/F/49</td>
<td>Left</td>
<td>AN</td>
<td>3.1</td>
<td>14</td>
</tr>
<tr>
<td>5/F/52</td>
<td>Left</td>
<td>Congenital</td>
<td>32.0</td>
<td>14</td>
</tr>
<tr>
<td>6/F/54</td>
<td>Left</td>
<td>Idiopathic</td>
<td>10.2</td>
<td>14</td>
</tr>
<tr>
<td>7/F/57</td>
<td>Right</td>
<td>Mastoid surgery</td>
<td>28.1</td>
<td>12</td>
</tr>
<tr>
<td>8/M/59</td>
<td>Left</td>
<td>AN</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>9/F/59</td>
<td>Left</td>
<td>AN</td>
<td>6.0</td>
<td>14</td>
</tr>
<tr>
<td>10/M/66</td>
<td>Left</td>
<td>SSNHL</td>
<td>1.5</td>
<td>8</td>
</tr>
</tbody>
</table>

Abbreviations: AN, acoustic neuroma; Baha, bone-anchored hearing device; SSNHL, sudden sensorineural hearing loss.

Table 2. Characteristics of Patients Treated With TransEar 380-HF

<table>
<thead>
<tr>
<th>Patient No./Sex/Age, y</th>
<th>Side</th>
<th>Cause of Hearing Loss</th>
<th>Duration of Hearing Loss, y</th>
<th>Duration of Device Use, mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/F/42</td>
<td>Right</td>
<td>Stapedectomy</td>
<td>3.0</td>
<td>33</td>
</tr>
<tr>
<td>2/M/62</td>
<td>Left</td>
<td>Meniere disease</td>
<td>1.5</td>
<td>12</td>
</tr>
<tr>
<td>3/F/62</td>
<td>Left</td>
<td>AN</td>
<td>1.5</td>
<td>13</td>
</tr>
<tr>
<td>4/F/63</td>
<td>Left</td>
<td>AN</td>
<td>2.1</td>
<td>23</td>
</tr>
<tr>
<td>5/F/63</td>
<td>Left</td>
<td>AN</td>
<td>10.0</td>
<td>23</td>
</tr>
<tr>
<td>6/M/66</td>
<td>Left</td>
<td>SSNHL</td>
<td>1.5</td>
<td>13</td>
</tr>
<tr>
<td>7/M/67</td>
<td>Right</td>
<td>AN</td>
<td>15.2</td>
<td>13</td>
</tr>
<tr>
<td>8/M/67</td>
<td>Left</td>
<td>AN</td>
<td>6.0</td>
<td>6</td>
</tr>
<tr>
<td>9/F/68</td>
<td>Left</td>
<td>SSNHL</td>
<td>2.5</td>
<td>25</td>
</tr>
<tr>
<td>10/F/68</td>
<td>Right</td>
<td>SSNHL</td>
<td>8.1</td>
<td>13</td>
</tr>
</tbody>
</table>

Abbreviations: AN, acoustic neuroma; SSNHL, sudden sensorineural hearing loss.
Comparison of the patient characteristics of the BP100 and the TransEar groups showed no significant difference in sex ($P = .24$), side ($P = .76$), or duration of hearing loss ($P = .32$). There was a significant difference in mean age ($P = .009$), with the BP100 group younger than the TransEar group (49.8 vs 62.8 years). There was also a significant difference in the mean duration of device use ($P = .03$), with the BP100 group using the device for a shorter period than the TransEar group (10.4 vs 17.4 months).

**LOCALIZATION ACCURACY**

The localization scores for unaided and aided groups compared with the control group are shown in Figure 4. There is a statistically significant better localization accuracy for the control group compared with the BP100 and TransEar groups for both unaided and aided conditions (all $P < .001$). The mean accuracy of speaker localization was 24% and 26% for the aided condition using the BP100 and TransEar devices, respectively. The mean localization accuracy for both the unaided (0.26) and aided (0.25) combined groups was only slightly better than chance level (0.15).

Figure 5 compares localization accuracy for the unaided vs the aided condition for the BP100 and TransEar groups. Points above the diagonal line represent a benefit in aided sound localization accuracy. Conversely, points below the diagonal line indicate a detriment in aided sound localization accuracy. There is scatter across the diagonal line, indicating an inconsistent effect of aid. There is, however, a slight benefit of aid in the TransEar group and a slight decrement in the BP100 group as indicated by a nearly significant 2 (aided vs unaided) × 2 (TransEar vs BP100) analysis of variance using aid as a repeated measure ($P = .06$).

There is a significant correlation between patient age and aided localization in which younger patients localize better ($r = -0.56, P = .01$). When unaided minus aided localization accuracy is plotted against age, however, there is no significant correlation ($r = -0.14, P = .56$). This latter finding indicates that the better localization in younger patients is not dependent on amplification. There is no correlation between duration of hearing loss ($r = -0.41, P = .07$) or duration of device use ($r = 0.18, P = .43$) with amplified localization accuracy.

Finally, the data from the BP100 and TransEar groups were combined to evaluate whether patients had better localization accuracy on their hearing or their deaf side, with and without amplification. In the unaided condition, localization accuracy is significantly better on the hearing side (proportion correct, 0.17 deaf side vs 0.28 hearing side) ($P = .005$). In the aided condition, there is no significant difference in localization accuracy of the hearing side compared with the aided (deaf) side (proportion correct, 0.21 deaf side vs 0.29 hearing side) ($P = .12$).

**LATERALITY JUDGMENTS**

The laterality scores for the unaided and aided groups compared with the control group are shown in Figure 6.
There is a statistically significant better lateralization judgment ability for the control group compared with the BP100 and TransEar groups for both unaided and aided conditions (all P < .001). Specifically, the mean accuracy of lateralization judgment was 59% and 69% for the aided condition using the BP100 and TransEar devices, respectively (all P < .001).

Figure 7 compares laterality judgment for the unaided vs the aided condition for the BP100 and TransEar devices. As in Figure 5 for localization, there is scatter across the diagonal line, indicating an inconsistent effect of aid. Again, a slight benefit of aid is seen in the TransEar group and a slight decrement in the BP100 condition using the BP100 and TransEar devices, respectively.

In summary, the results of our study are (1) localization accuracy is poor in UPSNHL patients in both unaided and BP100- and TransEar-aided conditions, and (2) duration of device use did not improve localization accuracy or laterality judgment in either aided group.

Sound localization is one of the major advantages of binaural listeners. There are 3 main acoustical cues that allow a binaural listener to localize sound. These 3 cues are sound intensity at each ear, arrival time at each ear, and variations in spectral shape.

The difference in sound intensity at each ear is known as the interaural level difference (ILD). The ILD is used in the localization of high-frequency sounds (primarily higher than 2800 Hz). High-frequency sounds have wavelengths shorter than the circumference of the head and thus are influenced by the head shadow effect. The head shadow effect blocks high-frequency sounds from reaching the other ear if the sound is originating on one side of the listener. In the horizontal plane, the ILD varies on the basis of the sound source’s location to the head and the frequency of the sound. For sounds originating on one side of the listener, the ILD at 5000 Hz is approximately 13 dB and the ILD at 1000 Hz is approximately 6 dB.

The difference in the time it takes for a sound to reach each ear after the onset of sound is known as the interaural time difference (ITD). Sound localization using ITD cues is best for low-frequency sounds (200-2800 Hz). Low-frequency sounds have wavelengths longer than the circumference of the head; therefore, sound originating to the right of the listener would have the same intensity at both ears but would arrive at the left ear later than at the right ear. With a sound source immediately to one side of the listener, the ITD is approximately 0.65 to 0.70 millisecond for low-frequency sounds (200-2800 Hz).

The BP100 and the TransEar devices are capable of capturing a wide range of sounds pertinent to the ILD and ITD. The frequency range is 250 to 7000 Hz for the BP100 device and 200 to 8000 Hz for the TransEar device. The peak energy output of the BP100 device is centered around 800 Hz, whereas the peak energy output of the TransEar device is from 2100 to 2300 Hz. Despite these differences in output, one device does not show improved localization ability in UPSNHL compared with the other.

Spectral shape cues are formed from the interaction of sound waves with the external ear. The convolutions of the external ear, particularly the concha, act to increase or decrease the amplitude of different frequency components of a sound as it enters the ear. The sound filtering effects of the external ear are dependent on the location of the sound, giving rise to spectral patterns—characteristic variations in amplitude with frequency—that vary with both the horizontal and vertical angle of the sound source. These spectral cues are most useful when the sound contains energy over a wide range of high frequencies.

Studies of sound localization are often separated into those that evaluate sound sources in the horizontal (azimuth) plane or sound sources in the vertical (midsagittal-
tal or median) plane. The horizontal plane is often defined at the level of the external auditory meati and the tip of the nose. The ILD and ITD cues are most important for sound localization in the horizontal plane because of the variable distance between ears and the sound source. Sounds in the vertical plane are equidistant from both ears; thus, ILD and ITD cues are nonexistent. Spectral shape cues, on the other hand, are most important for sound localization in the vertical plane. Spectral shape cues also have been found to contribute to horizontal plane sound localization but to a lesser degree than ILD and ITD. Studies that involve eliminating spectral shape cues by bypassing the pinnae also have found a decreased ability to discriminate sounds in front from those behind.

The ILD and ITD cues are absent for monaural listeners. Despite this, monaural listeners have been reported to localize sound well above chance levels, especially in the horizontal plane. Van Wanrooij and Van Opstal propose that the head shadow effect is the dominant cue for monaural sound localization, with spectral shape cues contributing to a lesser extent. Patients in our study were not allowed to move their heads during testing, which eliminated the opportunity to use the head shadow cue for localization. Allowing patients the opportunity to use the head shadow cue might confound the results of evaluating the potential of the BP100 and the TransEar devices to aid sound localization in UPSNHL patients.

Van Wanrooij and Van Opstal also state that the head shadow cue for monaural listeners is most effective for familiar environmental acoustic stimuli. For this reason, a barking dog and a police siren, sounds that should be readily familiar to all our patients, were used as acoustic stimuli in our study. In addition, the dog and siren sounds are broad-bandwidth stimuli, which help resolve the spatial ambiguities that may occur when using narrowband sound for sound localization.

The results of our study show that the localization accuracy and laterality judgment in UPSNHL patients is poor and only marginally better than chance, even with the use of the latest bone-conduction hearing devices. The results of our study are similar to those studies using earlier generations of the Baha device. Sound localization stimuli used in previous studies varied widely, ranging from real-world acoustic stimuli (eg, pistol shot or female vocal), multitalk babble noise from the revised Speech Perception in Noise test, or spectrally shaped noise to pure tones. Each of these previous studies also found that localization accuracy and laterality judgment was only slightly better than chance with the use of a Baha device.

Desmet et al recently compared sound localization abilities between Divino and BP100 users with UPSNHL. Sound localization was evaluated using the Spatial Hearing Questionnaire. Poor localization scores were reported for each device, with no differences between the Divino and the BP100.

Knowledge of bone-conducted sound is helpful to understand some of the results of our study. Bone-conducted sound is a complex process, with the sound attenuated as it travels from one side of the skull to the other. The attenuation is frequency dependent, with low-frequency sounds (0.2-1.0 kHz) attenuated approximately 5 to 0 dB and frequencies from 1 to 10 kHz attenuated from 5 to 10 dB.

Bone-conducted sound attenuation, however, is not sufficient to cause a significant ITD. Stenfelt and Goode have calculated the ITD for bone conduction to be 0.2 millisecond for frequencies higher than 0.8 kHz. This time difference is less than the 0.65- to 0.70-millisecond ITD for air-conduction sound. On the basis of this data, the ITD cue does not seem to be available for UPSNHL patients fitted with a bone-conduction device.

The other 2 sound localization cues for binaural listeners, ILD and spectral cues, are also apparently not available for UPSNHL patients wearing a bone-conduction device. The lack of ILD and spectral cues may be due to the inability of signal-processing strategies of the current bone-conduction devices and/or an inability of central processes to differentiate ipsilateral and contralateral signals coming from the same cochlea.

Previous authors have suggested that sound localization may improve with longer use of the Baha device for UPSNHL. Our study found that duration of device use did not improve sound localization, with 60% of BP100 patients and 90% of TransEar patients wearing their devices for 12 months or longer. The lack of correlation between length of device use and sound localization is in agreement with the study by Newman et al.

Clarification is necessary regarding the finding that older age is negatively associated with aided localization ability. Further review of our data indicates that this association may be skewed. Two younger patients in the BP100 group primarily drive the age vs localization correlation. If age is truly associated with aided localization, then the younger BP100 group should show better localization ability than the TransEar group. There is no difference in aided localization between the BP100 and the TransEar groups (P = .73). The bulk of the patients in both groups are older, and this dilutes any between-group difference.

Despite the findings of our study, our UPSNHL patients continue to report to us that, subjectively, their sound localization abilities improve when using either the BP100 or the TransEar 380-HF device. In addition, these patients report significant satisfaction with their devices in many listening situations.

In conclusion, the results of this study indicate that horizontal sound localization in UPSNHL patients is poor in the testing paradigm in this study, even with the latest technology available to treat UPSNHL. Sound localization did not improve with longer (12 months or greater) use of either the BP100 or the TransEar 380-HF device.

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Author Contributions: Dr Battista had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Battista. Acquisition of data: Bat-

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tista, Mullins, Wiet, Kim, and Rauch. Analysis and interpretation of data: Battista, Mullins, Sabin, and Rauch. Drafting of the manuscript: Battista and Kim. Critical revision of the manuscript for important intellectual content: Battista, Mullins, Wiet, Sabin, and Rauch. Statistical analysis: Sabin. Obtained funding: Battista. Administrative, technical, and material support: Kim and Rauch. Study supervision: Rauch.

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