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Intracochlear measurements of interaural time and level differences conveyed by bilateral bone conduction systems

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Abstract

Hypothesis—Intracochlear pressures (P_{IC}) and stapes velocity (V_{stap}) elicited by bilaterally-placed bone anchored hearing devices (BAHD) will be systematically modulated by imposed interaural time (ITD) and level differences (ILD), demonstrating the potential for users of bilateral BAHD to access these binaural cues.

Background—BAHD are traditionally implanted unilaterally under the assumption that transcranial cross-talk limits interaural differences. Recent studies have demonstrated improvements in binaural and spatial performance with bilateral BAHD; however, objective measures of binaural cues from bilateral BAHDs are lacking.

Methods—Bone-conduction transducers were coupled to both mastoids of cadaveric specimens via implanted titanium abutments. P_{IC} and V_{stap} were measured using intracochlear pressure probes and laser Doppler vibrometry, respectively, during stimulation with pure tone stimuli of varied frequency (250–4000 Hz) in ipsilateral, contralateral and bilateral ITD (–1 to 1 ms) and ILD (–20 to 20 dB) conditions.

Results—Bilateral stimulation produced constructive and destructive interference patterns that varied dramatically with ITD and stimulus frequency. Variation of ITD led to large variation of P_{IC} and V_{stap} , with opposing effects in ipsilateral and contralateral ears expected to lead to “ITD to ILD conversion”. Variation of ILD produced more straightforward (monotonic) variations of P_{IC} and V_{stap} , with ipsilateral-favoring ILD producing higher P_{IC} and V_{stap} than contralateral-favoring.

Conclusion—Variation of ITDs and ILDs conveyed by BAHDs systematically modulated cochlear inputs. While transcranial cross-talk leads to complex interactions that depend on cue type and stimulus frequency, binaural disparities potentiate binaural benefit, providing a basis for improved sound localization and speech-in-noise perception.

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Conflict of Interest Statement:

Stephen P. Cass is a consultant for Cochlear Corporation.

Introduction

Binaural hearing allows for evaluation of differences in inputs between two cochleae based on the location of the sound signal.^{1, 2, 3, 4} When sound waves originate from a location away from the mid-line (i.e. to the listener's left or right), their propagation through air results in the sound reaching one ear before the other, leading to an *interaural time difference* (ITD). Additionally, the head acts as an acoustic barrier, attenuating the sound at the ear further from the source sound, leading to an *interaural level difference* (ILD). Together, ITD and ILD cues enable listeners to localize and segregate sound sources in space, improving speech understanding and situational awareness (see Blauert⁵ for review). While these benefits are clear for air conducted sound, including that conveyed by conventional hearing aids and cochlear implants, benefits of binaural hearing via bone conduction are less clear.^{6, 7}

Bone anchored hearing devices (BAHD) are osseointegrated prostheses that generate bony vibration in response to sound, directly stimulating the cochlea. They have been utilized for the management of conductive hearing loss, mixed hearing loss, and single sided deafness. Historically, patients were only implanted unilaterally since a single BAHD is capable of stimulating both cochleae; consequently, BAHD patients did not receive any binaural cues via bone conduction. However, over the past two decades, there has been increased interest in the implantation of bilateral BAHD and evidence that non-negligible transcranial attenuation (TA) and transcranial delay (TD) may allow patients to access binaural cues.^{6, 8, 9} Multiple clinical studies have demonstrated improved sound localization and speech in quiet and speech in noise perception with bilateral (versus unilateral) BAHD.^{10, 11} Studies in normal-hearing listeners have also demonstrated spatial/binaural benefit with bilateral bone conduction device.^{6, 7} Moreover, subjective assessments indicate that patients prefer bilateral BAHD to unilateral BAHD and report improved overall quality of life when utilizing bilateral BAHD.^{12, 13}

While measurements and models suggest that binaural differences should arise under bilateral bone conduction stimulation due to TA and TD, the precise nature of bilateral stimulus interactions within the cochlea remains largely uncharacterized.^{6, 8, 9} Here we make direct measurements of intracochlear pressures in human cadaveric specimens implanted with BAHDs bilaterally. Our data provide an improved understanding of the complex interactions of bilateral bone-conducted sounds with the cochlea.

Method

Fourteen fresh-frozen whole heads with intact temporal bones and no history of middle ear disease were obtained and evaluated (MD Global, Aurora, CO, U.S.A.). The use of cadaveric human tissue complied with the University of Colorado Institutional Biosafety Committee (COMIRB EXEMPT No. 14-1464).

Temporal Bone Preparation

Temporal bone preparation was similar to methods described previously by our laboratory^{14–19} as well as other authors.^{20–22} The specimens were thawed in warm water

and inspected for any damage. A canal-wall-up mastoidectomy and extended facial recess approach were performed to visualize the incus, stapes, and round window. The cochlear promontory near the oval and round windows was thinned with a small diamond burr in preparation of pressure sensor insertion into the scala vestibuli (SV) and scala tympani (ST). A BI300 4-mm titanium implant fixture (Cochlear Ltd., Centennial, CO, U.S.A.) was placed on the temporal line approximately 55 mm from the external auditory canal.

The full cephalic specimens were suspended from a Mayfield Clamp (Integra Lifesciences Corp., Plainsboro, NJ, U.S.A.) attached to a stainless steel baseplate. Cochleostomies into the ST and SV were created under a droplet of water using a fine pick. Pressure sensors (FOP-M260-ENCAP; FISO Inc., Quebec, Canada) were inserted into the SV and ST using micromanipulators (David Kopf Instruments, Trujunga, CA, U.S.A.) mounted on the Mayfield Clamp and sealed to the cochlea with alginate dental impression material (Jeltrate; Dentsply International Inc., York, PA, U.S.A.).

Out-of-plane velocity of the middle ear structures was measured with a single-axis LDV (OFV-534 and OFV-5000; Polytec Inc., Irvine, CA, U.S.A.) mounted to a dissecting microscope (Carl Zeiss AG, Oberkochen, Germany). Microscopic retroreflective glass beads (P-RETRO 45–63 μm dia., Polytec Inc.) were placed on the stapes and incudostapedial joint to ensure a strong LDV signal. In all LDV measurements, the position of the laser was held as constant as possible between experimental conditions, although slight shifts were unavoidable when manipulating the specimen.

Stimulus Presentation and Data Acquisition

All experiments were performed in a double-walled sound-attenuating chamber (IAC Inc., Bronx, NY, U.S.A.). The method of sound stimuli production and response recording was performed in similar fashion to previously described protocols.^{14, 16} Stimuli were generated digitally, presented to the specimen via a bare (i.e., no sound processing) BC transducer or a closed-field magnetic speaker (MF1; Tucker-Davis Technologies Inc., Alachua, FL, U.S.A.) powered by one channel of a stereo amplifier (SA1; Tucker Davis Technologies Inc., Alachua, FL, U.S.A.) and driven by an external sound card (Hammerfall Multiface II; RME, Haimhausen, Germany) modified to eliminate high-pass filtering on the analog output. Stimuli were generated and responses were recorded at a sampling rate of 96,000 Hz and controlled by a custom program in Matlab (MathWorks Inc., Natick, MA, U.S.A.). During baseline air-conduction (AC) stimulation, sounds were delivered to the ear canal through a custom-made foam insert altered to accommodate flexible speaker tubing. The sound intensity in the ear canal was measured with a probe-tube microphone (type 4182; Bruel & Kjaer, Nærum, Denmark) which was also placed through the modified foam earplug. Baseline acoustic transfer functions were generated from presentation of short (1 s duration) tone pips between 250 and 6000 Hz ramped on and off with a Hanning window (5 ms rise/fall). Input from the microphone, LDV, and pressure sensors were simultaneously captured via the sound card analog inputs. The magnitude of the LDV signal was adjusted using a cosine correction ($1/\cos(u)$) based on an estimate of the difference in angle between the primary axis of the stapes and the orientation of the LDV laser (usually 45°). Signals

acquired were band-pass filtered between 15 and 15,000 Hz with a second-order Butterworth filter.

Next, baseline bone conduction (BC) stimulation was performed with both ipsilateral and contralateral bone-anchored hearing aids independently (Cochlear BAHA Cordelle II; Cochlear Ltd., Centennial, CO, U.S.A.) at 250, 500, 1000, 2000, and 4000 Hz. Once baseline measurements were obtained, effects of varying bilateral bone-conducted signals were examined at the same frequencies. ITD was varied from -1 to 1 ms in 0.05 ms increments, with positive values indicating that the ipsilateral signal led in time, and negative values indicating that the contralateral signal led in time. Next, effects of ILD were examined at the same frequencies, with ILD of ranging from -20 to 20 dB in 2 dB steps, with positive values indicating greater intensity in the ipsilateral signal, and negative values indicating greater intensity in the contralateral signal. A positive ITD and/or ILD thus corresponds to the situation in which a sound source would be present in the ipsilateral hemispace.

Data Analysis

Responses to pure-tone stimuli are shown as transfer functions, that is, measured velocities (V_{Stap}) and pressures (P_{IC}) are presented normalized to sound pressure level (SPL) in the external auditory canal for AC stimuli and to the voltage input to the BC transducer for BC stimuli. For ILD measures, data are presented in raw velocities and pressures without normalization in order to account for any nonlinearities in Baha output. The magnitude of the LDV signal was adjusted using a cosine correction based on the difference in angle between the primary axis of the stapes at the capitulum and the orientation of the LDV laser (usually ~ 45 degrees). All acquired signals were band-pass filtered between 15 and 15,000 Hz with a second-order Butterworth filter for data analysis. Responses are the average of at least three repetitions and are only shown for measurements with a signal-to-noise ratio (SNR) of greater than 3 dB.

Responses to BC stimuli were compared across experimental conditions using a method adapted from Rosowski *et al.* and the ASTM Standards for Middle Ear Implants F2504-05 (ATSM).²³ That is, transfer functions for BC ($H_{\text{Stap},SV,ST}^{BC}$) and AC ($H_{\text{Stap},SV,ST,\text{Diff}}^A$) stimulation were compared to derive the equivalent SPL in the ear canal required to elicit a given response magnitude. This method allows for natural comparisons across experimental conditions as all measures are represented as an estimate of the sound level produced by the transducer.

Results

Baseline responses

Closed-field acoustic transfer functions for stapes velocity (H_{Stap}^A) were determined to assess the temporal bone conditions prior to each experiment. Six of 14 temporal bones met inclusion criteria, defined by the baseline H_{Stap}^A falling within the 95% confidence interval

for normal healthy specimens.²³ Thus, cochleostomies were performed on the remaining 6 temporal bones.

After completion of cochleostomies and placement of pressure sensors, closed-field acoustic transfer functions for stapes velocity (H_{Stap}^A) were then reassessed to ensure that there were no significant changes in temporal bone conditions. Baseline acoustic transfer functions for scala vestibuli and tympani pressures (H_{SV}^A and H_{ST}^A) as well as the transfer function for the differential pressure (H_{Diff}^A) were also assessed. Figure 1 demonstrates the resulting transfer functions (H_{Stap}^A , H_{SV}^A , H_{ST}^A , and H_{Diff}^A) in response to closed-field acoustic (air-conducted) stimulation between 250 and 6000 Hz in each temporal bone that met inclusion criteria for the study. The transfer functions are shown superimposed on ranges of responses previously reported.^{20, 23} As demonstrated, the transfer functions were shown to be similar to prior reports in frequencies up to ~4000 Hz. Above 4000 Hz, there was more variation in the data that is likely related to the microphone, microphone placement, or sealing of the ear canal since these differences are not apparent with measurements made with bone-conducted stimuli.

After acoustic baseline had been established, the earplug was removed from the test ear in order to prevent an occlusion effect, and baseline ipsilateral and contralateral bone conducted transfer functions were determined (H_{Stap}^{BC} , H_{SV}^{BC} , and H_{ST}^{BC}). Prior studies by our group evaluated the transfer function magnitudes in response to ipsilateral and contralateral BC stimuli (unpublished data).¹⁶ Figure 2A demonstrates the average transfer function magnitudes in each specimen for ipsilateral and contralateral BC. Comparison of the ipsilateral and contralateral bone conduction transfer functions demonstrated that contralateral stimulation results in a 5–15 dB reduction in transfer function magnitude, primarily with high frequency stimuli (see Figure 2B). This relationship is consistent with other unpublished data from our group.

Bone-conducted Interaural Time Difference Evaluation

In order to determine the effect of ITD on bone conducted signals, V_{Stap} and P_{IC} were evaluated in response to interaural time delays ranging from –1 to 1ms. Figure 3 shows data for a single specimen. Despite inter-sample variation in magnitudes, there were consistent patterns in stapes velocity, scala vestibuli pressure, and scala tympani pressures as a function of ITD.

Figure 3A shows the stapes velocity transfer function magnitude at each octave frequency from 500 to 4000 Hz as a function of ITD. Variation of ITD gives rise to a sinusoidal fluctuation of stapes velocity magnitude. At 500 Hz, the sinusoid has a period of approximately 2ms, whereas for 1000, 2000, and 4000 Hz, the period was 1, 0.5, and 0.25 ms, respectively. The Matlab *Curve Fitting Toolbox* was used to generate sinusoidal functions fit to the individual data points, resulting in goodness of fit r^2 values >0.93 for all frequencies. As shown in Figure 3B, scala vestibuli transfer functions (H_{SV}^{BC}) also demonstrated a sinusoidal response that is frequency dependent. Scala tympani transfer

functions (not shown) demonstrate the same pattern. At 500, 1000, 2000, and 4000 Hz, the period of the sinusoid is about 2, 1, 0.5, and 0.25 ms, respectively. R^2 values were > 0.86 for the sinusoids fit to the raw data for both scalae and all frequencies, with the exception of 4000 Hz in scala vestibuli, in which $R^2=0.72$. See Table 1 for a list of functions for each fit and corresponding goodness-of-fit measures for both V_{Stap} and P_{IC} . Examination of the sinusoidal curves of scala vestibuli and scala tympani pressures also demonstrates that there is no common peak for either V_{stap} or P_{IC} at an ITD of 0 μs . Instead, the peaks were offset in a frequency-dependent fashion, likely due to varying transcranial delays.

Bone-conducted Interaural Level Difference Evaluation

Figure 4 compares the H_{Stap}^{BC} , H_{SV}^{BC} , and H_{ST}^{BC} to various interaural level differences with level differences for a representative sample with ILD varying from -20 dB to $+20$ dB in 10 dB increments. As seen in Fig. 4A, both V_{Stap} and P_{IC} increase as ILD increasingly favors the ipsilateral side. This effect is clearer when response magnitudes are compared against those elicited at 0 dB ILD (i.e., with equal-intensity stimuli to both ears): ILD systematically modulates response magnitude, with greatest magnitudes at the highest ipsi-favoring ILD ($+20$ dB) tested. Ipsi- and contra-favoring ILD responses also appear to separate increasingly with increasing frequency, though substantial variability across specimens makes it difficult to assess cross-frequency trends precisely.

Discussion

Bilateral implantation of BAHD is not traditionally performed due to the assumption that patients reliant on bone conducted sound cannot utilize binaural cues. Since cross-stimulation of bone conducted sound results in activation of both cochleae, access to binaural disparities should be limited.^{6, 8, 9} Here, we demonstrate that both ITDs and ILDs conveyed by bilateral BAHD create unique intracochlear responses in cadaveric specimens, potentiating access to binaural cues.

Bilateral Bone-Conduction in Patients

Multiple subjective and objective studies have demonstrated improved quality of life as well as improved sound localization and speech recognition in patients with bilateral hearing loss who were implanted with bilateral BAHD, further supporting the theory that patients who are bilaterally implanted may utilize binaural cues.^{12, 24, 25} In 2001, Bosman *et al.* evaluated sound localization and speech reception thresholds in noise and in quiet in 25 patients with bilateral BAHD.²⁶ They found that patients with bilateral BAHDs had significantly improved sound localization and improved speech recognition in quiet and in noise. Priwin *et al.* performed audiometric testing on 12 patients with bilateral BAHD's and found similar results.¹¹

Stenfelt and Zeitooni performed psychophysical testing on 20 normal-hearing subjects using bilateral bone-conducted signals.⁶ Overall, they found that subjects were able to gain some binaural benefit (e.g., in spatial release from masking) via bilateral bone conduction with transducers placed at the audiometric mastoid position, though benefit was less than that for

bilateral air conducted sound.⁶ In a follow-up study, similar binaural benefits were demonstrated with bone conduction transducers placed at the clinical BAHD position.⁷

Transcranial Attenuation and Delay

Multiple studies have demonstrated, contrary to audiologic dogma, that TA via bone conduction is non-negligible. For frequencies ranging from 250 to 4000 Hz, estimates of TA vary from 0 to 15 dB.^{27–29} Stenfelt and Goode demonstrated that TA is both frequency and transducer position dependent, with large inter-subject variability.³⁰ Our results study are consistent with previous studies demonstrating greater TA at frequencies >1000 Hz and minimal to no attenuation at frequencies <1000 Hz. Critically, significant TA enables ILDs to systematically modulate the relative amplitudes of the intracochlear pressures (between the ears), providing what is likely the most stable and useful cue for binaural hearing via BAHD.

In addition to TA, there is also a time delay of bone conducted sound between the cochleae, i.e. TD. Previous estimates of TD for bone conducted signals vary but are approximately 0.3 to 0.5 msec for frequencies above 1000 Hz^{30, 31}; previous studies have not definitively measured TD for low frequency signals.⁶ The co-occurrence of TA and TD mean that ipsilateral and contralateral bone conducted signals will not result in identical cochlear responses, and thus that *stimulus-related* interaural attenuation and delay (i.e. ILD and ITD) can lead to differential responses in the two ears. However, for the case of ITD in particular, this interaction is complex due to the phase-dependent interactions of ipsilateral and contralateral signals. This fact, first explored in detail by Rowan and Gray, is considered in the following section.³²

ITD to ILD Conversion

Rowan and Gray theorized that ITDs are converted to ILDs during bilateral bone conduction stimulation due to the direct and phase-dependent interaction of contralateral and ipsilateral signals at each ear.³² Psychophysical data were presented in support of this theory: Whereas normal-hearing listeners are wholly unable to detect ITDs carried by pure tones above ~1500 Hz, listeners tested with bilateral bone conduction systematically lateralized ITDs imposed on pure tones as high as 6000 Hz – presumably due to the systematic patterns of constructive and destructive interference produced, differing at each ear.³³ The results of our study support this theory: Bilateral BAHD stimulation led to ITD-dependent fluctuation of intracochlear pressures at all frequencies tested (including 4000 Hz). These variations in pressure are in theory symmetrically opposed in the two ears and should thus lead to an effective ILD. However, the correspondence between the eliciting ITD and resultant ILD is highly frequency-dependent, leading to a highly nonmonotonic relationship between “input” and “output.” It is possible that some frequency regions lead to a relatively more stable relationship, but this matter is beyond the scope of this study. In general it may prove difficult for listeners to use ITD cues for sound localization per se (i.e. perceiving the absolute position of a sound source), but perhaps the emergence of ITD-determined binaural disparities (i.e., “converted ILDs”) is sufficient for listeners to achieve binaural unmasking.⁷

Limitations

Though the results of this study demonstrate a direct effect of ITD and ILD on intracochlear responses, there are three main limitations that could possibly affect this relationship. First, it is possible that the freeze-thaw processing of our cadaveric samples could have compromised the quality of the tissue through tissue degradation³⁴, though intracochlear pressure measurements from included specimens falling within the expected range of previously established responses suggests that a change in cochlear input impedance is likely minimal, if present. In addition, only pure tone stimuli were presented in this study. Real-world acoustic signals are significantly more complex and interactions from more complicated bilaterally bone-conducted stimuli are more difficult to predict. Last, measurements in this study were made with only voltage-driven bone-conducted sound. Patients with bilateral conductive hearing loss who are fitted with bilateral BAHF likely perceive air-conducted sound in addition to bone-conducted sound, leading to intracochlear pressure responses that would be further complicated by the confounding presence of air-conducted signals.

Conclusion

In conclusion, we demonstrate that ITDs and ILDs conveyed by bilateral bone-conducted sound systematically modulate intracochlear responses. These results suggest that patients who are implanted with bilateral BAHF should have access to binaural disparities, which may allow for improved sound localization and speech recognition. However, further studies are required to elucidate the interactions between cues (e.g., co-occurring ITDs and ILDs) and intracochlear responses resulting for more ecologically relevant stimuli like speech.

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Figure 1.

Baseline closed-field acoustic transfer functions H_{Stap}^A , H_{SV}^A , H_{ST}^A and H_{Diff}^A for each of the included specimen. The black lines represent the individual transfer function magnitudes and the light grey bands represent the established 95% confidence intervals for stapes velocities and intracochlear pressures established in previous reports (Rosowski et al, 2007; Nakajima et al, 2009).

Figure 2.

Baseline unilateral bone conduction transfer functions (H_{Stap}^{BC} , H_{SV}^{BC} , and H_{ST}^{BC}). Mean $\pm$ SEM transfer function magnitudes are shown for stapes velocity, scala vestibuli pressure, and scala tympani pressure to ipsilateral (solid line) and contralateral (dashed line) stimulation (A). The difference in unilateral response magnitude was calculated between ipsilateral and contralateral stimulation (B). High frequency gain was generally consistent across stimulation condition, showing a 5–15 dB reduction for contralateral stimulation re: ipsi in all three measures.

Figure 3.

Bilateral transfer functions (H_{Stap}^{BC} , H_{SV}^{BC} , and H_{ST}^{BC}) in response to varied interaural time difference (ITD) by frequency in stapes velocity measurements (A) and intracochlear pressures (B). An ITD of 1ms corresponds to a 1ms delay of stimulation at the contralateral ear and ITD of -1ms corresponds to a 1ms delay of stimulation at the ipsilateral ear. There is a sinusoidal pattern to the stapes response which is frequency dependent. The periods of 500, 1000, 2000, and 4000 Hz are approximately 2, 1, 0.5, and 0.25 ms, respectively.

Figure 4.

Bilateral bone conduction transfer functions (H_{Stap}^{BC} , H_{SV}^{BC} , and H_{ST}^{BC}) in response to varying ILD. Mean +/- SEM transfer function magnitudes are shown for stapes velocity, scala vestibuli pressure, and scala tympani pressure to ipsilateral (solid line) and contralateral (dashed line) stimulation (A). An ILD of 20dB indicates that the signal is 20dB louder on the ipsilateral side and an ILD of -20dB indicates that the signal is 20dB louder on the contralateral side. The difference in unilateral response magnitude was calculated between 0 dB ILD and varied ILDs (20 dB, 10 dB, -10 dB, and 20 dB) (B). As ILD decreases on the ipsilateral side, there is a decreased magnitude of V_{stap} and P_{IC} .

Table 1

ITD Curve Functions and Goodness-of-fit Analyses

Frequency	Fit Function	R-square	Adjusted r-square
<i>Stapes Velocity</i>			
500	$f(x) = 0.5184\sin(3.145*x+3.058)+0.96$	0.9773	0.9761
1000	$f(x) = 0.8809\sin(6.288*x-2.954)+1.56$	0.9736	0.9722
2000	$f(x) = 0.9224\sin(12.6*x+2.837)+1.43$	0.934	0.9305
4000	$f(x) = 0.4425\sin(25.16*x+3.094)+0.69$	0.9896	0.9891
<i>Intracochlear Pressure</i>			
500	$f(x) = 41.83\sin(2.915*x+2.028)+66.44$	0.9421	0.9391
1000	$f(x) = 19.42\sin(6.189*x+1.972)+47.92$	0.8679	0.8609
2000	$f(x) = 12.52\sin(3.145*x+1.515)+54.85$	0.9161	0.9117
4000	$f(x) = 25.28\sin(3.145*x+2.535)+33.64$	0.7199	0.7051