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Comparison of umbo velocity in air and bone conduction

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Abstract

This study investigates the ossicular motion produced by bone-conducted (BC) sound in live human ears. Laser Doppler Vibrometry was used to measure air conduction (AC) and BC induced umbo velocity (V_u) in both ears of 10 subjects, 20 ears total. Sound pressure in the ear canal (P_{EC}) was measured simultaneously. For air conduction, V_u at threshold was calculated. For BC, V was defined as the difference between V_u and the tympanic ring velocity (an estimate of the skull velocity measured in the ear canal). V and P_{EC} at BC threshold were calculated and compared to the corresponding air conduction measurements.

V at BC threshold was significantly smaller than V_u at AC threshold between 500 Hz and 2000 Hz. Ear canal pressure at BC threshold tended to be smaller than for AC below 3000 Hz (with significant differences at 1000 Hz and 2000 Hz). Our results are most consistent with inertia of the ossicles and cochlear fluid driving BC hearing below 500 Hz, but with other mechanisms playing a significant role at higher frequencies. Sound radiated into the external ear canal might contribute to BC hearing at 3000 Hz and above.

Keywords

umbo velocity; bone conduction; middle ear inertia; cochlear inertia; sound radiated in the external ear canal

1. Introduction

Bone conduction (BC) is an alternative path for sound to stimulate the inner ear. It is the way noises of the body such as chewing, the flow of air and blood in the body, contraction of the muscles attached to the skull, and creaking of joints are perceived (Barany, 1938). It may also be a significant sound-conduction path in hearing underwater (Shupak et al., 2005). In the clinic, BC testing with tuning forks (Vikram and Naseeruddin, 2004) or

audiometry helps separate out conductive from sensorineural pathologies (Hulecki and Small, 2011).

Four different routes have been suggested for the transmission of bone conducted sound to the cochlea: a) The inertial effect of middle ear ossicles and inner ear fluid, b) sound radiated into the external ear, c) compression of the petrous bone, and d) sound transmitted through non osseous contents of the skull. These different routes are described below. Several of these suspected BC paths are thought to stimulate the inner ear via relative motions between the ossicles and the bone surrounding the inner ear.

The first route, the inertial component, results from differences between the moments of inertia of the skull and the coupled ossicles and cochlear fluids. When the skull is vibrated, the ossicles and the incompressible cochlear fluid, which are loosely constrained by the cochlear windows, also move but with a magnitude and phase determined by the moment of inertia of the ossicles and fluid and the compliance of the elements (the cochlear windows and ossicular ligaments) that constrain ossicular and fluid motion. The difference in displacement between petrous bone and the ossicles results in a relative displacement of the stapes footplate (Barany, 1938; Tonndorf, 1966) that is thought to drive the inner ear much like stapes motion in air-conducted sound (Barany, 1938). The second route is sound radiated into the external ear canal caused by vibrations of the bony and cartilaginous walls of the external ear canal that again produce relative motions of the ossicular chain and the skull. This sound also stimulates the inner ear in the same way as air conduction (AC) sound. The third route is compression and expansion of the petrous bone yielding displacement of the fluid in the cochlea. This displacement also produces ossicular motion, but unlike the other two paths in which the motions of the ossicles and round window are entrained by the intervening cochlear fluid, cochlear compression is thought to produce a differential motion between the ossicles and the round window. Therefore, the final stimulus to the inner ear in this route is not proportional to the motion of the ossicles themselves, but instead depends on the difference between the ossicular and round-window motions (Kim et al. 2011). The fourth and final path is the transmission of sound through the non osseous contents of the skull, such as CSF via the internal auditory canal or the vestibular aqueduct to the inner ear fluid. The importance and frequency dependency of these four mechanisms is not fully understood. The contribution of middle ear ossicles to BC hearing has been previously addressed in cadaveric human specimens (e.g., Barany, 1938; Stenfelt, 2006), but no measurements of bone-conduction associated ossicular motion in live humans were found in the literature.

The aim of this study is to compare the sound and vibration induced motion of the umbo in AC and BC stimulation in live human ears, where we assume the motion of the umbo is an indicator of stapes motion and therefore an indicator of those routes to the inner ear that depend on stapes motion. From this comparison we estimate 1) the contribution of the inertial effect of middle ear ossicles and cochlear fluid to BC hearing and 2) the contribution of sound radiated into the external ear canal to BC hearing. Our analysis is similar to the analysis of Stenfelt (Stenfelt, 2006) who summarized different sets of cadaveric human data for similar purposes. However, while Stenfelt (2006) found it difficult to quantify the

variation in his computations of umbo velocity at BC threshold, we provide direct estimates of inter-individual variations in this quantity.

2. Material and Methods

2.1 Human subjects

Ten subjects (4 female, 6 male) in good health and with a mean age of 36 years (range 24 to 59 years) participated in the study that was approved by the institutional review board of the Massachusetts Eye and Ear Infirmary. Informed consent and a brief medical and surgical history related to hearing were initially obtained. In all subjects, pure-tone audiometric thresholds for AC and BC, in addition to 226 Hz tympanograms, were gathered by a certified audiologist (author CH) in a sound proof chamber. Both ears were tested in all subjects.

Inclusion criteria were 1) no history of significant middle-ear disease or otologic surgery with the exception of myringotomy or tympanostomy tube placement over 2 years prior to measurement, 2) normal otoscopic exam of the external ear canal and tympanic membrane, 3) a mean air-bone gap (ABG) of less than 10 dB for the frequencies of 0.25, 0.5, 1, 2, and 4 kHz, and 4) normal, Type-A peaked tympanograms with peak pressures between -50 to $+50$ daPa, static compliance of 0.3 to 2.0 cc, total tympanometric volumes (static compliance + ear canal volume) between 0.7 and 2.7 cc, and normal-appearing shape that is neither rounded nor sharp.

Hearing thresholds for AC and ABG are shown in Figure 1A and 1B for all 20 ears. There was a high frequency sensorineural hearing loss in both ears of the eldest subject (likely an age-related loss) as indicated in the measurement range in Figure 1A. However, the ABG ranged from -10 to 10 dB in all ears (Figure 1B), indicating that the middle ear function was within normal range in all subjects. Our study aims at investigating the conductive mechanism of BC hearing. Therefore, a sensorineural hearing loss did not affect the measurement and there was no need to exclude the two ears with sensorineural hearing loss.

2.2 Measurement system and measurements

An HLV-1000 laser Doppler vibrometer (Polytec, Irvine CA) was used for measurements. The laser had a power of <1 mW (US FDA Class II), a minimum spot diameter of 100 micrometers, and was mounted on a Zeiss POMI-1 operating microscope. A speculum with a glass-backed sound coupler including an ER3 earphone and ER7 microphone (Etymotic Research, Elk Grove IL) was used to present controlled sound stimuli and provide visual access to the eardrum following the techniques described in previous publications (Whittemore et al. 2004, Rosowski et al. 2008, Rosowski et al. 2011).

Subjects lay comfortably on their back with their head turned to the side. For AC stimulation, the laser beam was aimed near the anterior border of the umbo where a reflection of light was generally visible. The measurements of umbo velocity (V_U) and sound pressure (P_{EC}) near the TM (between 1 and 0.5 cm from the umbo) were made during a one-second presentation of 9 simultaneous frequency tones between 0.3 and 6 kHz at 70–90 dB SPL. A bone vibrator (Radioear B71, Radioear Corp.) with a 1 Volt input was used

for BC stimulation. It was placed on the ipsilateral mastoid with a static force of 5 Newton provided by a steel headband. No occlusion effect was expected to occur because the speculum did not provide a tight seal to the external ear canal, and the volume enclosed by the glass backed sound coupler is much larger than the external ear canal volume. A series of single tone stimuli were presented in order to achieve better signal to noise ratio starting with the lowest frequency tone. The measurement was repeated with the laser beam additionally aimed at a bright spot on the skin over the tympanic ring to estimate tympanic ring velocity, V_{TR} . We assume the tympanic ring velocity is a good indicator of the vibration of the skull, as the skull motion could not be accessed directly. We compare V_U with AC stimulation, to the effective motion of the umbo in BC: V the complex difference between the velocity of the umbo and the tympanic ring.

Three to five responses were averaged in each condition. Generally, measurements for both ears took approximately 30 minutes. The test-retest variability was investigated by repeated measurements of one ear of each of two individuals.

The measurements also included a direct estimate of the noise in the velocity estimates. The basic velocity measurement was a time averaged laser voltage waveform, either in response to 9 tone (AC) or single tone (BC) stimulation. Fourier transforms of the averaged voltages produced response spectra with a 100 Hz frequency resolution. While the spectral magnitude and phases at the stimulus frequencies were used to define the response signal, the average of the spectral magnitude and phases on either side of the stimulus frequencies defined an estimate of the noise floor. The ratio of the signal-to-noise was used to determine the reliability of each measurement during later analyses (as described later).

2.3 Calibration

The BC vibrator was calibrated using an artificial mastoid (4930 Artificial Mastoid, Brüel & Kjær): The whole active surface area of the bone vibrator was placed in contact with the membrane of the artificial mastoid with a static force of 5.4 N that was checked with a force meter. The stimulus to the bone-conductor was a sequence of 1 Volt sinusoids of frequencies between 100 and 11000 Hz. The output of the artificial mastoid was connected to an amplifier and the output voltage recorded. The ratio of output voltage per input voltage was calculated (V_{out}/V_{in}). A recently performed calibration report provided by the manufacturer described the ratio of output voltage per force for the whole frequency range (V_{out}/F). By dividing our measured ratio of output to input voltage by the output voltage per force (from the calibration report), the force per input voltage could be calculated (F/V_{in}).

2.4 Analysis

We wish to compare V_U at threshold for both AC and BC. In AC analysis, simultaneous measurement of V_U and P_{EC} of each ear were used to calculate V_U at threshold, where the sound pressure at threshold, $P_{EC_threshold}$, was defined by ANSI standard S3.6-2010 (American National Standards Institute (ANSI), <http://www.ansi.org/default.aspx> (retrieved July 1st, 2011)). The velocity at threshold was defined as: $V_{U_threshold} = V_U / P_{EC}$ [measured] * $P_{EC_threshold}$.

Whether a specific data point was included in our analysis depended on our estimates of the signal-to-noise ratio (SNR) of the velocity estimate. It was generally possible to measure V_U with a SNR of 20 dB. However, we did exclude a few measurement points with SNR < 10 dB from further analysis.

For BC, the difference between V_U and V_{TR} defined the relative motion of the umbo ($V = V_U - V_{TR}$). Then the ratio of relative umbo velocity to the simultaneous measurement of the sound pressure in the external ear canal that also resulted from the BC stimulus was computed (V / P_{EC}). The standard for force at threshold, $F_{threshold}$ was defined by ANSI standard S3.6-2010 (American National Standards Institute (ANSI), <http://www.ansi.org/default.aspx> (retrieved July 1st, 2011)). We calculated the relative umbo velocity at threshold by multiplying the measured difference in velocity for a given voltage stimulus to the bone vibrator by (a) the calibration determined ratio between the stimulus voltage and the force produced by the vibrator, and (b) the force at threshold: $V_{threshold} = (V / stimulus\ voltage) * (stimulus\ voltage / Force) * F_{threshold}$. In a similar way, we calculated the bone-conductor induced sound pressure at hearing threshold by multiplying (a) the measured ear canal pressure per input voltage, (b) the ratio of stimulus voltage and vibrator's force, and (c) the force at the ANSI threshold: $P_{EC_threshold} = (P_{EC} / stimulus\ voltage) * (stimulus\ voltage / Force) * F_{threshold}$.

We also used our measurements of velocity SNR to restrict the bone-conduction data used in later analyses. A signal to noise ratio of 20 dB was achieved in most measurements of V_U and V_{TR} . In cases where the SNR for both measurements was 10 dB or better, we included an estimate of V based simply on the difference $V = V_U - V_{TR}$. In some individuals at higher stimulus frequencies (3, 4 and 6 kHz) we were able to measure V_U with an SNR of 10 dB or better, but V_{TR} was too small to measure accurately (SNR for V_{TR} was less than 10 dB). In these cases we included an estimate of $V = V_U$ when our noisy estimate of V_{TR} magnitude was less than 1/5 the magnitude of V_U . This ratio of V_{TR}/V_U was considered small enough that V_{TR} did not significantly affect the difference between V_U and V_{TR} . A V data point was excluded from further analysis either when both V_U and V_{TR} were measured with a SNR of less than 10 dB, or when V_U was measured with an SNR of 10 dB or better, the SNR of the V_{TR} was less than 10 dB, and V_{TR}/V_U was greater than 1/5.

2.5 Statistics

Student's t-test was used to determine if there were significant differences between the AC and BC results after converting the absolute values to a logarithmic scale. V_U at AC threshold was compared to $V = V_U - V_{TR}$ at BC threshold, as well as sound pressure at threshold for AC and BC. Two-tailed p values of 0.05 or less were considered significant.

3. Results

3.1 Air conduction

The umbo velocity transfer function V_U/P_{EC} that we determined from our measurements is very similar to other measurements of this quantity made in normal subjects using our techniques (Whittemore et al. 2004; Rosowski et al. 2011) and is not plotted here. The ear-canal pressure measurements we made simultaneously with the umbo velocity

measurements demonstrated stimulus sound pressures of 55 to 85 dB SPL. Consistent with the measurements of Dalhoff et al (Dalhoff et al., 2011), we assume linearity of the middle ear response to extrapolate our measurements to threshold levels. The extrapolated magnitude of the umbo velocity (in rms mm/s) at the standard normal hearing threshold for AC stimulation for all 20 ears measured is plotted in Figure 2. A signal to noise ratio of 20 dB was achieved for most measurement points. However, a signal to noise ratio of 10 dB was found for 14 measurement points: 6 at 300 Hz, 3 at 500 Hz, 1 at 700 Hz, 1 at 1500 Hz, and 3 at 6000 Hz. Additionally, two measurements at 500 Hz and two at 6000 Hz had a signal to noise ratio of < 10 dB and were excluded from further analysis. The magnitudes range from 1.5×10^{-6} mm/s to 2.02×10^{-5} mm/s. The largest magnitudes at threshold occurred at 300 Hz and 6000 Hz. The data show a range of about one order of magnitude at the highest and lowest frequencies, and a range of about a factor of 3–4 at the other frequencies. The differences between the mean velocities at the different frequencies are small; the similarity of the velocity at threshold across the entire measurement range is consistent with models in which the auditory threshold is determined by the velocity of the ossicles. Such models are discussed by Guinan and Peake (1967) and Puria et al. (1997) among others.

3.2 Bone conduction

Umbo velocity, tympanic ring velocity, and its difference per input voltage are shown in Figure 3 for one representative individual. Amplitude and phase for V_U and V_{TR} are similar between 300 Hz and 1500 Hz, and at 6000 Hz. V_U is larger than V_{TR} at 2000 Hz, 3000 Hz, and 4000 Hz. The phases of V_U and V_{TR} are very similar at frequencies of 2000 Hz and less. The frequency dependence of $V = V_U - V_{TR}$ depends on the relative magnitudes and phases of V_U and V_{TR} . At frequencies less than 1000 Hz, V_{TR} is of slightly larger magnitude relative to V_U and the difference in magnitude is smaller than the magnitude of either component, while the phase angle of the difference is one half cycle different than the phase angle of either V_U or V_{TR} . At 1, 1.5 and 2 kHz, the magnitude of V_U is somewhat larger than V_{TR} and the phase angle of the difference tracks the angle of V_U and V_{TR} . At 3 and 4 kHz the magnitude of V_U is at least a factor of 5 larger than the magnitude of V_{TR} and the magnitude and phase of their difference is similar to V_U .

The difference in velocity V produced by BC extrapolated to normal hearing bone-conduction threshold is illustrated in Figure 4 for all 20 ears measured. A signal to noise ratio of 20 dB was achieved in V_U for most subjects at all frequencies, and in the majority of measurements for V_{TR} . A maximum signal to noise ratio of 10 dB for V_U was measured in 1 ear each at 500 Hz, 1500 Hz, 2000 Hz, and 3000 Hz, in 2 ears at 4000 Hz and in 2 ears at 6000 Hz. At 6000 Hz, signal to noise ratio was below 10 dB in 6 ears. These values were excluded from further analysis. For V_{TR} a signal to noise ratio of 10 dB was measured in 6 ears at 300 Hz, in 7 ears at 500 Hz, in 5 ears at 700 Hz, in 3 ears at 1000 Hz, in 4 ears at 1500 Hz, in 8 ears at 2000 Hz, in 6 ears at 3000 Hz, in 5 ears at 4000 Hz, and in 4 ears at 6000 Hz. A signal to noise ratio below 10 dB was measured in 1 ear at 500 Hz, in 2 ears at 2000 Hz, in 5 ears at 3000 Hz, in 6 ears at 4000 Hz, and in 13 ears at 6000 Hz. These measurements of V_{TR} were excluded unless the estimated magnitude of V_{TR} was less than

1/5th of the corresponding V_U as described in the method section. One measurement at 3000 Hz and 2 measurements at 6000 Hz fulfilled this inclusion criterion.

The variation of V in our BC measurements is greater than V_U due to AC stimulation. It is largest at 6000 Hz, a frequency where only 4 ears met our signal to noise criteria. One reason for this larger variability is poor reflectivity of the tympanic ring in some ears, which decreased the signal to noise ratio in these measurements.

In Figure 5 we plot the sound pressure measured in the ear canal during BC stimulation, extrapolated to the sound pressure at BC thresholds. The P_{EC} for measurement of V_U and V_{TR} of the same ear is almost identical. Among individuals, P_{EC} differs considerably and ranges of up to two orders of magnitude for some frequencies. Variability is largest at 500 and 700 Hz. P_{EC} at BC threshold decreases from 300 Hz to 1000 Hz, remains low until 2000 Hz and reaches its highest values at 4000 Hz.

3.3 Repeatability

We repeated our measurements in one ear of each of 2 subjects (in one ear at 1 month after the initial measurements and at 3 months in the second ear). V_U at threshold for AC is shown in Figure 6a, and V at threshold for BC is shown in Figure 6b. The measurements were very reproducible for AC: the differences between the amplitudes were small. For BC, the repeatability was poorer but the variance between the repeated measurements was less than the variance between subjects. For one ear, measurements above 1500 Hz did not meet the signal to noise criteria in both measurements. Because the signal to noise ratio is low in both measurement, it might be possible that some anatomical factors such as poor reflectivity contributed to this finding.

3.4 Comparison Air- and Bone conduction

The comparison of V_U at threshold due to AC stimulation and the V at BC threshold stimulation illustrates difference in the magnitude and the frequency dependence of the computed threshold values (Figure 7). While V_U at AC threshold is similar in magnitude for all frequencies measured, V at the BC threshold varies with frequency and is highest at 300 Hz and 6000 Hz (although only a few measurements are available at 6000 Hz). The mean V due to BC stimulation is significantly larger than V_U due to AC stimulation at 300 Hz ($p \ll 0.001$) 3000 Hz ($p \ll 0.001$), 4000 Hz ($p < 0.001$), and 6000 Hz ($p = 0.02$). Mean V at BC threshold is a factor of two lower than the velocity at AC threshold at 500 Hz ($p = 0.008$), 700 Hz ($p < 0.001$), 1000 Hz ($p = 0.003$), 1500 Hz ($p < 0.001$), and 2000 Hz ($p \ll 0.001$). As a comparison, estimates of V_U at AC threshold from Hato et al. (Hato et al., 2003), and V at BC threshold from Stenfelt et al. (2006) are shown in Figure 7 as well. Our estimates of V_U at AC threshold are lower than those calculated from Hato et al., especially in the frequency range between 500 Hz and 3000 Hz, and our estimates of V at BC threshold are lower by factors of 2 to 10 than those from Stenfelt et al. (2006) at frequencies between 700 Hz and 2000 Hz. Possible reasons for these differences are raised in the Discussion section.

Figure 8 compares the calculated mean P_{EC} at threshold for BC with P_{EC} at threshold for AC taken from the ANSI standard. The BC P_{EC} is smaller below 3000 Hz and larger above

3000 Hz, while the differences at 3000 Hz are small. The differences are significant at 1000 Hz ($p < 0.001$) and 2000 Hz ($p=0.04$), while a only trend is seen at the other frequencies below 3000 Hz due to the large standard deviation.

5. Discussion

This study investigates the contribution of ossicular and cochlear fluid inertia and sound radiated into the external ear canal in BC hearing. In contrast to many previous investigations of bone-conduction mechanics (e.g. Barany, 1938; Stenfelt et al., 2002; Stenfelt et al., 2003; Stenfelt, 2006) measurements were performed in healthy human subjects with normal middle ear function and not in temporal bones or whole head specimens. This approach overcomes some of the disadvantage of temporal bone measurements for investigation of BC hearing such as the lack of the whole circumference of the skull and the skull content that might contribute to BC hearing, or the use of stimuli that do not adequately model all of the complexities of bone conduction (Ito et al., 2011; Sohmer et al., 2000; Sohmer and Freeman, 2004; Watanabe et al., 2008). The stimulus methods we use are those used in clinical audiometry, where bone conduction hearing thresholds are normally measured.

In our setup, it was not possible to directly measure the vibration of the skull. Instead, we measured the motion on the skin that covers a region of bone just lateral to the annular ligament of the tympanic membrane where the skin is thin and we believe firmly attached to the bony tympanic ring. Furthermore, we did not have access to the stapes for direct measurements of stapes velocity to determine the input into the cochlea, but measured umbo velocity. Stenfelt et al. (2002; 2006) compared stapes and umbo velocity for BC stimulation and described similar stapes and umbo velocities in temporal bones for frequencies below 7 kHz. At certain frequencies above 7000 Hz the motion of the umbo and stapes appeared 180 degrees out of phase with each other. The measured frequencies in our study ranged from 300 to 6000 Hz and were in a frequency range where stapes and umbo velocity are similar. For air-conducted stimulation, the frequency dependence of the stapes and umbo velocity are similar up to 2000 Hz with a larger magnitude of umbo velocity, and this magnitude difference increases above 2000 Hz (Hato et al. 2003).

In order to reduce the variability in our measurements, we averaged three to five measurements for each ear measured, applied the signal to noise criteria as described in the methods section and measured 2 ears twice. Measurements turned out to be fairly repeatable. At 6000 Hz, the BC measurements were often in the noise, most likely because this frequency is above the working range of the B-71 BC vibrator. Measurements of V_{TR} were more often in the noise than measurements of the V_U , which might be due to decreased reflection from the bony tympanic ring relative to the bright light-reflex near the umbo in most ears.

With AC stimulation, the motion of the ossicles at threshold level is the smallest motion to produce a hearing sensation. If the motion of the ossicles at the BC hearing threshold is smaller, then the sound transmitted by the ossicular motion should be inaudible. That V at threshold due to BC stimulation is significantly smaller than V_U at AC threshold at

frequencies between 500 Hz and 2 kHz is consistent with the idea that the motion of the umbo does not limit BC hearing in this frequency range. Therefore, we can conclude that those bone-conduction pathways that stimulate the inner via ossicular motion - the ear-canal radiation or inertial paths - do not completely determine the sensitivity of the ear to BC stimulation in that frequency range. This finding corresponds to findings by Stenfelt (2006) who predicted a larger displacement of umbo and stapes for AC in temporal bones at frequencies below 1500 Hz. However Stenfelt's methods did not allow an estimate of whether the differences they observed were statistically significant.

Stenfelt (2006) considered difference of the mean of more than 5 dB as significant. As shown in Figure 7, our measurements of the magnitude of V_U at AC threshold and V at BC threshold are low compared to Stenfelt (2006). The magnitude of our V_U at AC threshold measurements is within the range of others who measured V_U in normal hearing subjects (Whittemore et al., 2003; Huber et al., 2001; Goode et al., 1996). One reason for the difference could be the use of temporal bones with open mastoid cavities in the Hato study that Stenfelt used to compute V_U at AC threshold. The differences between our BC measurements and Stenfelt's (2006) estimates might also involve some of the multiple assumptions Stenfelt used to compute V from his multiple data sets.

Our measurements showed V for BC stimulation that were significantly larger than the AC V_U at 300 Hz, 3000 Hz, 4000 Hz, and 6000 Hz suggesting the existence of other paths than ear-canal radiation or inertial components that cancel the influence of ossicular motion. Some caution is needed interpreting these data. At 6000 Hz, only six measurement points with a large standard deviation met the signal to noise criteria because this frequency is above the bandwidth of the stimulator. At 300 and 3000 Hz, V at threshold due to BC is more variable than V_U at AC threshold.

The question arises how ossicular motion is generated over the range of our measurement frequencies. In our measurements, we could not find support for sound radiated in the external ear canal generating ossicular motion at frequencies below 3000 Hz: Comparisons of P_{EC} at threshold for AC and BC (Figure 8) shows lower values for P_{EC} due to BC stimulation below 3000 Hz. Again, assuming that the threshold sound pressure in AC is the lowest sound pressure that can, by itself, evoke a hearing response, these lower sound pressures at BC threshold are not in themselves sufficient to produce hearing. The combination of lower bone conducted P_{EC} and higher BC associated V suggests that the inertia of the ossicles and cochlear fluid, and not ear-canal radiation, are major contributors to BC hearing below 500 Hz.

At 3000 Hz and above, P_{EC} due to AC and BC are comparable, indicating that sound radiated to the external ear canal might contribute to BC hearing above 2000 Hz. According to Stenfelt et al. (2003), the BC stimulation of the inner ear is only minimally influenced by P_{EC} . Our findings are somewhat contradicting to these findings. One difference is that our experiments were performed in healthy subjects with audiotologically confirmed healthy middle ears and not in cadaver heads or temporal bones. A second difference is our use of a speculum-based sound delivery system that may have introduced an 'occlusion' of the ear canal, thereby increasing the radiated P_{EC} and increasing its effect on threshold above 3000

Hz. Such an event is not likely. Occlusion has its biggest effect on low-frequency sounds and we found smaller P_{EC} due to BC stimulation below 2000 Hz.

6. Conclusion

Relative V_U at BC threshold is significantly smaller than V_U at AC threshold between 500 Hz and 3 kHz. This is consistent with the idea that the motion of the umbo is not the principal drive to BC hearing in this frequency range. Also the P_{EC} generated at BC threshold is less than the P_{EC} at AC threshold at frequencies below 3000 Hz suggesting that radiation of sound in the external ear canal is not the primary contributor to BC hearing in this frequency range. In combination, our results are most consistent with the inertia of the ossicles and cochlear fluid driving BC hearing below 500 Hz, but other mechanisms playing a role in higher frequencies. Sound radiated into the external ear canal might contribute to BC hearing at 3000 Hz and above.

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Figure 1. Air conduction threshold and air bone gap for all 20 ears

AC thresholds (**A**) and air bone gap (ABG) (**B**) for all 20 ears measured. The thin vertical line indicates the range of the data, the box indicates the 25th to 75th percentile, and the short horizontal black line indicates the mean. Although there is some variability in AC threshold, especially at high frequencies, ABG was within ± 10 dB for all ears.

Figure 2. AC umbo velocity at AC threshold; $= V_U / P_{EC} * P_{EC}$ at threshold

The extrapolated magnitude of V_U / P_{EC} at AC threshold for all 20 ears measured (A), and the number of ears fulfilling the signal-to-noise criteria at each measurement point (B). The thin lines show the 20 individual measurements. The thick solid line with filled circles is the mean, and the dashed lines show ± 1 standard deviation. The differences between the mean velocity at different frequencies is small consistent with a constant V_U at threshold in the range from 300 to 6000 Hz.

Figure 3. Umbo velocity, tympanic ring velocity, and its difference (relative umbo velocity)

Magnitude (A) and phase (B) of umbo velocity V_U , tympanic ring velocity V_{TR} , and their difference $V = V_U - V_{TR}$ in response to bone-conducted sound for one representative individual.

Figure 4. Relative umbo velocity at BC threshold

The difference in velocity V produced by BC that is extrapolated to normal hearing BC threshold (A), and the number of ears fulfilling the signal-to-noise criteria at each measurement point (B). The thin lines show the 20 individual measurements. The thick solid line with filled circles is the mean, and the dashed lines show $\pm$ one standard deviation. The magnitude of V shows a greater variation than V_U due to AC stimulation. It is largest at 6000 Hz, a frequency where only 4 ears met our signal to noise criteria.

Figure 5. Sound pressure in the ear canal at threshold for BC

Sound pressure measured in the ear canal during BC stimulation, extrapolated to the sound pressure at BC thresholds. The thin lines show the 20 individual measurements. The thick solid line with filled circles is the mean, and the dashed lines show $\pm$ one standard deviation. P_{EC} at BC threshold differs considerably among individual ears and ranges by up to two orders of magnitude for some frequencies. Variability is largest at 500 and 700 Hz.

Figure 6. Umbo velocity for AC (top) and V for BC (bottom) for two individuals

Repeatability is shown for two ears (one individual in red, the second in blue). AC and BC measurements were repeated 30 days after the initial measurement in one ear, 90 days after the initial measurements in a second ear. The initial measurement is indicated with *, the repeated measurement with Δ . Differences for AC (**A**) were rather small for all frequencies. For BC (**B**), differences were small between the repeated measurements except at 300 Hz in one ear. In that same ear the BC measurements at frequencies > 1500 Hz did not pass our signal to noise requirements at either measurement time.

Figure 7. Umbo velocity at threshold for AC and BC

Plots of V_U during AC stimulation (in blue) and V produced by BC (in red). The solid lines show the mean of the 20 ears; the dashed lines show the ± 1 standard deviation. V_U during AC stimulation is significantly higher than V produced by BC between 500 Hz and 2000 kHz. At 300, 3000, 4000 and 6000 Hz, V produced by BC is significantly larger, which implies the existence of other paths that cancel the influence of the ossicular motion. The figure also includes Stenfelt's (2006) estimates of velocity at threshold, including extrapolations from Hato et al. (2003) measurements of V_U with AC stimulation (the solid black lines), and Stenfelt's own estimates of V at BC threshold (the dotted black lines).

Figure 8. P_{EC} at threshold for BC (umbo) and AC (ANSI)

A comparison of P_{EC} at threshold for AC and BC shows lower values for P_{EC} due to BC stimulation. The lower P_{EC} at BC threshold below 3000 Hz is not sufficient to generate the ossicular motion required to produce a threshold hearing response, as determined by the AC threshold pressure.