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Implications for contralateral bone-conducted transmission as measured by cochlear vibrations.

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Title:

Implications for contralateral bone conducted transmission as measured by cochlear vibrations.

Short running head:

Implications for contralateral BC transmission...

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Abstract

Hypothesis: The velocity response at the contralateral cochlea from bone conducted (BC) stimulation depends on the stimulation position.

Background: BC sound transmission in the human skull is complex and differs from air conducted sound. BC sound stimulates both cochleae with different amplitudes and time delays influencing hearing perception in a way that is not completely understood. One important parameter is the stimulation position on the human skull.

Method: By applying BC stimulation at 8 positions on both sides of seven human cadaver skulls the contralateral velocity response of the cochlear promontory was investigated in the frequency range 0.1 to 10 kHz. Using previous data from ipsilateral stimulation the transcranial transmission (TT) and effects of bilateral stimulation to one cochlea was calculated.

Results: The contralateral transmission from the 8 positions showed small differences but the TT showed a generally increased cochlear separation when the stimulation position approached the cochlea. The effect of simultaneous bilateral stimulation was calculated showing a low frequency negative effect for correlated signals while uncorrelated signals gave 3 dB gain. At higher frequencies there was less interaction of the combined stimulation due to the greater inter-cochlear separation. Also, the greatest time difference between ipsilateral transmission and contralateral transmission was at positions close to the cochlea.

Conclusion: The stimulation position only slightly affects the amplitude and phase of the contralateral cochlear velocity response. However, due to the great influence from the ipsilateral transmission, a position close to the cochlea would be beneficial for patients with bilateral BC hearing aids.

Introduction

Studies focusing on patients with symmetrical bilateral conductive hearing loss have shown improved aided pure tone thresholds, sound localization, and speech reception thresholds in both quiet and noise when fitted bilaterally with Baha® (Cochlear Bone Anchored Solutions AB, Mölnlycke, Sweden) compared to monaural fitting (1,2). Such studies indicate that this patient group uses binaural cues but to a lesser extent compared with air conduction hearing (3). The reason for this reduced binaural effect may originate in bone conducted (BC) sound that crosses over to the contralateral cochlea leading to a reduced stimulation difference between the two sides and less information to extract at the brainstem level.

Patients with single sided deafness (SSD) can be rehabilitated by a contralateral routing of signal (CROS) hearing aid (HA) (4) or by a Baha® on the deaf side. Both audiometric results and quality of life measures indicate benefit with the Baha® compared to CROS and the unaided situation (5-8) but, for an unknown reason, a substantial part of patients that test the Baha® on a head band do not proceed with surgery (9). It has been suggested that different individual transcranial transmission (TT) could explain this discrepancy (3).

A few studies on human cadavers have shown that BC sound transmission improves when the stimulation position approaches the cochlea (10-12) and especially if it is situated within the mastoid surface area that projects towards the petrous part of the temporal bone (MAPP) (10). This conclusion has led to an ongoing project of developing a bone conduction implant (BCI) in order to avoid the Baha® percutaneous solution and in this way get a BC HA with equal or better amplification and less risk of skin problems (13,14).

The aims of this study are to (i) describe BC sound transmission in terms of the velocity response at the contralateral cochlear promontory related to the stimulation force at eight separate stimulation positions and (ii) with data from a previous study on ipsilateral BC transmission (10) calculate the TT and investigate effects of bilateral stimulation to one cochlea.

Materials and method

This study was approved by the Regional Ethics Committee, Göteborg. The same cadavers and measurement setup was used in a previous study where a detailed description of the cadavers, calibrations, measurement setup, and test procedures can be found (10). In what follows, an overview of the measurements is presented.

The cadavers

Both sides of each skull of seven embalmed cadavers (2 males and 5 females, ages between 60 and 80 years) were used; neither macroscopic nor microscopic inspection showed any signs of previous ear disease. Eight stimulation positions were established on each side of the skull using 4 mm titanium fixtures (Cochlear Bone Anchored Solutions AB, Mölnlycke, Sweden). Position 1 was placed at the standard Baha® position 55 mm posterior and 30 mm superior to the ear canal opening. With a 10 mm spacing positions 2-6 were placed in a straight row between the Baha® position and the ear canal opening. Position 7 was placed in the root of the zygomatic process 5 mm superiorly and anteriorly to the ear canal opening and position 8 was placed close to or in contact with the otic capsule which was available after finishing the measurement procedures on the other positions, followed by a mastoidectomy (see Figures 1 and 2).

The fixture stability was measured with Resonance Frequency Analysis (RFA) (Osstell™ transducer and Osstell™ instrument, Integration Diagnostics AB, Göteborg) where the fixtures are given an Implant Stability Quotient (ISQ) (1-100) according to the resonance frequency of the RFA transducer attached to each fixture. High ISQ values indicates stable

fixtures (15). The mechanical point impedance gives information about the mechanical properties at a specific position on the skull (11,12,16) but can also be used to verify the fixture stability. A loose implant causes a significant decrease in impedance.

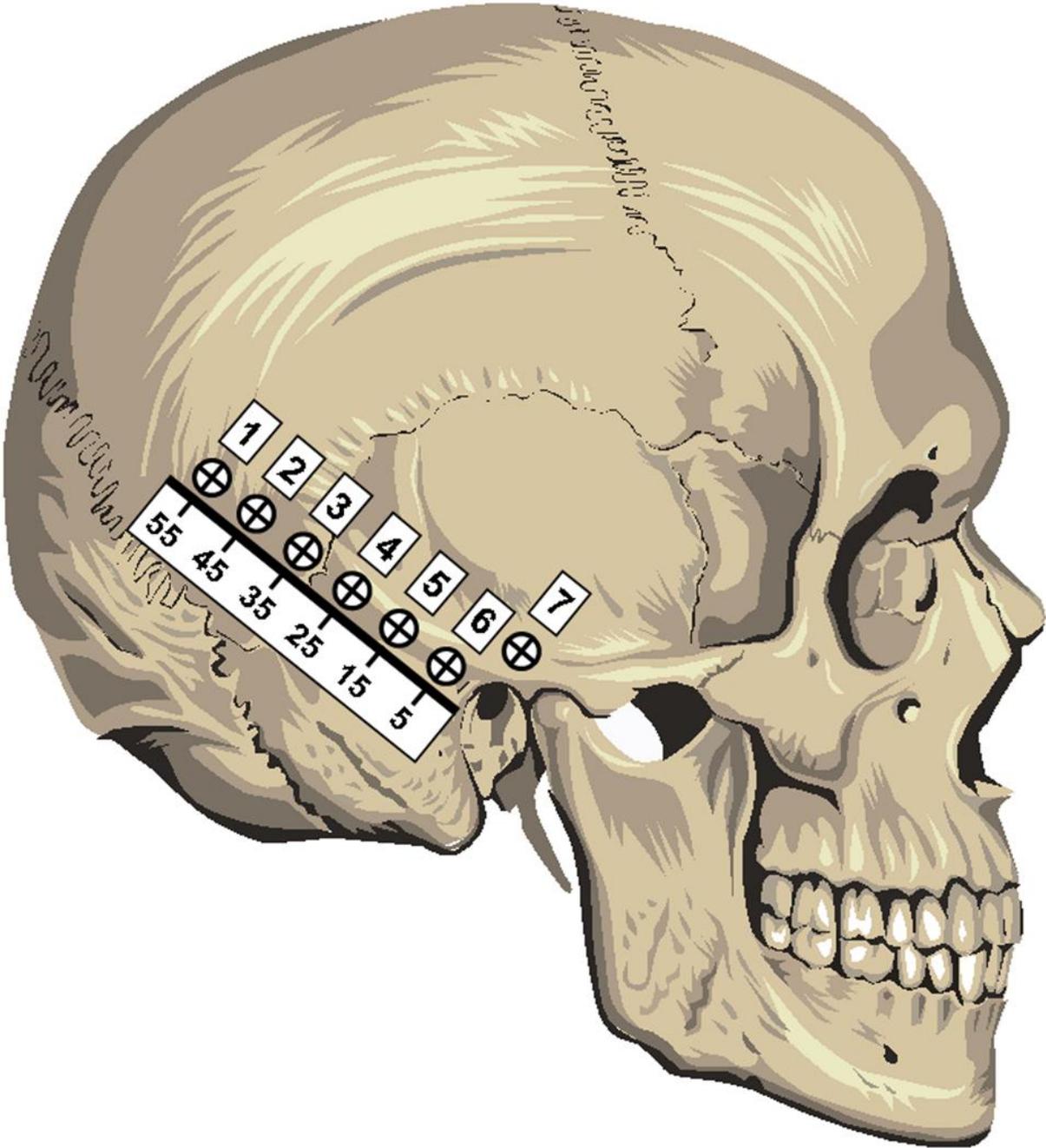


Figure 1 Illustration of the fixtures (circle with cross) on the right side of the skull. Above the row of fixtures the corresponding position number 1 to 7 is marked within a rectangle, and below the row of fixtures the distance in mm from the ear canal opening is shown with a ruler.

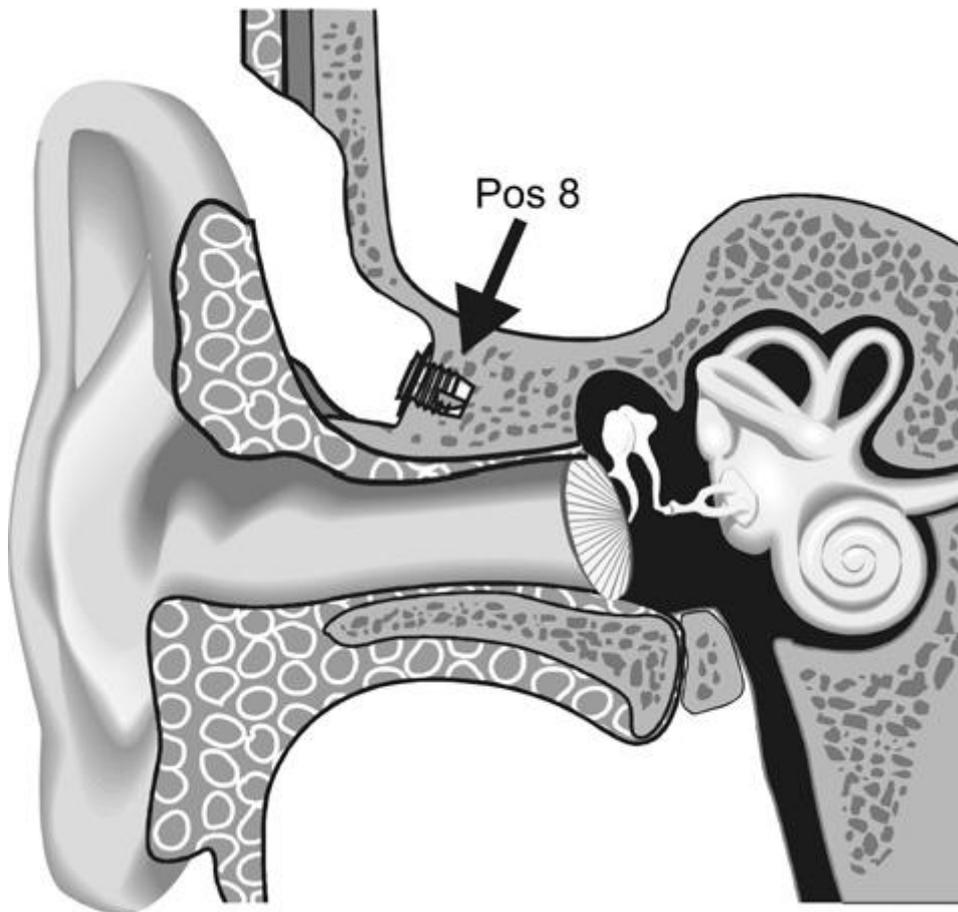


Figure 2 Illustration of the approximate location of position 8 in the opened mastoid.

Cochlear vibration

The velocity of the cochlear promontory as a response to a force stimulation from a transducer attached to one of the fixture positions on the cadaver skull was measured by a laser Doppler vibrometer (LDV) (HLV-1000, Polytech, Waldbronn, Germany). The tympanic membrane, malleus, and incus were removed to enable the laser beam to reach the cochlear promontory; small glass spheres were positioned on the promontory to enhance the reflection of the laser beam. The stimulation signal was provided by the measurement system, the Brüel & Kjær Pulse 9.0 (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark), that used a stepped sine procedure to measure the cochlear promontory vibration with a frequency resolution of 24 frequencies per octave in the 0.1 to 10 kHz range. The output from the

vibration transducer was first calibrated on the skull simulator TU-1000 (17) for the provided stimulation force.

Results

I. RFA and Impedance measurements

Average and standard deviation of the ISQ value (81.2 ± 2.8) indicated rigid attachment of the fixtures in all positions (18). The mechanical point impedance results were similar to measurements on human skulls *in vivo* (16) also indicating that the cadaver skulls had mechanical properties similar to live human skulls. For details regarding RFA results, see (10).

II. Transcranial transmission efficiency

In Figure 3 the contralateral cochlear responses from all skulls are shown in mm/s as measured by the LDV when the stimulation was 1 Newton at position 1. At low frequencies, between 100 Hz and 500 Hz, the magnitude of the velocity decreases with frequency at an approximately constant rate. This is a manifestation of the low-frequency mass-like behaviour of the skull. In the individual traces a first anti-resonance appears in the 0.9 to 1.1 kHz frequency region. Although there are numerous anti-resonances in the individual traces, they rarely appear at the same frequencies for all test ears and the median data (thick line) show a smooth response.

When comparing the median contralateral velocity response at the cochlea with stimulation at the different positions 1-8 (shown in Figure 4) the results are similar when stimulating at positions 1-5, generally lower when stimulation is at positions 6 and 7, and overall higher with stimulation at position 8. These results are even more obvious in Figure 5 where the median contralateral responses from stimulation at positions 2 to 8 are related to stimulation at position 1, i.e. the difference in sensitivity of the contralateral response when moving the

stimulation from position 1 to another position. At frequencies below 0.2 kHz noise affects the LDV signal and the results should be interpreted with care. However, there is a clear difference between positions 6 and 7 compared with the other positions at frequencies up to 0.8 kHz.

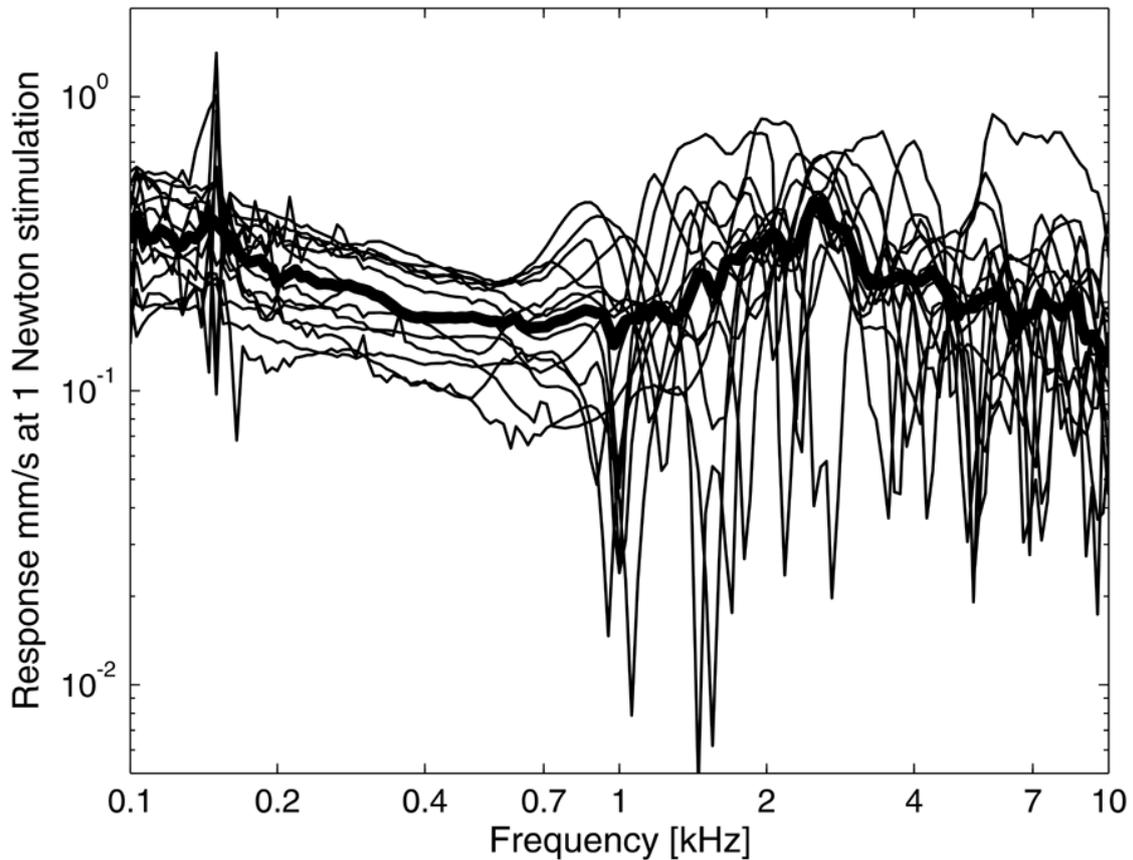


Figure 3 The magnitude of the velocity at the contralateral cochlea as measured by the LDV when the stimulation force is 1 Newton at position 1. The thin lines show the individual results from both sides of 7 subjects (14 ears). The thick line shows the median of the individual results.

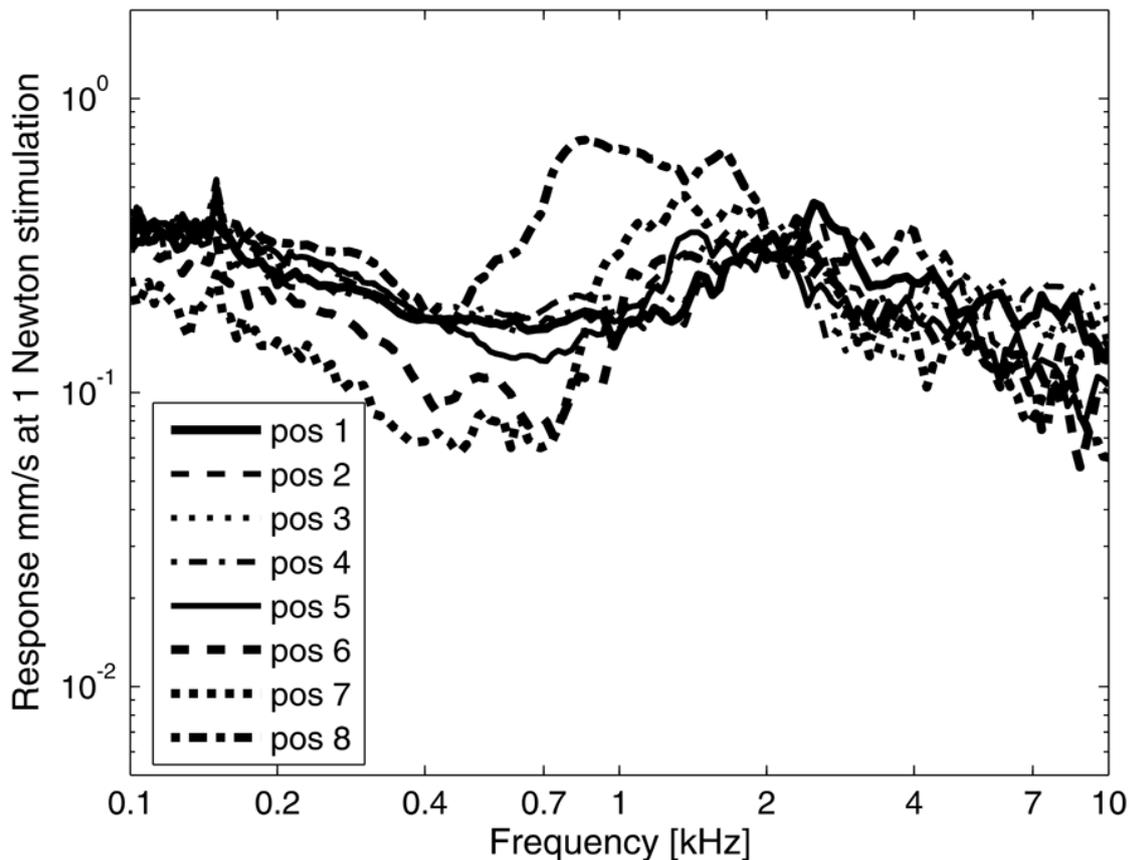


Figure 4 The magnitude of the velocity in mm/s at the contralateral cochlea as measured by the LDV when the stimulation force is 1 Newton. The results are presented for all eight stimulation positions where each line represents the median from 14 measurements (7 subjects x 2 sides). Stimulation at position 1: thick solid line; position 2: thin dashed line; position 3: thin dotted line; position 4: thin dashed-dotted line; position 5: thin solid line; position 6: thick dashed line; position 7: thick dotted line; position 8: thick dashed-dotted line.

The TT (Figure 6) for all positions shows similar results at low frequencies (below 0.3 kHz) which can be explained by rigid body motion of the skull at these frequencies. At frequencies above 0.3 kHz the TT from the different positions becomes spread, especially from 0.6 to 0.8 kHz where the contralateral transmission dominates the response for stimulation far from the cochlea (positions 1-5), with the opposite for positions close to the cochlea (positions 6-8). This pattern is explained by the anti-resonances in the ipsilateral transmission (positions 1-5) and the improved vibration transmission for ipsilateral positions close to the cochlea

(positions 6-8). At higher frequencies and for positions close to the cochlea the TT generally decreases but for positions far from the cochlea (positions 1 to 3) it stays on average within 0 to -5 dB.

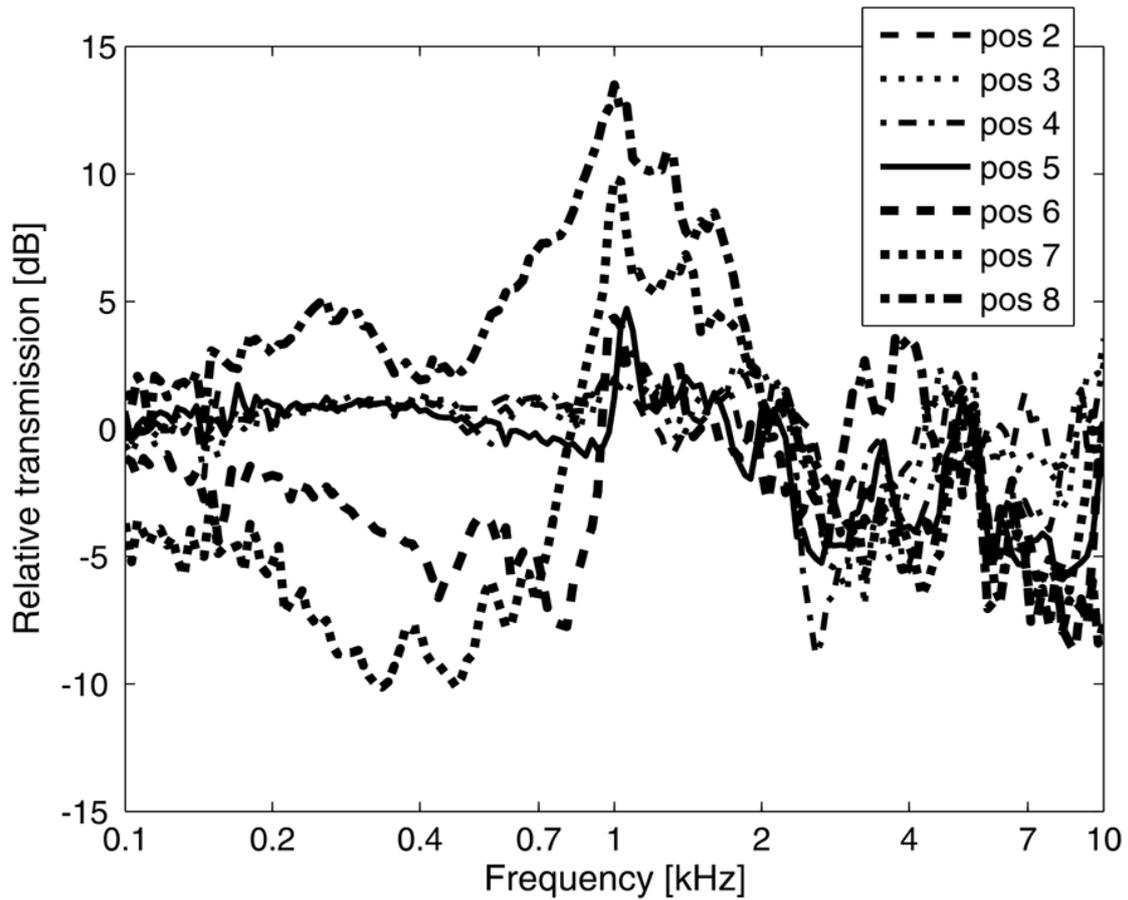


Figure 5 The relative transmission measured as the velocity of the contralateral cochlea with stimulation at positions 2 to 8 relative to that with stimulation at position 1. The line properties given in the plot are the same as in figure 2 except position 1 that is non-existent.

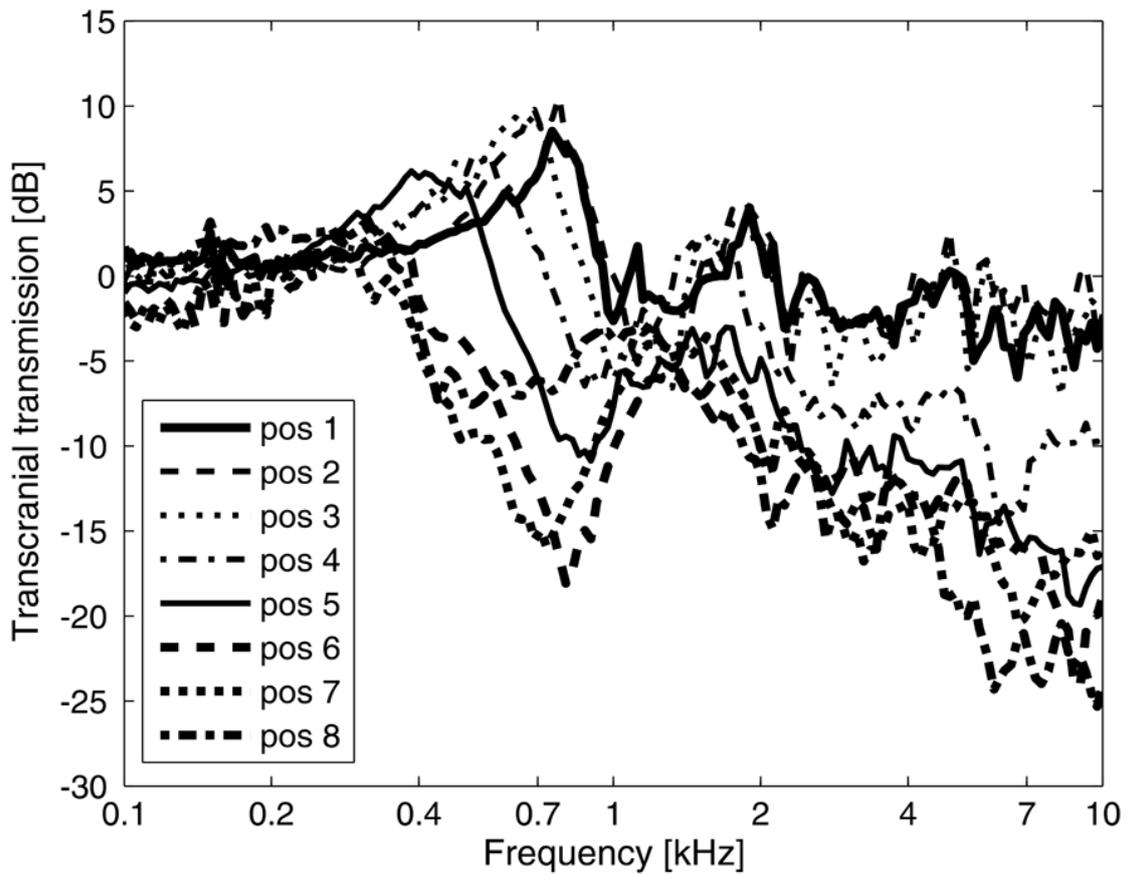


Figure 6 The transcranial transmission for stimulation at each position calculated as the relation between contralateral and ipsilateral transmission. Each line is the median of 14 ears (7 subjects x 2 sides). The same line properties as in figure 2 are used.

III. Bilateral stimulation calculations

Stationary and non-stationary signals

We will here discuss two interpretations of bilateral stimulation, (i) the stimuli at the two sides are stationary and equal (in amplitude and time) and (ii) the stimuli at the two sides is independent of each other or have a non-stationary behaviour. In the first interpretation, two equal and stationary signals, the result at one cochlea is the complex sum of amplitude and phase of the ipsilateral and contralateral transfer functions. This is displayed in Figure 7 as the increase of bilateral stimulation compared with ipsilateral stimulation only. Since both

amplitude and phase are included in the calculation, the result is either a constructive addition (signals in phase, level above 0 dB in Figure 7) or a destructive addition (signals is of opposite phase, level below 0 dB in Figure 7) which, in an extreme case, leads to a total cancellation.

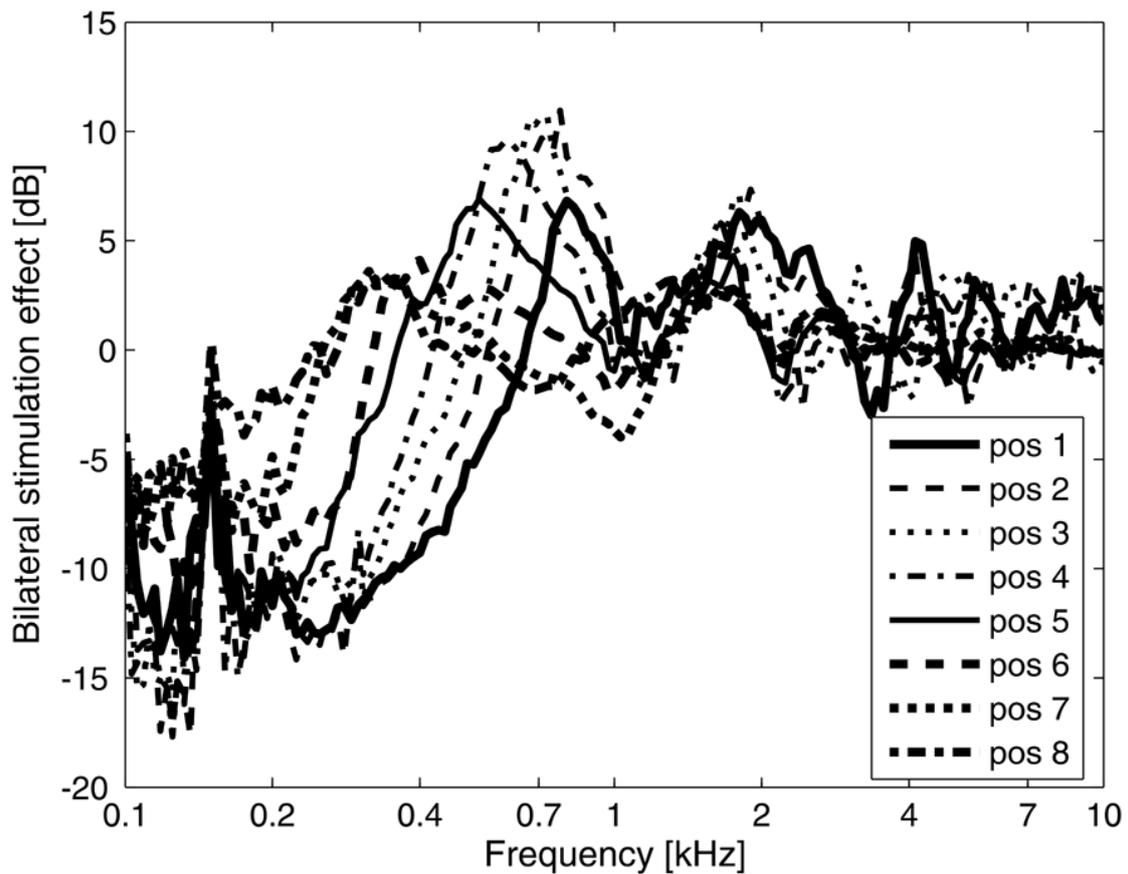


Figure 7 The effect of bilateral stimulation from each position at one cochlea presented as the relation between bilateral stimulation and unilateral stimulation. The bilateral stimulation of the cochlea is calculated as the complex sum of the ipsilateral and contralateral transmissions (includes both phase and amplitude). The same line properties as in figure 2 are used.

For all positions, a bilateral stimulation results in lower cochlear stimulation at low frequencies (Figure 7) since the vibrational force is applied with opposite direction and the difference in amplitude (see figure 6) and phase is small for ipsilateral and contralateral

stimulation. At higher frequencies, differences in both the amplitude and phase of the ipsilateral and contralateral transfer functions result in an addition that is interchangeably positive or negative, and for all positions the influence from bilateral stimulation compared to unilateral stimulation becomes less due to the worse amplitude transmission from the contralateral side. The great improvement in the frequency range 0.3 to 1.0 kHz (range depending on position) is primarily due to the anti-resonance in the ipsilateral pathway that is not equally present in the contralateral pathway.

In the second interpretation the influence from bilateral stimulation is the same as the sum of the sound energy transmitted from the two sides¹ (see Figure 8). With this type of calculation, the phase is irrelevant and the addition always results in a sum that is equal or greater than the sound from the ipsilateral transmission alone. According to this computation, if both sides contribute equally, the increase becomes 3 dB (doubling of the sound energy) which is the case for all positions at low frequencies. As in Figure 7 there is an increase for most stimulation positions in the frequency range 0.3 to 1.0 kHz, again due to the ipsilateral anti-resonance. At frequencies above 1 kHz, the results for the positions outside the MAPP (positions 1-3) show in general 2 to 3 dB increase with bilateral transmission while positions closer to the cochlea result in less addition due to the relatively lower contribution from the contralateral stimulation. It should be remembered that this analysis is only for one cochlea; no binaural effects can be seen.

¹ This is calculated as the sum of the power for each measured frequency component.

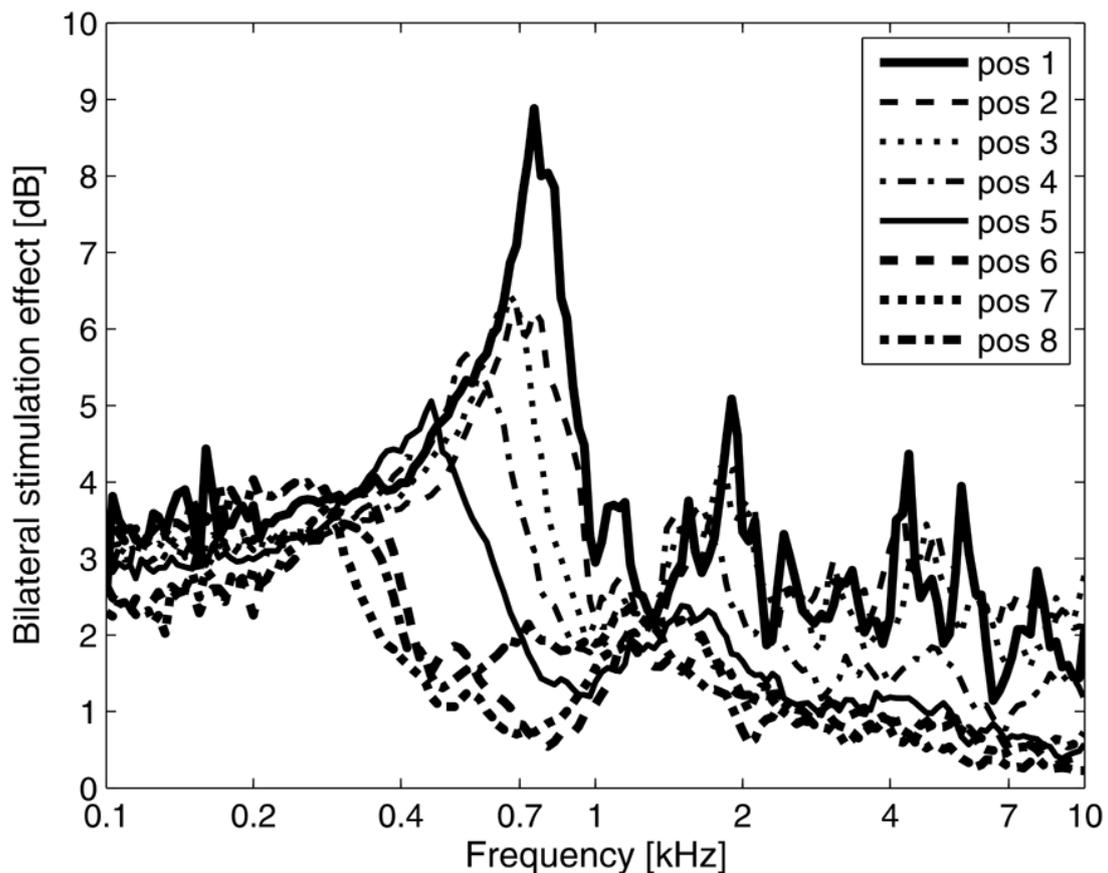


Figure 8 The effect of bilateral stimulation from each position at one cochlea presented as the relation between bilateral stimulation and unilateral stimulation. The bilateral stimulation of the cochlea is calculated as the sum of the power of the ipsilateral and contralateral transmissions (only includes amplitude). The same line properties as in figure 2 are used.

Time delay

Intuitively, since there is a distance difference between the ipsilateral and contralateral stimulation points and the cochlea, one may expect differences in the time delay between ipsilateral and contralateral stimulation. Time delays can be estimated from the phase of the transfer function according to

$$\tau_D = -\frac{\partial \phi(\omega)}{\partial \omega}$$

where τ_D is the group delay in seconds, Φ is the phase in radians and ω is the angular frequency. One prerequisite for the above calculation is that the phase function is smooth, i.e. it cannot be used to estimate time delays in frequency regions containing sharp resonances or anti-resonances or in frequency areas where the mode of wave transmission changes (11). Figure 9 illustrates the time delay difference between ipsilateral and contralateral stimulation for all eight positions calculated from the median of the phase function from each position in the 1 to 10 kHz frequency range. At frequencies 1 to 5 kHz, the greatest time difference is close to 0.5 ms for positions outside the MAPP and 1.0 ms for positions on the MAPP. Above this frequency the difference is limited comparing different positions and becomes 0.3-0.4 ms.

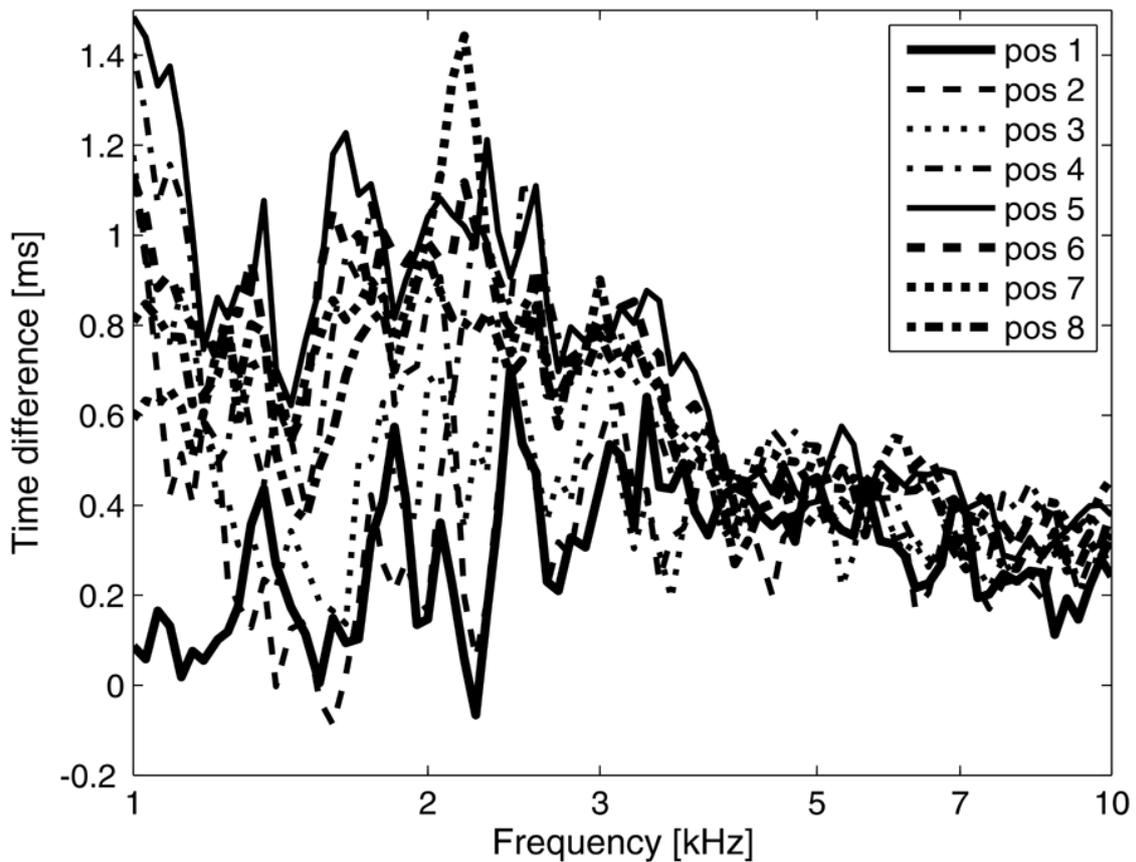


Figure 9 Estimation of the differences in time delay between contralateral and ipsilateral transmission. The same line properties as in figure 2 are used.

Discussion

Cochlear vibration as measure of BC sound

According to results both from the current study and from an earlier study on ipsilateral BC stimulation (10) the optimal position for a BC hearing aid would be as close to the cochlea as possible for unilateral and bilateral conductive hearing loss and, among the positions used here, at position 1 for SSD. We used the promontory velocity response from vibrational stimulation on the skull of human embalmed cadavers as a measure of BC cochlear stimulation. The relevance of this method can be argued since the correlation to hearing perception is currently unknown. Other factors that may contribute to the basilar membrane motion besides the vibration of the cochlea itself are not included. However, cochlear vibration relates to the inertia of the cochlear fluids as well as cochlear compression response leading to a basilar membrane motion; these stimulation modes are regarded as the most important contributors to BC sound (19).

When measuring the cochlear velocity response with stimulation at positions 1 to 7, 14 titanium fixtures were positioned in the cranial bone (7 at each side). A fixture gives higher stiffness than the original bone while the masses of both are in the same order. One may argue that this alteration of the local stiffness at points in the mastoid region would change the vibration transmission from the skull surface to the cochlea. However, according to Stenfelt and Goode (11) the speed of sound in the skull bone ranges between 250 to 400 m/s which means that the sound wavelength is approximately 10 times the size of the fixtures at the highest frequencies tested. We therefore believe that the fixtures at the skull surface only

minimally affected the measurements. The mastoidectomy performed for placing position 8 would greatly affect vibration transmission from the skull surface to the cochlea, but the opening of the mastoid was done after all measurements, both ipsilaterally and contralaterally, were finished.

One shortcoming of the current setup is that the LDV only measures the cochlear motion in one direction (the direction in-line with the ear canal) but the cochlea moves in all three space dimensions (11,12); it is not known if there is a major direction influencing the perception. However, it was shown that the cochlear movement in the x-direction is either dominating or similar to the other directions (11,12). Further, this vibration direction is within 5 dB from the sum of all directions and shows good agreement with the typical sensitivity difference between forehead and mastoid BC stimulation (ISO 389-3 (1994)) (3,11). According to Reinfeldt (20) the vibration of the cochlea in cadavers can be related to the relative BC hearing threshold change when stimulation is at different positions; at least for frequencies between 1 and 10 kHz. We therefore feel that the cochlear velocity is a good first approximation of sound stimulation of the cochlea by BC.

Transcranial transmission

In Figure 3 it is clear that the individual responses contain sharp anti-resonances and resonances. The resonances are well damped and do not affect perception of BC sound to a larger extent. The anti-resonances are of great magnitude but of a narrow bandwidth. Since they normally do not appear in all space dimensions at the same frequency (11) they have probably minor influence on speech perception by BC. However, for narrow band stimulation, such as pure tones for audiogram testing, they can affect the perception and may be the cause of the irregular BC transcranial thresholds seen.

In Figures 4 and 5 the average relative difference between stimulation at the different positions can be seen. One explanation for the deviations at positions 6 and 7 is that the angle of the stimulation force deviates from the skulls centre of gravity resulting in different rotational motion of the skull causing a lower response at the contralateral cochlea as measured by the LDV (11,16). A similar pattern was seen for the ipsilateral responses (10). The difference cannot be explained by the fact that these positions are on the MAPP because the skull moves as a rigid body up to 300 Hz and the response from stimulation at positions 6 and 7 should not differ from position 1 in this frequency range. Moreover, results from stimulation at position 5 is similar to position 1 up to 950 Hz despite that it is also fully on the MAPP. The higher response level at frequencies between 200-350 Hz for stimulation at position 8 may indicate that the petrous part of the temporal bone medially have a motion separated from the rest of the skull. However, it may also be a result of a more favourable angle of the stimulation relative to the measured response by the LDV.

In Figure 6 the TT is illustrated as the ratio between transcranial and ipsilateral transmission for the same positions (positions 1 to 8) displayed in dB. Although slightly different stimulation positions were used, the TTs found in this study are in line with the results reported by Stenfelt and Goode (11) using vibration measurements in human cadaver heads. In a study assessing the TT using psychoacoustic measures (hearing thresholds), Nolan and Lyon (21) reported the TT (approximately position 3-4 in this study) to show close to -10 dB in the frequency range 0.25 to 4 kHz with large individual variability; this differs from our results.

Bilateral stimulation

Two approaches for describing bilateral BC stimulation was used, (i) simultaneous and fully correlated stationary stimuli and (ii) uncorrelated and/or non-stationary stimuli. Speech, which can be regarded as a non-stationary signal would fall into the latter group. Examples of the first group are several types of test-signals for hearing evaluation (e.g. pure tone thresholds).

The 5 to 10 dB increase seen in the 0.5 to 0.9 kHz range is a result, once again, of the anti-resonance in the ipsilateral transmission. Since the anti-resonance probably has a small effect of the perceived BC signal we propose that the summation effects seen in Figures 7 and 8 in this frequency region do not reflect the perception of BC sound from bilateral stimulation. The perceived effect of adding a contralateral stimulation would probably show a smooth transition from the levels seen at the lowest frequencies in Figure 7 and 8 to the mid-frequency levels seen at around 1 kHz. Once again, this reasoning is limited to the effect of one cochlea.

Several studies investigating the benefit of using bilateral fitting of Baha® have used the binaural masking level difference (BMLD) test to assess the binaural effect from two aids (1,2). Although release of masking is most probably possible through BC stimulation, the BMLD test was designed for testing via air conduction transmission and the results found using BC stimulation may be a result of the addition of stationary signals rather than the true binaural effects. Since the BMLD test uses stationary signals at low frequencies, where the bilateral summation of stationary BC signals can result in large changes, we propose the BMLD test to be inappropriate to test binaural effects when BC stimulation is used, at least as it has been used in the above mentioned studies.

Time delay

Normally it is safe to assume that the further the distance is between the stimulation and response positions, the greater the travel time. The human skull has a complex structure with an anatomy and material composition that produces vibration transmission modes that depend on the stimulation position (11). Consequently, it is difficult to predict the difference in travel time for different stimulation positions. In this study we have used the phase function of the BC transmission to estimate time delays. There is a general trend of greater time delay the farther the stimulation positions are separated (see Figure 9). Although binaural hearing by BC is not studied *per se*, a time difference between the cochleae enable binaural information and would suggest that binaural cues can be obtained to some degree using BC stimulation. Figure 9 illustrates that time delay is larger in the mid-frequency range for positions on the MAPP and position 8 up to 3 kHz, above this frequency the time delay is shorter and similar for all positions. This is in accordance with time delays presented by Stenfelt and Goode (11).

Implications for bone conduction hearing aids

The greatest limitation for obtaining binaural cues are due to BC sound transmission crossing over to the contralateral side (Figure 6) decreasing the sound separation between the two cochleae. This leads to decreased ability to extract bilateral time and amplitude information in the brainstem (1). With this in mind a position as close to the cochlea as possible would provide the best signal separation (as amplitude and time difference) between the cochleae.

If using the BC hearing aid as a CROS-device in SSD the maximum of contralateral BC sound transmission is beneficial. Position 8 provides the best contralateral transmission but

not in the high frequency range where the head shadow effect is greatest. Among the positions investigated, position 1, where the Baha® is currently normally attached, provides the best overall transmission at high frequencies.

An implantable BC hearing aid, here termed BCI, is under development and evaluation (13,14) and the planned position for this device is approximately at position 6. From the ipsilateral data in Eeg-Olofsson (10) combined with the results in this study a BCI in position 6 would improve sound transmission ipsilaterally and for bilateral application give a reduced cross over transmission, hence provide for better binaural hearing. However, this position would not be optimal for the SSD indication; an alternative is to place the implanted transducer on the side of the normal ear and transmit the microphone signal wirelessly from the poor ear.

Conclusion

The BC sound transmission from the contralateral side to the cochlea was estimated by measurement of the cochlear promontory vibration using an LDV. Generally, there were only small contralateral transmission differences between the eight stimulation positions. However, the transcranial transmission showed large high-frequency differences where the greatest signal separation was achieved for the stimulation positions closest to the cochlea. When adding contralateral and ipsilateral stimulations, there was a low-frequency reduction when the signals were fully correlated while a 3 dB increase was seen with uncorrelated signals. At higher frequencies, adding the contralateral to the ipsilateral stimulation gave small effects due to the reduced transcranial transmission at these frequencies. Delay estimates from the phase functions of the ipsilateral and contralateral transmissions indicated a time separation for ipsilateral and contralateral stimulation, at least at frequencies above 1 kHz. According to the data, the best result with bilateral application of BC hearing aids is a position close to the cochlea (e.g. at position 6 as proposed with BCIs). However, using BC hearing aids for patients with SSD, a position away from the cochlea is slightly beneficial (current standard Baha® position).

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