Response of Human Skull to Bone Conducted Sound

in the Audiometric to Ultrasonic Range

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Abstract

Some new therapies for tinnitus employ bone conducted sound in the high audio and ultrasonic frequencies, but there has been little previous research on sound transmission through the head at these frequencies. The vibrational characteristics of two dry skulls, in comparison to a live human head, were measured in the 2 – 52 kHz range. White noise was played and received through piezoelectric transducers, and Fourier analyzed. Complex resonances and antiresonances were found in both the dry skulls and live head, which varied with small changes in the position of the transducers. There were also pronounced differences between the skulls. In comparison to the skulls, the live head showed greater attenuation, and less prominent resonances and antiresonances, reflecting greater damping. The attenuation of the skulls and the head did not increase consistently with frequency, but was dominated by resonances at a variety of frequencies. For designing high audio and ultrasonic tinnitus maskers and hearing aids, these results suggest that wide bandwidth must be used to compensate for the unpredictability of the resonances.

Keywords: tinnitus, bone conduction, audio, ultrasound, hearing aids, skull
Introduction

Bone conduction refers to the response of the bones of the skull to audio and higher frequency vibrations, and to
the transmission of such vibrations to, and the reception by, the auditory organ. Direct stimulation of the cochlea by a
vibrator through bone conduction is routinely employed in audiological evaluations to distinguish hearing losses
attributable to the outer and/or middle ear defects from those of sensorineural impairments. Bone conduction hearing aids
are useful in cases of conductive hearing loss. Bone conduction is also being used in new methods of tinnitus therapy,
both for masking [1,2] and long-term residual inhibition [3].

Conventional bone conduction hearing aids and bone conduction audiometry assume that (1) the frequency response
of the skull to vibration is relatively flat across the range of interest, and (2) that there is little attenuation across the skull,
allowing binaural perception from a single transducer on one side of the head. While this is largely the case below 5 kHz,
which is the range of most interest for perception of unmodified speech, there is great variability both in frequency
response and attenuation across the skull in the higher frequencies. An understanding of this complex response to bone
conducted vibration is of less importance for deep insertion transcranial hearing aids, but is important for technologies
using high audio (10-20 kHz) and ultrasound (> 20 kHz) for remediation of hearing loss and tinnitus.

Vibrational Characteristics of the Human Skull in the Audiometric Frequencies

Several researchers have performed vibrational experiments in the audiometric frequency range (up to 10 kHz) on
human heads, cadaver heads and animals, as well as human dry skull preparations, both gel-filled and empty, in an effort
to understand bone conduction hearing [4 – 15]. All studies have found a variety of resonances and antiresonances in the
audiometric frequencies.
The most recent work, with the greatest frequency range, is that of Stenfelt et al., in which the vibrational response of the skull over the 0.1 to 10 kHz range was measured [12]. The vibrational response was found to be complex, including an antiresonance below 1 kHz in the ipsilateral transmission path that would lead to a lateralization of perception on the contralateral side for some frequencies. Above 4 kHz, beyond the range of major importance for speech reception, even sharper and deeper antiresonances were apparent. In addition, Stenfelt et al. looked separately at the x, y, and z axes, and found differences in the frequencies of the antiresonances depending on the orientation of the transducer. The higher the frequency of vibration, the more complex the resonances in both frequency and orientation.

Vibrational Characteristics of the Human Skull above the Audiometric Frequencies

Although hearing by air conduction is limited to about 20 kHz, hearing by bone conduction extends to at least 100 kHz [16, 19]. Lenhardt et al. demonstrated that speech modulating an ultrasonic carrier could be understood to some degree [17], and Staab have presented further speech recognition data using an ultrasonic hearing aid based on the Lenhardt et al. work [18]. Meikle et al. and Goldstein et al. have used frequencies in the high audio to ultrasonic range for tinnitus therapy [2, 3].

Prior to the current study, the only report on the ultrasonic characteristics of the skull has been that of Dunlap et al., who performed low resolution measurements of attenuation across the dry skull up to 64 kHz [19]. They found an attenuation on the contralateral side of about 12 dB per octave. Attenuation ranged from 0 to 20 dB in the audiometric range (< 10 kHz), and increased to about 40 dB in the high audio range (10-20 kHz), and about 80 dB at 64 kHz. However, because they averaged across 1/3 octave bands, they were not able to detect sharper resonances and antiresonances in the higher frequencies.

Here we report the first high-resolution (64 Hz resolution) measurements of the vibratory response of the skull up to 50 kHz, in comparison to the response of a live human head.
Method

Materials

Two dry human skulls (gender and age unknown) weighing 432g and 506g respectively, sectioned through the calvarium along the horizontal plane, were used for vibrational measurements. Measurements were made on both the top and bottom parts of the sectioned skulls. Dunlap et al. note that propagation of high frequencies across the skull is primarily through the cranial vault, and that the thick base bones do not support high frequency transmission from one side of the skull to the other [19]. Their data show little difference between sectioned and intact skulls.

No damping material was attached to either the exterior or the interior of the skulls. Although damping might more closely simulate a live head (as in the measurements of Stenfelt et al. [12], there are no existing data to suggest appropriate damping for the frequencies used. Instead, comparison measurements were performed on the head of one live adult male human subject (age 49 years). Three other adult males (aged 44, 57 and 63) listened to frequencies swept through the range of interest to determine if the perception was lateralized or detected in the midline.

The Measurement Setup

A. Coordinate System on the Skull

Because of the roughly spherical yet highly irregular shape of the human skull, a pseudo-polar coordinate system was set up on the outer surface of each skull. The apex of the skull was chosen as the polar spot, and concentric circles were drawn with a 2-cm increment in radius. Then a measuring site was marked counter clockwise every 2-cm apart along the circles beginning from the intersection with the midline. Measurements were made over the surface of the entire cranium, down to the level of the top of the eyes. Below this point the surface of the skull was too irregular for attachment of the transducers.
B. Transducers and Attachment

The actuator (Blatek Industrial transducer from Blatek, State College, PA) was a piezoelectric ultrasonic transducer about 32mm in diameter and 3mm in thickness. Two other piezoelectric pickup transducers, a Dean Markley Artistic (from Dean Markley, California) and a Fishman SBT-C (from Fishman Transducers, Inc., Wilmington, MA), were used as sensors. The Markley transducer is 18mm in diameter and 6mm in thickness, with the piezoelectric core fixed with plastic-wax in a wood case. The Fishman transducer, 10 mm in diameter, is less than 1mm in thickness, with the thin piezoelectric metal piece attached directly to the wire. Both transducers were originally designed as wide-frequency-response musical instrument transducers, intended for surface mounting with adhesive. The frequency responses of the actuator/sensor combinations varied by about plus/minus 15 dB across the range from 2 to 52 kHz.

The transducers were glued onto the measuring sites on the skulls with commercial double-sided clear tape (3M®). Enough adhesion was achieved by applying small pieces of tape on both the measurement site and the transducer. No additional pressure was applied to the transducers during any experimental trial. Pieces of tape were replaced frequently to ensure consistent adhesion.

Accelerometers, more commonly used in studies of vibration, were not used in this study for most measurements. Obtaining the full frequency response of an accelerometer sensitive to frequencies up to 50 kHz requires a hard attachment with a screw mounting, not possible in multiple locations on a skull without potentially affecting the skull’s properties with multiple screw holes. Since the goal was a method of measurement that would allow comparison with a live human head, all attachments of transducers on the dry skulls were conducted in the same manner as they would be on a human head. No drilling or any kind of permanent change was made to the skull structure. For comparison, measurements were made at a single skull location with an accelerometer (AMP 01, MSI, Inc.). The spectra of the accelerometer measurements closely resembled those of the piezoelectric transducers.
C. Measurement Setup

Measurements were performed using a Hewlett-Packard HP 35670A Dynamic Signal Analyzer both as signal source and analyzer, over a frequency range of 2 to 53.2 kHz. The signal was random noise, fed into a power amplifier designed for piezoelectric transducers (Model EPA-102 from Piezo Systems, Inc., Cambridge, MA), which was connected to the Blatek transducer. The output voltage was monitored by a digital multimeter (Tektronic CDM250) and adjusted to be 2.0 volts. Responses picked up by the sensor transducers (either the Markley or the Fishman) were amplified by an audio preamplifier and fed to the FFT analyzer. A flat top window was chosen with 100 averages per scan. The resolution was set at 800 lines (64 Hz per line). All the data were stored as ASCII text in external disks and later analyzed on PC.

D. Measurement Procedure

Measurements were made to explore the following aspects of skull vibration: (1) frequency-dependent vibratory patterns over the entire surface of the cranium, and (2) frequency-dependent transcranial attenuation. During each measurement, the tested part of the skull was supported by high-density foam of 5 cm thickness covered by a low-density foam sheet about 2 cm thick. Here we report measurements made with the actuator on the left parietal bone just above the ear. For the mapping of the entire cranium, the pick-up transducer was moved around the skull surface to each of the predetermined 2-cm-apart locations, and measurements were taken on each site while the actuator was kept at the same location. For transcranial attenuation, measurements were made at several locations within 4 cm of each other on the ipsilateral and contralateral parietal bones. All measurements were repeated at least 3 times and averaged.

E. Human Head Transcranial Attenuation

For frequency-dependent transcranial attenuation only, an identical set of measurements was performed on a live human head. Exactly the same procedure was followed as with the dry skull, with the transducers attached on the skin surface over the parietal bones on opposite sides of the head just above the ear.
Results

A spectrum plot of the vibration at any given point on the skull shows complex resonances and antiresonances. These change substantially in frequency and amplitude with small changes in transducer location. Figure 1 is an example of spectra obtained at 2 locations 2 cm apart on the ipsilateral parietal bone of Skull 1, corrected for transducer frequency response. Figure 2 is an example of the same measurements made on the live human head. Note that the live head shows fewer and shallower resonances and antiresonances than the skull.

To visualize the vibration pattern over the entire cranium, a three-dimensional model was set up in MATLAB®. Selected frequencies at resonances and antiresonances were graphed, using data from all the points on the cranial surface. Figures 3 through 6 give examples of the vibration patterns on the 2 skulls, comparing frequencies in the audio and ultrasonic ranges. The actuator, signified by the arrow, is on the left parietal bone in these examples; the front of the skull is on the right. Note the complex amplitude distribution on the surfaces of both skulls. Small changes in location lead to amplitude changes of up to 50 dB. On Skull 1, in the ultrasonic range, the amplitude on the entire contralateral side is greatly attenuated, in contrast with Skull 2, which does not show this effect to the same degree.

Transcranial attenuation patterns are also complex, especially above 10 kHz. The two skulls differ, with Skull 1 showing greater attenuation in the high frequencies than Skull 2. Figure 7 shows the transcranial attenuation for Skulls 1 and 2, calculated by subtracting the spectrum for the ipsilateral parietal bone (from an average of 12 measurements at 4 sites within 4 cm) from the spectrum for the contralateral parietal bone. Figure 8 shows the same calculation for the live human head. Although there are substantial peaks and valleys, there is no systematic change in attenuation with frequency.

Finally when a tone is swept in frequency while the transducer is placed over one or the other mastoid bone the perception is that of a tone bouncing between positions lateralized to one side or the other or in midline. These individual
differences in precisely which tone is localized in which position in the head vary, likely reflecting head geometrically determined resonances and antiresonances.

**Discussion**

The vibrational response of the skull above 10 kHz is clearly complex. At any single location on the skull there are multiple resonances and antiresonances, which can change substantially with small changes in position of the transducers (Figure 1). Stevanovic et al. used the range of 4 to 7 kHz in ovine heads to measures changes in impedance and phase with changes in intracranial pressure [20]. Even at these low frequencies, the variability in the spectra led them to use an average of the whole frequency range. Averaging over a distance of several centimeters can smooth out some of the sharp dependence on location, and reveals a more general pattern of attenuation across the skull (Figure 7). In contrast to Dunlap et al., with higher resolution analysis it is clear that the attenuation across the skull is not a smooth function. Dunlap et al. also reported much greater transcranial attenuation due to a difference in methodology [19]. They measured the ipsilateral intensity with the accelerometer attached directly to the shaker; due to impedance differences, some of the energy is not coupled into the skull. We were interested in the difference in intensity between the two cochleas; the closest approximation in the intact skull and live head is the parietal bone over the ear. Comparison of ipsilateral and contralateral parietal bones corrects for impedance mismatches between the transducers and the head.

The live head presents a somewhat different picture. The resonances and antiresonances are present but relatively damped (Figure 2). The transcranial attenuation does not vary systematically with frequency (Figure 8) and individual differences would be expected, including difficulty in tracking threshold for higher frequencies by bone conduction and in threshold repeatability since the perception can change position with frequency. It is very difficult to replace a transducer exactly where it was located previously and slight changes in position can alter the energy delivered to the ear. Reliable air conduction testing in the very high frequencies is limited by canal acoustics, so too it seems bone conduction is also limited by skull acoustics.
How can we account for the differences between the dry skull and the live human head? In the dry skull, there is no damping material, and the individual bones are less tightly coupled. In Skull 1 there was much looser coupling at the sutures than in Skull 2, reflected in the much poorer ultrasonic transmission across Skull 1. In contrast, the head has damping material both on the inside (meninges, brain, cerebrospinal fluid) and the outside (skin, muscle, fascia). In addition, the bones of the head are not able to vibrate independently because of the tight coupling between them. In addition to bone conduction, there is also a non-osseous mechanism for conduction of vibration through the fluid components of the head (e.g., the brain) [17, 21].

These results have consequences for use of high audio frequencies and ultrasound in audiometry, hearing aids, and tinnitus treatment. Above about 10 kHz there will be large and rather unpredictable gaps in the frequency response. This is important in selection of transducers with a particular frequency response, and algorithms that convert sound from the audible range into a higher range. For example, a bone conduction hearing aid or tinnitus masker would ideally choose the resonances for maximum amplitude, rather than the antiresonances, and would distribute the energy across a sufficient bandwidth so that the antiresonances would not have a significant effect on the signal. The algorithm needs to distribute energy across at least 10 kHz, and be insensitive to narrow antiresonances.

These same considerations would also be important for using these frequencies for non-invasive monitoring of intracranial pressure (ICP). The same problem will exist at ultrasonic frequencies, requiring use of a wide bandwidth.

References


Figure Legends

Figure 1. Spectra obtained from two locations on the ipsilateral side of Skull 1, illustrating differences in resonances and antiresonances.

Figure 2. Spectra obtained from two locations on the ipsilateral side of the live head, illustrating differences in resonances and antiresonances.

Figure 3. Vibrational pattern of Skull 1 at 7.3 kHz, vibrating on the left parietal bone (arrow indicates the actuator position).

Figure 4. Vibrational pattern of Skull 1 at 41.4 kHz, vibrating on the left parietal bone (arrow indicates the actuator position).

Figure 5. Vibrational pattern of Skull 2 at 11.5 kHz, vibrating on the left parietal bone (arrow indicates the actuator position).

Figure 6. Vibrational pattern of Skull 2 at 43.8 kHz, vibrating on the left parietal bone (arrow indicates the actuator position).

Figure 7. Transcranial attenuation for Skull 1 (dotted line) and Skull 2 (solid line).

Figure 8. Transcranial attenuation for live head.
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Figure 7. Transcranial attenuation for Skull 1 (dotted line) and Skull 2 (solid line).

Figure 8. Transcranial attenuation for live head.