Response of Human Skull to Bone-Conducted Sound in the Audiometric-Ultrasonic Range

Zhi Cai, Douglas G. Richards, Martin L. Lenhardt, and Alan G. Madsen

Program in Biomedical Engineering, Virginia Commonwealth University, Richmond, VA

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- to 52-kHz range. White noise was played and received through piezoelectric transducers and was Fourier-analyzed. Complex resonances and antiresonances were found in both the dry skulls and the live head and 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.

Key Words: audio; bone conduction; hearing aids; skull; tinnitus; ultrasound

*B*one 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- 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 for long-term residual inhibition [3].

Conventional bone conduction hearing aids and bone conduction audiometry assume that the frequency response of the skull to vibration is relatively flat across the range of interest and that there is little attenuation across the skull, allowing binaural perception from a single transducer on one side of the head. Although this is largely the case with sound at less than 5 kHz (the range of most interest for perception of unmodified speech), there is great variability in both 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 AUDIOMETRIC FREQUENCIES

Several researchers have performed vibrational experiments in the audiometric frequency range (up to 10 kHz) on human heads, cadaver heads, and animal and 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 in the greatest frequency range is that of Stenfelt et al. [12], in which the vibrational response of the skull within the 0.1- to 10-kHz

Reprint requests: Martin L. Lenhardt, Ph.D., Box 980168, Virginia Commonwealth University, Richmond, VA 23298-0168. Phone: 757-833-6794; Fax: 757-833-7406; E-mail: lenhardt@hsc.vcu.edu

range was measured. The vibrational response was found to be complex, including an antiresonance of less than 1 kHz in the ipsilateral transmission path that would lead to a lateralization of perception on the contralateral side for some frequencies. In excess of 4 kHz, beyond the range of major importance for speech reception, even sharper and deeper antiresonances were apparent. In addition, Stenfelt et al. [12] 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 were the resonances in both frequency and orientation.

VIBRATIONAL CHARACTERISTICS OF THE HUMAN SKULL BEYOND THE AUDIOMETRIC FREQUENCIES

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

Prior to the current study, the only report on the ultrasonic characteristics of the skull has been that of Dunlap et al. [19], who performed low-resolution measurements of attenuation across the dry skull of up to 64 kHz. They found an attenuation on the contralateral side of approximately 12 dB per octave. Attenuation ranged from 0 to 20 dB in the audiometric range (<10 kHz) and increased to approximately 40 dB in the high audio range (10–20 kHz) and approximately 80 dB at 64 kHz. However, because they averaged across one-third 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.

MATERIALS AND METHOD

Materials

Two dry human skulls (gender and age unknown) weighing 432 g and 506 g, respectively, and sectioned through the calvarium along the horizontal plane, were used for vibrational measurements. Measurements were

taken from both the top and bottom parts of the sectioned skulls. Dunlap et al. [19] noted 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. Their data showed 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 by 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 male adults (ages 44, 57, and 63) listened to frequencies swept through the range of interest to determine whether the perception was lateralized or detected in the midline.

Measurement Setup

Coordinate System on the Skull

Because of the roughly spherical yet highly irregular shape of the human skull, a pseudopolar 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 counterclockwise every 2 cm 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.

Transducers and Attachment

The actuator (Blatek Industrial Transducer; Blatek, State College, PA) was a piezoelectric ultrasonic transducer approximately 32 mm in diameter and 3 mm thick. Two other piezoelectric pickup transducers, a Dean Markley Artistic (Dean Markley, Inc., Santa Clara, CA) and a Fishman SBT-C (Fishman Transducers, Inc., Wilmington, MA), were used as sensors. The Markley transducer is 18 mm in diameter and 6 mm thick, with the piezoelectric core fixed with plastic wax in a wood case. The Fishman transducer, 10 mm in diameter, is less than 1 mm thick, 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 approximately ±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, St. Paul, MN). 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. As 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 used 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.

Measurement Setup

Measurements were performed using a Hewlett-Packard (Palo Alto, CA) 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; Piezo Systems, Inc., Cambridge, MA), which was connected to the Blatek transducer. The output voltage was monitored by a digital multimeter (Tektronix CDM250, Tektronix, Beaverton, OR) 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 fast Fourier transform 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 were analyzed on a personal computer.

Measurement Procedure

Measurements were made to explore two aspects of skull vibration: frequency-dependent vibratory patterns over the entire surface of the cranium and frequency-dependent transcranial attenuation. During each measurement, the tested part of the skull was supported by high-density foam 5 cm thick covered by a low-density foam sheet approximately 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
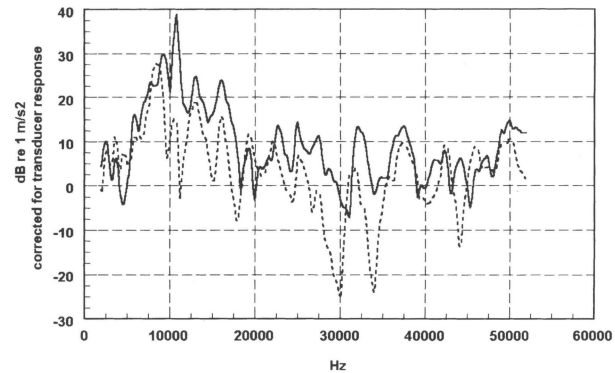

Figure 1. Spectra obtained from two locations on the ipsilateral side of skull 1, illustrating differences in resonances and antiresonances.

the skull surface to each of the predetermined locations 2 cm apart, 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 three times and were averaged.

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 as that with the dry skull was followed, 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 antireso-
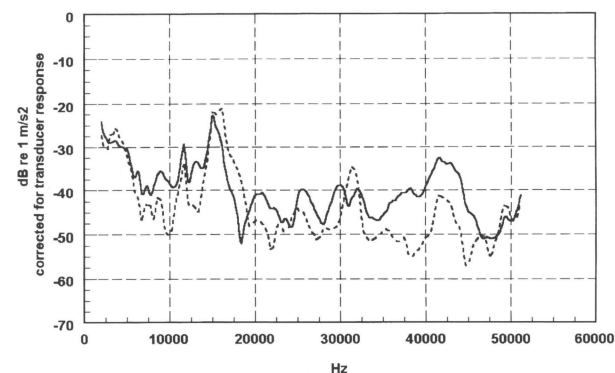

Figure 2. Spectra obtained from two locations on the ipsilateral side of the live head, illustrating differences in resonances and antiresonances.
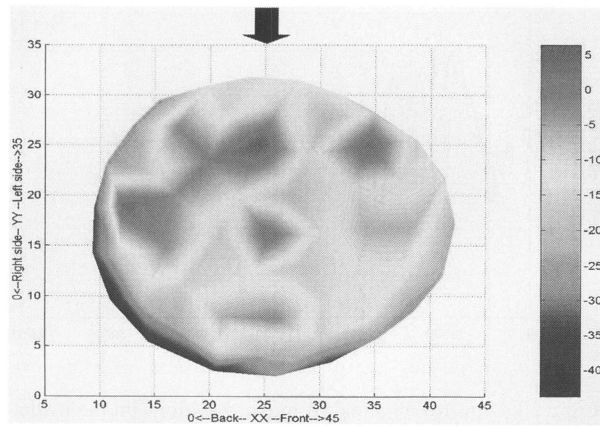
Figure 3. Vibrational pattern of skull 1 at 7.3 kHz, vibrating on the left parietal bone (*arrow* indicates actuator position).
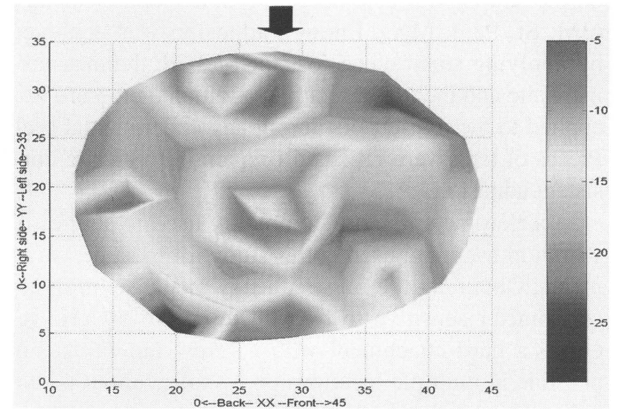

Figure 5. Vibrational pattern of skull 2 at 11.5 kHz, vibrating on the left parietal bone (*arrow* indicates actuator position).

nances. These change substantially in frequency and amplitude with small changes in transducer location. Figure 1 is an example of spectra obtained at two 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 those on the dry 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 3–6 give examples of the vibration patterns on the two 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 beyond 10 kHz. The two skulls differ, with skull 1 showing attenuation in the high frequencies greater than that of 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 four 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.
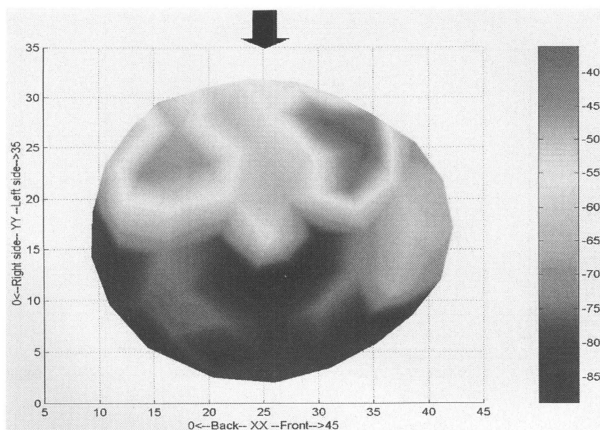

Figure 4. Vibrational pattern of skull 1 at 41.4 kHz, vibrating on the left parietal bone (*arrow* indicates actuator position).
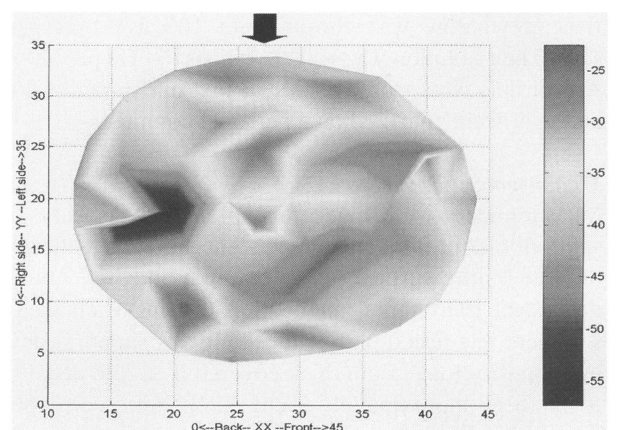

Figure 6. Vibrational pattern of skull 2 at 43.8 kHz, vibrating on the left parietal bone (*arrow* indicates actuator position).
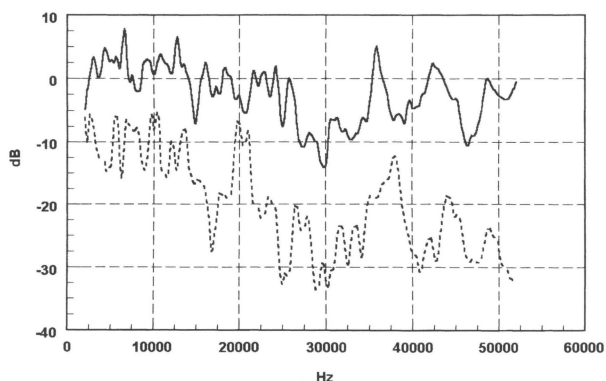
Figure 7. Transcranial attenuation for skull 1 (*dotted line*) and skull 2 (*solid line*).

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 vary in precisely which tone is localized in which position in the head, likely reflecting geometrically determined head resonances and antiresonances.

DISCUSSION

The vibrational response of the skull beyond 10 kHz is clearly complex. At any single location on the skull, there are multiple resonances and antiresonances that can change substantially with small changes in position of the transducers (see Fig. 1). Stevanovic et al. [20] used the range of 4 to 7 kHz in ovine heads to measures changes in impedance and phase with changes in intracranial pressure. Even at these low frequencies, the variability in the spectra led them to use an average of the entire frequency range. Averaging over a distance
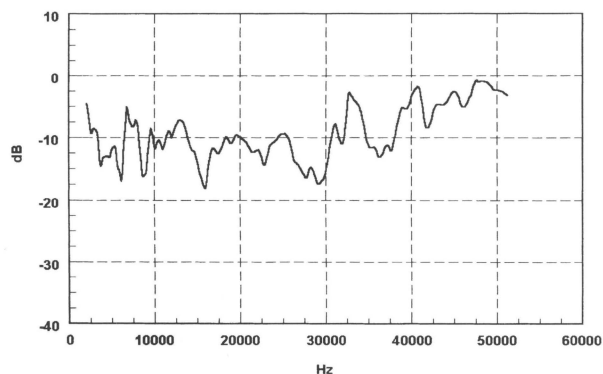

Figure 8. Transcranial attenuation for live head.

of several centimeters can smooth out some of the sharp dependence on location and reveals a more general pattern of attenuation across the skull (see Fig. 7). In contrast to Dunlap et al. [19], with higher-resolution analysis, it is clear that the attenuation across the skull is not a smooth function. Dunlap's group also reported much greater transcranial attenuation owing to a difference in methodology. They measured the ipsilateral intensity with the accelerometer attached directly to the shaker; owing 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 (see Fig. 2). The transcranial attenuation does not vary systematically with frequency (see Fig. 8), and individual differences would be expected, including difficulty in tracking threshold for higher frequencies by bone conduction and in threshold repeatability, as 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 that 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 live 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 nonosseous 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. Beyond approximately 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 bandwidth sufficient so that the antiresonances would not have a significant effect on the signal. The algorithm must 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 noninvasive monitoring of intracranial pressure. The same problem will exist at ultrasonic frequencies, requiring use of a wide bandwidth.

REFERENCES

1. Holgers K-M, Hakansson B. Tinnitus retraining therapy with bone conductive sound stimulation. In *Proceedings of the Sixth International Tinnitus Seminar*. London: The Tinnitus and Hyperacusis Centre, 2000:485–486.

2. Meikle MB, Edlefsen LL, Lay JW. Suppression of tinnitus by bone conduction of ultrasound. Poster presented at the Twenty-First Annual Meeting of the Association for Research in Otolaryngology, 1999.

3. Goldstein BA, Shulman A, Lenhardt ML, et al. Long-term inhibition of tinnitus by UltraQuiet therapy: Preliminary report. *Int Tinnitus J* 7(2): 122–127, 2002.

4. von Bekesy G. Vibration of the head in a sound field and its role in hearing by bone conduction. *J Acoust Soc Am* 20:749–760, 1948.

5. von Bekesy G. Response of the human skull to mechanical vibration. In *Handbook of Experimental Psychology*. New York: Wiley, 1951.

6. Franke E. Response of the human skull to mechanical vibrations. *J Acoust Soc Am* 28:1277–1284, 1956.

7. Kirikae I. An experimental study on the fundamental mechanism of bone conduction. *Acta Otolaryngol Suppl* 145:1–111, 1959.

8. Tonndorf J. A new concept of bone conduction. *Arch Otolaryngol* 87:49–54, 1968.

9. Khalil TB, Viano DC, Smith DL. Experimental analysis of the vibrational characteristics of the human skull. *J Sound Vib* 63:351–376, 1979.

10. Nolan M, Lyon DJ. Transcranial attenuation in bone conduction audiometry. *J Laryngol Otol* 95:597–608, 1981.

11. Hakansson B, Brandt A, Carlsson P, Tjellstrom A. Resonance frequency of the human skull *in vivo*. *J Acoust Soc Am* 95:1474–1481, 1994.

12. Stenfelt S, Hakansson B, Tjellstrom A. Vibration characteristics of bone conducted sound *in vitro*. *J Acoust Soc Am* 107:422–431, 2000.

13. Fry FJ, Barger JE. Acoustical properties of the human skull. *J Acoust Soc Am* 63:1576–1590, 1978.

14. Martin B, McElhaney JH. The acoustic properties of human skull bone. *J Biomed Mater Res* 5:325–333, 1971.

15. McElhaney JH, Fogle JL, Melvin JW, et al. Mechanical properties on cranial bone. *J Biomech* 3:495–511, 1970.

16. Corso J. Bone-conduction thresholds for sonic and ultrasonic frequencies. *J Acoust Soc Am* 35:1738–1743, 1963.

17. Lenhardt ML, Skellett R, Wang P, Clarke A. Human ultrasonic speech perception. *Science* 253:82–85, 1991.

18. Staab W, Polashek T, Nunley J, et al. Audible ultrasound for profound losses. *Hear Rev* 2:28–36, 1998.

19. Dunlap SA, Lenhardt ML, Clarke AM. Human skull vibratory patterns in audiometric and supersonic ranges. *Otolaryngol Head Neck Surg* 99:389–391, 1988.

20. Stevanovic M, Wodicka GR, Bourland JD, et al. The effect of elevated intracranial pressure on the vibrational response of the ovine head. *Ann Biomed Eng* 23:720–27, 1995.

21. Sohmer H, Freeman S. The pathway for the transmission of external sounds into the fetal inner ear. *J Basic Clin Physiol Pharmacol* 12(suppl 2):91–99, 2001.