International Tinnitus Journal, Vol. 13, No. 2, 81–86 (2007)

Bone-Conduction Propagation in the Human Body: Implications for High-Frequency Therapy

Martin L. Lenhardt,[1] Abraham Shulman,[2] and Barbara A. Goldstein[2]

[1] *Ceres Biotechnology, LLC, and Program in Biomedical Engineering, Virginia Commonwealth University, Richmond, VA, and* [2] *Martha Entenmann Tinnitus Research Center, Forest Hills, and Department of Otolaryngology, Health Science Center at Brooklyn, State University of New York, Downstate Medical Center, Brooklyn, New York, USA*

Abstract: We assessed ultrasonic transmission in a dry skull; in a dry skull with water, simulating the living condition; in a cadaver head; and in six human subjects, one of whom exhibited no measurable hearing. By using these preparations, we concluded that fluid conduction is essential in the propagation of sound across the head, whereas the bone pathway is far less effective in that regard. Thus, there is little ear isolation beyond 10 dB even up to 80 kHz, extending the masking dilemma in cases of unilateral hearing loss.

Key Words: interaural attenuation; masking dilemma; tinnitus; ultrasonic hearing

In a series of studies of bone-conduction (BC) hearing [1–4], we demonstrated that there was little attenuation (~10 dB) across the head in the audiometric range (<10,000 Hz), in the high audio range (10–20 kHz), and in the lower ultrasonic range (20–50 kHz). BC hearing results from placing a vibrator in contact with the skin of the head; however, the process is a complex interaction of the vibration and the physical structures of brain-skull-skin. One characteristic of BC hearing is that movement of the vibrator just a few centimeters on the skin can shift the threshold [5,6]. This placement effect is more profound for the higher audiometric frequencies and for individuals with severe hearing loss [7]. Békésy [5] suggested that placing the vibrator on the forehead midline would reduce the threshold variability, as slight shifts in position did not affect threshold in the audiometric frequencies. Though forehead placement has long since fallen out of clinical favor, the utility of alternative vibrator placement for high-frequency BC tinnitus therapy [8] has not been systematically explored.

We noted that attenuation across a dry skull is similar for a vibrator placed on the frontal, parietal, or occipital bones [1,4]; however, a dry skull is much different from a living head in terms of its acoustic properties. As ultrasound can propagate by fluid conduction [9–11], we will explore ultrasonic frequency mapping over the body, not just the head, and through the use of a cadaver extend our ultrasonic intra-aural study to 80,000 Hz.

An alternative view [12] is that ultrasound propagates principally owing to the piezoelectric properties of bone itself [13,14]. In fact, the osseous nonlinearities (apatite crystals) could be the source of demodulated, amplitude-modulated ultrasound, which presumably is the mechanism involved in electric BC hearing using the Tonndorf audiometer. Bennett [12] assumed that the principle operating in electric BC hearing also applies to all forms of ultrasonic hearing and proposed a simple test (which we performed) to clarify the role of bone in BC.

PATIENTS AND METHODS

Five young, normal-hearing adults (three male, two female; mean age, 31 years), one young, profoundly deaf adult woman (aged 29, with no measurable audiometric hearing), and the first author served as subjects. The vibrator and accelerometer (Wilcoxon Research F3/F9, Rockville, MD) were mounted, one to each mastoid (then reversed), using a custom-designed isolated spring caliper yielding 5.5 Newtons (N) of force. Contact force was continually monitored, as variations in force would

Reprint requests: Martin L. Lenhardt, AuD, PhD, Box 980168 MCV, Virginia Commonwealth University, Richmond, VA 23298-0168. Phone: 804-343-1047; Fax: 804-828-4454; E-mail: lenhardt@vcu.edu

translate into changes in attenuation owing to coupling disparities. In the case of contralateral recordings, a second accelerometer was used (508BP, Quest Electronics, Okanawac, WI). All acceleration readings were referenced to 1 gravity unit (1*g* RMS).

The vibratory stimuli consisted of 2-second tone pulses of 25 and 62.5 kHz delivered to the body using a stacked quartz crystal (Wilcoxon Research F9). The signals were monitored by a real-time spectral analyzer (Hewlett-Packard 3561A). The vibrator was placed on the mastoid and moved until the lowest threshold was detected. This served as the reference for all other vibrator positions on the body, recorded in decibels, regarding sensation level (SL). The transducer had a driving surface area of approximately 1.5 cm^2.

The maximal power was maintained within the upper limits as defined by the Occupational Safety and Health Administration [15]. Additionally, a dry skull obtained randomly from the anatomical collection at the Anatomy and Neurobiology Department of Virginia Commonwealth University, Richmond, Virginia, and the head of a very recently deceased (4 hours) middle-aged male adult (~50 years of age) were used for vibratory measurements using intense levels for frequencies >50 kHz. The vibration recording from the dry skull (weighing 501 g) was carried out using the procedure outlined by Cai et al. [1], differing only in the instrument manufacturer (Cai et al. used a Buel and Kjaer spectral analyzer), which was, however, comparable to that used by Dunlap et al. [16]. A water balloon was secondarily placed in the dry skull to simulate a brain, because water has about the same acoustic properties [17]. The same procedure used for threshold detection was repeated using 25- and 62.5-kHz tones to measure attenuation across the skull. As an intermediary between the water-filled skull and a living head, we tested the head of a very recently deceased male (fresh cadaver) of approximately 50 years of age with no signs of head or neck trauma, who apparently died of natural causes. We fitted the transducer and accelerometer in the same fashion as in the living subjects; however, the intensity of the ultrasonic stimulation, especially for frequencies >50 kHz, was increased (+30 dB) until we obtained reliable measurements. The force again was monitored to assure informality in coupling. We calculated the interaural attenuation after physical measurement of head or skull diameter (range, 13.4–14 cm).

A test of the role of BC as a principle—if not exclusive—mechanism of ultrasonic hearing was replicated as suggested [12]. To do so, the stimulus must be double-sideband-modulated. This was accomplished by using a commercial ultrasonic hearing aid (HiSonic, Misonx, Farmington, NY). We set the suppressed carrier at 25 kHz, which was modulated by either a 1-kHz tone or speech. We applied the ultrasound to the skin at the level of the ankle and the lower tibia. We monitored sound generation, if any, by this application at the tibia with a microphone and by monitoring aurally with the subject (MLL) listening. Though the ultrasonic hearing aid device is FDA-approved for hearing loss, the energy level was rapidly increased from minimum to maximum. Because of the potentially intense exposure to someone with normal hearing, only the first author served as a subject in this experiment, using due care.

RESULTS

Ultrasonic Threshold Mapping

The threshold data taken over various parts of the body are summarized in Table 1. For simplicity, the data are portrayed as decibels of attenuation using the mastoid threshold as the reference. For normal-hearing subjects, the neck site was nearly as sensitive as the mastoid, but the head sites were 5–6 dB poorer than the mastoid. The vertex was the least sensitive site, and pinna ultrasonic vibration was not detected. Stimulation of the upper limb was generally perceptible, with increased energy over the head sites for 25 kHz but not at 62.5 kHz. The totally deaf subject could not detect 62.5 kHz and could detect only 25 kHz at her mastoid, neck, clavicle, and sternum and all with almost equal sensitivity. With this in mind, sternum sensitivity is also demonstrated for both frequencies in the normal-hearing subjects. At the maximal stimulation levels, no responses were detected at the knee or ankle. However, responses were

Table 1. Body Map of Ultrasonic Detection

Mastoid Reference	25 kHz Normal (decibels)	25 kHz Deaf (decibels)	62.5 kHz Normal (decibels)
Vertex	8	NR	NR
Occiput	5	NR	4
Forehead	5	NR	4
Nose	6	NR	3
Below nose	6	NR	5
Pinna	NR	NR	NR
Ear canal	5	NR	−4
Neck	3	−0	4
Larynx	6	NR	5
Clavicle	6	~−1	NR
Sternum	1	~−1	4
Upper thorax	10	NR	6
Elbow	13	NR	NR
Wrist	NR	NR	NR
Knuckle	13	NR	NR
Knee	NR*	NR	NR
Ankle	NR*	NR	NR

*Not tested above standard limits [15].
NR = no response.

obtained using more powerful stimulation of an ultrasonic hearing aid (discussed later).

Transducer placement on the mastoid was critical in determining threshold. Slight movement (1–2 cm) of the transducer could alter threshold. A larger area of maximal sensitivity (3–4 cm) was found on the neck and sternum.

Interaural Attenuation to 80 kHz

We measured interaural attenuation in a single cadaver in both a fresh and an embalmed state. The mastoid-to-mastoid attenuation values ranged from 5 to 21 dB over the frequency range of 25–80 kHz. The embalming preservative did increase the attenuation values below 50 kHz but only some 5 dB, likely owing to the increased viscosity of the embalming fluid (Fig. 1). There is also good agreement between the physical properties of the live head and that of the fresh cadaver as measured by mastoid-to-mastoid attenuation below 50 kHz, with the cadaver exhibiting ~6 dB more attenuation across that range. The peaks and troughs in the fresh cadaver data likely represent brain resonances and antiresonances [1,2,9]. Note that the pattern of interaural attenuation is the same for the fresh and embalmed conditions, and only the range of attenuation differs (smaller for the embalmed). Cadaver mastoid-to-mastoid attenuation is about 20 dB when ignoring resonances and antiresonance. In the embalmed condition, there is <15 dB attenuation between mastoids at frequencies of >50 kHz. Thus, only low levels of vibration produced strictly ipsilateral stimulation for the wet skull with intact contents. The data on a dry or wet (brain and vascular contents intact) skull is neatly separated from the wet skull, as seen in Figure 2, by the values above and below 25 dB of attenuation. The condition of only dry bone does impede sound transmission from side to side but not so in the presence of fluid (or brain), verifying fluid conduction.

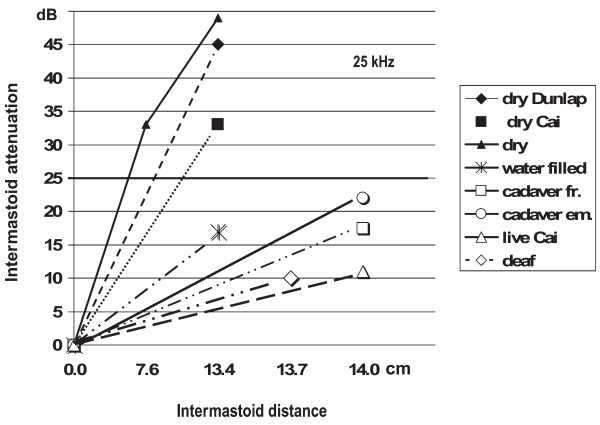

Figure 1. Mastoid-to-mastoid attenuation in the audible ultrasonic frequencies. The attenuation values (not behavioral thresholds) from mastoid to mastoid are plotted for a fresh (*cadaver fr*.) and embalmed cadaver (*cadaver em*.) and for a live head (Cai et al. [1]) for frequencies from 25 to 80 kHz for the cadaver and from 25 to 50 dB for the living head. Note the good agreement between results from the fresh cadaver and those from the live head. The same cadaver was embalmed after the first measurement, and the attenuation from mastoid to mastoid changes somewhat, likely owing to the increased viscosity of the embalming fluid. Nonetheless, the data show generally only a 5 dB increase in attenuation across the ultrasonic frequency range of measurement. The peaks and troughs in the data are most likely reflections of resonances and antiresonances, damped to some degree by the embalming fluid. The overall conclusion is that there is little (~15 dB) attenuation across the mastoids in the ultrasonic region when skull contents (brain and fluid) are intact.

Bone Demodulation

With a transducer placed on the ankle or lower part of the tibia, we could detect demodulation of the 1,000-Hz tone or speech by the left microphone. However, stimulation of the ankle and tibia did result in an audible high-pitched tone, much like placing the transducer directly on the head [7,9] at a somewhat reduced volume. We also detected speech from ankle stimulation, but no systematic intelligibility study was carried out. Suffice it to say that the stimulation was readily identified as speech.

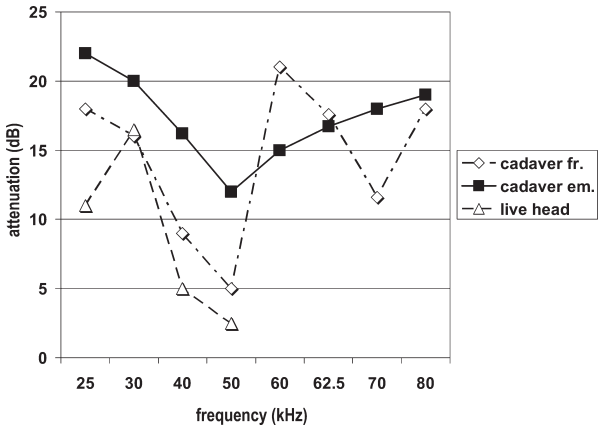

Figure 2. Mastoid-to-mastoid attenuation at 25 kHz. The attenuation from mastoid to mastoid is plotted for a dry skull used in this study (dry) and for dry-skull data from Cai et al. [1] and Dunlap et al. [16]. These data are contrasted with those from a water-filled skull; a fresh (*cadaver fr*.) and embalmed cadaver (*cadaver em*.); a live head (physical measurements across the head; Cai et al. [1]); and behavioral thresholds of a profoundly deaf subject. A line at 25 dB attenuation separates these measurements into the dry-skull group and those with brains intact or simulated (water-filled). Taken as a whole, there is approximately 15 dB attenuation at 25 kHz between mastoids when a brain is present, suggesting that fluid (brain and vascular contents) play a notable role in propagation of ultrasound from ear to ear.

DISCUSSION

Collectively, these data demonstrate three clinically important points. First, mastoid detection is somewhat better than that in other head locations, but neck and sternum are very effective stimulation areas, with less specificity in location. Second, the low-level interaural attenuation of bone-conducted sound extends from the low audiometric to the high audible ultrasonic frequencies, extending caution in regard to masking. Third, electric BC differs from direct coupled ultrasonic hearing in that the former is dependent on the bones' rectifying qualities, whereas the latter may benefit from its piezoelectric qualities.

Ultrasonic Threshold Mapping

Using a mastoid reference, we found that generally the energy applied to the transducer must be increased as the distance from that site increases. That is, it takes ~5 dB more energy to detect ultrasound at other distant head regions, with two important exceptions: the neck and selected portions of the thorax. The neck is only 3–4 dB less sensitive than the mastoid, accounting for the frequent reports that ultrasound could be evoked by stimulation of this area (see Lenhardt [7,9] for review). As Ranke [18] pointed out, there exist fluid windows to the ear that include all vascular channels. The neck is rich in such channels, thus confirming the fluid conduction nature of ultrasonic BC hearing that may be independent of BC. The neck may, in fact, be as sensitive as the mastoid, as there is a greater mismatch in impedance between soft tissue and bone using the brass-encased crystal transducer that we employed. Piezoelectric transducers [17] have acoustic impedance similar to soft tissue and can be very effective in transmitting ultrasound. The impedance difference between the transducers is about 3 dB, the same order of threshold difference found in this study. Vibrator position was not as critical on the neck as compared to the mastoid for detecting ultrasound; nonetheless, an idiosyncratic area of best sensitivity was identifiable in all subjects.

The more surprising finding is the sensitivity of the sternum. This site approximates the mastoid in sensitivity; intuitively this should not be the case, given the distance from the ear. Bone has piezoelectric properties: That is, bending bone produces electrical energy. Electrical energy generated by bone movement can induce more movement in bone. The sternum can be readily displaced and thus conceived of as acting like an amplifier. There may also be resonant properties that provide additional energy. Either way, some physical process is activated. We did note that vibrator position is not as important in that a larger area seems equally sensitive.

The pathway from the sternum to the ear is not at all clear from this study. There is a clear osseous route; however, numerous blood vessels in communication with the thorax could also serve as propagation channels after local amplification. The third possibility is that both pathways may be functional. We performed one additional measure on the dry skull. The attenuation from the base of the skull to the mastoid averaged 41 dB at 25 kHz and 44.5 dB at 62.5 dB. These values would also argue against a pure BC route from the sternum to the ear, given the little attenuation measured behaviorally. There is a fourth possibility: that thoracic ultrasonic vibration could excite a tactile response via sensory hairs in the respiratory tract owing to airborne ultrasound-induced standing waves. This concept was applied to airborne ultrasound for the nasal and oral cavities and is consistent with standard acoustic theory [19]. The fact that the neck and mastoid areas were equally sensitive would also argue against a possible respiratory tract mechanism, but it cannot be excluded. From a clinical perspective, a transducer that was completely out of sight and could deliver ultrasonic, modulated tinnitus therapy of modulated speech would garner much cosmetic appeal.

There are clear differences between 25 and 62.5 kHz in the mapping experiment. When the output power remains within the Occupational Safety and Health Administration limits, 62.5 kHz is less audible. The relative pattern of site sensitivity remained fairly consistent. Absolute thresholds are simply 20 dB higher at 62.5 kHz (145 dB SLP re 1 Pa) than at 25 kHz [4,7]. The data in Table 1 reveal physical attenuation from the mastoid to various body regions of interest for 25 and 62.5 kHz in five normal-hearing subjects (mean values) and one profoundly deaf subject based on behavioral thresholds referenced to the threshold of the right mastoid. The mastoid and neck are generally very sensitive, as is the sternum.

Interaural Attenuation (>50 kHz)

Consistent with our previous reports [1–4], there is only about a 10 to 15 dB attenuation across the skull, depending on frequency, resonance, and antiresonance; this remains the case up to 80,000 Hz. Thus, cochlear separation or isolation is likely on the order of 10 dB SL. This is true in both the conventional audiometric frequencies (<10 kHz) and the ultra-high (>10–20 kHz) and ultrasonic frequencies (>20 kHz). There are frequencies of greater or lesser interaural attenuation owing to resonances and antiresonances that, without careful measurements, cannot be identified. The use of a fresh cadaver preparation was essential in making repeated measures at very high intensities (measured in

acceleration re 1 *g* and then referenced to 145 dB SPL in water, as reported previously) [8].

Electrical and Vibrational Bone Conduction

Electrical BC as exemplified by the use of the Tonndorf Audiometer (model 500, Audimax, Wayne, NJ) is employed regularly in assessing high-audiofrequency hearing in our patients [20–22]. Briefly, the audiometer consists of Mylar-coated electrodes placed over the mastoids, with the head electrically coupled into a low-voltage circuit. Audio tones are amplitude-modulated on an ultrasonic carrier of 60 kHz [23]. The non-linearities in the skin-bone demodulate the audio tones; however, in the process the electrodes vibrate at the audio frequencies. Thus, the stimulation to the electrodes is electrical, but the induced effect is vibratory. By placing a piezoelectric film sensor, constructed of a piezoelectric polymer polyvinylidene fluoride [17], between the electrodes and skin, the full amplitude modulation signal is recorded. By placing an accelerometer on the skin near the electrodes, the demodulated audio vibration is also recordable [24]. This is the exact test Bennett [12] suggested for contact ultrasound. Though piezoelectric properties of bone, acting as a rectifier, can demodulate an electric ultrasonic signal (as in the Tonndorf system), no such demodulation occurs for direct-contact ultrasonic bone vibration (for a proposed mechanism see [9]). It is important that, in the case of electrical BC, if electrodes are placed around dry bones, no audio demodulation occurs and no audio sound is heard [12]; in contrast, direct ultrasound vibration readily propagates in dry bones, as evidenced in this study.

The Masking Dilemma

As a consequence of little separation of ears by BC, the masking dilemma is present even at higher frequencies (>10 kHz), including electrical BC (Tonndorf) audiometry [23] and into the ultrasonic range (>20 kHz). Masking can be delivered by either air conduction or bone conduction, but calibration for deep insertion in frequencies can be difficult. The use of an insert ear phone for masking will provide adequate interaural attenuation for Tonndorf thresholds, assuming the noise is low-frequency (<10 kHz) and attenuated by filtering. In the case of ultrasonic stimulation, BC masking of more than 10 dB presents the dilemma of masking spreading to the test ear.

CONCLUSIONS

There is little interaural attenuation for BC hearing extending to the upper reaches of audible ultrasonic detection (~ 80 kHz). Deep-insert air conduction is recommended for BC and electrical BC for frequencies below 20 kHz. The mastoid should not necessarily be considered the optimal site for high-frequency BC therapy.

REFERENCES

1. Cai Z, Richards DG, Lenhardt ML, Madsen AG. Response of human skull to bone-conducted sound in the audiometric-ultrasonic range. *Int Tinnitus J* 8(1):1–8 2002.
2. Lenhardt ML, Richards DG, Madsen AG, et al. Measurement of bone conduction levels for high frequencies. *Int Tinnitus J* 8(1):9–12, 2002.
3. Shulman A, Strashun AM, Goldstein B, Lenhardt M. Congenital atresia of the external ear and tinnitus: A new syndrome. *Int Tinnitus J* 12(1):17–30, 2006.
4. Lenhardt M, Goldstein B, Shulman A. Binaural hearing, atresia, and the masking dilemma. *Int Tinnitus J* 12(2): 28–34, 2006.
5. Békésy G. *Experiments in Hearing*. New York: McGraw Hill, 1960.
6. Kirikae I. A contribution to bone conduction audiometry. *Jpn Oto Lartyngol* 58:224–228, 1955.
7. Lenhardt ML, Skellett R, Wang P, Clarke AM. Human ultrasonic speech perception. *Science* 253:82–85, 1991.
8. Goldsteim BA, Shulman A, Lenhardt ML. Ultra-high-frequency ultrasonic external acoustic stimulation for tinnitus relief: A method for patient selection. *Int Tinnitus J* 11(2):111–114, 2005.
9. Lenhardt ML. Ultrasonic hearing in humans: Applications for tinnitus treatment. *Int Tinnitus J* 9(2):69–75, 2003.
10. Sohmer H, Freeman S, Geal-Dor M, et al. Bone conduction experiments in humans—a fluid pathway from bone to ear. *Hear Res* 146:81–88, 2000.
11. Sohmer H, Freeman S. Further evidence for a fluid pathway during bone conduction auditory stimulation. *Hear Res* 193:105–110, 2004.
12. Bennett WR. Radiofrequency hearing: Electrostrictive detection. *J Acoust Soc Am* 103(4):2111–2116, 1998.
13. Fukada E, Yasuda I. On the piezo-electric effect of bone. *J Phys Soc Jpn* 12:1158–1163, 1957.
14. Aschero G, Gizdulich P, Mango F, Romano SM. Converse piezoelectric effect detected in fresh cow femur bone. *J Biomech* 29:1169–1174, 1996.
15. Occupational Safety and Health Administration. *Technical Manual*, sec. III, chap. 5, subchap. V: Ultrasonics. Washington, DC: U.S. Department of Labor, 2002.
16. Dunlap SA, Lenhardt ML, Clarke AM. Human skull vibratory patterns in audiometric and supersonic ranges. *Otolaryngol Head Neck Surg* 99:389–391, 1988.
17. Lenhardt ML. Eyes as fenestrations to the ears: A novel mechanism for high-frequency and ultrasonic hearing. *Int Tinnitus J* 13(1):3–10, 2007.
18. Ranke OF. Physiologie des Gehors. In OF Ranke, L Lullies (eds), *Gehor Stimme Sprache*. Berlin: Springer, 1953: 3–110.

19. Parrack HO. Effects of airborne ultrasound on humans. *Int Aud* 5:294–308, 1996.

20. Shulman A. Medical Evaluation. In A Shulman, J Tonndorf, H Feldmann, et al. (eds), *Tinnitus: Diagnosis/Treatment*. Philadelphia: Lea and Febiger, 1991:253–292.

21. Shulman A, Strashun AM, Avitable J, et al. Ultra-high-frequency acoustic stimulation and tinnitus control: A positron emission tomography study. *Int Tinnitus J* 10(2): 113–125, 2004.

22. Goldstein BA, Lenhardt ML, Shulman A. Tinnitus improvement with ultra-high-frequency vibration therapy. *Int Tinnitus J* 11(1):14–22, 2005.

23. Tonndorf J, Kurman B. High frequency audiometry. *Ann Otol Rhinol Laryngol* 93:576–582, 1984.

24. Clarke AM., Lenhardt ML, Wang P. External validation of high frequency hearing thresholds in man. *Assoc Res Otolaryngol Abstr* 123, 1988.