International Tinnitus Journal, Vol. 12, No. 2, 96–100 (2006)

Binaural Hearing, Atresia, and the Masking Dilemma

Martin L. Lenhardt,[1] Barbara A. Goldstein,[2,3] and Abraham Shulman[2,3]

[1] *Ceres Biotechnology, LLC, and Program in Biomedical Engineering, Virginia Commonwealth University, Richmond, Virginia;* [2] *Martha Entenmann Tinnitus Research Center, Forest Hills, New York; and* [3] *Department of Otolaryngology, Health Science Center at Brooklyn, State University of New York, Downstate Medical Center, Brooklyn, New York*

Abstract: A masking dilemma occurs when energy from a non-test ear crosses over the head to a test ear. In cases of bilateral atresia, obtaining thresholds on the poorer ear is problematic. Near threshold, however, sufficient ear-bone isolation exists to test with validity but not so much above threshold, even for the ultra-high (>10 kHz) frequencies. This aspect of the bone audiogram should not be overlooked. We suggest two uses of binaural bone conduction hearing to help resolve the dilemma—one an auditory brainstem response variation, the other a high-frequency lateralization procedure. Both are also applicable in unilateral atresia with and without a sensorineural component. The use of an insert earphone for masking in the unobstructed ear will provide adequate interaural attenuation to resolve most but not all dilemmas. That is to say, the maximum isolation of an insert earplug is on the order of 100 dB, so it has a limit. The dilemma extends through the ultra-high frequencies (>10 kHz) because the intra-aural attenuation is no more than 10 dB. In the cited case of unilateral congenital atresia of the external ear, the intra-aural threshold differences in the high frequencies plus the resolution of the masking dilemma in the low frequencies (without the need for more masking) leads us to conclude that the unmasked thresholds are valid. Masking can be extended above 10 kHz, but this is not generally within the capacity of commercial audiometers, a feature that should be included.

Key Words: atresia; audiometry; auditory plasticity; masking dilemma; tinnitus; ultrasound

A sound in space propagating directly toward us will stimulate both ears at an equal level, yet we know, as a result of sophisticated temporal processing by our auditory systems, which results in a binaural image, that the sound is not to our left or right but head-on. Our perception dramatically changes when both ears are stimulated with the same sound at the same level through earphones; the perception is then internally centered in the middle of our heads. If one ear has less sensitivity (hearing loss) than the other, the perception is skewed or lateralized to the better-hearing ear. Compensating for the degree of loss by adding energy in the poorer ear will result in a recentering of the sound image. Almost 50 years ago, Zwislocki [1] isolated the external and middle ears and found that sound at approximately 50–60 dB sound pressure level would penetrate the body and reach the inner ears; thus, the maximum level of ear protection that plugs and muffs will provide, as deduced from the experiment, is near 50 dB. Atresia is a natural earplug formed by abnormal bone growth in the ear canal; it produces a conductive hearing loss of approximately the same order of sound attenuation [2].

The impetus for this study was the clinical audiological findings for both conventional pure-tone thresholds and those of ultra-high-frequency thresholds in two patients with unilateral atresia of a primarily conductive hearing loss having a sensorineural component. Clinically, discrepancies exist between bone conduction theory and the clinical audiological experience. We wanted to establish thresholds of residual neural cochlear func-

Reprint requests: Dr. Martin L. Lenhardt, Box 980168-MCV, Virginia Commonwealth University, Richmond, VA 23298-0168. Phone: 804 828 9687; Fax: 804 828 4454; E-mail: lenhardt@vcu.edu

tioning—cochlear reserve—in ears with significant conductive loss of hearing recently presented by a patient with congenital atresia of the external ear. This brought into question the masking dilemma.

In our practice, we routinely perform both air- and bone-conduction masking using TDH-39 supra-aural and insert (EA3a) earphones (Etymotic Research, Inc., Elk Grove Village, IL). In the recently published illustrative case of unilateral atresia with a mixed loss [3], the masking dilemma was present at 500 Hz. The use of an insert earphone for masking eliminated the masking dilemma in the conventional audiometric frequencies (<10 kHz). The result for this case with the use of an insert earphone for masking indicated that adequate masking was obtained with the standard earphone, and the masking dilemma was resolved with verification of the threshold through the use of the insert phone for the audiometric frequencies (<10 kHz).

BONE-CONDUCTION THEORY

The brainstem nuclei that code the binaural cues of intensity and time differences between the ears in normally hearing listeners have been shown to be functional in the case of binaural atresia [4]; this is accomplished by shifting the sound image from midline to one ear or the other via bone-conducted (BC) stimuli of differing intensities. The clinical importance of this finding is that it indicates that the binaural central auditory nervous system is operational even in the presence of bilateral osseous conductive loss and that further binaural stimulation through fitting BC hearing aids may contribute to increased binaural facility as a result of auditory neuroplasticity. A unilateral BC aid will not stimulate ear cochlea equally and will not code traditional binaural cues needed for localization.

The study of binaural cues in bilateral atresia raises an interesting issue in regard to audiometric testing. Sound—delivered to the head as vibration—can readily pass from one side to the other in the audiometric frequencies (i.e., crossover). Thus, with a notable difference in sensitivity (>10 dB), only the better ear may contribute to an affected patient's response, regardless of the side of the head on which the transducer is placed, demonstrating that the ears are not well insulated acoustically from each other. The classical solution of masking the non-test ear with noise is not applicable because the masking can cross the head, activating the test ear, a phenomenon that Ralph Naunton termed the *masking dilemma*. The experiment by Schmerber et al. [4] posed an interesting, although partial, solution to the dilemma. If both cochleae are functional and nearly equal in sensitivity, vibrators placed on each side of the head would allow increasing the intensity on one side to shift the sound image perceptually. By noting the intensity needed for shifting and recentering the image, an estimate of the threshold of the poorer ear could theoretically be obtained, assuming a shift is possible. Such lateralization studies require two 1-dB attenuators and sophisticated audiometric equipment— clinically not a very applicable dilemma solution.

INTRASKULL ATTENUATION AT VERY HIGH FREQUENCIES

With modern technology, very high BC testing not only is possible but is seen as essential in numerous clinical circumstances [5–7]. Would the decreasing wavelength and increased absorption coefficients of higher frequencies (>4 kHz) have any effect on the masking dilemma? That is to say, does more interaural attenuation occur at higher frequencies owing to the interaction of the physical characteristics of high-frequency sound with the skull-brain?

We measured attenuation across one dry skull in the frontal, temporoparietal, and occipital regions. We applied the methodology propounded by Cai et al. [8]: We delivered frequencies from 1,000 through 50,000 at a reference intensity and recorded the energy propagated to the opposite side of the skull using as close to the same coordinates as possible, given skull asymmetrical geometries. The values were reported in acceleration of relative intensity (decibels). We averaged four replications to produce the final values. The instrumentation (depicted in Fig. 1A) consists of a spectrum analyzer and related filters and signal conditioners. The intraskull attenuation values are depicted in the records in Figure 1B. Note indeed, at higher frequencies, the greater attenuation across the skull on the order of 50–60 dB at 40,000 Hz. However, these attenuation levels drop to 5–10 dB when a water-filled balloon (modeling the brain) is inserted in the skull. More to the point, when the same coordinates are used on a living head, the similar 5- to 10-dB attenuation values are recorded. Thus, stimulating at higher frequencies will not assist with the masking dilemma but, even more to the point, the dilemma extends into these high frequencies.

THE SPECIAL CASE OF UNILATERAL MIXED LOSS IN ATRESIA

The blocking of one external ear canal with bone produces a unilateral conductive hearing loss of some 50–60 dB across the audiometric frequencies [2]. This condition of unbalanced hearing sensitivity pressures the brain to attend to the opposite side of space from the atretic ear, likely altering the normal binaural hearing

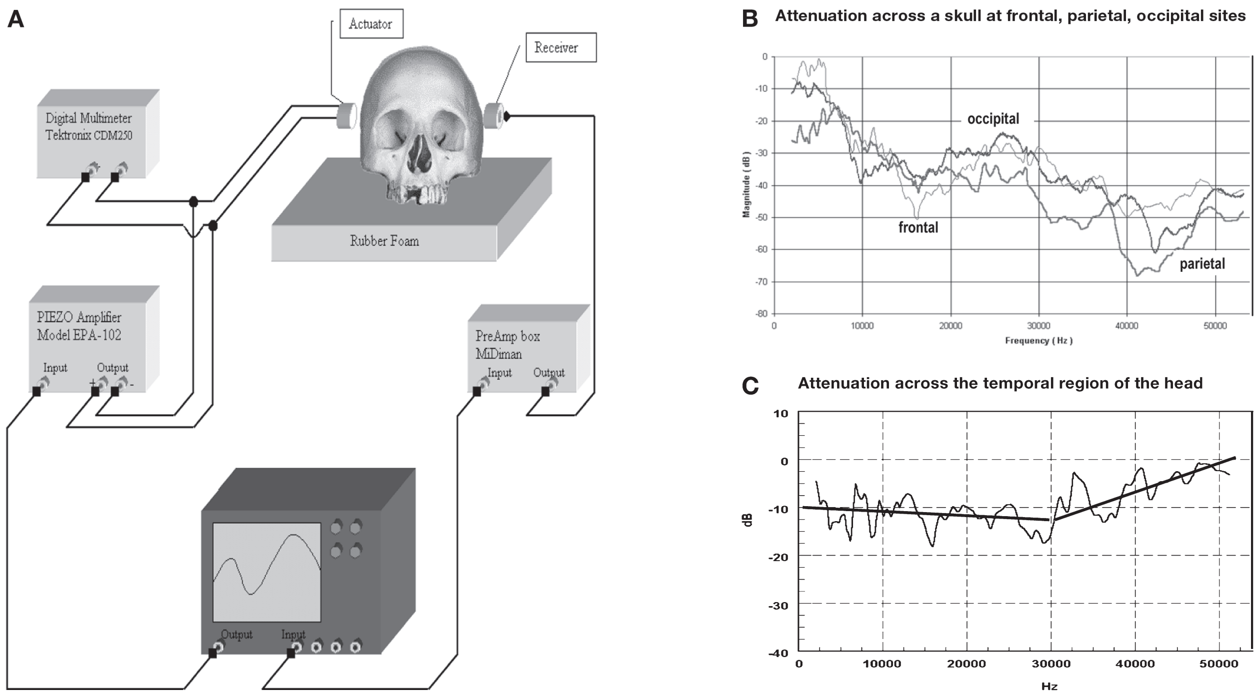

Figure 1. Method for measuring the attenuation of sound across the skull in three areas of interest. Attenuation increases with frequency. When the same methodology is applied to the live head, the attenuation is essentially constant.

process [4]. Because the ear is preferentially wired to the contralateral hemisphere, there may be additional pressure to enhance the ipsilateral pathway as well. It would be safe to conclude that unilateral atresia likely results in central auditory adaptations or maladaptations over time.

In the presence of a mixed loss, unilateral atresia exacerbates the masking dilemma. The maximum conductive loss possible is 60 dB, but estimating the true threshold may not be achievable, because masking noise from the non-test ear will reach the test ear such that its threshold will continue increasing proportionally to the level of masking noise. At no point will the test ear threshold not shift with changes in the non-test ear masking level. If the threshold became stable with increased masking, the classic plateau would indicate effective masking (neither under- or over-masking). The general solution to the masking dilemma in the instance of a sensorineural component in the atretic ear is the use of air-conduction masking with insert earphones in the non-test ear [3].

Insert earphones produce increased low-frequency noise exclusion as compared to standard supra-aural earphones and, for example, the commercially available ER3A, and exhibit a 98-dB and 80-dB interaural attenuation at 0.5 and 4 kHz, respectively. The use of inserts represents an additional attenuation of 38 and 18 dB over TDH-39 supra-aural earphones; however, insert earphones will not eliminate the masking dilemma in some cases.

Recently, we published an illustrative case of unilateral atresia with a mixed loss and tinnitus [3]. A masking dilemma was present at 500 Hz but not at the higher frequencies (>1 kHz). Our confidence in the accuracy of our interpretation was based on the rising audiometric curve, normal radiological studies of the middle and inner ears, and clinical impression. The masking dilemma at 500 Hz was resolved by the additional use of masking through an insert phone in the left ear for both air- and bone-threshold testing in the contralateral ear (Fig. 2B). The bone threshold on the right may have been ambiguous without masking, owing to little attenuation of low-frequency vibration in the skull. The air threshold on the right may also have been ambiguous even with supra-aural masking, as masking the left without masking the right is impossible with supra-aural phones; however, an insert on the left would likely allow better resolution of the threshold if in doubt. The full audiogram is presented in Figure 3.

THE QUESTION OF FREQUENCY

The masking dilemma is not limited to the conventional audiometric frequencies (<10 kHz) but can be present at higher frequencies (>10 kHz) in the ultra-high range, as assessed with high-frequency air-conduction or elec-

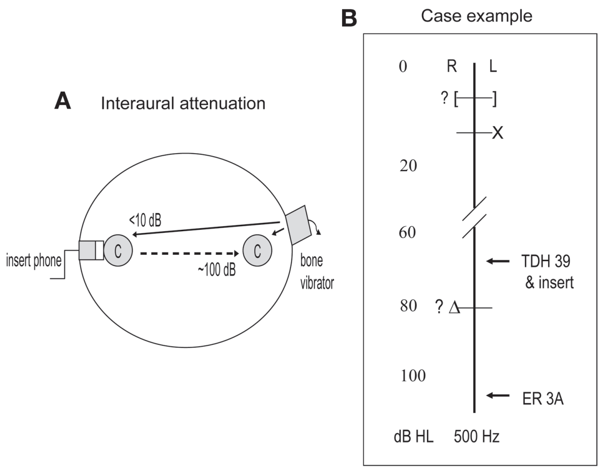

Figure 2. (A) Attenuation across the head for bone conduction depicted as <10 dB. Insert earplug can provide approximately 100 dB of masking. (B) Masking dilemma graphically displayed for a frequency of 500 Hz for our reference patient with atresia. The dilemma is the validity of the masked threshold given the limits of masking using a TDH 39 earphone. The threshold was verified using an insert earplug with far greater interaural attenuation.

tric bone-conduction (Tonndorf) audiometry (or both) [3,5–7]. Masking can be delivered by either air or bone conduction, but no standard source with calibrated values is available. In our experience, even if the masking dilemma is resolved in the audiometric frequencies, some degree of uncertainty remains in the ultra-high-frequency range without spectral specific masking.

OTHER MEASURES OF INTEREST

In the case of a single-subject research design, additional measures with replications are often needed, and two additional procedures, based on binaural interaction, may have value in this regard. In each, the approach is not to isolate the ears acoustically but rather to stimulate them simultaneously. Auditory brainstem responses can be recorded using BC clicks. The digital sum of the left ear response and the right ear response can be digitally subtracted from a binaural evoked response, and the resulting product is termed the *binaural interaction component* (BIC), which represents the activity of the binaural auditory system [9–11]. The BC BIC has a characteristic latency (7.3 msec) overlapping in time with the wave IV–V complex, suggesting principle generators are in the olive and trapezoid bodies [12,13]. A BC BIC would imply two functioning cochleae. Applying the lateralization technique [3], the BIC could be systematically modified by altering monaural click intensity at one and then the other ear. One drawback is that BC intensity must be 45 dB sensation level (SL) consistently to elicit an auditory brainstem response, clearly resulting in crossover between ears; however, the crossover effect is minimized by the digital subtraction process, though this is a complicated procedure.

In placing a BC vibrator on either mastoid and sweeping frequencies slowly (~5 sec) from 5 to 40 kHz, the perception of the ear stimulated will shift back and forth, influenced by the sound wavelength as it interacts with the brain-skull geometry. The effect is robust as the sound appears first in one ear and then categorically in the other. Although not systematically studied in atresia, this movable-image effect does not occur in cases of unilateral hearing loss (>30 dB) in our experience. Even a single frequency can be moved from ear to ear by changing the contact angle on the head or even the elbow, likely owing to the generation of standing waves in the brain. Picking the proper frequency is problematic in that it is related to individual resonances; the swept-tone approach is superior. A sweep oscillator, amplifier, and wide-frequency response vibrator combination appears to be a possible screening tool for identifying near-equal cochlear reserve when encountering the masking dilemma and is available as a custom product through some manufacturers.

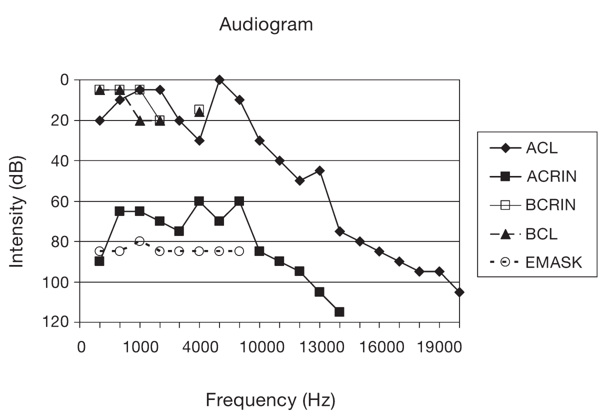

Figure 3. Complete audiogram for our reference patient with atresia. The AC thresholds above 8 kHz are not masked.

OBSERVATIONS AND PRECAUTIONS

The old audiometric axiom that zero attenuation occurs across the skull is not exactly true but was likely promulgated to induce needed caution in examinations. Using sensitive vibrational techniques, no study has yet to demonstrate 0-dB attenuation across the head. What has been well established [8,14,15] is that the interaural difference for bone conduction is at least 5 dB (probably 10 dB) and may even approach 15 dB at some frequencies. Thus, cochlear separation or isolation is likely between 5 and <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).

If thresholds for unmasked frequencies differ by 10 dB and if both ears have superior threshold at some frequencies, the initial presumption of near-equal cochlear reserve may be assumed. This by no means eliminates the need for masking and other test measures in differential diagnosis. Precise placement of bone vibrators and accelerometers can be difficult, and slight movements can result in notable variability in response. Consider Figure 1C: The line of best fit reflecting the midpoint in the response tells the story of ~10-dB interaural attenuation, but note the variations from the line. The numerous nodes and antinodes reflect skull-brain resonance and antiresonance that are the products of individual geometries. One can never be certain of 10-dB separation between ears at any particular frequency, as it might be <5 or ~20 dB. This variability can be further increased by changes in spectra when vibrators are mass loaded with the head [8,15]. Vibrators also have resonances, and frequency response can be further altered if the coupling force to the head is not constant. Thus, the purpose of the old axiom—caution—remains true.

BONE-CONDUCTION HEARING AID

We join others [10] in recommending binaural BC aids especially for children who have atresia and in whom the central auditory system is developing. A long-term goal would be to develop BC devices that foster sound localization skills in children and adults.

CONCLUSIONS

Nothing replaces careful audiometric testing and awareness of crossover. Insert earphones allow greater flexibility than standard earphones as regards intra-aural attenuation, but the application of binaural BC testing procedures may provide additional options in assessing the cochlear reserve when a masking dilemma is present. In the case cited, resolution of the masking dilemma in the low frequencies, plus progressively smaller threshold differences between ears, suggested an accurate picture using unmasked high-frequency and electric bone-conduction audiometry, which supported the concept of a new syndrome.

REFERENCES

1. Zwislocki J. In search of the bone conduction threshold in a free sound field. *J Acoust S Am* 29:795–804, 1957.
2. Gill NW. Congenital atresia of the ear: A review of the surgical findings in 83 cases. *J Laryngol Otol* 83:551–587, 1969.
3. Shulman A, Strashun A, Goldstein B, Lenhardt ML. Congenital atresia of the external ear and tinnitus: A new syndrome. *Int Tinnitus J* 12(1):17–30, 2006.
4. Schmerber S, Sheykholeslami K, Mohammad HK, et al. Time-intensity trading in binaural congenital aural atresia patients. *Hear Res* 202(1–2):248–257, 2005.
5. Goldstein B, Shulman A. Tinnitus Evaluation. In A Shulman, J Tonndorf, H Feldmann, et al. (eds), *Tinnitus: Diagnosis/Treatment*. Philadelphia: Lea and Febiger, 1991: 293–318.
6. Shulman A. Medical Evaluation. In A Shulman, J Tonndorf, H Feldmann, et al. (eds), *Tinnitus: Diagnosis/Treatment*. Philadelphia: Lea & Febiger, 1991:253–292.
7. Goldstein BA, Lenhardt M, Shulman A. Tinnitus improvement with ultra-high-frequency vibration therapy. *Int Tinnitus J* 11(1):14–22, 2005.
8. Cai Z, Richards DG, Lenhardt ML, Madsen AG. Response of human skull to bone conducted sound in the audiometric to ultrasonic range. *Int Tinnitus J* 8(1):1–8, 2002.
9. Kaga K, Tanka Y. Auditory air and bone conduction brainstem responses and damped rotation test for young children with bilateral congenital atresia of the ears. *Int J Pediatr Otolaryngol* 31(1):13–21, 1995.
10. Sheykholeslami K, Mohammad HK, Sebatein S, Kaga K. Binaural interaction of bone conduction auditory brainstem responses in children with congenital atresia of the external auditory canal. *Int J Pediatr Otolaryngol* 670(10): 1083–1090, 2003.
11. Prat H, Polyakok V, Aharonson AD, et al. Effects of localized pontine lesion on auditory brain-stem evoked potentials and binaural processing in humans. *Electroencephalogr Clin Neurophysiol* 108:511–520, 1998.
12. Moller AR, Jannetta PJ, Sekhar LN. Contributions from the auditory nerve to the brain-stem auditory evoked potentials (BAEPs): Results of intracranial recordings in man. *Electroencephalogr Clin Neurophysiol* 71:198–211, 1988.
13. Moller AR, Jho HD, Yokota M, Jannetta PJ. Contribution from crossed and uncrossed brainstem structures to the brainstem auditory evoked potentials: A study in humans. *Laryngoscope* 105:596–605, 1995.
14. Tonndorf J. Bone Conduction. In WD Keider, WD Neff (eds), *Handbook of Sensory Physiology*, vol. 3. New York: Springer-Verlag, 1976:37–83.
15. Dunlap SA, Lenhardt ML, Clarke AM. Human skull vibratory patterns in audiometric and supersonic ranges. *Otolaryngol Head Neck Surg* 99:389–391, 1988.