Measurement of Bone Conduction Levels for High Frequencies

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Abstract: For assessment of safety, it is necessary to measure the maximum possible force exerted by a bone conduction device coupled to the human head. Calibration of bone conduction hearing aids and vibrators in the audiometric range is based on measurement of acceleration and force using an artificial mastoid. Extending the measurement to the high audio range was accomplished using a live head. To assess safety of the UltraQuiet tinnitus treatment system, as an example, acceleration was measured from 5 to 20 kHz on a live human head as compared with calibrated levels at 6 kHz on an artificial mastoid and the live head. Using head acceleration and anchoring it to established calibration levels is a means of establishing clinical safety. Stimulation in the high audio frequencies at low levels was found to be safe. In contrast, stimulation with ultrasound requires more energy (approximately 75–90 dB re 6 kHz), which may increase the risk of damage to the ear.

Key Words: high-frequency hearing thresholds; tinnitus; UltraQuiet

For assessment of safety, it is necessary to measure the maximum possible force exerted by a bone conduction device coupled to the human head. The force exerted by bone conduction vibrators in audiometry and its relation to hearing level is normally measured according to American National Standards Institute standard S3.43-1992, for frequencies up to 4 kHz. The UltraQuiet is a tinnitus therapy device that uses bone-conducted vibration up to 20 kHz [1]. There is no standard for calibration of bone conduction force in the UltraQuiet range from 6 kHz to 20 kHz. There is also no artificial mastoid with impedance calibrated in this range; for example, the Brüel & Kjaer (B&K, Naerum, Denmark) 4930 is calibrated to 10 kHz. In our study, we measured the UltraQuiet system on a live human head to 20 kHz and on a B&K 4930 artificial mastoid to 10 kHz, in comparison with standard audiometric levels at 6 kHz from a Radioear (New Eagle, PA) B-71 vibrator on the artificial mastoid and the live head [2].

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METHODS

The measurement system consisted of a Brüel & Kjaer 4374 accelerometer with a Brüel & Kjaer Pulse 3560 analysis system. As reference levels for our calibration, we used a Radioear B-71 bone vibrator with its standard headband as the static force (measured at 4.4 N), as compared to a plastic headband with a static force of 1.5 N and an Interacoustics (Assens, Denmark) AC40 audiometer, at 0 dB and 55 dB hearing level (HL), on a live human head, as no artificial mastoid is calibrated in the higher frequency range. There was no difference between the two headbands; with complete coupling, the difference in static force made no difference in the measured acceleration.

Measurements were made by placing the B&K accelerometer between the transducer (either the Radioear B-71 or the UltraQuiet piezoelectric) and the head, with the accelerometer-transducer combination held in place by the headband. Although the standard is given in force, for practical reasons measurements often are made in acceleration and are converted to force. In their calibration of direct bone conduction, Hakansson et al. [3] faced a similar need to extrapolate from existing standards.

The formula for calculation of force is

$$F = |Z| \times A/\omega$$

where F = force (in N), A = acceleration in m/sec^2, |Z| = mechanical point impedance in nsec/m, and ω = angular frequency (radians/sec)

Using the foregoing equation, the following numbers apply to 6 kHz [3], based on the reference equivalent threshold force levels (RETFL) as proposed in International Standards Organization/Draft International Standard (ISO/DIS) 7566, and the mechanical impedance of the head at the skin surface in the draft revision of International Electrotechnical Commission (IEC) publication 373, 1971.

- Frequency 6,000 Hz
- RETFL (dB re 1 μN) 40.0 dB
- Mechanical impedance (dB re 1 Nsec/m) 34.0 dB
- Reference equivalent threshold acceleration level (dB acceleration re 1 cm/sec^2) 17.5 dB (−2.5 dB re 1 m/sec^2)

RESULTS

Five UltraQuiet systems were measured. The maximum output of the loudest of the five systems at 6 kHz was 30 dB of acceleration, or 70 dB of force re 1 μN. This is equivalent to 42.5 dB HL or roughly equivalent to a 58.0-dB sound pressure level (SPL) at 6 kHz (rough SPL estimate based on addition of a 15.5-dB conversion factor for SPL to HL for TDH-49 audiometric headphones [Telephonics, Inc., Huntington, NY]). Figure 1 shows the average acceleration response of five systems through the 6- to 20-kHz frequency range, using random noise. The average at 6.0 kHz was 27.0 dB of acceleration, or 67.0 dB of force, equivalent to 39.5 dB HL.

On the basis of the foregoing parameters, using an artificial mastoid, at 0 dB HL and 6 kHz, the force should be 40.0 dB, and the acceleration should be −2.5 dB. In our experimental arrangement, the acceleration was −12.5 dB re 1 m/sec^2. Thus, a correction factor of 10.0 dB must be added to our data to yield measurements comparable to the standard. This is similar to the method used by Hakansson et al. [3] to arrive at correction factors for direct bone conduction via a screw attached to the skull. In the same experimental arrangement, the 55-dB HL signal from the audiometer produced a 42.0-dB re 1 m/sec^2 acceleration (54.5 dB more than the acceleration of −12.5 dB at 0 dB HL), confirming the linearity of the system within 0.5 dB.

DISCUSSION

Safety is always a concern in delivering high frequencies to human listeners. Figure 2 shows the average

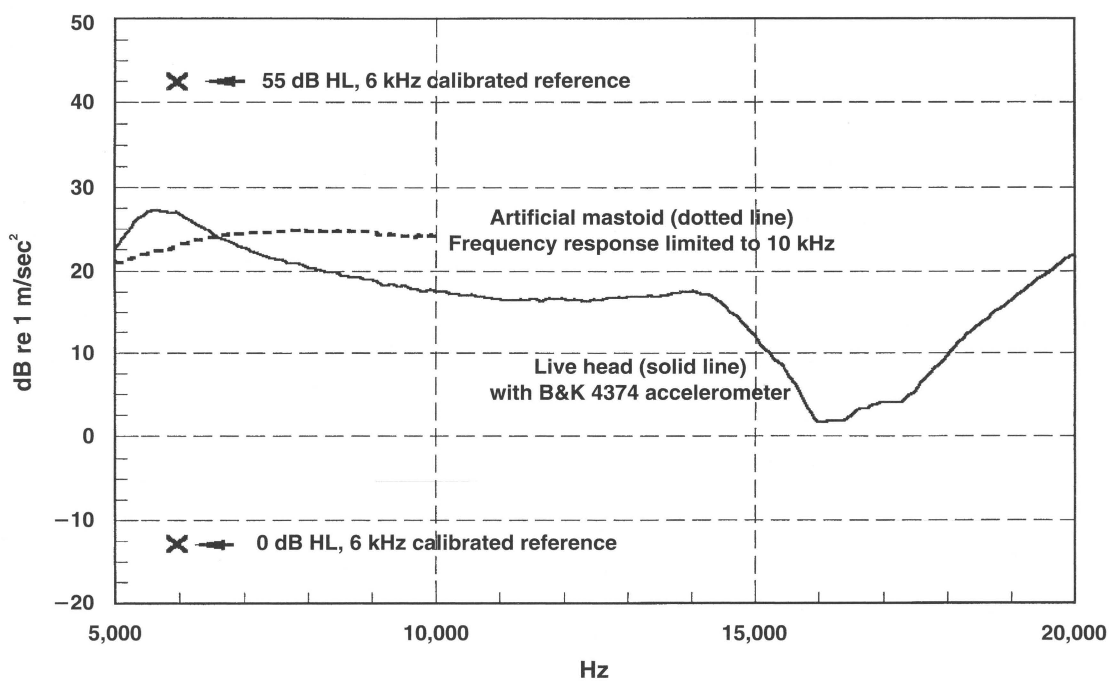

Figure 1. Comparison of the frequency response on the Brüel & Kjaer 4930 artificial mastoid and the live head in the UltraQuiet system (average of measurement of five systems). Reference calibration at 6 kHz at 0 dB and 55 dB HL with a Radioear B-71 vibrator.

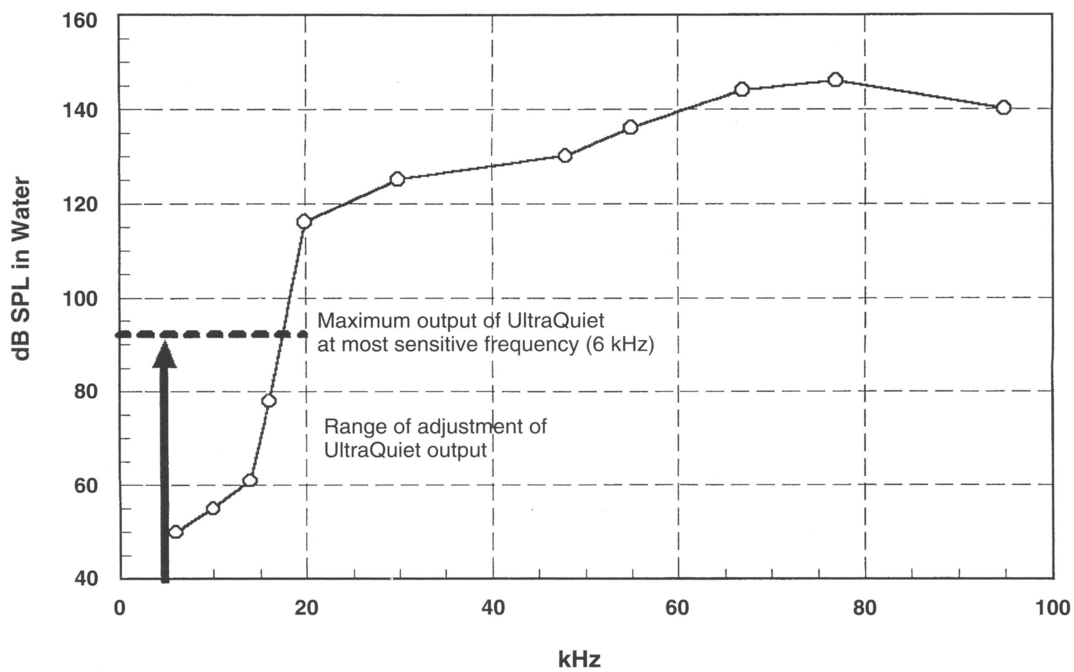

Figure 2. Hearing thresholds in water (decibels of sound pressure level) from Corso [4], as compared with range and maximum output of the UltraQuiet device at the frequency in its output range of greatest intensity and most sensitive hearing (6 kHz).

bone conduction thresholds in water measured by Corso [4], as compared to the range and maximum output of the UltraQuiet device at 6 kHz. This is the frequency at which hearing would normally be most sensitive within the range of the UltraQuiet and at which the threshold would be determined to set the listening level. At the recommended listening level (12 dB sensation level) for the UltraQuiet, the high-frequency cutoff would be approximately 15 kHz and, for the highest listening level possible, the high-frequency cutoff would be approximately 18 kHz. Note that for a person with normal hearing, there is a 60-dB increase in threshold over the octave of 10–20 kHz. Thus, the steep rise in human hearing thresholds plus the digital sampling rate (44.1 kHz) and anti-aliasing filtering limitations ensure that such devices as the UltraQuiet are not ultrasonic in frequency content.

There is no such steep threshold rise with audible ultrasonic frequencies (17.5 dB/octave from 20 to 80 kHz); further thresholds for ultrasonic frequencies (25–55 kHz) are some 75–90 dB above that at 6 kHz. Thus, ultrasonic stimulation involves much higher intensity and, consequently, more concern for damage risk than do high audio frequencies. Working with a water-coupled 50-kHz tone, Deatherage et al. [5] reported thresholds comparable to those reported by Corso (after conversion of reference value), and the first author incurred high-frequency hearing loss plus persistent tinnitus as a result of ultrasonic loudness judgments. The current U.S. Occupational Safety and Health Administration ultrasonic standard sets a value of 1 *g* rms + 15 dB at the mastoid as a level not to be exceeded to avoid risk if there is direct ultrasonic coupling to the body with simultaneous airborne exposure. This level is conservative; however, tones 30 dB above threshold at any ultrasonic frequency are reported to be loud and unpleasant [6], and damage risk date are lacking. Clearly, there may be little room for a safety margin when people with and without hearing loss are listening to ultrasound [7]. Ultrasonic standards for bone conduction hearing are needed to assess risk.

CONCLUSIONS

Therapeutic high-frequency bone conduction devices must be safe, and safety is addressed by measuring the maximum force exerted when a device is coupled to the head. Calibration of the force applied to the head, which results in a specific level of acceleration, can be determined with an artificial mastoid and can be extended to the high audio range by measuring the acceleration from 5 to 20 kHz on a live human head, in comparison with standard audiometric levels at 6 kHz with the vibrator on the artificial mastoid and the live head. Using the example of the UltraQuiet tinnitus device, we determined safe listening levels. Calibration in the ultrasonic range is more problematic, and safety standards must be developed in light of the substantially higher energy levels involved.

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