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Research Article

Very High Frequency Bone Conduction Transducer for Audiometric Testing

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Abstract

A prototype piezo ceramic transducer is described which will address the need in hearing testing for a compact, light weight device that will allow measurement of hearing thresholds in the 10-20 kHz range by bone or fluid conduction. This transducer will permit comparisons with well-established high frequency air conduction procedures. Calibration protocols have not been developed, but a preliminary approach is suggested. This transducer represents an advance that eliminates external and middle ear coupling.

Keywords: Air Conduction Hearing; Bone Conduction Hearing; Fluid Conduction Hearing; Acoustic Transducer Design and Spectrographic Analysis

Introduction

Humans hear by at least three mechanisms: air, bone and fluid conduction [1]. Air conduction (AC) is the most familiar. Sounds pass into the ear canal, vibrate the tympanum (eardrum) which in turn vibrates the three middle ear bones (the ossciles), which then vibrates the inner ear (cochlea). Hearing by bone conduction (BC) is a bit more complicated. The head is coupled to a vibrating object; the fluid chambers (of differing volumes) are set into vibration. The cochlear windows oscillate displacing the basilar membrane which supports the sensory cells. For high frequencies this is sufficient to activate the auditory nerve. For lower frequencies the middle ear ossicles are also set into vibration, but lag behind due to their inertia. The oval window is also displaced much like in AC. Fluid conduction (FC) or tissue conduction has only been described in the last two decades [2-5].

Technology used for BC, when placed on soft tissue, can allow vibration to be propagated to the inner ear, which activates the basilar membrane and sensory cells. A good example of FC is the so-called eye hearing. When a BC transducer is place over the eyelid, carefully avoiding contact with bone, an audiogram can be obtained that is similar in sensitivity with that obtained by BC [5,6]. FC goes back to the mid-1940s when the phenomenon of ultrasonic hearing in humans (see Lenhardt, et al., 1991 for review) was reported. An ultrasonic vibrator could be heard if it was coupled to the skin covering bone (as in the mastoid region or on the skin of the neck with no bone contact). The application of a wide frequency range high audio/ultrasonic transducer as an adjunct to conventional BC hearing is described in the report.

Somewhat surprisingly, there are few accepted audiometric transducers. The dominant AC form is a head piece produced by Telephonics, Inc. for more than fifty years. Sound is propagated in the ear canal and calibrated by a coupler that approximates the acoustics of the canal. Because of the interaction of high frequencies with the geometry of the canal, which acts as a closed-end resonant tube, the upper limit of stable sound pressure is ~16-18 kHz; at higher frequencies there are interactions of the canal space with the short wavelengths that result in idiosyncratic cancelations and amplifications. Attenuation of sound in the canal is limited to about 50 dB, beyond that sound may be detected in the other ear [7]. This is a problem in unilateral hearing loss. Is it the poorer ear response to sound generated in that ear or the response of the better ear to energy crossing the head? The solution developed some years ago is the use of a transducer inserted into the canal. This increases the intra aural attenuation to about 90 dB, but the upper frequency range of valid testing remains the same.

Early BC transducers were mechanical shakers with a frequency response of about 100 Hz to ~ 6 kHz. The majority in use 50 years ago and as well as today is produced by Radioear Corporation in the US. Calibration is possible using an artificial mastoid approximating the mass of the skull when loaded by the transducer with a static force of 1.5 N. BC audiograms and AC audiograms were assumed to reflect the same auditory threshold over each calibrated frequency range (0.25-6 kHz). This range was sufficient for clinical diagnosis of hearing loss and auditory disorders. AC and BC sounds also interact within the cochlea, i.e., each elicits the same pitch, each can mask the other and one can cancel the other. Very high frequency BC audiometry became available in the 1980s through the use of the Tonndorf audiometer. This is a system developed from transdermal therapy for hearing improvement. Audiofrequencies are multiplied by an ultrasonic carrier and the stimulation is delivered to the head by Mylar covered steel electrodes. The head is effectively capacitive coupled into the circuit. The stimulus is demodulated by the non-linear properties of the skin and the audiofrequencies activate the cochlea in the standard fashion. The audiometer (Tonndorf) based on this principle was very effective in delivering high frequency sound without the confounding of external and middle ear acoustics [8]. Calibration was based on normal human thresholds. The technique never became popular chiefly due to a lack of objective calibration procedures. However, if piezoelectric film is placed between the Mylar and the skin, the modulator and carrier frequencies can be identified and their intensity measured at the head. The behavioral calibration was also limited by the energy requirements to generate tones in the conventional (<8 kHz) range. The calibration levels were adjusted to reflect accurate thresholds in frequencies from 10-20 kHz, but the threshold values of lower frequencies was 25 dB too high. While the technique was not inaccurate, the use of correction factors and the clumsiness of placing the electrodes on the head led to general dissatisfaction in the clinical community.

During this period in the mid-1980s, modern work on human ultrasonic hearing began [9]. Using stacked piezo crystal transducers human ultrasonic audiograms from 20 to 90 kHz were reported. The transducers were bulky and often generated heat. Calibration was determined behaviorally in reference to thresholds at 6 and 8 kHz as well as in acceleration (re:1g). The goal was to build an ultrasonic hearing aid for the deaf because a large number of individuals with profound hearing loss could detect ultrasound and evidenced the limited ability to learn speech modulated by an ultrasonic carrier. A commercial device was premarket approved by the FDA and sold under the name Hi Sonic.

Ultrasound and high audiofrequencies, delivered by BC, were also found to be effective in the treatment of long standing tinnitus [10,11]. Two new transducers were developed for that use which also received premarket approval from the FDA and used clinically [12]. The broader use of a piezo ceramic transducer and its modification for hearing testing will be explored in this report.

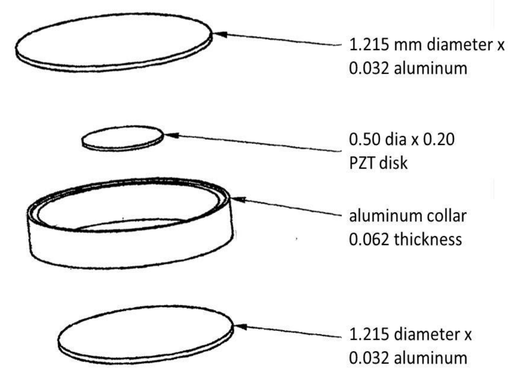

Figure 1. Components and dimensions of the prototype piezo ceramic transducer.

Materials and Methods

The goal of this research was to produce a compact and light weight high frequency transducer for BC and FC studies. The ideal device should be similar in size to the standard version i.e., B-71 bone transducer manufactured by Radioear Corporation (New Eagle, PA). The material selected as the base was aluminum for its light weight, ceramic was the choice for high frequency fidelity. This so-called aluminum ceramic bimorph was evaluated both for its physical properties and effectiveness when mass loaded with a human head. Both the Radioear B-71 vibrator and the piezo ceramic prototype were mounted on a standard Radioear headband for testing mass loading by a human adult head. A Brüel & Kjaer high frequency accelerometer (4734) was placed near the transducer on the skin of the mastoid. Input to the Radioear B-71 was 50 dB of calibrated white noise generated by a Hewlett Packard 3561A Dynamic Signal Analyzer (Agilent Technologies, Inc., Santa Clara CA). The piezo ceramic transducer's noise input was 500 mV (near the maximum). For validity, a second sensor was also used; a piezoelectric accelerometer (model ACH-01, Measurement Specialties, Inc., Hampton VA) with an upper frequency limit beyond 20 kHz. Both head mounted sensors fed signals into a Brüel & Kjaer Pulse 3560 real time spectral analyzer and the spectrum for each mass loaded transducer was determined (Figure 2). Spectra were also recorded directly from each transducer and fed into a Hewlett Packard 3561A Dynamic Signal Analyzer for averaging (Figure 3).

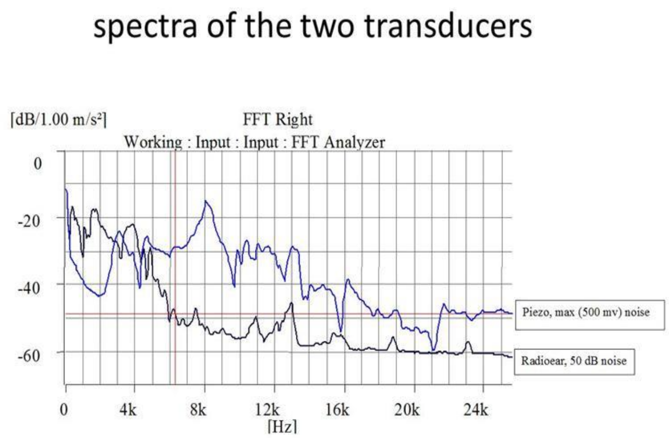

Figure 2. Spectrographs of the standard Radioear B-71 transducer and the prototype piezo ceramic transducer in acceleration with sensor on the mastoid bone near the transducers mounted in a Radioear head band. The passband for the Radioear B-71 is from approximately 100 Hz to 6 kHz using a criterion of energy >-50 dB (see double horizontal lines). The piezo ceramic has a passband of 4.5 kHz to ~ 20 kHz (with a few frequencies just below the 50 dB criterion). The upper range of audiometric hearing is ~20 kHz. The recorded spectrum represents the resonances of both the transducer and the head.

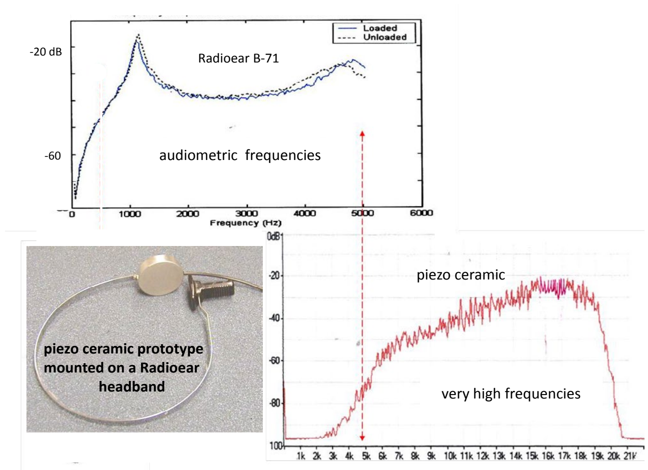

Figure 3. Frequency responses were recorded off the two BC transducers. The response amplitudes at the crossover frequency of 5 kHz are different. Each transducer will have the amplitude adjusted to meet ANSI standards using an artificial mastoid. Above 10 kHz, for the piezo ceramic only, acceleration will be used as a reference. That reference will be based on human thresholds yet to be determined. When the transducer spectra are overlapped at 5 kHz, this would allow testing of BC hearing from 100 to ~20,000 Hz. The accelerometer was placed on each transducer and not mass load by a head, reflecting only the resonances of the transducers. The responses were signal averaged (10x). The piezo ceramic prototype is depicted in the low left mounted on a Radioear head band.

Results and Discussion

An examination of Figure 2 reveals that the Radioear B-71 has good low frequency responses (<5 kHz) and the piezo ceramic has good high frequency responses (>5 kHz). More specifically, the Radioear B-71 has a band pass of 100 to 6,000 Hz; whereas the piezo ceramic has a band pass of 4.5 to ~20 kHz. The resonances in Figure 2 reflect that of the transducers and the head. The actual upper limit for the piezo ceramic transducer is in the 36-40 kHz range depending on resonance; however that is not an issue with audiometric BC hearing testing.

Mass loading with the head had little effect on the frequency response, although more resonant peaks were observed which are probably based on idiosyncratic head geometries and mass. Both transducers can be overloaded. The Radioear B-71 is a mechanical shaker which simply fails and stops shaking. The piezo ceramic transducer develops cracks in the ceramic disk before failing. On one occasion of over driving, sparking arose from the ceramic; having the transducer capped avoids injury with over driving.

Calibration of the Radioear B-71 is described in the ANSI bulletin S3.43-1992. Calibration of the transducer for tinnitus treatment is described in earlier work [13] pertaining to the development of a tinnitus masker and suppressor (UltraQuiet). The details of that approach are referenced to BC implants [14]. Essentially the use of a Brüel & Kjaer artificial mastoid was used for the Radioear B-71 as prescribed by the ANSI standard (S3.43-1992). The artificial mastoid is not calibrated above 10 kHz. For the piezo ceramic, the artificial mastoid was used to 10 kHz and a human head with a B&K 4374 accelerometer was used from 10-20 kHz. There were minor differences in measurement values, so an uncertainty factor of < ~5 dB exists for the piezo ceramic transducer for frequencies 5-10 kHz. With the accumulation of human threshold data in the future this uncertainty can be minimized.

Thus, by combining the Radioear B-71 and the piezo ceramic transducers as part of a BC test battery, threshold data from 100 to 20,000 Hz can be obtained. The frequency responses recorded off the transducers are presented in Figure 3. The piezo ceramic prototype transducer response is depicted in the lower panel (left), whereas the Radioear B-71 response is depicted in the upper panel. The output of the Radioear was adjusted to meet the ANSI standard (S3.43-1992) using an artificial mastoid. The artificial mastoid is not calibrated above 10 kHz, so only the lower range of the piezo ceramic was adjusted to audiometric reference. For higher frequencies (>10 kHz), the piezo ceramic transducer was coupled to a human head (on the skin over the mastoid bone), the transducer response was recorded using a high frequency accelerometer and the spectrum was determined by a Hewlett Packard 3561A Dynamic Signal Analyzer (Agilent Technologies, Inc., Santa Clara CA). Thus, by using the calibrated mass of the artificial mastoid, the energy level of each transducer was equated to the human hearing threshold reference by BC.

Conclusions

A compact, light weight high frequency transducer can be inexpensively manufactured (<$100) that meets the needs of modern audiometric testing. The piezo ceramic transducer can be mounted on a standard Radioear head band and can be easily incorporated into the clinic for BC and FC testing. The difficulties with the Tonndorf audiometer are not applicable and the high frequency (short wavelengths) acoustic interactions with the ear canal are also avoided. The middle ear is not involved in high frequency BC. A formal calibration procedure needs to be developed for frequencies >10 kHz. The exact placement of the two transducers on the head has yet to be determined.

Acknowledgements

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References

1. Lenhardt ML. Hearing mechanisms in Encyclopedia of Biomaterials and Biomedical Engineering, Marcel Dekker, 2004.

2. Sohmer H, Freeman S, Geal-Dor M. Bone conduction experiments in humans - a fluid pathway from bone to ear. Hear Res. 2000, 146: 81–88.

3. Sohmer H, Freeman S. Further evidence for a fluid pathway during bone conduction auditory stimulation. Hear Res. 2004, 193(1-2): 105–110.

4. Lenhardt ML. Eyes as fenestrations to the ears; a novel mechanism for high frequency hearing. Int Tinnitus J. 2007, 13(1): 3-10.

5. Sinha T, Lenhardt ML. Eyes as Windows on Brain Pressure. Int Tinnitus J. 2011, 16(2): 130-134.

6. Lenhardt ML, Ward KR, Kotihal R. Noninvasive Acoustic Intracranial Pressure Measurement Through the Eye. Int Tinnitus J. 2011, 16(2): 154-160.

7. Shulman A, Strashun A, Goldstein B, Lenhardt ML. Congenital atresia of the external ear and tinnitus: a new syndrome. Int Tinnitus J. 2006, 12 (1): 17-30.

8. Walker S, Lenhardt ML, and Bowie R. High frequency hearing thresholds in Hospital based helicopter pilots using the Tonndorf Audiometer. Symposium on Aircraft Noise, Abatement and Receiver Technology, North American Treaty Organization (CCMS), Vol. II, 1994.

9. Lenhardt ML, Skellett R, Wang P and Clarke AM. Human Ultrasonic Speech Perception. Science. 1991, 253: 82-85.

10. Goldstein B, Shulman A, Lenhardt ML, Richards DG, Madsen A et al. Long-term Inhibition of Tinnitus by UltraQuiet™ Therapy: Preliminary Report. International Tinnitus Journal. 2001, 7(2): 122-127.

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

12. Goldsteim BA, Shulman A Lenhardt ML. Ultrahigh frequency ultrasonic external acoustic stimulation for tinnitus relief: a method for patient selection. International Tinnitus Journal. 2005, 11(2): 111-114.

13. Lenhardt ML, Richards DG, Madsen AG, Goldstein BA, Shulman A and Guinta R. Measurement of Bone Conduction Levels for High Frequencies. International Tinnitus Journal. 2002, 8(1): 9-12.

14. Hakansson B, Tjellstrom A, Rosenhall U. Acceleration levels at hearing threshold with direct bone conduction vs. conventional bone conduction. Acta Otolaryngol. 1985, 100: 240-252.