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Research paper

A comparison of the nonlinear response of the ear to air and to bone-conducted sound

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ABSTRACT

The nonlinear response of the ear to air-conducted sound has been studied to some depth. However, the nonlinear response of the ear to bone-conducted sound has received less attention. A comparison of the nonlinear response of humans to air and bone-conducted sound is presented. Two different human subject test techniques were combined in this investigation. The first was a psychoacoustic investigation measuring the perceived cancellation of a bone-conducted sound stimulus with another air-conducted sound stimulus. The measurement was accomplished through a loudness-matching technique. The second investigation used distortion product otoacoustic emissions (DPOAEs) to make objective measurements of the response of the ear to both air-conducted sound and bone-conducted sound. The results were compared to determine whether the measured compression effects were similar for the different types of stimuli. Results show that both the measured psychoacoustic response and the measured objective response of the ear to air-conducted sound and to bone-conducted sound were similar at 2 and 4 kHz.

1. Introduction

Bone conduction (BC) transmission paths have been shown to limit the maximum attenuation that can be achieved with in-ear and circumaural hearing protection (Berger et al., 2003; Dietz et al., 2005). This is because sound is transmitted to the inner ear through transmission paths that bypass the hearing protection device. This bypass sound is commonly referred to as BC sound, and the attenuation limit is known as the bone conduction limit. One area of interest to improve hearing protection for high noise environments is the ability to cancel BC sound through the air conduction (AC) path. In addition, there is some uncertainty regarding the ability to localize sound when high level sound reaches the cochlea primarily through the BC path, when, for example, individuals are fitted with very highly attenuating hearing protection (Brungart et al., 2003). As a result, comparison of the cochlear response to AC and BC sound is of continued interest, in particular at relatively high BC sound levels.

At levels close to the threshold of hearing, the human cochlea responds linearly to sound excitation. However, at mid to high levels, the response becomes nonlinear, and cochlear sound compression increases the dynamic range of the ear. It has been shown that the bone conduction transmission paths are linear (Hakansson et al., 1996), and it has been postulated that the cochlear response to BC sound is identical to its response to AC sound (von Békésy, 1932). Experiments in the cancellation of BC sound with AC sound are the basis for this assumption. von Békésy (1932) reported on the first psychoacoustic binaural cancellation experiments of BC sound with AC sound. Lowy (1942) and others (Bárány, 1938; Wever and Lawrence, 1954; von Békésy, 1960; Tonndorf, 1966) also showed that the cochlea appears to respond identically to both BC and AC sound. Kapteyn et al. (1983) demonstrated successfully the cancellation of BC sound with AC sound to calibrate a forehead mounted BC vibrator with audiometer headphones.

In a rare study looking at BC sound in a sound field (instead of using a bone vibrator), McKinley (2009) reported on experiments performed at the Air Force Research Laboratory to compare the linearity of loudness judgments between AC and BC sound. Seven subjects were asked to match perceived loudness of band-limited noise at 2 kHz, between signals presented through deep insert earplugs, and those presented through an external sound field. Tests were performed in sound field levels ranging between 70 and 110 dB SPL. The mean attenuation of the earplugs was close to the 40 dB bone conduction limit reported by Nixon and von Gierke (1959) and Berger (1986). Three additional subjects conducted the same experiment, but with earmuffs in addition to earplugs. A mean attenuation of 40 dB was measured for this double hearing protection condition, confirming that bone conduction sound transmission paths were dominant. In both cases, the loudness

Abbreviations: DPOAEs, distortion product otoacoustic emissions; OHC, outer hair cells; AC, air conduction; BC, bone conduction; SPL, sound pressure level

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judgments of air and bone-conducted sound were comparable, demonstrating the linearity of the bone-conducted sound transmission paths in this loudness range.

Some questions remain regarding the linearity of the cochlear stimulation by BC sound as compared to AC stimulation. Stenfelt and Hakansson (2002) performed loudness matching experiments with both AC and BC stimuli between 0.25 and 4 kHz. They found a difference in the loudness functions between the two paths on the order of 4–5 dB at frequencies above 1 kHz and on the order of 6–10 dB at the lower frequencies. To explain their results, they suggest that in part, the two transmission paths were affected by the stimulus levels, and that the outer hair cells (OHCs) in the cochlea could be affected by BC stimulation of the higher order (central) hearing system. In a separate study, Stenfelt (2007) conducted a series of tests to simultaneously cancel BC sound at two separate frequencies with AC tones. While results seemed to indicate similarity in the cochlear stimulation by AC and BC sound, small deviations from perfect linear cancellation did not conclusively prove or disprove the possibility of small differences in the way the cochlea processes the two sources of stimulus. The linearity of BC sound was also questioned by Khanna et al. (1976) who showed that even after cancellation of a BC stimulus with AC sound, a second harmonic remained and increased with stimulus levels. Their explanation rejected the possibility that the non-linearity was due solely to the transducer (based on prior measurements) and instead suggested either a non-linearity due to the coupling of the vibrator to the skull or asymmetry in the compressional cochlear response to BC sound as described by Tonndorf (1962).

The psychoacoustic studies of response linearity using loudness matching and cancellation techniques have been supplemented by objective studies of the cochlear response to air and bone-conducted sound using measurements of otoacoustic emissions. The frequency- and level-dependent amplification that occurs in the human cochlea has been attributed to the mechanical feedback controlled by the OHCs on the basilar membrane (Dallos, 1992; Müller and Janssen, 2004). Otoacoustic emissions result from this nonlinear feedback mechanism and distortion product otoacoustic emissions (DPOAEs) have been used with some success to study the nonlinear behavior of the cochlea. DPOAEs result from nonlinear interactions of two primary tones in the cochlea. When two tones at frequencies f_1 and f_2 and levels L_1 and L_2 are presented in the ear canal, the nonlinear response of the cochlea generates a number of DPOAEs, the largest of which usually occurs at the frequency $2f_1 - f_2$. When the level of this distortion product is measured at fixed primary frequencies f_1 and f_2, but for varying primary levels L_1 *and* L_2, a DPOAE input/output (I/O) curve referred to as an I/O function is obtained.

Dorn et al. (2001) and Neely et al. (2003) compared the compressive response of the cochlea as measured with DPOAEs to the compression observed in the loudness data acquired by Fletcher and Muson (1933). They found the two responses to be similar, with the compression in both cases growing linearly with stimulus level between 25 dB SPL and 70 dB SPL. These experiments demonstrated the use of otoacoustic emissions to investigate the nonlinear response of the cochlea, as cochlear compression is driven by the active feedback of the OHCs, and that DPOAEs are a direct measurement of OHC activity.

If excitation of the travelling waves in the basilar membrane is similar for sound transmitted through AC or BC paths, then excitation of the OHCs will be similar and so should the otoacoustic emissions. Using this hypothesis, Purcell et al. (1999) objectively calibrated bone conductors on adult humans using measurements of DPOAEs excited with BC and AC stimuli. Purcell et al. obtained I/O functions where both frequencies were air-conducted sound (AC/AC), and where one frequency was generated using a bone vibrator (AC/BC). The bone vibrator was calibrated by determining the level of the BC signal that caused the AC/BC I/O function to match the AC/AC I/O function. In general, a good correlation between the two I/O functions was obtained. However, in another study, Hazelbaker (2004) found differences on the order of 18 dB in the shift between hearing thresholds for AC and BC sound versus the shift observed for DPOAE I/O functions obtained with AC/AC stimuli and AC/BC stimuli when the bone oscillator was located at the forehead.

The hypothesis that the response of the cochlea is similar for both AC and BC excitation is explored further here. In particular, non-linearity of the cochlea is examined in response to both types of stimulus. The results of an experiment using AC and BC stimulation are presented in which human subjects were asked to perform two consecutive tests: one relying on the psychoacoustic technique of sound cancellation to match BC and AC tone levels at several levels; the second relying on an objective DPOAE measurement technique to compare the cochlea's nonlinear response to both types of excitation at equivalent levels. Similar DPOAE levels would then confirm similar nonlinear response of the cochlea. Results from a prior experiment using the cancellation technique are also reported here as they provide insight into the interpretation of the results.

2. Materials and methods

2.1. Subjects

Five subjects participated in the experiments. The subjects were healthy males and females between 18 and 50 years of age with normal audiograms (AC thresholds better than 20 dB HL in the frequency range of 125 Hz and 8 kHz).

2.2. Procedure

Subjects performed two different tests to compare the BC and AC pathways. The first was based on the cancellation technique, and the second was based on the measurement of DPOAEs produced by AC and BC sound. The cancellation technique is a loudness-matching technique that requires the subject to match the loudness of an AC tone with that of a BC stimulus. The subject first adjusts the amplitude of the AC tone to match the perceived loudness of the BC stimulus, while presented signals alternating between the two sources. The subject then adjusts the relative phase between the two stimuli until the combination tone is no longer perceived. The DPOAE technique is an objective way of comparing the BC stimulus to the AC tone by measuring the DPOAE levels at the emission frequency generated by two AC tones or one AC tone and one BC vibration. All testing occurred in a $2\ \text{m} \times 1.5\ \text{m} \times 1.5\ \text{m}$ semi-anechoic sound room. Subjects completed the entire protocol three separate times. The protocol used in this research and all human subject tests performed were approved by the New England Institutional Review Board.

Subjects were fitted with an in-ear probe designed for DPOAE measurements in one ear, a circumaural headset on the contralateral ear, and a bone oscillator applied against the forehead. The DPOAE probe included two speakers and a microphone (GSI DPOAE probe, Cardinal Health, Madison, WI) and connected directly to a modified PCMCIA sound card (Echo Indigo, Echo Digital Audio, Carpinteria, CA). The in-ear probe speakers were calibrated using an ear simulator (Brüel and Kjaer type 4157, Nærum, Denmark) according to ANSI standard S3.6-1996. The ear simulator provides an acoustic impedance representative of a human ear so that pure tones are presented at the proper acoustic level in the ear. The in-ear microphone was calibrated using a sealed acoustic fixture approximating the volume of an adult human ear canal and a