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Research paper

Effects of ear-canal pressurization on middle-ear bone- and air-conduction responses

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ABSTRACT

In extremely loud noise environments, it is important to not only protect one's hearing against noise transmitted through the air-conduction (AC) pathway, but also through the bone-conduction (BC) pathways. Much of the energy transmitted through the BC pathways is concentrated in the mid-frequency range around 1.5–2 kHz, which is likely due to the structural resonance of the middle ear. One potential approach for mitigating this mid-frequency BC noise transmission is to introduce a positive or negative static pressure in the ear canal, which is known to reduce BC as well as AC hearing sensitivity. In the present study, middle-ear ossicular velocities at the umbo and stapes were measured using human cadaver temporal bones in response to both BC and AC excitations, while static air pressures of ±400 mm H_2O were applied in the ear canal. For the maximum negative pressure of -400 mm H_2O, mean BC stapes-velocity reductions of about 5–8 dB were observed in the frequency range from 0.8 to 2.5 kHz, with a peak reduction of 8.6(±4.7) dB at 1.6 kHz. Finite-element analysis indicates that the peak BC-response reduction tends to be in the mid-frequency range because the middle-ear BC resonance, which is typically around 1.5–2 kHz, is suppressed by the pressure-induced stiffening of the middle-ear structure. The measured data also show that the BC responses are reduced more for negative static pressures than for positive static pressures. This may be attributable to a difference in the distribution of the stiffening among the middle-ear components depending on the polarity of the static pressure. The characteristics of the BC-response reductions are found to be largely consistent with the available psychoacoustic data, and are therefore indicative of the relative importance of the middle-ear mechanism in BC hearing.

1. Introduction

Conventional hearing-protection devices (HPDs), such as earplugs and earmuffs, reduce the risk of hearing damage by reducing the noise transmitted through air conduction (AC). AC is the normal mode of hearing in which the inner ear (cochlea) is excited through the eardrum vibrations that result from acoustic pressure in the ear canal. However, the maximum level of hearing protection provided by a conventional HPD is normally limited by bone-conduction (BC) sound transmission, where the sound energy is transmitted to the cochlea through acoustically-induced skull-bone vibrations that bypass the ear canals occluded by an HPD. The limitation on hearing-protection performance imposed by this BC sound transmission is commonly referred to as the "BC limit". The effects of the BC sound transmission are normally of little concern in most noise environments, but they become critically important in an extremely loud environment such as on the flight deck of an aircraft carrier, where the noise can reach levels as high as 140–150 dB SPL (sound pressure level). In such extreme environments, even wearing an HPD that can attenuate noise down to the BC limit may not be sufficient, since the BC-transmitted sound may still be loud enough to cause permanent hearing loss.

The most noticeable feature of the HPD BC limit is a peak feature in the mid-frequency range centered around 1.5–2 kHz (Zwislocki, 1957; Berger et al., 2003; Reinfeldt et al., 2007), which indicates prominent BC sound transmission in this frequency range. Assuming that the noise has a broadband spectrum, such as the exhaust noise of an aircraft jet engine, and also assuming that one is wearing an HPD that provides noise attenuation down to the BC-limit level, the overall BC sound spectrum will then be dominated by the sound energy associated with this mid-frequency peak around 1.5–2 kHz. Therefore, one needs to improve

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Abbreviations: AC, air conduction; BC, bone conduction; FE, finite element; HPD, hearing protection device; SPL, sound pressure level; TM, tympanic membrane; LP, lateral process

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the HPD attenuation especially in this mid-frequency range in order to substantially improve the HPD performance.

BC sound transmissions are said to be primarily comprised of the following three components: (a) "compressional", (b) "inertial-ossicular", and (c) "external-canal" (Silman and Silverman, 1991; Stenfelt et al., 2002). The compressional BC component results when skull vibrations are transmitted directly to the cochlea via distortional vibrations of the bone surrounding the cochlea. The inertial-ossicular BC component results when the BC excitation is transmitted to the cochlea through middle-ear ossicular vibrations. This is called the "*inertial*-ossicular" component since it is the mass inertia of the middle-ear structures that introduce relative motions of the ossicles with respect to the vibrating base bone structure, which in turn excite the cochlea through stapes vibrations. The external-canal BC component results when the BC-induced vibrations of the ear canal, primarily the cartilaginous part, produce acoustic pressures that excite the tympanic membrane (TM).

There have been indications that the prominent mid-frequency BC limit originates from the inertial-ossicular BC component (Carhart, 1971; Tonndorf, 1972; Linstrom et al., 2001). Although this component is typically called "inertial-ossicular", a more precise term may be the "ossicular-resonance" mechanism, since it likely involves a middle-ear structural-resonance phenomenon which is not just the result of the ossicular-mass inertia. Recent studies have shown that the middle-ear system resonates on average at around 1.5–2 kHz in response to BC excitations (Stenfelt et al., 2002; Homma et al., 2009).

In light of the evidence for the middle-ear origin of the mid-frequency BC-limit feature, one potential approach for BC-sound mitigation is to apply static air pressure in the ear canal, which is known to reduce the hearing sensitivity through a reduction in the middle-ear mobility. Previous psychoacoustic studies have indicated that such ear-canal pressurization not only reduces hearing sensitivity for AC, but also for BC (Humes, 1979; Aazh et al., 2005). Humes (1979) further observed that there is a prominent peak reduction in BC hearing at 2 kHz, which he attributed to the loss of the middle-ear BC contribution.

In this study, human temporal-bone measurements were performed to observe the effects of ear-canal pressurization on the middle-ear BC as well as AC responses. Previous temporal-bone measurements have obtained such data for AC responses (Murakami et al., 1997; Gan et al., 2006), but not for BC responses. A finite-element (FE) model of a human middle ear was also used to gain further insight into the dynamics of the BC- and AC-response alterations due to ear-canal pressurization. An improved understanding of the mechanisms of BC-hearing suppression due to ear-canal pressurization is a critical step toward the potential future utilization of this phenomenon for hearing protection in extremely noisy environments.

2. Methods and materials

2.1. Temporal-bone measurements

The effects of ear-canal pressurization on middle-ear dynamic responses to both BC and AC excitations were measured with human cadaver temporal bones. The experimental setup is largely based on the setup described in Homma et al. (2009), except for additional provisions to control the ear-canal static air pressure and to measure stapes velocity. The experimental setup is illustrated in Fig. 1.

2.1.1. Temporal-bone preparation

Temporal bones were extracted from human cadavers using a Schuknecht bone saw at the time of autopsy. The TM and the middle ear were inspected in each bone using an operating microscope; bones with abnormal TMs or middle ears were excluded from the investigation. A total of eight temporal bones were used in this study. Five of them were used in the experiment within 48 h of death; these were labeled as TB1 (78-year-old male, right ear), TB2 (68-year-old male, right ear), TB3 (68-year-old male, left ear), TB4 (73-year-old male, left ear), and TB5 (86-year-old male, right ear). The remaining three temporal bones, TB6, TB7, and TB8, were previously frozen for one month before being thawed and used in the experiment. No subject information on these three bones was available. For all preparations, the attached connective tissue was removed and the bony wall of the external ear canal was drilled down to 2 mm from the TM annulus. A 25-mm-long plastic tube with an internal diameter of 8.5 mm was placed against the bony ear-canal remnant; it was placed so that the axis of the tube was approximately perpendicular to the plane of the TM annulus. The plastic tube was held in place with epoxy in order to minimize air leaks around the plastic tube. In addition, a transparent plastic lid was attached to the tube opening using beeswax and glue in order to maintain static pressures in the tube, and also to acoustically isolate the tube canal from background noise. Preliminary measurements of AC and BC middle-ear responses with and without this transparent lid did not show significant differences, which indicated that the potential loading of the TM due to the closed air volume in the tube was minimal. For stapes-velocity measurements, a simple mastoidectomy and posterior hypotympanotomy were performed using a surgical drill. Removal of the mastoid portion of the facial nerve and surrounding bone was also performed in order to obtain a good view of the stapes footplate. The average diameter of the individual stapes access holes was about 3 mm. The access hole was covered with a transparent glass plate.

2.1.2. AC- and BC-excitation methods

Each temporal-bone specimen was encased in plaster, and then attached to a shaker (B&K type 4810) in order to simulate BC excitations. The shaker was rigidly connected to the bone by a screw held in place with cement. The shaker was attached in such a way that the vibration axis was approximately perpendicular to the plane of the TM annulus. This particular BC-excitation axis was chosen to be consistent with two previous investigations (Stenfelt et al., 2002; Homma et al., 2009). The previous temporal-bone data by Stenfelt et al. (2002) also indicated that the ossicular BC vibration may be most sensitive to the vibration given in this direction, although the differences in BC-vibration responses appear to be rather small for BC excitations given in different directions. For the AC excitation, a hearing aid receiver (Knowles, #2955) was used to introduce acoustic pressure to vibrate the TM. The peak sound pressure level for the AC stimulation was 90–93 dB, which is well below the 120–130 dB SPL range where nonlinear distortions are expected to occur (Voss et al., 2000). The middle-ear vibration levels produced by the BC excitation were comparable to those produced by the AC excitation, which ensured that the middle-ear structures were not overdriven during the measurements.

2.1.3. AC- and BC-response measurements

A laser-vibrometer sensor head (Polytec, HLV-1000) was used to measure velocity responses of the middle ear. In order to achieve good reflection of the laser light, retro-reflective beads were positioned at measurement locations. These micro beads were negligibly small in size (about 5–10 μm in diameter and 1 μg in mass), and thus introduced negligible mass loading. All measurement data were acquired by using a PC-based data acquisition system (SYSid, Berkeley, CA). A probe-tube microphone (Etymotic Research, ER-7C, Elk Grove Village, IL) was also installed