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Interaction between osseous and non-osseous vibratory stimulation of the human cadaveric head

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ABSTRACT

Bone conduction (BC) stimulation can be applied by vibration to the bony or skin covered skull (osseous BC), or on soft tissue such as the neck (non-osseous BC). The interaction between osseous and non-osseous bone conduction pathways is assessed in this study. The relation between bone vibrations measured at the cochlear promontory and the intracranial sound pressure for stimulation directly on the dura and for stimulation at the mastoid between 0.2 and 10 kHz was compared. First, for stimulation on the dura, varying the static coupling force of the BC transducer on the dura had only a small effect on promontory vibration. Second, the presence or absence of intracranial fluid did not affect promontory vibration for stimulation on the dura. Third, stimulation on the mastoid elicited both promontory vibration and intracranial sound pressure. Stimulation on the dura caused intracranial sound pressure to a similar extent above 0.5 kHz compared to stimulation on the mastoid, while promontory vibration was less by 20–40 dB. From these findings, we conclude that intracranial sound pressure (non-osseous BC) only marginally affects bone vibrations measured on the promontory (osseous BC), whereas skull vibrations affect intracranial sound pressure.

1. Introduction

A hearing sensation can be elicited when a stimulus is presented not only by air conduction (AC) but also by bone conduction (BC), or by a combination of the two. Several different pathways and their interactions have been demonstrated to contribute to BC hearing (Stenfelt, 2006; Stenfelt and Goode, 2005; Tonndorf, 1966). The importance of these pathways depends on frequency and the state of the middle ear ossicles (Stenfelt, 2015). Both osseous and non-osseous pathways contribute to the final sensation of hearing. Four osseous BC pathways have been identified: a) pathways involving bone vibration (compression and expansion of the otic capsule (Stenfelt, 2015; Tonndorf, 1966; von Bekesy, 1960); b) sound radiated in the external auditory canal (Brummund et al., 2014; Stenfelt et al., 2003); c) inertia of the ossicles (Homma et al., 2010; Stenfelt, 2006; Stenfelt et al., 2002); d) inertia of the inner ear fluid (Kim et al., 2011; Stenfelt, 2015). One non-osseous BC pathway has been documented (Sohmer and Freeman, 2004). The non-osseous pathway may involve a possible mechanism that includes dynamic sound pressure transmission from the contents of the skull, such as brain tissue and cerebrospinal fluid via the internal auditory canal, cochlear aqueduct and/or vestibular aqueduct to the cochlea. Evidence for the non-osseous mechanism has come from studies both on experimental animals (Sohmer and Freeman, 2004) and humans (Sohmer et al., 2000).

In order to induce a hearing sensation, a BC transducer can be placed at various locations on the body. Besides stimulating on the skull or skin covered bone, stimulation on soft tissue (soft-tissue stimulation) such as the eye, neck or thorax can cause a hearing sensation. For example, distortion product otoacoustic emissions can be elicited by a combination of an air conducted stimulus using an earphone in the ear canal and a stimulus on the eye delivered via

Abbreviations: AC, air conduction; BC, bone conduction; MRI, magnetic resonance imaging; BERA, brainstem evoked response audiometry; LDV, laser Doppler vibrometry; SNR, signal-to-noise ratio

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a BC transducer (Watanabe et al., 2008). Further, soft-tissue stimulation is an additional pathway of sound transmission in a high-energy sound field. For example, during an explosion, limiting the air conduction pathway to the ear with earplugs and earmuffs does not offer complete protection against damage. Protection is limited to 38–43 dB from 1 to 1.4 kHz (Ravicz et al., 2000), or it may be frequency dependent, ranging from 40 to 60 dB (Reinfeldt et al., 2007).

It has been proposed that soft-tissue stimulation by a BC transducer induces an auditory response via a predominantly non-osseous pathway (Adelman et al., 2015; Freeman et al., 2000; Sohmer et al., 2000). Evidence for this assumption comes from experimental studies using clicks as stimuli during brainstem evoked response audiometry (BERA). Such studies found no acceleration of the bone measured for stimulation of the eye in human (Sohmer et al., 2000) or for stimulation of the brain in experimental animals (Freeman et al., 2000). In amphibians, similar mechanisms have been described and although concurrent bone vibrations could not be ruled out completely, they were deemed to be unlikely (Seaman, 2002). In contrast, skull vibrations, as measured on the teeth following stimulation on the eye have been described on normally hearing humans (Ito et al., 2011). While vibration of the teeth was clearly measurable, no direct correlation between the BC threshold and vibration of the teeth was found, suggesting that non-osseous pathways contribute to hearing for this mode of stimulation. One caveat is that vibration of the teeth may not directly correspond to vibrations of the bone surrounding the cochlea.

Osseous pathways can be investigated by measuring bone vibrations at the cochlear promontory (Eeg-Olofsson et al., 2013), and non-osseous pathways can be assessed by measuring intracranial sound pressure in the head. The aim of this study was to investigate the interaction between non-osseous and osseous pathways following stimulation with a BC transducer by comparing the relation between bone vibrations measured at the cochlear promontory and intracranial sound pressure for stimulation on the dura and on the mastoid (Fig. 1). We hypothesized that intracranial sound pressure and skull vibrations would be correlated for the two stimulation modalities depending on stimulation frequency and the presence or absence of cranial fluid in the cadaver heads.

2. Materials and methods

2.1. Preparation of specimen

The experiments were reviewed and approved by the institutional Ethics Committee (KEK-ZH-Nr. 2012-0136). Measurements were made on four cadaveric whole human heads that were conserved using a technique described by Thiel (Thiel, 1992). This method does not significantly change the properties of the soft tissue (Guignard et al., 2013). An endaural incision was performed between the helix and the tragus. Next, the tympanomeatal flap was elevated to expose the middle ear to gain direct access to the promontory (Fisch et al., 2008). Two self-retaining retractors were placed to allow good visualization of the promontory and access for the Laser Doppler Vibrometry (LDV) beam, which was used to measure promontory vibrations. To enhance reflectivity of the laser beam, a small piece of retro-reflective foil (i.e., <1 mm^2) was placed onto the cochlear promontory near the round window on the measurement position. A groove was drilled in the mastoid bone for placement of the BC transducer (*Bonebridge, Med-El, Austria*), just posterior to the wall of the external auditory canal and inferior to the dura of the middle cranial fossa with the dura remaining covered by bone. The BC transducer was secured in its position in the cortical bone with two self-tapping screws of 2 mm diameter and 6 mm length. The attachment of the screws was controlled by tightening them to 0.2 Nm using a torque wrench. A craniotomy (2 × 2 cm) above the frontal sinus was then made and in a second step, the same BC transducer, which was also used for mastoid stimulation, was pressed against the dura with a controlled coupling force and a contact area with the dura of approximately of 2 cm^2. The coupling force was varied from 1 to 5 N via an elastic band in 1-N steps, controlled with a spring force gauge (*Light Line, Pesola, Switzerland*). The effect of increasing coupling force on intracranial sound pressure and bone vibration was analyzed. Care was taken to assure that the BC transducer was in contact only with the dura and not with the skull. Finally, the skull was opened at the vertex and a tube of 10-mm diameter was tightly sealed to the opening in order to keep a physiologic intracranial static pressure of 15 cm water column.

2.2. Measurement setup

The measurement setup, shown in Fig. 2, consisted of an LDV system, hydrophone, and a BC transducer coupled to the cadaveric head at either the mastoid (MastStim) or the dura (DuraStim). For both positions, the BC transducer was directly driven by stepped-sine signals in the frequency range of 0.2–6 kHz with a stimulus intensity of 1 V peak, which was generated by the measurement system Audio Precision APx585 (*Audio Precision Inc., USA)*. The 81 stimulus frequencies used were equally spaced on a logarithmic scale, resulting in approximately 50 frequency points per decade. Measurements were performed on a stainless steel table to minimize random vibrations from external sources. A hydrophone (*Type 8103, Brüel & Kjær, Denmark*), used for measurements of sound-induced pressure variations in the intracranial fluid, was inserted into the intracranial space through the tube. The hydrophone was carefully positioned at the center of the cranial hemisphere such that it did not have contact with the skull, and its position was monitored by an x-ray in two perpendicular planes (Fig. 2c). A physiologic static intracranial pressure of 15 cm H_2O was maintained by a water column in the tube attached to the skull (Steiner and Andrews, 2006).

During measurements, the cadaver heads were supported on a soft gel head ring (Model 4006.0200, MAQUET Medical Systems USA), positioned on a stainless steel table, in order to minimize the coupling of mechanical vibrations from external sources to the skulls.

Following stimulation, motions of the cochlear promontory were measured at a single point using a 1-dimensional LDV system (*CLV-2534*, *Polytec GmbH, Germany*). Simultaneously, intracranial sound pressure was measured using the hydrophone with a charge amplifier (*Type 2690-0S, Low noise version, Brüel & Kjær, Denmark*). Both signals, as well as the driving signal to the BC transducer, were recorded by the Audio Precision APx585 measurement system (Fig. 2).

In order to provide sufficient temporal resolution for frequency, magnitude and phase (not shown but recorded for future research) in the desired measurement frequency range (0.2–6 kHz), the maximum sampling rate of the available equipment was used without any compromise on the other sampling parameters (e.g., sampling time, input range, noise floor). The sampling frequency was set at 192 kHz with a sampling time of per frequency, resulting in a 5-Hz frequency resolution per measurement. All of the measurement procedures were controlled by the Audio Precision software APx500 (*Audio Precision Inc., USA*) and custom LabView Virtual Instrument (VI) software, created in LabView 2013 SP1 (*National Instruments, Texas, USA*) and installed on a personal computer.

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