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Research Paper

In-vivo assessment of osseous versus non-osseous transmission pathways of vibratory stimuli applied to the bone and the dura in humans

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ABSTRACT

Background: Bone conduction (BC) is an alternative to air conduction (AC) for stimulation of the inner ear. Stimulation for BC can occur directly on the skull bone, on the skin covering the skull bone, or on soft tissue (i.e., eye, dura). All of these stimuli can elicit otoacoustic emissions (OAE). This study aims to compare OAEs generated by different combinations of stimuli in live humans, including direct stimulation of the intracranial contents via the dura, measured intraoperatively.
Methods: Measurements were performed in five normal-hearing ears of subjects undergoing a neurosurgical intervention with craniotomy in general anesthesia. Distortion product OAEs (DPOAEs) were measured for f_2 at 0.7, 1, 2, 3, 4, and 6 kHz with a constant ratio of the primary frequencies (f_2/f_1) of 1.22. Sound pressure L_1 was held constant at 65 dB SPL, while L_2 was decreased in 10 dB steps from 70 to 30 dB SPL. A DPOAE was considered significant when its level was $\geq$6 dB above the noise floor. Emissions were generated sequentially with different modes of stimulation: 1) pre-operatively in the awake subject by two air-conducted tones (AC-AC); 2) within the same session preoperatively by one air- and one bone-conducted tone on the skin-covered temporal bone as in audiometry (AC-BC); 3) intra-operatively by one air-conducted tone and one bone-vibrator tone applied directly on the dura (AC-DC). A modified bone vibrator (Bonebridge; MED-EL, Innsbruck, Austria) was used for BC stimulation on the dura or skin-covered mastoid. Its equivalent perceived SPL was calibrated preoperatively for each individual by psychoacoustically comparing the level of a BC tone presented to the temporal region to an AC tone at the same frequency. Simultaneously with the DPOAEs, vibrations at the teeth were measured with an accelerometer attached using a custom-made holder.
Results: It was possible to record DPOAEs for all three stimulation modes. For AC-DC, DPOAEs were not detected above the noise floor below 2 kHz but were detectable at the higher frequencies. The best response was measured at or above 2 kHz with $L_2 = 60$ dB SPL. The acceleration measured at the teeth for stimulation on the dura was lower than that for stimulation on the bone, especially below 3 kHz.
Conclusion: We demonstrate a proof-of-concept comparison of DPOAEs and teeth acceleration levels elicited by a bone vibrator placed either against the skin-covered temporal bone, as in audiometry, or directly against the dura mater in patients undergoing a craniotomy. It was demonstrated that DPOAEs could be elicited via non-osseous pathways within the skull contents and that the required measurements could be performed intra-operatively.

1. Introduction

Bone conduction (BC) is a means of transmission of energy from a vibratory stimulus applied to the skull that can elicit a hearing sensation. The sensation is similar or equal to that resulting from

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stimulation by air conduction (AC). Bone conduction testing is used in clinical audiometry to differentiate between a conductive, sensorineural or mixed hearing loss. The investigation of BC has been ongoing for decades, and several different pathways of sound transmission have been described (von Békésy, 1932; Bárány, 1938; Stenfelt and Goode, 2005; Stenfelt, 2015; Tonndorf, 1966). The contribution of each of these pathways to the final sensation of hearing is still a matter of debate. Assuming vibrations are conducted along the bone to the outer ear canal, the middle ear, and the cochlea, the following pathways may be considered: (a) vibration of the cartilage, the bone and the overlying skin of the outer ear canal inducing an air-conducted sound (Stenfelt et al., 2003), (b) inertia of the middle ear ossicles (Stenfelt et al., 2002; von Békésy, 1960), (c) inertia of the cochlear fluids (Stenfelt, 2015), and (d) compression and expansion of the cochlear walls (Tonndorf, 1966; Stenfelt, 2015; von Békésy, 1960). In recent years, several studies have concluded that vibratory stimuli could also be transmitted through non-osseous vibratory pathways, in that vibratory stimuli induce intracranial sound pressures that reach the cochlea through non-osseous connections such as the cochlear or vestibular aqueducts, and perivascular or perineural spaces (Sohmer et al., 2000; Freeman et al., 2000; Ito et al., 2011; Tonndorf and Tabor, 1962). Experiments have shown that placing a vibrator directly on the brain of animals or on different soft-tissue sites without underlying bone in humans can elicit hearing sensations and auditory brainstem responses (ABR), even without inducing significant vibrations of the skull bone (Sohmer et al., 2000; Freeman et al., 2000). Examples of such soft-tissue sites include the fontanelle in infants, the skin over permanent craniotomies, or the eye. Furthermore, vibratory stimuli applied to other parts of the human body, such as the thorax or the neck have also been shown to reach the cochlea (Adelman et al., 2015; Berger et al., 2003; Ravicz and Melcher, 2001).

Ito et al. found similar hearing thresholds for vibratory stimulation on the eye and on the forehead in humans; however, stimulation on the eye induced smaller bone vibrations in the frequency range of 0.5–2 kHz. This finding suggests that low-frequency vibratory stimulation applied to the eye may reach the inner ear via pathways other than skull bone vibrations, indicating different pathway distributions to the inner ear for osseous and non-osseous stimulation sites. A recent study performed on cadaver heads with preservation of intracranial structures and pressures showed that stimulation on the dura and on the mastoid resulted in both bone vibrations and intracranial sound pressures, but with little mutual correlation (Sim et al., 2016). Stimulation of the dura and the mastoid induced comparable intracranial sound pressures above 0.5 kHz; however, promontory vibrations were considerably smaller during dural stimulations. Dural stimulation below 0.5 kHz elicited higher intracranial sound pressures than stimulation on the mastoid.

The influence of intracranial cerebrospinal fluid (CSF) pressure on hearing thresholds has been shown in rats (Freeman et al., 2000). Auditory brainstem response thresholds were temporarily increased after mannitol injection, which reduces the intracranial pressure osmotically. The common clinical observation of a hearing loss primarily in the low frequencies in humans with reduced CSF pressure, for example in dural leakage after spinal anesthesia (Michel and Brusis, 1992) or myelography (Nakaya et al., 2005), supports the assumption of an interaction between CSF and perilymph for hearing. Another possible interaction of CSF and cochlear fluid may result in a low-frequency air-bone gap in pure-tone audiometry that occasionally occurs together with supranormal BC thresholds in patients with semicircular canal dehiscence (SCD) syndrome (Merchant and Rosowski, 2008) and, to a lesser extent, in patients with large vestibular aqueduct (LVA) syndrome (Merchant et al., 2007). Sohmer et al. (2009) suggested that the enlargement of the fluid connections between the cranial cavity and the cochlea results in lower impedance and therefore a more effective sound wave propagation directly from the CSF to the perilymph. However, the mechanism of low-frequency air-bone gap in SCD and LVA has been controversially discussed. Merchant et al. (2007) assumed an increased pressure difference between the scala vestibuli and scala tympani due to decreased impedance in the scala vestibuli by the third window in SCD and LVA, resulting in better BC thresholds. In summary, the actual contribution of such non-osseous pathways to hearing is still controversial.

Laser Doppler vibrometry (LDV) and accelerometry are most commonly used to analyze skull bone vibrations experimentally. Bone vibration is preferentially measured on the skull by pointing an LDV or by coupling an accelerometer directly to bony structures because skin decreases the acceleration response by 16–28 dB, mainly in frequencies above 1 kHz (Ito et al., 2011; Håkansson et al., 1985). Such a direct coupling can be reached using exposed skull bone or an abutment for a bone-anchored hearing aid (BAHA). The dampening effect of the skin has been shown to depend on skin thickness (Mattingly et al. 2015). Teeth as a natural and easily accessible bone-integrated structure are an additional possibility for a direct coupling to facial bones. However, teeth do not directly represent the bone vibrations of the otic capsule (Ito et al., 2011), because skull vibrations may differ depending on location on the skull. Teeth have been identified as an adequate site for BC stimulation in assessment and use of a vibratory BAHA (Stenfelt and Håkansson, 1999).

Additional methods such as threshold measurements or otoacoustic emissions (OAE) are required for investigation of pathways not inducing skull bone vibration. Otoacoustic emissions are objective acoustic responses following cochlear activation and are generated by outer hair cells (Kemp, 1978), and are used routinely for objective evaluation of hearing such as hearing screening in newborns (Probst, 2000). Distortion-product OAE (DPOAE) are commonly elicited in humans by two primary tones (f_1 and f_2) with a frequency ratio (f_2/f_1) of 1.22 and level differences (L_1-L_2) of 0–10 dB (Harris et al., 1989; Hauser and Probst, 1991). They can be elicited by a combination of AC and BC stimuli, providing objective evaluation of the outer hair cells' response (Purcell et al.,1998, 1999; Watanabe et al., 2008; Clavier et al., 2010), and interactions in the cochlea. Purcell et al. (1999) calibrated bone vibrators for individual subjects objectively comparing DPOAE growth functions elicited with two AC primaries (AC-AC) to the function obtained by one AC and one BC primary (AC-BC). Watanabe et al. (2008) elicited DPOAE by applying a vibratory stimulus to the eye, yielding comparable DPOAE responses as with vibratory stimulation to the forehead. None of these studies measured the skull vibrations induced by BC stimuli to elicit DPOAE.

The goals of this study were 1) to establish a method of eliciting DPOAE with a combined AC stimulus and a stimulus on the dura (DC) and 2) to evaluate how bone vibrations measured at the teeth differ from AC, BC and DC stimulation in humans. We hypothesized that dural stimulation has a comparable sensitivity to mastoid stimulation inducing equivalent DPOAE, and that the induced bony vibrations measured on the teeth would be relatively less at lower than at higher stimulation frequencies. Non-osseous transmission mechanisms may be supposed in the presence of relatively high-amplitude DPOAE together with relatively low-amplitude bone vibrations. Conversely, osseous transmission mechanisms seem more likely in the presence of relatively low DPOAE and high vibration amplitudes.