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Model predictions for bone conduction perception in the human

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ABSTRACT

Five different pathways are often suggested as important for bone conducted (BC) sound: (1) sound pressure in the ear canal, (2) inertia of the middle ear ossicles, (3) inertia of the inner ear fluid, (4) compression of the inner ear space, and (5) pressure transmission from the skull interior. The relative importance of these pathways was investigated with an acoustic-impedance model of the inner ear. The model incorporated data of BC generated ear canal sound pressure, middle ear ossicle motion, cochlear promontory vibration, and intracranial sound pressure. With BC stimulation at the mastoid, the inner ear inertia dominated the excitation of the cochlea but inner ear compression and middle ear inertia were within 10 dB for almost the entire frequency range of 0.1–10 kHz. Ear canal sound pressure gave little contribution at the low and high frequencies, but was around 15 dB below the total contribution at the mid frequencies. Intracranial sound pressure gave responses similar to the others at low frequencies, but decreased with frequency to a level of 55 dB below the total contribution at 10 kHz. When the BC inner ear model was evaluated against AC stimulation at threshold levels, the results were close up to approximately 4 kHz but deviated significantly at higher frequencies.

1. Introduction

Today, it is well accepted that bone conducted (BC) sound excites the inner ear and creates a traveling wave on the basilar membrane (BM) similar to air conduction (AC) stimulation. This notion is based on the ability to cancel a BC tone by an AC tone (Stenfelt, 2007; von Békésy, 1932), the ability to generate distortion-product otoacoustic emissions using BC stimulation (Purcell et al., 1998; Watanabe et al., 2008), and the similarity of BM vibration pattern with AC and BC excitation (Stenfelt et al., 2003a). However, the way the sound is transmitted from the excitation position, often at the mastoid or forehead of the skull, to the inner ear and causing the BM vibration is not clarified.

Through history, several explanations have been presented for the perception of BC sound. Early investigators proposed one or two contributors for the perception of BC sound (Bárány, 1938; Herzog, 1926; Krainz, 1926) while von Békésy suggested contribution from the outer, middle and inner ear (von Békésy, 1960). The number of contributors and their relative importance has varied over time and in total seven contributors for BC sound perception was proposed by Tonndorf (1966) from studies in cats. Lately, five different contributors for BC sound have been suggested (Stenfelt, 2011; Stenfelt and Goode, 2005b). These five contributors are (1) generation of sound pressure in the ear canal, (2) relative motion of the middle ear ossicles caused by inertial effects from the mass of the ossicles, (3) inertial forces acting on the inner ear fluid, (4) compression and expansion of the cochlear space, and (5) transmission of sound pressure from the skull interior.

Several investigations have been presented to experimentally estimate the contribution and its relative importance from these five contributors. The one component that is easiest to measure is the contribution from sound pressure in the ear canal. This contribution can be estimated by measuring the ear canal sound pressure during AC and BC stimulation and compare its level at hearing thresholds. Huizing (1960) found that the sound pressure in the ear canal was greater with AC stimulation than with BC stimulation causing the same hearing sensation, at least for frequencies above 500 Hz. Khanna et al. (1976) estimated the contribution from the ear canal sound pressure by canceling an AC tone by a BC tone. They reported the AC and BC sounds to be similar for frequencies up to 1.5 kHz, while above 1.5 kHz the AC tone was 10–20 dB greater than the BC ear canal sound at cancellation. The caveat with their study is that they occluded the ear to provide the AC sound, and thereby increased the low-frequency ear-canal

Abbreviations: AC, air conduction; BC, bone conduction; BM, basilar membrane; CA, cochlear aqueduct; CSF, cerebrospinal fluid; OW, oval window; RW, round window; SV, scala vestibule; ST, scala tympani; VA, vestibular aqueduct

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sound pressure generated by BC, known as the occlusion effect (Huizing, 1960; Reinfeldt et al., 2013; Stenfelt and Reinfeldt, 2007). Another approach was used in Stenfelt et al. (2003b) where the umbo (tip of the malleus) vibration was compared to AC and BC generated ear canal sound pressure. It was concluded in that study that AC sound in the ear canal gave approximately 10 dB lower umbo velocity compared to BC generated sound in an open ear canal. This indicates that there are other mechanisms driving the relative motion of the middle ear ossicles than the sound in the ear canal during BC stimulation, and that the sound pressure in the ear canal generated by BC is some 10 dB below the contribution from the middle ear, most probably driven by inertia of the middle ear ossicles. However, when the ear canal was occluded, the sound pressure driven umbo motion in Stenfelt et al. (2003b) was equal for AC and BC sound at frequencies below 1.2 kHz indicating that for low frequencies, the ear canal sound pressure is a dominant contributor for hearing BC sound when the ear is occluded.

The relative importance of the other four contributors are more difficult to assess. One attempt to estimate the contribution from the middle ear inertia has been done by comparing the motion of the ossicles at hearing thresholds when stimulation was by AC and BC (Röösli et al., 2012; Stenfelt, 2006). Both studies indicate greater ossicle motion with AC stimulation than BC stimulation for frequencies at 3 kHz and below, but the opposite at higher frequencies. The interpretation was that the middle ear inertia was not dominant at frequencies below 3 kHz for BC stimulation. This is somewhat opposite to interpretations of clinical findings of otosclerosis of the stapes footplate, where a depression of the BC thresholds at and around 2 kHz of up to 20 dB is seen, often termed the Carhart notch (Carhart, 1971). This depressed BC thresholds has been attributed to the lack of middle ear inertia (Tonndorf, 1966) as the ossicles resonance frequency for BC stimulation is close to 2 kHz (Homma et al., 2009; Stenfelt et al., 2002). However, in a model simulation of BC excitation of the inner ear (Stenfelt, 2015), the depressed BC thresholds close to 2 kHz could be simulated as a result of increased impedance at the oval window (OW). In those simulations, the effect of middle ear inertia was not included but the Carhart notch was seen as a result of increasing the impedance at the OW seen from inside the inner ear.

The latter is a general problem for experimental manipulations investigating BC sound. It is nearly impossible to isolate one contributor without affecting one or more of the other contributors and the results become difficult to interpret. One way to circumvent this problem is to use a model that can simulate BC excitation. Several such models have been devised to investigate a specific aspect of BC stimulation, for example the occlusion effect (Brummund et al., 2014; Schroeter and Poesselt, 1986; Stenfelt and Reinfeldt, 2007), middle ear inertia (Homma et al., 2009; Williams and Howell, 1990), and inner ear fluid inertia and compression (Bohnke and Arnold, 2006; Kim et al., 2011; Schick, 1991; Stenfelt, 2015). These models are often specific meaning they only investigate a single or a couple of phenomena and not the complete response of the ear to BC stimulation. Another important aspect is the excitation of the BC sound itself. The vibration of the bone surrounding the ear is complex showing several modes of wave transmission with translational as well as rotational motion in all three dimension (Eeg-Olofsson et al., 2013; McKnight et al., 2013; Stenfelt and Goode, 2005a; Stenfelt et al., 2000). Most models have used a simple excitation pattern preventing extrapolations of the results to clinical reality. One exception is a three-dimensional whole-head finite element model for BC sound (Taschke and Hudde, 2006). However, that model have not been used to investigate contributors for BC sound in detail.

Recently, an inner ear model for BC sound was presented that used excitation based on the motion of the inner ear boundary (Stenfelt, 2015). The motion of the surrounding bone was based on experimental investigations of bone vibration transmission in the skull base, and the model was able to simulate several experimental and clinical findings for BC sound reported in the literature. That model is the core for the current simulations and is extended to be able to predict relative importance from the five components listed above.

The aim of the current study is to use a model to predict the relative importance of five contributors for BC sound in the human. The model is based on mechano-acoustic impedances of the middle and inner ear as well as data from experimental studies of BC sound in the human reported in the literature.

2. The model

2.1. Ear model

The model depicted in Fig 1 shows a simplified sectional image of the ear. This layout is used for the predictions of the five components for BC hearing listed above. Fig. 1 does not constitute a model in itself, but shows the steps and pathways used to compute predictions of the five components. The layout comprises the ear canal, the middle ear, the inner ear, the skull bone surrounding the peripheral auditory organ, and the skull interior composed of the brain surrounded by the cerebrospinal fluid (CSF). Also indicated in Fig. 1 is the compliant pathways between the inner ear and the skull interior, the cochlear aqueduct (CA) and the vestibular aqueduct (VA).

All computations is made for a mastoid placement of the BC transducer, approximately at the audiological placement of a BC transducer, 20–30 mm behind the ear canal opening. The data used are for a transducer attached to the skull bone, but similar results are expected for positions on the skin covered bone at or close to the used position. Other stimulation positions, for example stimulation at the forehead or at positions dominated by pure soft tissues, would alter the relative importance of the pathways making the current predictions invalid.

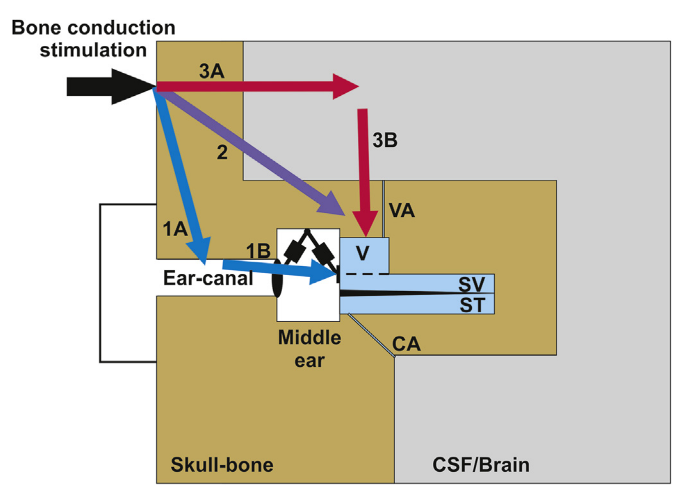

Fig. 1. A layout of the ear. The ear canal, middle ear, and inner ear are shown and three pathways are indicated. The BC stimulation is at the mastoid bone and pathway 1 (blue arrow) indicates the sound transmission for the ear canal sound pressure with sound generated to in the ear canal (1A) and subsequent transmission to the inner ear via the middle ear (1B). Pathway 2 (purple arrow) indicates the bone vibration transmission to the bone surrounding the inner ear and pathway 3 (red arrow) indicates the transmission for skull interior with intracranial sound pressure (3A) and the subsequent transmission to the inner ear via the vestibular aqueduct (3B).