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Research Paper

Sound wave propagation on the human skull surface with bone conduction stimulation

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A B S T R A C T

Background: Bone conduction (BC) is an alternative to air conduction to stimulate the inner ear. In general, the stimulation for BC occurs on a specific location directly on the skull bone or through the skin covering the skull bone. The stimulation propagates to the ipsilateral and contralateral cochlea, mainly via the skull bone and possibly via other skull contents. This study aims to investigate the wave propagation on the surface of the skull bone during BC stimulation at the forehead and at ipsilateral mastoid.
Methods: Measurements were performed in five human cadaveric whole heads. The electro-magnetic transducer from a BCHA (bone conducting hearing aid), a Baha® Cordelle II transducer in particular, was attached to a percutaneously implanted screw or positioned with a 5-Newton steel headband at the mastoid and forehead. The Baha transducer was driven directly with single tone signals in the frequency range of 0.25–8 kHz, while skull bone vibrations were measured at multiple points on the skull using a scanning laser Doppler vibrometer (SLDV) system and a 3D LDV system. The 3D velocity components, defined by the 3D LDV measurement coordinate system, have been transformed into tangent (in-plane) and normal (out-of-plane) components in a local intrinsic coordinate system at each measurement point, which is based on the cadaver head's shape, estimated by the spatial locations of all measurement points.
Results: Rigid-body-like motion was dominant at low frequencies below 1 kHz, and clear transverse traveling waves were observed at high frequencies above 2 kHz for both measurement systems. The surface waves propagation speeds were approximately 450 m/s at 8 kHz, corresponding trans-cranial time interval of 0.4 ms. The 3D velocity measurements confirmed the complex space and frequency dependent response of the cadaver heads indicated by the 1D data from the SLDV system. Comparison between the tangent and normal motion components, extracted by transforming the 3D velocity components into a local coordinate system, indicates that the normal component, with spatially varying phase, is dominant above 2 kHz, consistent with local bending vibration modes and traveling surface waves.
Conclusion: Both SLDV and 3D LDV data indicate that sound transmission in the skull bone causes rigid-body-like motion at low frequencies whereas transverse deformations and travelling waves were observed above 2 kHz, with propagation speeds of approximately of 450 m/s at 8 kHz.

1. Introduction

Bone conduction hearing aids (BCHAs) have become a widely used tools in hearing rehabilitation for patients with conductive or mixed hearing loss (i.e. ear atresia, or chronic inflammation with discharge) who cannot wear conventional hearing aids. Another indication for BCHAs is patients with single-sided deafness (SSD).

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The aim of BCHAs in this situation is to route sound from the deaf side to the hearing side. The efficacy of the sound propagation in BC hearing, from the BCHA to the target ear, depends of several important aspects.

First, the propagation path of the sound energy could involve several possible pathways, through which sound reaches and stimulates the cochlea. Most authors agree that these pathways and their interactions depend on frequency and on the state of the middle ear ossicles (Stenfelt, 2006, 2016; Stenfelt and Goode, 2005a; Tonndorf, 1966). The following pathways have been identified: a) pathways involving bone vibration resulting in compression and expansion of the otic capsule (Stenfelt, 2014; Tonndorf, 1966; Von Békésy, 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, 2014). e) non-osseous pathway including sound pressure transmission by 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 (Sohmer and Freeman, 2004; Sohmer et al., 2000; Sim et al., 2016; Röösli et al., 2016).

Second, the site of stimulation influences the perception. The closer the BCHA is placed to the cochlea, the more efficient the stimulation is (Eeg-Olofsson et al., 2011). For patients with SSD, stimulation occurs at the contralateral ear and sound propagates across the head, via one of the above-mentioned pathways, to finally stimulate the ipsilateral cochlea. The loss of sensitivity between ipsilateral and contralateral stimulation is called transcranial attenuation. Clinically, transcranial attenuation is important because it defines the amount of masking necessary for measuring monaural BC thresholds (Hood, 1960; Studebaker, 1964). However, it varies considerably between individuals ranging from 0 to 15 dB between 0.25 and 4 kHz (Hurley and Berger, 1970; Snyder, 1973; Nolan and Lyon, 1981). Further, it has been shown that stimulation superior-anterior to the pinna is more efficient than behind the pinna even with the same distance from the cochlea (Dobrev et al., 2016; Ito et al., 2011).

For patients with SSD, where sound from a BCHA mounted contralaterally have to stimulate the ipsilateral cochlea, four different mechanism of sound propagation are possible; waves a) tangential and b) normal to the skull bone surface, c) rigid body motion, and d) direct propagation through cerebrospinal fluid and brain tissue. Knowledge about how sound reaches the contralateral ear is important for patients with SSD using BCHA as the device should be designed and implanted (or worn) to minimize interaural attenuation and resulting in maximum amplification. However, for patients with bilateral BCHA, large transcranial attenuation is desired because it may be beneficial for binaural hearing (Stenfelt, 2012; Håkansson et al., 2010).

The aim of this study is to investigate the mode of transcranial sound propagation for BC stimulation. Our hypothesis is that the mode of sound propagation is frequency dependent, and that a transversal wave is dominant at high frequencies (>1 kHz).

2. Methods

This study was approved by the Ethical Committee of Zurich (KEK-ZH-Nr. 2012-0136).

2.1. Sample preparation

Five Thiel-fixed (Thiel, 1992) adult cadaver heads were used. The intracranial space was filled with water and remnants of brain. To maintain the pressure level of the intra-cranial fluid in the cadaver head similar to the physiological condition, a tube was attached to the skull through a hole at the superior center, and the water column inside the tube was controlled to have a height of 15 cm (Steiner and Andrews, 2006). The heads were positioned such that the posterior part of the skull was supported by a soft gel head ring (Model 4006.0200, MAQUET Medical Systems, USA), positioned on a stainless-steel table to decouple vibrations from external sources.

2.2. Measurement setup

The electro-magnetic transducer from a BCHA (bone conduction hearing aid), a Baha® Cordelle II transducer (Cochlear, Australia) in particular (referred to as simply Baha or Baha transducer), was used for stimulation. In order to compare the response of the skull at multiple excitation conditions and locations, the effective stimulation force from the transducer in each condition needed to be calibrated. The dynamic stimulation forces acting on the skin (stimulation with the steel headband) were estimated using an artificial mastoid Type 4930 (Brüel and Kjær, Denmark). The stimulation forces acting on the screw attached to the skull was calibrated using a skull simulator (TU-1000, Cochlear Bone Anchored Solutions AB, Sweden).

The Baha transducer was placed either at its typical location on the mastoid, 5 cm behind the opening of the external auditory canal, or at the forehead, in the midline 5 cm above the root of the nose. The Baha was attached to the head either using a 5-Newton steel-headband (Baha headband 90138, Cochlear AG, Australia) or screw implanted in the bone. The Baha transducer was driven directly by single tone stimuli, of 10 V peak in the frequency range of 0.25–8 kHz. For measurements with the 1D scanning laser Doppler vibrometer (SLDV), the velocity signal from the skull response and the driving signal to the BC transducer are generated and recorded at 25.6 kHz with a NI PCI-4461 (National Instruments Corp., USA) integrated within a PSVW401-B data acquisition system, controlled via PSV 9.0 software (Polytec GmbH, Germany). Due to timing constrains, the 1D LDV recording was done with 40 ms sampling time (25 Hz frequency resolution), repeated and averaged in the complex domain 10 times. For the 3-dimensional laser Doppler vibrometer (3D LDV) measurements, the velocity and the driving signals are recorded and generated with DS 2102 DAC and DS 2004 ADC boards, respectively, integrated within a dSpace DS1006 data acquisition system (dSpace, Germany), controlled via custom made MATLAB script (MathWorks, Natick, MA, USA). The 3D LDV recording was done with 80 ms sampling time (12.5 Hz frequency resolution), repeated and averaged in the complex domain 15 times. An overview of the block diagram of the measurement system is presented in Fig. 1A, with corresponding sampling points grid, shown in Fig. 1B.

Noise floor measurements were conducted for each experimental configuration by not providing a signal to the BC transducer, while keeping the corresponding experimental configuration unchanged. Data with signal-to-noise ratio (SNR) below 10 dB was discarded. Additional signal quality check was done based on the signal coherence between the velocity signal(s) for each LDV and the corresponding stimulus signal. Coherence varied from 1 (for ideal coherence between the response velocity and stimulation signal at the excitation frequency) and 0 for no coherence, and data with coherence below 0.85 was discarded in further processing steps. Since the response at each frequency is recorded individually, discarding one measurement results in discarding only one of the full set of measurement frequencies, but not the whole set. The coherence calculations for the LDV measurements were done based on the complex frequency spectrum of the velocity and stimulus signals, as defined in the PSV 9.0 software (Polytec GmbH, Germany).

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