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Research Paper

Impedances of the inner and middle ear estimated from intracochlear sound pressures in normal human temporal bones

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ABSTRACT

For almost a decade, we have measured intracochlear sound pressures evoked by air conducted (AC) sound presented to the ear canal in many fresh human cadaveric specimens. Similar measurements were also obtained during round window (RW) mechanical stimulation in multiple specimens. In the present study, we use our accumulated data of intracochlear pressures and simultaneous velocity measurements of the stapes or RW to determine acoustic impedances of the cochlear partition, RW, and the leakage paths from scala vestibuli and scala tympani, as well as the reverse middle ear impedance. With these impedances, we develop a computational lumped-element model of the normal ear that illuminates fundamental mechanisms of sound transmission.

To calculate the impedances for our model, we use data that passes strict inclusion criteria of: (a) normal middle-ear transfer function defined as the ratio of stapes velocity to ear-canal sound pressure, (b) no evidence of air within the inner ear, and (c) tight control of the pressure sensor sensitivity. After this strict screening, updated normal means, as well as individual representative data, of ossicular velocities and intracochlear pressures for AC and RW stimulation are used to calculate impedances. This work demonstrates the existence and the value of physiological acoustic leak impedances that can sometimes contribute significantly to sound transmission for some stimulation modalities. This model allows understanding of human sound transmission mechanisms for various sound stimulation methods such as AC, RW, and bone conduction, as well as sound transmission related to otoacoustic emissions.

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1. Introduction

Passive macro-mechanics in fresh cadaveric human temporal bones are similar to the living, as is evidenced by similarities in measurements of sound-induced stapes vibration in live ears and fresh cadaveric specimens (Chien et al., 2009). “Passive macro-mechanics” of the cochlea refers to the gross mechanical properties of the inner ear. These do not include the active mechanical processes within the cochlear partition of live ears. For example, the inner-ear sound pressures in scala vestibuli (P_{SV}) and scala tympani (P_{ST}) measured close to the surrounding bone (not the partition near the traveling wave), quantifies the human *cochlear input pressure drive* (P_{SV} - P_{ST}), the complex differential pressure across the cochlea partition at the cochlear base that is dominated by fast wave sound pressure and starts the traveling wave along the cochlear partition (Olson, 1998). The cochlear input pressure drive

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Abbreviations: AC, air conduction; RW, round window; OW, oval window; SV, scala vestibuli; ST, scala tympani; P_{EC}, sound pressure in the ear canal; P_{ST}, sound pressure in the scala tympani; P_{SV}, sound pressure in the scala vestibuli; V_{act}, velocity of the actuator on the RW; Z_{Diff}, differential impedance across the partition including the helicotrema; Z_{RW}, RW impedance; $Z_{ME'}$, middle ear impedance from the cochlea looking out; Z_{lkSV}, leakage impedance of the SV to the exterior of the otic capsule; Z_{lkSTRW}, leakage impedance of the ST and RW; U_{stap}, volume velocity of stapes during AC stimulation; U_{Diff}, volume velocity across the partition; U_{RW}, volume velocity of RW during AC stimulation; U'_{stap}, volume velocity of stapes during RW stimulation; U_{lkSV} and U'_{lkSV}, volume velocity through the SV leakage for AC and RW stimulation; U_{lkST}, volume velocity through the ST leakage for AC stimulation; U'_{lkSTRW}, volume velocity through the ST and RW leakage for RW stimulation; U_{act}, volume velocity entering the cochlea during RW stimulation with actuator

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has been shown to have the same frequency response as sensory potentials (cochlear microphonic) measured at the same location in animals (Dancer and Franke, 1980; Lynch et al., 1982). Furthermore, the effects of middle and inner ear lesions (e.g. ossicular discontinuity and superior canal dehiscence) on the cochlear input drive in temporal bones are similar to clinical findings for hearing in live humans (Nakajima et al., 2009; Niesten et al., 2015; Pisano et al., 2012).

Measurements of intracochlear sound pressures and ossicular motions quantify important mechano-acoustic properties of the ear. Knowledge of the impedances of the middle and inner ear are necessary to understand the intricacies of sound transmission through the inner ear (Elliott et al., 2016; Nakajima et al., 2009; Stieger et al., 2013). Our pressure measurement techniques combined with velocity measurements of the stapes and round window are valuable in determining the sound transmission mechanisms that dominate during various forms of inner-ear stimulation (e.g. air conduction (AC), bone conduction (BC), round window (RW) stimulation, soft tissue stimulation, etc.).

Previously, we showed that the paths of sound-related volume velocity through the inner ear differ between ear-canal AC and actuator-driven RW stimulation (Stieger et al., 2013). For AC stimulation, evidence supports the two-window hypothesis: the input to the inner ear – the volume velocity produced by stapes motion (U_{stap}) at the oval window (OW) – and the output of volume velocity from the inner ear via the compliant RW (U_{RW}) are approximately equal (Kringlebotn, 1995; Stenfelt et al., 2004a). Therefore, in AC, other potential sound paths, such as vestibular and cochlear aqueducts, contribute little to sound transmission and have insignificant volume velocity sound flow.

Different from AC, RW stimulation results in inner-ear volume velocities that do not well conform to the two-window hypothesis (Stenfelt et al., 2004a; Stieger et al., 2013), where the volume velocity elicited by the RW actuator flowing into scala vestibuli does not all flow through the oval window, but splits, such that a significant fraction flows through a leakage path on the vestibular side of the cochlear partition (likely the vestibular aqueduct and/or neurovascular channels) (Dancer and Franke, 1980; Stieger et al., 2013; Tonndorf, 1972). A physical factor that contributes to this leak with RW stimulation is that the volume velocity elicited by stimulation faces an impedance at the OW (the reverse middle-ear impedance) that is similar in magnitude to the high impedance of the scala vestibuli leakage path (Stieger et al., 2013).

The major goal of the present study is to determine the values of the impedances that influence sound transmission within the inner ear. As a prerequisite for this task, we determine a "standard" set of sound-pressure transfer functions for "normal" human temporal bones – those without history of ear disease and with normal middle and inner ear macro-mechanics. From our accumulated measurements of intracochlear sound pressures and ossicular velocities during normal air conduction (AC) and round window (RW) stimulation, we implement strict inclusion criteria to describe the intracochlear sound pressure characteristics in normal ears. This set of standards, expressed as transfer functions, is useful for a) comparisons to past and future experiments, b) validation of computational models of the ear, and c) improving our understanding of the mechanism of sound transmission within the inner ear.

Using this data, we focus on the impedances that most influence the transmission of sound: the differential impedance across the partition measured at the base of the cochlea (Z_{Diff}, which includes the influence of the helicotrema), the RW impedance (Z_{RW}), the reverse middle-ear impedance from the cochlea looking out towards the middle ear ($Z_{ME'}$), the leakage impedance of the SV to the exterior of the otic capsule (Z_{lkSV}), and the leakage impedance of the ST and RW (Z_{lkSTRW}) to the exterior of the otic capsule. We use a combination of AC and RW stimulation results to determine these impedances. Based on these results we develop a lumped-element model that can help us understand more complex sound transmission mechanisms, such as bone- or soft-tissue-conducted sounds (Perez et al., 2016; Stenfelt, 2016; Stenfelt and Goode, 2005). This model can also impact our understanding of inner-ear sound transmission in pathological and perturbed states, where the flow of volume velocity through the inner ear is altered by changes in the relevant impedances or by the introduction of new volume velocity paths (e.g. superior canal dehiscence).

2. Methods

A total of 37 fresh human cadaveric temporal bones provide normative data. Pressure data from 22 specimens were already published including AC stimulation data from Nakajima et al. (2009), Stieger et al., 2013, Pisano et al., 2012, and Niesten et al., 2015. The RW stimulation data came from Stieger et al. (2013). In the aforementioned studies, except for Nakajima et al., 2009, there was a computational error such that the reported intracochlear pressures were 7 dB lower than the actual level; this error is now corrected. The methods for the present study were detailed in previous publications (Nakajima et al., 2009, 2010; Stieger et al., 2013). Therefore, only brief descriptions are given here.

2.1. Temporal bone preparation

The temporal bones were harvested within 24 h of death with surrounding dura kept intact, and used either fresh or after freezing and thawing. Inspection of the ear with a surgical microscope was normal with no noticeable pathology. The major difference between fresh and previously frozen was that fresh bones rarely showed evidence of air in the inner ear, while several of the thawed bones did (Ravicz et al., 2000). Prior to specimen preparation, the fresh and thawed specimens were stored at 4 °C in 0.9% normal saline. A mastoidectomy was performed to widely open the facial recess, and the stapedial tendon was usually removed to allow access to the area surrounding the oval window. In the RW stimulated ears, the bony overhang around the perimeter of the RW was reduced to facilitate the coupling of the actuator to the RW membrane.

2.2. AC and RW stimulation

For AC stimulation, a loudspeaker (either Radio Shack 40–1377 or Beyer Dynamic DT48) was coupled to the bony ear canal. Pure tones of 77 ms length at 74 logarithmically-spaced frequencies between 0.1 and 10 kHz were presented and responses averaged 25 or 50 times. The sound pressure within the ear canal (P_{EC}) was recorded with a probe microphone (ER-7C, Etymotic) with the tip located 1–2 mm from the umbo. The stimulus sound pressures were generally between 50 and 120 dB SPL.

For RW stimulation we used a piezoelectric actuator firmly coupled to a transparent-glass rod (1 mm diameter). In 5 specimens the tip of the rod was coupled to the RW membrane directly or with an interfacing disk (1.5 mm diameter) punched out of a soft contact lens. The glass rod was brought into contact with the RW membrane and pushed towards the inner ear in small increments until the stapes velocity and intracochlear pressure measurements stopped increasing in magnitude (Maier et al., 2013; Schraven et al., 2012). The RW stimulator was driven at the same frequencies as for AC stimulation. The magnitude of the stimulus displacement was generally between 55 nm and 85 nm.

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