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Research paper

Controlled exploration of the effects of conductive hearing loss on wideband acoustic immittance in human cadaveric preparations

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ABSTRACT

Current clinical practice cannot distinguish, with any degree of certainty, the multiple pathologies that produce conductive hearing loss in patients with an intact tympanic membrane and a well-aerated middle ear without exploratory surgery. The lack of an effective non-surgical diagnostic procedure leads to unnecessary surgery and limits the accuracy of information available during pre-surgical consultations with the patient. A non-invasive measurement to determine the pathology responsible for a conductive hearing loss prior to surgery would be of great value. This work investigates the utility of wideband acoustic immittance (*WAI*), a non-invasive measure of middle-ear mobility, in the differential diagnosis of pathologies responsible for conductive hearing loss.

We focus on determining whether *power reflectance* (*PR*), a derivative of *WAI*, is a possible solution to this problem. *PR* is a measure of the fraction of sound power reflected from the middle ear when a sound stimulus is presented to the ear canal. *PR* and other metrics of middle-ear performance (such as ossicular motion via laser Doppler vibrometry) were measured in well-controlled human temporal bone preparations with simulated pathologies. We report measurements before and after simulation of stapes fixation (n = 8), malleus fixation (n = 10), ossicular disarticulation (n = 10), and superior canal dehiscence (n = 8). Our results are consistent with the small set of previously published reflectance measurements made in temporal bones and patients. In this present study, these temporal bone experiments with different middle- and inner-ear pathologies were compared to the initial normal state by analyzing both *WAI* and ossicular motion, demonstrating that *WAI* can be a valuable tool in the diagnosis of conductive hearing loss.

1. Introduction

The causes of conductive hearing loss are often difficult to determine despite the frequent presentation of patients with various middle-ear diseases in the clinic (Merchant et al., 1998). The transmission of sound energy to the inner ear is affected by a wide range of factors that involve many segments of the peripheral auditory system: from the ear canal through structures within the inner ear. A pathological change anywhere within this sound transmission path can produce a 'conductive' hearing loss. Current clinical practice falls short in the differential diagnosis of patients with conductive hearing loss when they have an intact tympanic membrane and a well-aerated middle ear. Conductive hearing losses in such middle ears are generally associated with stapes immobilization (commonly called a 'fixation') due to otosclerosis, but can also be caused by a discontinuity in the ossicular chain, fixation of the malleus or incus, or a pathological opening in the bony inner ear wall such as a superior semicircular canal dehiscence (SCD) (Minor et al., 2003; Merchant and Rosowski, 2008). These pathological inner-ear openings are called 'third window'

Abbreviations: WAI, Wideband Acoustic Immittance; R, Reflectance; PR, Power Reflectance; UV, Normalized Umbo Velocity; SV, Normalized Stapes Velocity; RWV, Round Window Velocity; LDV, Laser-Doppler Vibrometry; SD, Standard Deviation; SNR, signal-to-noise ratio

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pathologies because they – like the normally occurring oval and round windows – are low-impedance paths for air-conducted sound energy to flow into and out of the cochlea.

In common practice, precise determination of the cause of a conductive hearing loss is not achieved without exploratory middle-ear surgery (Merchant and Rosowski, 2010). Even during surgery, diagnosis can be challenging (e.g. hair fracture of the anterior crus or a lesion near the incudo-malleal joint). A non-invasive measurement that objectively distinguishes among possible ossicular and inner-ear pathologies would be of value as it would (1) aid in preoperative counseling and pre-surgical planning, (2) prevent unnecessary middle-ear surgery in cases of patients with third window pathologies, and (3) help screen patients who should be referred for further time consuming and costly testing such as a high resolution computed tomography (CT) scan and vestibular evoked myogenic potential (VEMP) testing. Furthermore, a sensitive objective indicator of the presence of a canal dehiscence, even in the absence of hearing loss, would be a useful part of the diagnostic workup for these bony defects (Merchant et al., 2015).

Clinicians make limited use of objective assessments of middle-ear mobility in diagnosing middle-ear disease. Recently, measurements of *umbo velocity* using laser-Doppler vibrometry (LDV) and *wideband acoustic immittance* (*WAI*) measured in ear canals over a wide frequency range have been shown to aid in the non-invasive diagnosis of conductive disorders with aerated middle ears, including ossicular fixation, disarticulation, and SCD (e.g. Rosowski et al., 2003; Whittemore et al., 2004; Feeney et al., 2003; Allen et al., 2005; Rosowski et al., 2008; Feeney et al., 2009; Shahnaz et al., 2009a, 2009b; Withnell et al., 2009; Voss et al., 2012; Nakajima et al., 2012, 2013; Prieve et al., 2013; Merchant et al., 2015). Collectively, these studies demonstrate that broadband measurements of middle-ear mobility, including *WAI,* can aid in the non-invasive differential diagnosis of conductive pathologies. However, diseased ears can only be compared to an average population of normal ears, as the "normal" condition for a given pathological ear is unknown. Furthermore, substantial variability exists in *WAI* measurements across normal ears such that the normal range is rather broad (Keefe et al., 1993; Voss and Allen, 1994; Margolis et al., 1999; Shahnaz and Bork, 2006; Rosowski et al., 2012), even though small test-retest differences in *PR* in individual ears (Vander Werff et al., 2007; Werner et al., 2010; Rosowski et al., 2012) attest to the reliability of current *WAI* measurement techniques.

Precise measurements of *WAI* and its related quantities made in individual ears *before and after* the development of specific pathologies would provide the most controlled assessment of the effect of the pathology on the measurement. Unfortunately, this is not practical in patients where, typically, only measurements of the pathological states are available. The human temporal bone preparation, on the other hand, enables measurements that can be made on a normal ear with no signs of conductive pathology and also after subsequent manipulation of the ear to simulate specific pathologies. Furthermore, reversal of the manipulation can ensure that measured changes were indeed caused by the manipulation. Temporal bone studies enable detailed assessment of the effect of pathology on measurements such as *WAI.*

Limited *WAI* measurements have been published on temporal-bone preparations simulating various middle-ear pathologies including positive and negative static pressure, middle-ear fluid, ossicular fixations, ossicular disarticulation, and tympanic-membrane perforations (Feeney et al., 2009; Voss et al., 2012). In the present study, we investigate a more extensive list of pathologies. We also use *LDV* measurements of ossicular sound conduction as independent measures of the normality of the specimens as well as objective measures of the effects of the simulated pathology on sound conduction (Nakajima et al., 2005b; Chien et al., 2007).

2. Research design and methods

2.1. Human temporal bone inclusion criteria

Twenty-five non-identified human cadaveric temporal bones that were normal on microscopic evaluation were collected from donors with no known history of ear disease. Each specimen was either fresh or previously frozen and was prepared no more than 24 h prior to measurements. If initial velocity measurements suggested abnormality (either because of suspected air or a leak in the cochlea, as determined by the ratio of the stapes velocity to the round window velocity at low frequencies deviating from half cycle phase differences, or abnormal ossicular motion), the bone was not included in this study (Ravicz et al., 2000; Nakajima et al., 2005b; Rosowski et al., 2007). Three bones were determined to have air in the cochlea and eight either had pre-existing abnormalities or were damaged at some point during the experiment and were not used, leaving data from fourteen temporal bones in this report. Fig. 1 shows the half cycle low-frequency phase difference between the stapes and the round-window velocities for all fourteen preparations used in this study (in black), as well as an example of one preparation (in dashed gray) that did not pass the half-cycle criterion indicating intracochlear air or fluid leak.

Preparation of the bone involved opening the facial recess and epitympanum and severing the stapedial tendon to gain access to the malleus, stapes, and round window. Small pieces (~250 μm squares) of reflective tape (consisting of a collection of 20–50 μm plastic auto-reflective beads) were placed on the umbo (ear-canal side of the tympanic membrane), the posterior crus of the stapes, and the round window to increase the reflected light intensity for laser-Doppler vibrometry.

2.2. Temporal bone manipulations

Initial velocity and *WAI* measurements were made on each bone in the *normal* state, and repeated after each pathological

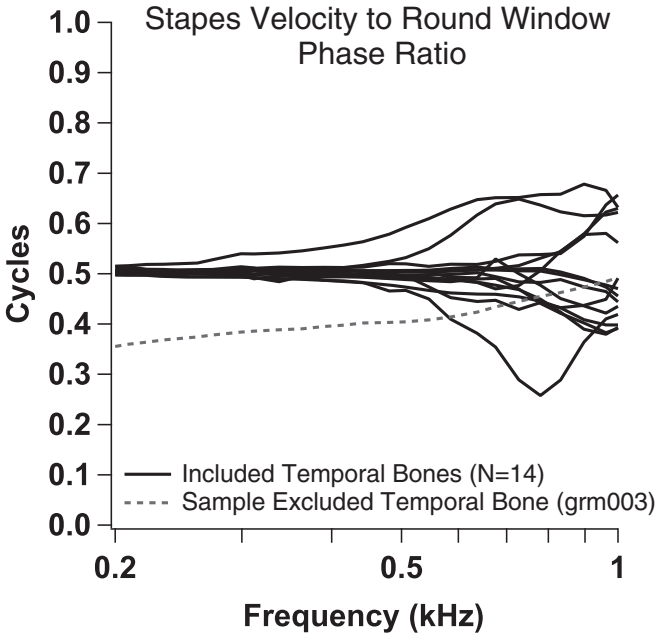

Fig. 1. Phase ratio between stapes and round window velocity. Half cycle low-frequency phase difference between the stapes velocity and the round window velocity for all fourteen preparations used in this study (black), as well as an example of one preparation (dashed gray) that was excluded due to suspected intracochlear air or fluid leak.