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Research Paper

Intracochlear pressure measurements during acoustic shock wave exposure

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ABSTRACT

Introduction: Injuries to the peripheral auditory system are among the most common results of high intensity impulsive acoustic exposure. Prior studies of high intensity sound transmission by the ossicular chain have relied upon measurements in animal models, measurements at more moderate sound levels (i.e. < 130 dB SPL), and/or measured responses to steady-state noise. Here, we directly measure intracochlear pressure in human cadaveric temporal bones, with fiber optic pressure sensors placed in scala vestibuli (SV) and tympani (ST), during exposure to shock waves with peak positive pressures between ~7 and 83 kPa.

Methods: Eight full-cephalic human cadaver heads were exposed, face-on, to acoustic shock waves in a 45 cm diameter shock tube. Specimens were exposed to impulses with nominal peak overpressures of 7, 28, 55, & 83 kPa (171, 183, 189, & 192 dB pSPL), measured in the free field adjacent to the forehead. Specimens were prepared bilaterally by mastoidectomy and extended facial recess to expose the ossicular chain. Ear canal (EAC), middle ear, and intracochlear sound pressure levels were measured with fiber-optic pressure sensors. Surface-mounted sensors measured SPL and skull strain near the opening of each EAC and at the forehead.

Results: Measurements on the forehead showed incident peak pressures approximately twice that measured by adjacent free-field and EAC entrance sensors, as expected based on the sensor orientation (normal vs tangential to the shock wave propagation). At 7 kPa, EAC pressure showed gain, calculated from the frequency spectra, consistent with the ear canal resonance, and gain in the intracochlear pressures (normalized to the EAC pressure) were consistent with (though somewhat lower than) previously reported middle ear transfer functions. Responses to higher intensity impulses tended to show lower intracochlear gain relative to EAC, suggesting sound transmission efficiency along the ossicular chain is reduced at high intensities. Tympanic membrane (TM) rupture was observed following nearly every exposure 55 kPa or higher.

Conclusions: Intracochlear pressures reveal lower middle-ear transfer function magnitudes (i.e. reduced gain relative to the ear canal) for high sound pressure levels, thus revealing lower than expected cochlear exposure based on extrapolation from cochlear pressures measured at more moderate sound levels. These results are consistent with lowered transmissivity of the ossicular chain at high intensities, and are consistent with our prior report measuring middle ear transfer functions in human cadaveric temporal bones with high intensity tone pips.

1. Introduction

Noise induced hearing loss and related diseases are a major concern for the modern military: tinnitus and hearing loss are the

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two most common disabilities for which the U.S. Department of Veterans Affairs provides compensation (VBA, 2017). A majority of all injuries in veterans returning from Iraq and Afghanistan are a result of exposure to blast from improvised explosive devices (Owens et al., 2008), thus auditory dysfunction, defined in this paper as hearing loss and tinnitus, is more likely to be correlated with a blast-related traumatic brain injury (TBI) than any other type of TBI, affecting upwards of 60% of these patients (Fausti et al., 2005; Lew et al., 2007). Understanding the mechanisms underlying these auditory injuries thus may enable better predictions of injury, and enhanced protection and recovery from blast exposure.

The literature contains many case reports describing human exposure to blast waves (e.g. Bruins and Cawood, 1991; Chandler and Edmond, 1997; Remenschneider et al., 2014; Yetiser and Ustun, 1993), and the effects of blast exposure on hearing outcomes has been evaluated systematically in animals (Cho et al., 2013; Price and Wansack, 1989) and humans (Patterson and Johnson, 1994a, 1994b). However, fewer studies have investigated the propagation of energy into the inner ear during an exposure directly. Prior studies of high intensity sound transmission by the ossicular chain have relied upon either measurements in animal models (e.g. Guinan and Peake, 1967; Price, 1974b) or measurements at more moderate sound levels (e.g. < 130 dB SPL: Hato et al., 2003; Nakajima et al., 2009). In particular, the effects of nonlinearities in ossicular chain motion on sound transmission (Greene et al., 2017; Guinan and Peake, 1967; Price, 1974a) are not well understood, complicating predictions of injury resulting from high level impulse noise (Henderson and Hamernik, 1986).

Several tools have been developed to estimate injury and determine safe exposure limits to impulse noise. The recently adopted MIL-STD-1474E (DoD, 2015) military acquisition standard includes two such tools, $L_{IAeq100\,ms}$, an “equal energy” model that computes the noise dose equivalent to a 100 ms impulse, and that *may* be used by the Air Force and Navy, and the Auditory Hazard Assessment Algorithm for Humans (Price and Kalb, 1991) which *must* be used for Army Materiel acquisition. The AHAAH model is an electroacoustic analog model of the human ear designed to predict injury from impulse noise exposure (Price and Kalb, 1991). The AHAAH model represents an interesting approach to injury prediction, and significant insights have been derived from the model; however, the model was designed using data from studies in animals (particularly cat; Kalb and Price, 1987), and several components need to be updated and the results validated (Wightman et al., 2010). In particular, ossicular chain nonlinearities have a substantial effect on AHAAH model results, but the extent and degree of nonlinear effects have not been well characterized in the human ear.

Frequency and level dependent nonlinearities in ossicular chain motion, particularly due to the limiting effect of the stapedial annular ligament (SAL), have been shown to reduce sound transmission into the cochlea during continuous sound exposure in the cat (Price, 1974a). When adapted to the human, this transmission reduction leads to the counterintuitive and contentious prediction of a non-monotonic dose-response function for large caliber weapons in the output of the AHAAH model, above which higher intensity exposures are predicted to cause reduced injury (Price, 2007). In support of such a result, reports have provided evidence in support of a compressive nonlinearity in the ossicular chain motion (Price et al., 2017). Others, however, have suggested that while the displacement limitation is present, the implementation in the AHAAH model is overly-compressive, and that reduction (but not elimination) of the SAL compliance eliminates this behavior (Smoorenburg, 2003; Zagadou et al., 2016). The controversy surrounding the dose-response inversion (in addition to other controversial aspects) of the AHAAH model have been discussed previously (Wightman et al., 2010), and have been the subject of a recent exchange in the literature (Price et al., 2017; Zagadou et al., 2016, 2017).

We have previously shown that stapes motion is indeed limited at high sound exposure levels in a cadaveric human preparation, but that this limitation occurs at a higher sound level (by at least 10 dB) than predicted by the AHAAH model, thus supporting the assertion that the model is overly compressive (Greene et al., 2017). That report established, for pure tones, that ossicular chain displacement and the sound pressure level generated in the cochlea may be limited at high levels; however, results indicated substantial frequency dependence in the relationships between incident sound pressure level, stapes displacement, and the generated intracochlear sound pressure level. The AHAAH model is explicitly designed to predict injury in response to impulse noise exposure, which is by definition a broad-band stimulus, thus cross-frequency effects may lead to further unanticipated effects in the sound transmission to the cochlea. Empirical measurements are necessary to fully characterize the relationship between impulse noise exposure and the risk to hearing, and the accuracy of the AHAAH model in predicting this injury. To begin to fill this gap, here we report results of intracochlear pressure measurements in the scala vestibuli (SV) and scala tympani (ST), in human cadaveric temporal bones, during exposure to shock waves with peak positive pressures between ~7 and > 83 kPa.

2. Materials and methods

The use of temporal bone tissue was in compliance with the University of Colorado Anschutz Medical Campus Institutional Biosafety Committee. Eight fresh-frozen whole-head specimens with no history of middle ear disease (except presbycusis) were evaluated. Tissue was obtained from cadavers undergoing autopsy with permission to use tissues and organs for research (Lone Tree Medical Donation, Littleton, CO).

2.1. Temporal bone preparation

Temporal bone preparation procedures were similar to several recent reports from our laboratory (e.g. Deveze et al., 2010; Greene et al., 2017; Greene et al., 2015; Mattingly et al., 2015; Maxwell et al., 2017). Briefly, the temporal bones were prepared bilaterally: The pinna and surrounding skin were reflected during preparation but left intact. Temporal bones were prepared with a canal-wall-up mastoidectomy with an extended facial recess. The facial canal was opened and the facial nerve removed to maximize access and visibility of the middle-ear structures, which were inspected for damage and abnormalities. The ossicular chain was not disturbed (including the stapedius muscle/tendon). The cochlear promontory was thinned near the oval and round windows in preparation for pressure probe insertion.

2.2. Instrumentation

Sensor placement is illustrated in Fig. 1A: specimens were outfitted with an array of sensors in the ears bilaterally, as well as on the surface of the skull, and in the air adjacent to the front surface of the head. The exposure level was measured in the free field adjacent to the specimen's forehead with a “pancake”, or “splitter” style pressure probe (Endevco 8530C), oriented with the sensor surface 90° to the long-axis of the shock tube. Surface sensors were attached ~2–3 cm above the pinna (in line, vertically, with the entrance of the ear canal) outside the area of coverage by a set of ear muffs (note: results of hearing protection use are not discussed in this report, see section 2.4 for additional details), as