Hearing Research xxx (2018) 1–10

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Intracochlear pressure in response to high intensity, low frequency sounds in chinchilla

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A R T I C L E I N F O

Article history:
Received 15 February 2018
Received in revised form
8 June 2018
Accepted 19 June 2018
Available online xxx

Keywords:
Laser Doppler vibrometry
Intracochlear pressure
Blast overpressure
Acoustic shock wave
Stapedial annular ligament

A B S T R A C T

Exposure to high intensity (blast) sounds can result in both conductive and sensorineural damage to hearing. This includes rupture of the tympanic membrane and dislocation of the middle ear ossicles, as well as damage to the inner and outer hair cells in the cochlea. A clearer understanding of how the hearing system responds to blast could help us better prevent auditory trauma, and support those who have been exposed to such sounds.

Chinchillas are often used in studies of hearing due to the similarity between the chinchilla and human audiograms. The suitability of their use in research on auditory trauma from blast noise will depend on the extent to which cochlear pressures generated in chinchillas compare to those in humans. In order to gain a more detailed understanding of the response of the ear to high intensity sounds, a custom built sound concentrating horn was used to expose chinchilla cadaveric ears to a series of single frequency tones between 10 and 1280 Hz, with varying intensities from 90 to 194 dB SPL while intracochlear pressures were measured simultaneously in the scala vestibuli and scala tympani. These results were then compared to similar, previously published data from human cadavers.

In both human and chinchillas, intracochlear pressures increased with applied sound pressure up to about 120 dB SPL, but began to saturate at higher intensities. The exact saturation point and the saturation pressures showed a strong frequency dependence. Intracochlear pressure magnitudes in chinchillas show some similarities with those measured in humans, but also significant differences, particularly at very high intensity levels such as those found in a blast. These differences should be taken into account when conducting blast studies in chinchillas.

1. Introduction

High intensity sound exposure is a concern in the civilian world, but is naturally of particular importance to individuals in the military (Cooper et al., 2014; Fausti et al., 2009; Gee et al., 2013). Auditory injury from noise and blast overpressure is the leading cause of medical referral for soldiers returning from Operation Enduring Freedom and Operation Iraqi Freedom, with 71% reporting exposure to loud noises and 15.6% reporting ringing in the ears (Geckle and Lee, 2004). Exposure to high intensity impulsive sounds, such as those produced by gunfire or the detonation of explosives, can result in both conductive and sensorineural damage to hearing. This includes rupture of the tympanic membrane and dislocation of the middle ear ossicles (Chandler and Edmond, 1997; Mayo and Kluger, 2006), as well as damage to the inner and outer hair cells in the cochlea (Patterson and Hamernik, 1997). Additionally, propagation of the blast wave through the brain tissue can be responsible for a spectrum of neuronal injury, from cognitive impairment to disruption of central auditory function (Okie, 2005; Rosenfeld and Ford, 2010; Salat et al., 2017).

The diagnoses following noise and blast overpressure exposure range from eardrum perforation to hearing profiles that would likely disqualify the individual from duty (Tufts et al., 2009). The problem of assessing injury is compounded because the symptoms of central auditory dysfunction can be difficult to separate from the deficits associated with traumatic brain injury (Fausti et al., 2009; Gallun et al., 2012). A clearer understanding of the response of the middle and inner ear to high intensity sounds would be of value in assessing the risk posed to individuals exposed to such sounds, and in better diagnoses of the damage such sounds cause. The need for a

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https://doi.org/10.1016/j.heares.2018.06.013
0378-5955/© 2018 Published by Elsevier B.V.

broadly validated model of auditory hazard has long been recognized.

Towards this goal, a number of methods have been developed to assess the potential of loud sounds to cause hearing injury, and evaluate the effectiveness of related hearing protection devices. Perhaps the best known of these is the Auditory Hazard Assessment Algorithm in Humans (AHAAH) used by the U.S. Department of Defense (AHAAH, 2015; Binseel et al., 2009; Department of Defense, 2015; Fedele et al., 2013; Price, 2011; Price and Kalb, 1991). AHAAH is an electro-acoustic circuit analog of the human auditory system that is comprised of three elements simulating the outer ear (pinna through eardrum), middle ear (ossicular chain and air volume), and the inner ear (cochlea). The AHAAH model links these three components in order to simulate the propagation of acoustic stimuli into the inner ear and is capable of predicting threshold shifts due to a range of auditory events.

Unfortunately the AHAAH model has identified limitations (Wightman et al., 2010; Zagadou et al., 2016); for example, the current AHAAH model is overly compressive and is thus not predictive of human auditory damage at very high input levels (Smoorenburg, 2003). The over compressiveness was due in part to the use of stapes displacement data from cats, and not humans. While the motion of the ossicles and the pressures in the cochlea in response to sound have been studied previously, and some of these results used in the AHAAH model, much still remains unclear.

To begin to fill some of these knowledge gaps, intracochlear pressures and stapes displacement have been measured in response to high intensity, low frequency sound (Greene et al., 2017), and to acoustical shock waves (Greene et al., 2018), similar to those that occur as a result of an explosion (Reed, 1977). Greene et al. (2017) showed that stapes displacement and intracochlear pressures maintained a linear relationship up to the point where stapes displacement saturates, at ~200 μm in humans, as opposed to ~30 μm measured in the cat (Guinan and Peake, 1967; Price, 1974). While Greene et al. (2017) observed substantially larger stapes displacements than those reproduced in the AHAAH model, the study only characterised responses at a sparse number of frequencies and levels. Importantly, an extension of this study into living humans was naturally not possible, limiting the direct application of these results to human health hazard assessments development.

Damage criteria predicted by AHAAH were determined by comparing AHAAH model output to hearing damage observed in humans under controlled or semi-controlled conditions (e.g., the ‘Albuquerque Blast Overpressure Walk-up Studies’, see Zagadou et al., 2016 for review), but questions still remain. To more directly understand the anatomical, physiological and functional consequences to hearing due to blast exposure, animal models including rats, guinea pigs and chinchilla have been used (Chen et al., 2013; Cho et al., 2013; Ewert et al., 2012; Gan et al., 2016; Hamernik et al., 1984; Mao et al., 2012; Patterson and Hamernik, 1997; Race et al., 2017; Sindelar et al., 2017).

Chinchillas are a common model for such research because their hearing range is quite similar to human (Heffner and Heffner, 1991; Miller, 1970), and thus have been used extensively in hearing (Koka et al., 2011; Salvi et al., 1990) and hearing loss studies (Dunn et al., 1991; Lupo et al., 2011; Patterson and Hamernik, 1997). The anatomical, physiological, and behavioural sequelae of noise exposure have been thoroughly described in chinchilla (Dunn et al., 1991; Hamernik et al., 1993, 1984). The stapes displacements and intracochlear sound pressure levels generated in chinchilla cochlea by moderate level sounds have been described previously (Chhan et al., 2013; Ravicz et al., 2010; Ravicz and Rosowski, 2013; Slama et al., 2010). Nevertheless, the suitability of the use of chinchilla, or any animal model for that matter, in research on auditory trauma from blast noise depends on the extent to which the low-frequency components of blast waves are effectively transmitted to the inner ear and secondarily whether the intracochlear pressures in the chinchilla are similar to those in humans at high exposure levels.

To gain a more detailed understanding of the response of the ear to high intensity sounds, and to compare the response of human ears to those of chinchillas, we made direct, simultaneous measurements of scala vestibuli pressure and scala tympani pressure in response to a series of single frequency tones of varying sound intensities. A goal of these studies was to determine the ear canal sound pressure levels in human and chinchilla that result in equivalent cochlear pressures in the two species. These data may then be used in reverse to estimate the ear canal sound pressures that cause permanent hearing loss in human based on the ear canal sound pressures in chinchilla that led to permanent hearing loss. Damage risk criteria in the AHAAH or similar auditory hazard models could then be updated accordingly.

In this paper we report the results of the ear canal to cochlea pressure transfer function measurements in chinchilla in response to low-frequency high intensity sound, discuss the similarities and differences between our results and previously reported measurements in human cadavers, and discuss the use of these measurements in future studies on blast-related injury to the auditory system.

2. Methods

2.1. Animal preparation

These experiments followed the general methodology outlined by (Chhan et al., 2016, 2013). Six adult cadaveric chinchillas were used for this study. The chinchillas had been frozen shortly after euthanasia, and were fully thawed before measurements. The skull of the chinchilla was opened to expose the bulla and allow access to the middle ear ossicles and the turns of the cochlea. The tensor tympani and stapedius muscles were left intact.

Pressures in the scala vestibuli were measured by inserting small-diameter (250 μm), off the shelf fiber optic pressure probe (FOP-M260-ENCAP, FISO Inc., Canada) into a small hole drilled in the vestibule near the oval window. To measure scala tympani pressure, the posterior bulla was opened and a small hole was drilled near the round window. The fiber optic pressure sensors were precisely positioned and held in place using micromanipulators (Kopf, Tujunga, CA), and were sealed in place after insertion with Jeltrate Alginate Impression Material.

2.2. Sound presentation

All experiments were performed in a double-walled sound attenuating chamber (IAC Inc., Bronx, NY, USA). Sounds were generated and data collected using a Hammerfall Multiface II soundcard (RME, Haimhausen, Germany), and signals were designed and analysed in custom-built programs in MATLAB (Mathworks, Natick, MA, USA). Sound stimuli consisted of 29 logarithmically spaced tones with frequencies between 10 and 1280 Hz.

The low-frequency, high intensity sound delivery system was similar to that described by Greene et al. (2017). Briefly, sounds were presented to the specimen with a ~30 cm subwoofer (Morel UW 1258) driven by a 300 W amplifier (Keiga KG5230) and two Selenium D408Ti 2-Inch Titanium Horn Drivers driven by a Crown amplifier (XLi 3500), all three drivers attached to a custom-built stainless steel sound concentrating horn, and were directed into the ear canal with flexible copper tubing. The total length of the sound concentrating horna and copper tubing was ~3 m; it's diameter tapered from ~30 cm to ~1.25 cm.