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Research paper

Mechanical damage of tympanic membrane in relation to impulse pressure waveform – A study in chinchillas

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ABSTRACT

Mechanical damage to middle ear components in blast exposure directly causes hearing loss, and the rupture of the tympanic membrane (TM) is the most frequent injury of the ear. However, it is unclear how the severity of injury graded by different patterns of TM rupture is related to the overpressure waveforms induced by blast waves. In the present study, the relationship between the TM rupture threshold and the impulse or overpressure waveform has been investigated in chinchillas. Two groups of animals were exposed to blast overpressure simulated in our lab under two conditions: open field and shielded with a stainless steel cup covering the animal head. Auditory brainstem response (ABR) and wideband tympanometry were measured before and after exposure to check the hearing threshold and middle ear function. Results show that waveforms recorded in the shielded case were different from those in the open field and the TM rupture threshold in the shielded case was lower than that in the open field (3.4 ± 0.7 vs. 9.1 ± 1.7 psi or 181 ± 1.6 vs. 190 ± 1.9 dB SPL). The impulse pressure energy spectra analysis of waveforms demonstrates that the shielded waveforms include greater energy at high frequencies than that of the open field waves. Finally, a 3D finite element (FE) model of the chinchilla ear was used to compute the distributions of stress in the TM and the TM displacement with impulse pressure waves. The FE model-derived change of stress in response to pressure loading in the shielded case was substantially faster than that in the open case. This finding provides the biomechanical mechanisms for blast induced TM damage in relation to overpressure waveforms. The TM rupture threshold difference between the open and shielded cases suggests that an acoustic role of helmets may exist, intensifying ear injury during blast exposure.

1. Introduction

Exposure to high intensity sound or blast overpressure waves is considered to be an intrinsic situation faced by military personnel involved in most operational activities. The direct consequences of high-intensity noise and blast injuries to the auditory system are acute hearing loss, which immediately affects the normal functioning of soldiers in combat operations, and the resultant long-term hearing disabilities that occur in a significant fraction of veterans (Patterson and Hamernik, 1997; Garth, 1994; Karmy-Jones et al., 1994; Gondusky and Reiter, 2005; Fausti et al., 2009).

Blast overpressure is a high intensity disturbance in the ambient air pressure that creates high intensity sound (impulse) over 170 dB SPL. When exposed to a blast, the human auditory system is vulnerable to both peripheral and central damage from the overpressure (Patterson and Hamernik, 1997; Mayorga, 1997). Rupture of the eardrum or tympanic membrane (TM) is the most frequent injury of the ear and has been investigated in animals and humans with wide variability (Hirsch, 1966; Patterson and Hamernik, 1997; Richmond et al., 1989). The literature indicates that mechanical damage to components of the auditory system is the major cause for hearing loss after blast exposure. However, it is not clear how the severity of injury graded by different patterns of TM rupture is related to the overpressure waveforms induced by blast exposure. Particularly, no quantitative study on biomechanical changes of the TM in response to different pressure waveforms has been reported

Abbreviation: ABR, Auditory Brainstem Response; AML, Anterior Malleal Ligament; EA, Energy Absorbance; FE, Finite Element; FSI, Fluid–Structure Interaction; PIL, Posterior Incudal Ligament; PST, Posterior Stapedial Tendon; SAL, Stapedial Annual Ligament; S.D., Standard Deviation; TM, Tympanic Membrane; TMA, Tympanic Membrane Annulus; TTT, Tensor Tympani Tendon

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in the literature.

In this paper, we report our currently completed study on relationships between the TM rupture threshold, the TM damage pattern, and the overpressure waveforms using a chinchilla animal model. The chinchilla is a commonly used animal model for auditory research with large TMs, ossicular dimensions, and middle ear spaces for an animal of its size. The chinchilla's range of hearing is similar to that of humans (Heffner and Heffner, 1991; Richmond et al., 1989; Jensen and Bonding, 1993). In the present study, two groups of animals were exposed to high intensity sound pressure under two conditions: the open field without a shield and the shielded case with a stainless steel cup covering the animal head. By increasing the blast peak pressure level, the TM was finally ruptured and the pressure waveforms at the entrance of the ear canal were recorded simultaneously. The goal of this study was to determine whether there is a change of overpressure waveform under the shield and how the waveform change affects the TM rupture threshold.

In addition to experimental testing in animals, impulse pressure energy spectra analysis of the waveforms recorded under open and shielded conditions was performed to determine signal energy flux over 10 frequency bands. The 3D finite element (FE) model of the chinchilla middle ear recently developed in our lab was employed to calculate the distributions of the stress and strain in the TM with impulse pressure profiles recorded in open and shielded conditions. The FE modeling results reveal that a waveform pattern consisting of both positive and negative pressures in the shield case (under a stainless steel cup) contributes more greatly to TM damage than the positive overpressure in the open case. This finding provides the biomechanical mechanisms for blast induced TM damage in relation to overpressure waveforms. The TM rupture threshold difference between the open and shielded cases suggests that an acoustic role of helmets may exist, intensifying ear injury during blast exposure.

2. Methods

2.1. Animal study protocol

Eighteen chinchillas (*Chinchilla laniger*) weighing between 600 and 800 g were included in this study. The study protocol was approved by the Institutional Animal Care and Use Committee of the University of Oklahoma and met the guidelines of the National Institutes of Health and the United States Department of Agriculture (USDA). All animals were established to be free from middle ear disease, as evaluated by wideband tympanometry.

A well-controlled compressed air (nitrogen)-driven blast apparatus located inside an anechoic chamber in the Biomedical Engineering Laboratory at the University of Oklahoma was used to create a blast overpressure wave or blast exposure in this study (Hawa and Gan, 2014). Polycarbonate film (McMaster-Carr, Atlanta, GA) of varying thickness (130 μm and 260 μm) was employed to generate blast overpressure of at least 30 psi (200 dB SPL). The overpressure level was controlled by varying the distance from the blast reference plate. Fig. 1A shows a schematic of the blast apparatus with the animal holder placed at the center.

The animals were divided into two groups: one group of 9 animals was exposed to blast in an "open field" (Fig. 1A) and another group of 9 animals was exposed to blast with a shield covering the animal head as shown in the schematic of Fig. 1B and the picture of Fig. 1C. The animals in both groups were first tested with the pre-exposure measurements, including middle ear energy absorbance (EA) using wideband tympanometry (Model AT235h, Interacoustics, MN) and auditory brainstem response (ABR) using TDT system III (Tucker–Davis Technologies, Alachua, FL). The EA measurement applied tone-burst stimuli at frequencies of 0.5, 1, 2, 4, and 8 kHz in the ear canal (Guan and Gan, 2011; Jeselsohn et al., 2005; Petrova et al., 2006; Qin et al., 2010). The EA measurement was used as a check of the TM integrity and normal function of the middle ear. The ABR measurements provided the change of hearing threshold of the ear after blast exposure. The animal was anesthetized with mixed ketamine (10 mg/kg) and xylazine (2 mg/kg). To maintain consistent measurement of ABR, tympanometry, and blast pressure level, the pinna was removed.

After pre-exposure testing, the animal was placed into a specially designed animal holder. A pressure sensor (Model 102B16, PCB Piezotronics, Depew, NY) was placed at the entrance of the ear canal (1 cm lateral to the ear canal opening) with the sensing surface facing the blast in both open and shielded conditions. During the shielded test, the entire animal head was covered by a stainless steel cup with a thickness of 2 mm. The edge of the cup was flushed with the sensor which was also covered by the shield (Fig. 1C). Note that the chinchilla head shield was adjustable with relative position from the animal head and there was a distance of about 3 cm from the animal head to the internal top surface of the shield. The stainless steel shield was finally fixed on the animal holder. The animal within the holder was then moved to the testing chamber for blast exposure.

The pressure sensor signal was measured by cDAQ 7194 and A/D converter 9215 (National Instruments Inc., Austin, TX) with the sampling rate of 100k/s (10 μs dwell time). The LabVIEW software package (NI Inc.) was used for data acquisition and analysis. The waveform of each blast test was saved in a PC for further analysis.

It usually took 2–3 iterations of blast tests to reach the TM rupture threshold defined as the peak pressure before the TM rupture. That means if the TM ruptured after the third blast, the threshold was the peak pressure level of the second blast. The initial blast pressure level was selected based on the system calibration using different films and changing the distance between the sensor surface and the blast reference plane. The number of blast tests also varied with individual chinchillas due to the variation among the animals and setups. To confirm the TM damage, an otoscopic examination of both ears was performed first and further verification was done using wideband tympanometry to determine whether the TM was ruptured. When the TM was found without rupture, the next blast test was conducted with an increase of overpressure level. The testing stopped when one ear was ruptured.

Post-exposure measurements included wideband tympanometry to verify whether the TM was ruptured or damaged in both ears and ABR measurement in the ears with intact TMs to determine the hearing threshold shift after exposure. The TM damage pattern was recorded by taking pictures after the animal was euthanized and the bulla was dissected.

2.2. Waveform analysis

Impulse pressure energy spectra analysis on recorded waveforms in the time domain was conducted in MATLAB to determine the signal energy distribution over the frequencies under open and shielded conditions. First, the recorded pressure waveforms were converted to pressure distributions over the frequencies of 20–5000 Hz by using FFT spectral analysis. Next, following the methods of impulse signal energy distribution theory reported by Hamernik et al. (1991), Hamernik and Keng (1991), Hamernik and Qiu (2001) and Young (1970), the total sound exposure was divided by the standard characteristic impedance of the air ρc as impulse energy flux (energy per unit area) and expressed as:

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