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Research paper

Impulse noise injury prediction based on the cochlear energy

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ABSTRACT

The current impulse noise criteria for the protection against impulse noise injury do not incorporate an objective measure of hearing protection. A new biomechanically-based model has been developed based on improvement of the Auditory Hazard Assessment Algorithm for the Human (AHAAH) using the integrated cochlear energy (ICE) as the damage risk correlate (DRC). The model parameters have been corrected using the latest literature data. The anomalous dose–response inversion behavior of the AHAAH model was eliminated. The modeling results show that the annular ligament (AL) parameters are the dominant cause of the non-monotonic dose–response behavior of AHAAH. Based on parametric optimization analysis, a 40% reduction of the AL compliance from the AHAAH default value removed the dose–response inversion problem, and this value was found to be within the physiological range when compared with experimental data. The transfer functions from the new model are in good agreement with those of the human ear. A dose–response curve based on ICE was developed using the human walk-up temporary threshold shift (TTS) data. Furthermore, the ICE values calculated for the German rifle noise tests show excellent comparison with the injury outcomes, hence providing a significant independent validation of the improved model. The ICE was found to be the best DRC to both large weapons and small arms noise injury data, covering both protected and unprotected exposures, respectively. The new AHAAH model with ICE as the dose metric is adequate for use as a medical standard against impulse noise injury.

1. Introduction

Hearing loss from exposure to impulse noise remains one of the top medical problems for the military, resulting in huge long-term medical costs and the loss of personnel due to hearing disability. According to the U.S. Department of Veterans Affairs, 21% of nearly 7 million cases contain the pathological outcomes of auditory damage (US Department of Veterans Affairs, 2011).

A system acquisition standard (MIL-STD-1474E) was recently adopted that includes the option of using the current Auditory Hazard Assessment Algorithm for Human (AHAAH) software (Price, 2007a, 2007b; Price and Kalb, 1991), which was developed by the Army Research Laboratory (ARL), or a variant of the LAeq8 model (LIAeq100ms). Both of these models have limitations. The LIAeq100ms model has not been validated, and the AHAAH is still under a rigorous investigation for verification, validation, and improvement. However, MIL-STD-1474E is not a medical standard against impulse noise. A medical standard is needed that consistently predicts injury from both small arms and large weapon noise with accurate differentiation between HPDs to replace the historical military standard, MIL-STD-1474D (Dept. of Defense, 1979).

The American Institute of Biological Sciences (AIBS) panel (Wightman et al., 2010) recommended that a biomechanically-based model relating the noise insult to the hearing organ response be used to accurately predict auditory injury from

Abbreviations: ARU, Auditory Risk Unit; AHAAH, Auditory Hazard Assessment Algorithm for Human; AIBS, American Institute of Biological Sciences; AL, Annular Ligament; AR, Acoustic Reflex; ARL, Army Research Laboratory; ATF, Acoustical Test Fixture; BM, Basilar Membrane; BOP, Blast Overpressure Project; CI, Confidence Interval; DRC, Damage Risk Correlate; GME, Middle ear pressure gain; HPD, Hearing Protection Device; ICE, Integrated Cochlear Energy; LAeq8, Standard equivalent 8 hours equal energy model-based metric; LIAeq100ms, Equal energy model-based metric integrating the impulse over 100 ms; MIL-STD-1474D, Historical military standard; MIL-STD-1474E, System acquisition standard; OC, Organ of Corti; PPL, Peak Pressure Level; REAT, Real Ear Attenuation at Threshold; SELA, A-weighted Sound Exposure Level; SVTF, Stapes velocity transfer function; TF_{EC2ED}, Transfer function from the ear canal to the eardrum; TTS, Temporary Threshold Shift; USAMRMC, USA Military Research and Materiel Command; WKB, Wentzel-Kramers-Brillouin; Z_0, Cochlear input impedance

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impulse noise exposures to provide a model-based standard to replace MIL-STD-1474D. The AHAAH model is an electro-acoustic model of the peripheral hearing organ simulating the traumatic response of the auditory system to impulse noise. The model includes three components: the outer ear from pinna to eardrum, the middle ear comprised of the air spaces and ossicles, and the inner ear formed by the cochlea. The three components are electro-acoustically connected to each other to allow the propagation of external noise to the cochlea (Price and Kalb, 1991).

The AIBS panel recommended continued research and development to improve the AHAAH model with rigorous validation so that it can be used as a model-based standard against impulse noise injury. While the accomplishment of the AHAAH model is recognized, controversies about some of its modeling approach and simulation results have not been resolved among impulse noise experts. For instance, the parameters of the current AHAAH model, originally developed for the cat, were assigned to the human model by assuming that cats and humans have the same ear properties, but a rigorous verification of the adequacy of these parameters was not provided. This paper presents an improved AHAAH model whose parameters have been calibrated based on human data from recent literature to correctly reproduce the human ear transfer functions. One critical aspect that is also addressed by the present study is the non-monotonic dose–response behavior of AHAAH against large weapon noise as shown in (Price, 2007b), which suggests that an exposure at higher intensity will result in lower risk of injury, although this is not supported by field data (Smoorenburg, 2001). Smoorenburg (2001) found indeed that the AHAAH model is overly compressive. Even though many biological systems are characterized by a nonlinear response, an inverted V-shaped risk curve displayed by the current AHAAH is questionable. The consistent and dramatic reduction of risk of injury as the blast intensity is increased is not substantiated by human data. On the contrary, the field data support that injury rate increases with blast intensity. Therefore, a biomechanically-based model for prediction of impulse noise injury should also be characterized by a monotonically increasing dose-response. The critical improvements to AHAAH that removes this non-monotonic dose–response behavior are presented in this paper. The modeling of the acoustic reflex (AR) is another controversial aspect of AHAAH that suggests a significant difference in auditory risk between warned and unwarned exposures but will not be addressed by this study because of the lack of available data. Instead, the unwarned exposure condition is assumed for all calculation results presented in this paper.

A method also needs to be developed to account for use of the hearing protector with the model. For unprotected exposures, AHAAH uses the free field data as model input. For protected exposures, AHAAH requires the input of ear canal data (under the HPD) as input. Although limited work has suggested the possibility of the coupling of AHAAH to a hearing protector model, the development of a generalized hearing protector model is a separate research effort that is still ongoing. The present work will show the use of an acoustical test fixture (ATF) to collect eardrum pressure as the input to AHAAH when HPDs are involved.

Two sets of historical data were used to validate the improved AHAAH model. The first set of data was collected from human volunteers exposed to simulated large weapon noise in a test series conducted by the US Army Medical Research and Material Command (USAMRMC) at the blast test site at Kirtland Air Force Base in Albuquerque, NM, commonly known as the “Walk-up” or “Albuquerque” study as part of the Blast Overpressure Project (BOP). In the Walk-up study, a range of earmuffs and earplugs were used as HPDs and injury data from over 300 volunteers were collected. The results from the AHAAH model validation against the Walk-up test data also produced the model-based dose–response curves. Historical German rifle noise data from (Brinkmann, 2000; Pfander et al., 1980) were then used to independently validate the dose–response curves.

Previous analysis of the Walk-up study data has produced an empirical model fit that confirmed that the existing impulse noise auditory criteria are overly conservative by at least 9.6 dB (Chan et al., 2001) but the extension of that to small arms conditions without HPDs has not been tested. It has long been recognized that reconciliation of empirical model fits between large weapons exposures involving HPDs and small arms exposures for unprotected ears is not easy without a validated biomechanical method to handle the HPDs. This paper demonstrates that the use of the ATF is needed to enable the model-based standard to be used for protected and unprotected noise exposures.

The objective of this paper is to present the results from a 3-year research effort to develop and validate a biomechanical model-based medical standard against impulse noise injury. The biomechanical model is based on the AHAAH model with critical improvements based on published material property data and validation against human data. This work pursues a deep and thorough research of the AHAAH model by examining every component and model parameter by going into the source code with rigorous verification against literature data. The work includes detailed evaluation of the model behavior by performing extensive parametric studies. The end goal will lead to the development of a biomechanically valid correlate for construction of a dose–response relationship using human outcome data. In addition, a test method using the ATF has been developed to collect eardrum data as model input to account for the effects of HPD attenuation and head orientation.

2. Materials and methods

2.1. The human BOP Walk-up study

The historical Walk-up study conducted by the USAMRMC produced the largest human dataset known to-date (Johnson, 1994). The data include the waveforms of simulated large weapon noise for three standoff distances (1, 3, and 5 m) from the noise source and the resulting human temporary threshold shift (TTS) data from over 300 human volunteers for five types of HPDs. The HPDs used included an intact (unmodified) earmuff, a modified earmuff with 8 tubes inserted in the cushion to reduce sound attenuation, simulating a poor fitting condition, and three earplugs (French No. 1 plug, Rucker plug, and perforated plug). The waveforms were collected in the free field using pencil gauges and also under the earmuffs with a microphone for selected subjects.

The statistical design of the Albuquerque human Walk-up study was to estimate the dose threshold for 95% protection of the subjects 95% of the time against auditory injury. Injury was defined as TTS measured 2 min after exposure exceeding 25 dB (at any frequency in the exposed ear). A typical test series consisted of exposures from one of the test distances with the test subjects fitted with one of the HPDs according to the test matrix shown in Fig. 1. For each test series, there were 7 exposure levels with the peak pressure level (PPL) increasing by about 3 dB for each higher level as shown on the left side of the walk-up matrix, and an increasing number of shots (N) were given from 6 to, 12, 25, 50, and 100 at level 6, with some groups split between levels 6 and 5 at 100 shots. The vertical and horizontal arrows indicate the progression of the Walk-up study. Beginning with 6 shots, each group of n subjects was exposed at level 1; only uninjured subjects were allowed to advance to the next level. For those subjects who passed level 7, they were exposed at level 6 with the number of shots increased from 12 to 100 following the horizontal arrow; again only