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Noise dosimetry for tactical environments

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ABSTRACT

Noise exposure and the subsequent hearing loss are well documented aspects of military life. Numerous studies have indicated high rates of noise-induced hearing injury (NIHI) in active-duty service men and women, and recent statistics from the U.S. Department of Veterans Affairs indicate a population of veterans with hearing loss that is growing at an increasing rate. In an effort to minimize hearing loss, the U.S. Department of Defense (DoD) updated its Hearing Conservation Program in 2010, and also has recently revised the DoD Design Criteria Standard Noise Limits (MIL-STD-1474E) which defines allowable noise levels in the design of all military acquisitions including weapons and vehicles. Even with such mandates, it remains a challenge to accurately quantify the noise exposure experienced by a Warfighter over the course of a mission or training exercise, or even in a standard work day. Noise dosimeters are intended for exactly this purpose, but variations in device placement (*e.g.*, free-field, on-body, in/near-ear), hardware (*e.g.*, microphone, analog-to-digital converter), measurement time (*e.g.*, work day, 24-h), and dose metric calculations (*e.g.*, time-weighted energy, peak levels, Auditory Risk Units), as well as noise types (*e.g.*, continuous, intermittent, impulsive) can cause exposure measurements to be incomplete, inaccurate, or inappropriate for a given situation. This paper describes the design of a noise dosimeter capable of acquiring exposure data across tactical environments. Two generations of prototypes have been built at MIT Lincoln Laboratory with funding from the U.S. Army, Navy, and Marine Corps. Details related to hardware, signal processing, and testing efforts are provided, along with example tactical military noise data and lessons learned from early fieldings. Finally, we discuss the continued need to prioritize personalized dosimetry in order to improve models that predict or characterize the risk of auditory damage, to integrate dosimeters with hearing-protection devices, and to inform strategies and metrics for reducing NIHI.

1. Introduction

Noise exposure and the subsequent hearing loss are well documented aspects of military life. Numerous studies have indicated high occurrences of noise-induced hearing injury (NIHI) in active-duty Service Men and Women (Ahroon et al., 2011; Helfer et al., 2011; Yankaskas, 2013), and recent statistics from the U.S. Department of Veterans Affairs indicate a population of veterans with hearing loss that is growing at an increasing rate (US Dept. of Veterans Affairs, 2015). Some surveys are limited in scope to certain wars, such as those in Iraq and Afghanistan (Theodoroff et al., 2015), while a comprehensive U.S. Department of Defense (DoD) study is currently underway to understand the overall scope and cost of hearing impairment in active-duty personnel (Cooper et al., 2014). Hearing loss also has been shown to reduce the operational capabilities of Warfighters (Sheffield et al., 2015), thus extending the burdens of NIHI for the military community beyond the financial and physiological.

In an effort to control the growth in hearing loss within the military, the DoD updated its Hearing Conservation Program in 2010 to further address such topics as combat-related hearing conservation measures and occupational and operational noise exposure computation and monitoring (US Dept. of Defense, 2010). Also recently revised is the DoD Design Criteria Standard, Noise Limits (MIL-STD-1474E), which mandates allowable noise levels in the design of all military acquisitions including weapons and vehicles (MIL-STD-1474E, 2015). Even with such guidelines, however,

Abbreviations: AHAAH, Auditory Hazard Assessment Algorithm for Humans; ARU, Auditory Risk Unit; COTS, Commercial Off the Shelf; DoD, U.S. Department of Defense; HPD, Hearing Protection Device; NIHI, Noise-Induced Hearing Injury; PTS, Permanent Threshold Shift; SPL, Sound Pressure Level; SWaP, Size, Weight, and Power; TTS, Temporary Threshold Shift; TWA, Time-Weighted Average

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it remains a challenge to accurately quantify the noise exposure experienced by an individual over the course of a mission or training exercise, or even over the course of a standard work day.

A noise dosimeter is a device that measures noise exposure and reports the dosage accumulated over a period of time. The challenges of accurate noise dosimetry are due to a number of factors, including the variety of noise types and environments encountered, and the demands this variety places on dosimeters and their use. Different military environments have been studied for noise characterization, including aircraft carriers (Yankaskas and Shaw, 1999; Rovig et al., 2004) and ground-vehicle interiors (Nakashima et al., 2007), and while noise measurements typically are not made during ground operations for mounted or dismounted Warfighters (see Section 4.1 for an exception), weapon noise has been the subject of considerable research (Nakashima and Farinaccio, 2015). Such environments tend to contain complex, time-varying noise fields that complicate the collection of data and the subsequent determination of auditory risk.

Noise generally is classified as continuous (exhibiting only small changes in level over time), intermittent (interrupted by occasional increases in level), impulsive (containing components with sharp rises and rapid decays), or complex (a combination of the above), and the frequency range and level can vary with the type and source of the noise. Typical commercial noise dosimeters are required to operate only up to 140 dB sound-pressure level (SPL) and cover a frequency range similar to that of human hearing (ANSI, 1991). However, weapons fire, blasts, and other impact noises can exceed this SPL limit, and impulses can exhibit acoustic bandwidths extending well beyond the audio spectrum due to their short durations (Kardous and Willson, 2004; Kardous et al., 2005). Thus, dosimeter design, for example with respect to microphone and analog-to-digital converter performance, is critical for measurement success. Dosimeter placement also can affect measured results, as free-field, on-body, and in/near-ear microphone positions can yield variations in measured spectra and levels due to absorption by clothing, head shadowing, and pinna resonances (Kuhn, 1979). Fixed dosimetry "stations" may be the most practical to set up and maintain, but spatially varying noise fields and moving subjects require individually worn dosimeters to assess personal noise exposure accurately.

Once measured, noise-exposure data can be compared against established limits or other criteria to determine a need for hearing protection or predict the risk of hearing loss. As described in Section 2.2, such metrics come in many forms with a range of limitations and applicability. For continuous noise, MIL-STD-1474E uses 8-h time-weighted average (TWA) SPLs. In contrast, for impulse noise, it specifies limits for peak-pressure levels, equal-energy equivalent levels averaged over 100 ms intervals ($L_{IAeq100ms}$), and Auditory Risk Units generated by the Auditory Hazard Assessment Algorithm for Humans (AHAAH) (Price, 2007; Kalb and Price, 2015). Despite the long list of existing metrics, noise-exposure and risk-assessment metrics remain an active area of research, with recent proposed changes to the AHAAH model to compute integrated cochlear energy (Zagadou et al., 2016), and a new approach for assessing risk from complex noise exposure (Sun et al., 2016). Ultimately, the development of more useful assessments and accurate predictions of risk and damage requires a combination of accurate dosimetry and a deeper understanding of how noise exposure affects different parts of the auditory system.

In this paper, we first provide an overview of noise-dosimetry basic principles in Section 2. We then describe the design of a dosimeter for near-ear acquisition and analysis of continuous and impulsive noises characteristic of military environments, developed at Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) with funding from the U.S. Army, Navy, and Marine Corps. Details related to hardware, signal processing, and testing efforts are provided in Section 3, along with example military noise data, including samples from a unique collection during combat operations, and lessons learned from early fieldings in Section 4. Finally, Section 5 discusses the continued need to prioritize personalized noise dosimetry in order to improve models that predict or characterize the risk of auditory damage and inform strategies and metrics for reducing NIHI.

2. Basics of noise dosimetry

2.1. Overview

Noise dosimetry involves measuring sound pressure levels in an environment with the goal of estimating the total dosage to which an individual is exposed over the course of a day, work shift, or event of interest. Often the dose is estimated in terms of A-weighted energy in conjunction with the equal-energy hypothesis (EEH), which assumes that accumulated noise *energy* is sufficient to determine risk of NIHI and that the underlying temporal characteristics of the noise are irrelevant. Under the EEH, two exposures are equivalent if the respective average noise levels and durations comply with a specified exchange rate. For example, a 3-dB exchange rate often is employed such that a halving or doubling of the exposure time is accommodated with a +3 or −3 dB adjustment, respectively, to the allowable noise level.

In an effort to conserve hearing in industrial and military settings, guidelines on the maximum allowable daily noise exposure are recommended by regulating agencies such as National Institute for Occupational Safety and Health (NIOSH) and military branches under the DoD Hearing Conservation Program. This allowable daily noise dosage is expressed as a percent relative to the recommended limit, *i.e.*, 100% dose represents maximum allowable noise exposure for an individual. For exposure in a continuous noise environment, the current military standard design criteria MIL-STD-1474E (2015) sets a limit of 85 dBA for a duration of 8 h, where the exposure duration and level may be traded off to satisfy an equal-energy criterion using a 3 dB exchange rate.

To understand the needs of a dosimetry device, it can be informative to classify noise into three general types – continuous, intermittent and impulsive – as illustrated in Fig. 1. Of these types, impulsive noise may be the most demanding with respect to dosimeter design due to its highly dynamic nature and extreme levels, for example from weapons fire. This challenging range of conditions drives the need for a broadband dosimetry device with a high sampling rate and a wide dynamic range to avoid clipping or distortion from large blasts. A fourth noise type, complex noise, combines background (continuous or intermittent) and impulsive noise, each independently contributing sufficiently high levels to induce temporary threshold shifts (TTS). Dosimetry device specifications are discussed further in Section 3.

In practice, dosimetry data can be collected with free-field, on-body, or in-ear devices. Free-field noise surveys typically are short in duration (lasting no more than a few hours) and characterize the noise levels of an environment rather than for an individual. As described further in Section 5, accurately translating a free-field survey to the dose for a Warfighter can be challenging. For example, reverberating noise within closed spaces can produce spatially varying noise levels for which the level at the eardrum can vary dramatically (10 dB or more) depending on the exact positioning of body and ear relative to the noise source (Shaw and Vaillancourt, 1985). This variability is particularly problematic for impulsive noise, due in part to its broad spectrum. High frequency (short duration, short wavelength) components are susceptible to reflections from shorter spatial scales, resulting in reverberation