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Development and Evaluation of a Body-Worn Dosimeter for Continuous and Impulsive Noise

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Abstract— **Noise exposure is encountered nearly everyday in both recreational and occupational settings, and can lead to a number of health concerns including hearing-loss, tinnitus, social-isolation and possibly dementia. Although guidelines exist to protect workers from noise, it remains a challenge to accurately quantify the noise exposure experienced by an individual due to the complexity and non-stationarity of noise sources. This is especially true for impulsive noise sources, such as weapons fire and industrial impact noise which are difficult to quantify due to technical challenges relating to sensor design and size, weight and power requirements. Because of this, personal noise dosimeters are often limited to a maximum 140 dB SPL and are not sufficient to measure impulse noise. This work details the design of a body-worn noise dosimeter (mNOISE) that processes both impulse and continuous noise ranging in level from 40 dBA-185 dBP (i.e. a quiet whisper to a shoulder fired rocket). Also detailed is the capability of the device to log the kurtosis of the sound pressure waveform in real-time, which is thought to be useful in characterizing complex noise exposures. Finally, we demonstrate the use of mNOISE in a military-flight noise environment.**

Clinical Relevance—**On-body noise exposure monitoring can be used by audiologists, industrial hygiene personnel, and others to determine threshold of injury, adequate hearing protection requirements and ultimately reduce permanent noise-induced hearing loss.**

I. INTRODUCTION

Noise exposure is encountered nearly everyday in both recreational [1] and occupational settings, with over one billion individuals at risk of permanent hearing loss [2]. Hearing loss and noise tinnitus are well established clinical outcomes related to noise exposure, and recent concerning evidence suggests a possible causal link between hearing loss and the onset of dementia [3].

The relationship between noise and damage to the cochlea and auditory pathway has been studied extensively through the use of animal models and epidemiological approaches, but it remains a challenge to understand the short-term and long-term dose-response relationship between noise exposure and hearing damage for human listeners [4]. One major reason for this is that human noise noise exposures vary considerably from day-to-day [5] and are hard to characterize over an extended period even when substantial efforts are devoted to environmental noise monitoring. Other contributing factors are variations in the use and efficacy of hearing protection devices and genetic variations in the susceptibility of individual listeners to long-term hearing damage [6,7].

The best way to account for day-to-day variability in noise exposures is personal noise dosimetry, which uses a wearable noise dosimeter to continuously monitor the noise environment and compute risk metrics based on the cumulative exposure of an individual listener [8]. Many commercial devices exist for occupational noise monitoring, and smartphones and smartwatches have been recently proposed as ways to measure exposures in free-living conditions with minimal burden to the participant [9,10].

These existing noise dosimeter devices work well for continuous noise exposures, but in general they are not well suited for environments that contain impulsive or impact noise greater than 140 dB [5]. For environments that contain both impulsive and continuous noise (i.e. complex noise), the challenge is even greater because of the extremely wide measurement range required (i.e. potentially as much as 150 dB). Military personnel in particular are often exposed to complex noise [11], and it may be one of the factors resulting in millions of claims of hearing loss and tinnitus in the veteran population each year [4].

Industrial noise exposures also may contain complex noise. In a recent study by Qui et. al, accumulated evidence from a study of thousands of factory workers suggests that current noise metrics under-predict the risk of hearing-loss due to complex noise exposures [12]. However, that study was limited to measurements below 140 dB, and relied on raw acoustic pressure recordings that potentially contain speech, posing a privacy concern.

This work details the design of a body-worn noise dosimeter, mNOISE (monitoring Noise On-body and In-ear for Serviceperson Exposures), that allows for study of complex and impulsive occupational noise exposures that are traditionally difficult to measure. mNOISE is designed to have a very wide measurement range of 40dBA-185dBP (i.e. a quiet whisper to a shoulder fired rocket). It also enables capture of impulsive raw pressure waveforms (on the order of 100 ms at a time), while maintaining privacy by limiting recording of speech or continuous noise. Also detailed is the capability of the device to log the kurtosis of the sound pressure waveform

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in real time, which is thought to be useful in characterizing complex noise exposures. Finally, we demonstrate the use of mNOISE in a military-flight noise environment.

II. METHODS

A. Hardware

The open-source audio platform “Tympan” (tympan.org) was used as the basis for the mNOISE recorder [13]. The original purpose of the Tympan was as an open-source platform for hearing-aid algorithm research. This mNOISE system allows for sampling, processing, and storing multi-channel audio to an SD card at a sample rate of 96 kHz. The mNOISE recorder is built upon a Tympan RevD, which is itself built upon the Teensy® 3.6 development platform. The audio interface includes two Texas Instruments TLV320AIC3206 audio codecs, which enable the system to independently digitize and process up to 4 analog audio inputs, though only 2 inputs are currently employed. The system is battery powered via a built-in, rechargeable, Lithium-Polymer battery. The system includes Bluetooth communication for interacting with mobile devices. The system can be programmed through the Arduino development environment or through any other environment supported by the Teensy community.

The mNOISE uses a two-microphone configuration to extend its dynamic range enough to measure both continuous and impulse noise. The first microphone, selected for continuous noise, is a micW i436. This microphone is also used with the NIOSH (National Institute for Occupational Safety and Health) Sound Level Meter app and has an approximate measurement range of 40 dBA to 140 dBP. The second “impulse” microphone, a G.R.A.S. 47BX-S7, is specifically tuned to capture levels from 80 dBA-185 dBP and has a bandwidth up to 50 kHz. This microphone requires ICP® power, which is provided by custom circuitry added to the Tympan-based mNOISE. By combining the two microphones, the measurement range of the system becomes 40 dBA - 185 dBP, which spans the range of many continuous and impulse noise sources.

B. Algorithm Design

Our algorithm design aims to store important information about complex exposures that contain both continuous and impulse noise sources [14]. The A-weighed energy or L_{Aeq} is perhaps the most common way to express the noise level of an environment [15]. Equation 1 details how each digital pressure sample is divided by the reference pressure $p_{ref} = 20\ \mu Pa$, then squared to calculate the energy over a unit of time. The A-weighted pressure x_A, refers to a band-pass filter applied to the raw pressure data that approximates the sensitivity of the human ear. Finally, the L_{Aeq} is then often expressed as a time-weighted average where the 8 hour time-weighted average L_{Aeq} has a recommended limit of 85 or 90 dB for daily exposure.

$$L_{Aeq} = 10log10\frac{1}{N}\sum_{n=0}^{N}\left(\frac{x_A[n]}{p_{ref}}\right)^2 \qquad (1)$$

Fig. 1. A photograph of the mNOISE microphone enclosure, recorder, and a depiction of the real-time smart-phone application.

where $N = 0.1s$ corresponds to the default, fast update interval.

For impulse noise, the L_{Aeq} is also used as a damage risk metric, but there are other metrics such as the AHAAH model that require access to the original pressure waveform [16,17]. Because of this, we designed our system to log the raw acoustic impulse waveform, lasting only on the order of a few hundred milliseconds. In between impulse events below a threshold (e.g. 140 dB SPL), the acoustic pressures are not logged for privacy reasons as well as to reduce data storage requirements.

Figure 2 illustrates the overall system architecture for our design. The resulting raw impulse waveforms are stored via SD card, while relevant metrics such as the LAeq8 (8-hour time weighted exposure) are also stored or can be accessed in real-time via smartphone. While this algorithm was first conceptualized and run offline in our prior work [5], this is the first time the algorithm has been implemented in real-time during data collection to enable widespread measurement without privacy concerns.

C. Kurtosis Corrected L_{Aeq}

For complex environments that contain both impulsive and continuous noise, the LAeq is thought is thought to underestimate the risk of injury [18]. Goley et. al, proposed an adjustment to the LAeq, L'_{Aeq} (in Eq 3) for these types of environments, that has shown promise in large-scale measurements of factory workers [19]. The adjustment is based on the kurtosis (β) of the acoustic signal (Eq 2), which describes the impulsiveness of the complex noise.

$$\beta[X] = \mathrm{E}\left[\left(\frac{X-\mu}{\sigma}\right)^4\right] = \frac{\mathrm{E}\left[(X-\mu)^4\right]}{\left(\mathrm{E}\left[(X-\mu)^2\right]\right)^2} = \frac{\mu_4}{\sigma^4} \tag{2}$$

$$L'_{Aeq} = L_{Aeq} + \lambda log10\frac{\beta}{\beta_G} \tag{3}$$

where β is the kurtosis of the noise and $\beta_G = 3$ the kurtosis of Gaussian noise, and $\lambda = 4.02$ is a model constant determined to best fit prior changes in audiometric threshold [18].

However, current noise dosimeters are unable do this adjustment, and research on the kurtosis adjustment has been limited to devices that record all audio in the environment followed by offline calculation. We implemented a kurtosis calculation using a running estimate [20,21] based on an extension of the Welford algorithm for computing standard deviation. The resulting kurtosis is then stored in 60 second non-overlapping windows in a time-stamped file on the SD card. This alleviates the need to store the raw pressure waveform and the resulting privacy concerns.

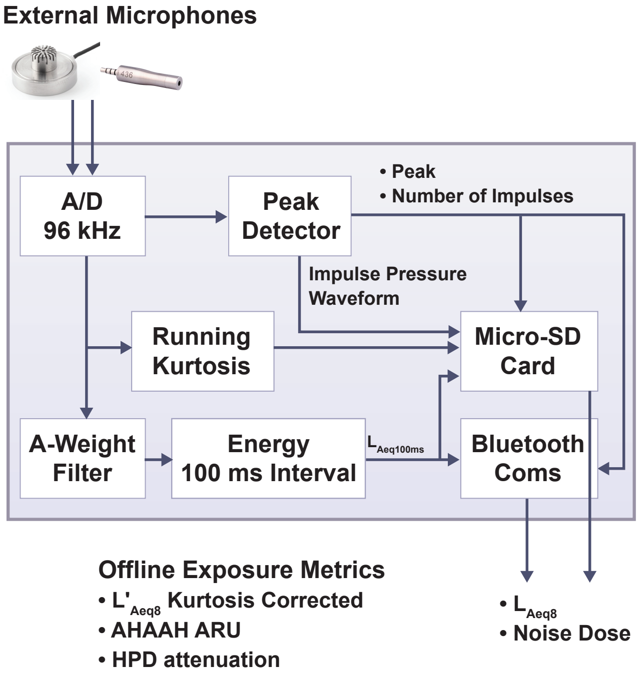

Fig. 2. Audio is input into the mNOISE through two microphones, one intended for impulse noise measurement, the other for continuous noise. The impulse channel is passed through a peak detector which detects impulse events and stores them to disk. A second path records the A-weighted energy of the pressure waveform and logs that to disk in a separate file stream. This design enables both immediate access to predicted exposure and offline assessment of impulse waveforms.

D. Validation

Accuracy of the noise measurement system was evaluated in the laboratory using a compressed-air shock tube [22,23]. A National Instruments data acquisition system (PXI 4462) was used as a gold standard measurement and sampled acoustic pressures from a G.R.A.S. 46DP 1/8” pressure microphone. Measurements were made at 200 kHz for the gold standard system, and 96 kHz for the mNOISE. The two microphones were co-located approximately 12 inches from the opening of the shock tube.

III. RESULTS

Twenty-two Friendlander-like impulse noise waveforms with peak pressures ranging from 150-180 dB SPL were recorded from both the gold standard measurement system and the mNOISE. The peak pressures are compared in Figure 3. An example of a single pressure waveform is shown in the inset plot, where the mNOISE pressure waveform is shown in blue, and the reference gold standard is shown in red. These results suggest very accurate measurement of the peak pressure across a range of impulse noise levels ($R = 0.99$), as well visual similarity in the actual pressure waveform.

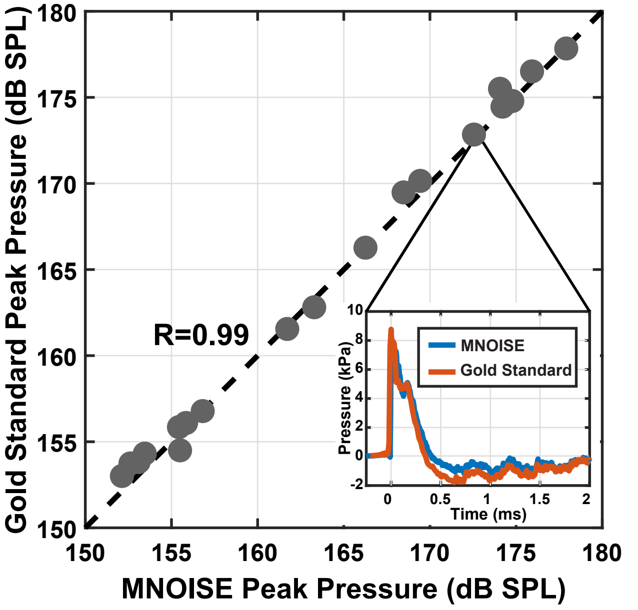

Fig. 3. Comparison of the peak pressure measurements made from mNOISE device as compared to a gold-standard national instruments measurement system. A correlation of 0.99 was achieved between the peak-pressures of the two asynchronously acquired pressure waveforms. The inset plot displays the pressure waveform for the gold standard (blue) and mNOISE waveforms (red), for a single impulse at 172 dBP.

A. Field Test Results

Figure 4 illustrates a field noise recording obtained during flight of a military heavy lift helicopter with the crew chief firing 600 rounds from the GAU 21 .50 caliber machine gun. The mNOISE dosimeter microphone assembly was attached near the shoulder of the participant. The start of the flight can be seen visually occurring shortly after 1200 hours,

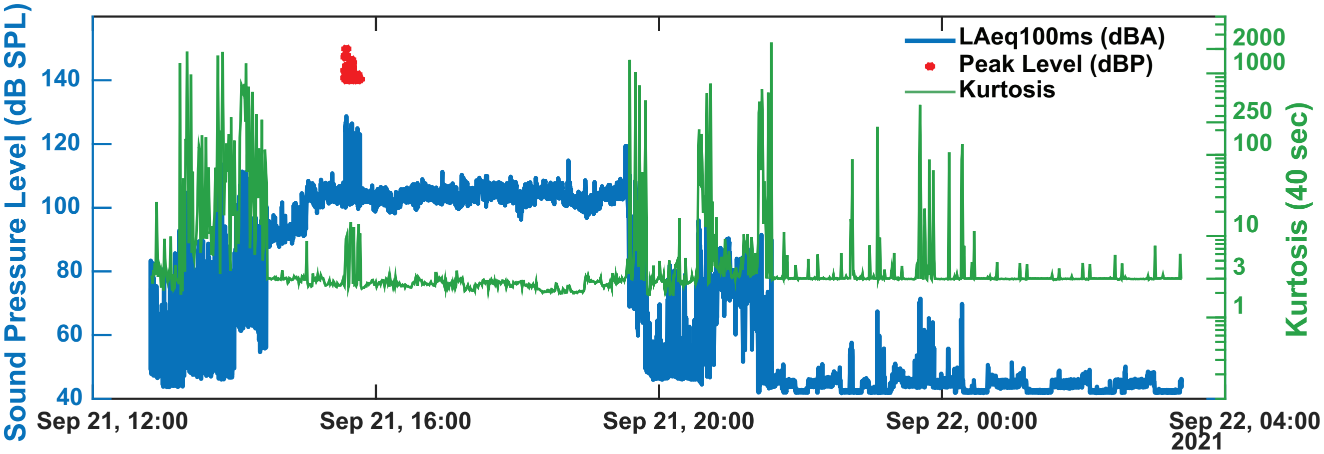

Fig. 4. Time-pressure history for a noise recording during military helicopter flight. The complex noise exposure included both weapons fire from a GAU 21 0.50 caliber machine gun in addition to the engine noise, with an average kurtosis of 34.1.

where the continuous noise level in blue reaches a steady state level near 105 dBA. Impulse noise events are indicated as red dots, while the running kurtosis is shown in green. This noise environment is emblematic of complex noise, and is particularly difficult for traditional noise dosimeters to capture, since the impulse peak levels can reach 150-160 dBP, beyond the range of most commercial noise meters. The resulting LAeq8 was 110.1 dBA, while the mean kurtosis was 33.1, giving a corrected L'_{Aeq8} of 114.3 dBA (See Table I. The device achieved a run-time of at least 13 hours, sufficient to capture the entire noise exposure event.

The kurtosis adjustment L'_{Aeq} is suggested as a correction factor for this type of complex environment. The Noise Reduction Rating (NRR), required to be labeled on all hearing protectors in the US, suggests the amount of attenuation needed in dB to meet the NIOSH 85 dB 8-hour time-weighted exposure criterion. The de-rating is an adjustment paramer used to reduce NRR in typical usage in the field [24], where we show a 0% (no de-rating) and a 25% derating.

L_{Aeq8}	110.1 dBA SPL
Average Kurtosis	33.1
L'_{Aeq8}	114.3 dBA SPL
NRR needed at 25% derating	44 dB
NRR needed at 0% derating	34 dB

TABLE I

COMPLEX NOISE EXPOSURE FIELD TEST SUMMARY

IV. DISCUSSION

In this paper, we detail the algorithmic design of the mNOISE dosimeter, validate its performance across a wide range of acoustic pressures, and demonstrate its capability in a complex noise environment. Because the original pressure waveform for any impulses (e.g. weapons fire, impact noise) are stored, offline analysis can support research on damage risk criteria as new models are developed, in particular for complex noise environments. Calculations that must be done on the continuous-pressure waveform, such as the energy and kurtosis must be done online; this can be rapidly implemented in this platform. The two unused audio inputs of the system also make it possible to measure protected exposures by using microphones embedded under the hearing protector. This type of measurement may lead to a more accurate estimate of the true exposure experienced by the individual [6].

Our validation dataset showed good agreement between a gold-standard measurement system and the mNOISE for impulses generated with a compressed-air shock tube across a range of peak sound-pressure levels. While this validation does not include many different types of real-world noise sources, in general the accuracy of noise exposure measurement system will be governed by factors including the frequency response of the sensor (microphone) and electronics, as well as the measurement noise floor, maximum sound pressure level and digital sampling-rate. Other comparisons of the mNOISE have been performed by the authors with other impulsive noise sources such as artillery; the measurement accuracy was found to be consistent to what is reported in Figure 3.

While their are potential size-weight and power trade-offs with measurement accuracy, the real-world benefits of a simple-to-use, wearable mixed-noise dosimeter like the mNOISE available to the hearing conservation community are expected to be substantial. In most occupational environments, the responsibility for monitoring noise exposures falls on audiologists or industrial hygienists who are able to operate traditional sound level meters but lack the considerable expertise required to measure and analyze high-level blast exposures using laboratory-grade equipment. A system like the mNOISE that could partially automate impulse noise monitoring and conduct a preliminary analysis on the results would greatly increase the number of number of complex noise environments that could be analyzed for potential noise hazards. This would allow hearing conservation personnel to mitigate the hearing risks experienced by personnel in high-noise environments. The exposure data could also be combined with data on the hearing changes experienced by noise-exposed listeners, both from studies that conduct field audiometry measurements immediately pre- and post-exposure [25] and from hearing surveillance programs that monitor the long-term hearing health on noise-exposed individuals. Combining both data sets would greatly increase number of noise exposure data points where both the dose (e.g. LAeq, AHAAH) and the biological outcome (e.g. temporary hearing threshold shift) are known. This dose-response data is critically important for refining the existing models for estimating the hearing hazard associated with different types of high-level noise exposures. As the available data set grows, machine learning based approaches [26] may prove particularly useful in capturing dynamics of noise induced hearing loss due to complex, everyday exposures.

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