Workers and military personnel exposed to high noise levels increase their risk of noise induced hearing loss (NIHL). In addition, individuals do not always use hearing protection devices (HPD) or, if they do, the HPD may not fit properly or provide adequate protection against high level noise. Hearing Conservation Programs conduct annual hearing monitoring which unfortunately provides limited ability to intervene before potential noise-induced damage to the cochlea; instead, these programs typically serve to document irreversible hearing loss. Monitoring noise exposure is an ideal way to assess risk before damage occurs, but it is difficult to measure complex noise environments that include high-intensity impulse sounds. We present on the development of an integrated device that (1) provides hearing protection; (2) measures the noise in the ear canal to generate an estimate of dose and correlate in-ear dose to ambient noise levels; and (3) monitors distortion product otoacoustic emissions (DPOAE) and extended high frequency hearing over time. A prototype was built and tested in the laboratory using acoustic test fixtures in both continuous and impulsive noise. Measured noise attenuation reached 30dB or better at frequencies above 250Hz and was on par with a commercial earmuff (NRR of 28 dB) in the presence of impulse noise. The internal microphone could accurately measure impulses as high as 120 dB SPL [Peak Free-Field Equivalent], and as high as 152 dB SPL [Peak Free-Field Equivalent] when placed under commercial earmuffs. The prototype uses an SD card to record raw data during human studies and the battery was measured to last 3 hr during continuous recording. This “SuperPlug” will allow users to monitor the potential impact of auditory insults as close to the injury as is possible, and eventually enable real-time intervention such as pharmaceuticals, to mitigate pre-clinical hearing damage and prevent noise-induced hearing loss (NIHL).

Keywords: Hearing protection, dosimetry, otoacoustic emissions

1. Introduction

1.1 Noise-induced hearing loss

Ten percent of Americans have some hearing loss that affects their ability to communicate normally and noise-induced hearing loss is the second most common cause (after age-related) of sensorineural hearing loss in the U.S. It has been estimated that as many as 30 million Americans are regularly exposed to potentially harmful noise levels as part of their standard workplace environments and that as many as 10 million Americans have hearing loss at least in part caused by noise exposure in the work-
place or during recreational activities. Further, economic costs of occupational hearing loss have been estimated to be in the billions of dollars annually. While noise-induced hearing loss is so common, it is also preventable if individuals exposed to high noise levels could be adequately monitored and protected from the harmful effects of high noise exposure. Furthermore, studies have shown that noise-exposed individuals may have no or minimal changes on their audiogram, yet still have difficulty understanding speech in noise [1] [2]. Hearing conservation programs (HCP) in occupational settings are designed to reduce the impact of NIHL and recent data suggests that enrolment in an HCP can in fact reduce the risk of long-term hearing loss [3] [4]; yet more needs to be done to reduce the incidence of hearing loss, especially in the military, due to the unique work environments and exposures.

1.2 Noise monitoring in tactical environments

Exposure to impulsive sounds can cause acute acoustical trauma, which may be followed by symptoms such as tinnitus and temporary hearing impairment [5]. Unfortunately there is currently no consensus among experts in the occupational, military, and scientific communities as to the extent of the hazard to hearing as a result of exposure to impulsive sounds. Until recently, the underlying assumption for damage risk criteria was that hearing loss was related to the total energy exposure (a time-intensity relationship), but was independent of the temporal distribution of this exposure. However, a number of studies have demonstrated that this is not always the case [6]. High-intensity impulse sounds are generally considered to be more damaging than continuous sounds [7], yet there is no commercial dosimetry system available for surveying impulsive noise environments or for qualifying weapons systems that produce impulse noise. Engineers, scientists, and industrial hygienists involved in measuring human exposure to impulsive noise continue to rely on non-standard, and often outdated equipment to collect exposure data. Field studies are especially challenging due to the size, portability, and performance limitations of such equipment [8].

2. Objectives

The objectives of this research are to design, build, and test an integrated device that will (1) provide hearing protection during activities in hazardous noise; (2) measure the noise in the ear canal to generate an estimate of dose and correlate in-ear dose to ambient noise levels; and (3) monitor distortion product otoacoustic emissions (DPOAE) and extended high frequency hearing over time. This integrated monitoring plug could allow users to monitor the potential impact of auditory insults as close to the injury as is possible, and eventually enable real-time intervention. The device has the following requirements:

- It fits at the ear, and under earmuffs.
- It connects wirelessly to a mobile device to transmit data and generate alerts.
- It records noise levels continuously for a minimum of 3 hours.
- It connects to an external sound level meter to compare in-ear noise levels to those measured using standard noise monitoring techniques.

In this paper, we report on the preliminary data obtained with a prototype designed to evaluate the feasibility of such a device.

3. Feasibility evaluation

A first prototype was built using a low-cost, wireless, otoacoustic emissions (OAE) probe prototype that had originally been developed by Creare LLC (Hanover, NH) to conduct objective hearing tests on patients that cannot perform a behavioural test [9]. This prototype, shown in Fig. 1, includes two speakers and a microphone in a single device that fits at the ear.
3.1 Attenuation performance

The prototype was modified to accept a foam tip and increase noise attenuation characteristics (as compared to standard “mushroom” plastic tips used for OAE tests). The probe was fitted with an isolation tip and placed in the ear of a G.R.A.S. 45 CB (G.R.A.S., Denmark) Acoustic Test Fixture (ATF). The head simulator was placed in a reverberant sound chamber with four calibrated speakers located in the corners of the room. The speakers were used to play third octave noise bands from 100 Hz to 10 kHz at 85 dB SPL. The Comply Isolation 100 tip (Hearing Components Inc., St Paul, MN) performed the best for this purpose. The tests revealed several leak paths, primarily at the base of the tip. After sealing the leak, attenuation to air-conducted sound ranged from 30 dB at 250 Hz to greater than 38 dB at 1 kHz and above.

We also measured the attenuation of the prototype in the presence of impulse noise. Tests were conducted at the MIT Lincoln Laboratory facility that includes a shock tube setup to measure the attenuation provided by hearing protectors to impulsive blasts. The apparatus includes a chamber that is sealed with a thin sheet of Mylar. Once pressurized, the Mylar is pierced to create an impulsive blast wave that travels through the horn. Just beyond the exit of the horn, there is a blast probe microphone and a G.R.A.S. 45CB ATF. We collected three sets of trials where the blast peak varied from approximately 130 to 170 dB Peak. These preliminary data (Fig. 2) show that the prototype device provides protection that is on par with the 3M X3A earmuffs and better than the combat arms earplug (CAE).

3.2 Microphone performance

We evaluated the measurement accuracy of the microphone (Sonion O11AC03) used in the original OAE probe. For this test, one OAE probe prototype was placed in the free field, just atop the ATF, while a second probe was placed in the right ear of the ATF. A reference microphone hung above the ATF, just above the prototype probe and about 18 in. in front of the speaker (Fig. 3) inside a reverberant sound chamber. In the case of continuous noise, in-ear, the OAE probe tracked the ATF microphone for all third-octave band levels from 50 dB SPL to 70 dB SPL. In the free-field, the OAE probe prototype tracked the reference microphone for all third-octave band levels from 55 dB SPL to 9 dB SPL.
Figure 2: Attenuation performance in the presence of impulse noise. The four lines show the noise attenuation provided by the Creare probe, the Creare probe with a 3M X3A circumaural hearing protector (i.e., double-protection), the X3A alone, and the Combat Arms Earplug (CAE).

Figure 3: The ATF (a) in the reverberant chamber with the speaker (b), the reference microphone (c), and the prototype OAE probe (d) above the ATF and in the right ear (e).

To evaluate the probe at higher impulse levels, the response of the OAE probe microphone was compared to the G.R.A.S. ATF in-ear microphone during the attenuation tests conducted at MIT LL. Figure 4 shows the levels measured by the blast microphone, the ATF in-ear microphone, and the prototype probe microphone for the double-hearing protection case. For the 135 dB [Peak Free-Field Equivalent, PFFE] and 152 dB PFFE impulses, the probe microphone levels tracked the levels at the ATF in-ear microphone (in-ear peaks of 110 and 125 dB SPL, respectively). However, as the sound level increased to 167 dB PFFE, it appears the prototype probe microphone no longer tracked the level at the ATF.

For the single-protection case (i.e., no 3M X3A earmuff placed over the probe), the probe microphone did not track the in-ear ATF microphone under any of the conditions. This may be due to the
design of the probe which exposes the microphone to a larger acoustic wave through the circuit board as compared to the sound transmitted to the ear canal.

![Figure 4. Impulse noise measurements at MIT LL with, from left to right: levels at the blast microphone, ATF left ear microphone, and in-ear probe microphone. Top to bottom show increasing impulse levels as measured at the blast microphone.](image)

### 3.3 Recording capability

The original OAE probe was not intended to record waveform data during measurements, so the electronics were redesigned to add two features: (1) the ability to save raw data to an SD card; and (2) add one accelerometer to differentiate acoustic impulses from mechanical shock (which appears as an impulse on a microphone). This was achieved with a second board connected to the first, to host and power the SD card. Using this two-board approach, the primary board maintains its original size and the new design is marginally deeper than the wireless OAE probe (Fig. 5). The new design was manufactured and tested to evaluate the power consumption of the SD card. The power draw was measured to be around 30 mA\(\text{h}\) and the prototype recorded data continuously at 48 kHz for three hours (with a 90 mA\(\text{h}\) battery).

![Figure 5. Original OAE probe used in the feasibility study (left) and new design that incorporates an SD card to record sound files in real time.](image)
4. Discussion and conclusion

The data obtained during the feasibility study demonstrated that a small form-factor device designed to measure otoacoustic emissions could also be used to provide significant attenuation in the presence of noise, and could accurately measure in-ear noise levels with peaks as high as 125 dB SPL in the ear. When worn under earmuffs, this would correspond to peak impulses of 152 dB SPL PFFE as measured by a blast probe.

Mechanical design modifications should aim to improve the isolation of the microphone from the external impulse to accurately measure the ear canal levels when the device is worn without double hearing protection. In addition, the overall profile and fit of the probe will need to be evaluated thoroughly in a human study to ensure the device cannot be dislodged during donning of earmuffs or helmets and to encourage users to wear it for long durations.

The product of this research will be an in-ear device that can monitor personal noise dose and hearing function while still providing sufficient noise attenuation to act as a hearing protection device. Such a product has significant potential as a research tool to support the development of damage risk criteria based on personal exposure, hearing profile, and susceptibility. Eventually, the device can be produced as a customized earplug that provides individual warnings regarding excessive noise exposure for individuals working in hazardous noise environments, especially those where overall noise dose may be difficult to predict.

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