Ear Overpressure Protection using an Ear Canal

Jeffrey Levine, Jean-Philippe Dionne, Aris Makris

Abstract A 3D-printed headform comprising a realistic ear canal was developed to don both earmuff- and earplug-style protection for the ear. This headform was exposed to shocktube air blasts ranging from a blast simulator of 14 kPa to 62 kPa nominal overpressure, meant to be representative of potentially injurious overpressure exposure. While ear overpressure profiles observed between the two types of measuring methodology (flush-mounted sensor vs. realistic ear with canal) diverged, the detailed ear canal did allow for the evaluation of different types of earplug, earmuff and combination protection. Results indicate that different earplug-style protection yielded similar levels of protection, regardless of type. Finally, the combination of types of ear protection used in concert did not yield significantly enhanced protection.

Keywords Blast Injury, Ear Overpressure, Ear Protection, Headform, Blast Simulator.

I. INTRODUCTION

The most sensitive human organ to blast overpressure is the ear. As such, individuals exposed to blast (e.g. bomb technicians, soldiers potentially exposed to improvised explosive devices (IEDs), explosive breaching, or large weapons fire training, etc.) are likely to suffer from ear overpressure injuries, as highlighted in recent studies [1-2]. While typically not life-threatening, eardrum perforation from blast exposure affects quality of life. An injury threshold of 5 psi (34.5 kPa) was determined in the 1960s by Hirsch [3], one of the earliest rigorous studies on this topic. Over the years, other researchers have developed ear injury criteria for blast exposure, including a simple criterion developed by Garth *et al*. [4] and more detailed ones by Kalb and Price [5-6], Richmond *et al*. [7-8] and James *et al*. [9]. In addition to the direct threat of blast to the ear (e.g. eardrum rupture) addressed by the above criteria, it has been argued that the ear could also potentially serve as a conduit to trigger mild Traumatic Brain Injuries (mTBI), through significant amplification of the shockwave through the ear canal [10-11].

As such, adequate ear protection is required to mitigate the effects of blast exposure. An investigation of the effectiveness of hearing protectors was conducted by NATO [12] in the context of impulse noise. While that study did not directly address blast overpressure exposure, focusing instead on noise levels and associated frequency content, it did highlight a few requirements for the assessment of hearing protectors. In particular, the authors emphasised that acoustic head simulators must contain a realistic ear structure able to include earplugs. Jetté *et al.* [13] conducted such a study whereby a headform featuring a simplified ear canal based on the geometry of a life-size ear model was exposed to the blast from explosive charges, with or without protection systems (helmets, visors, earmuffs and earplugs). This study showed that ear overpressures could be effectively reduced by fully enclosed helmets and by open-face helmets equipped with a visor, based on the measurements made inside the ear canal.

On the other hand, Anctil *et al*. [14] further investigated the same headform used by Jetté *et al*. [13], focusing on the effect of the ear canal itself. Their analysis suggested that the ear canal model overamplified the pressure in comparison with the human response. More specifically, they measured an amplification factor of 3.9 compared to a reference side-on pressure sensor, which led to much higher injury predictions than expected. Similarly, using human cadaver ears, Gan *et al*. [15] conducted lower level blast trials showing amplifications on the order of 1.6 when comparing the ear entrance and at the tympanic membrane itself. As such, while the trends in reduction in ear overpressure measured with the ear canal model using inner-ear

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protection within their studies might still be appropriate, the absolute pressure values measured might not be realistic.

To address this gap, the current study introduces a realistic ear and ear canal that is likely to provide representative pressure values inside the ear, while being rugged enough for use in repeated blasts. Similar to the ear model used in the three studies using ear canals referenced above [12-14], this suggested ear model also allows for earplugs to be tested in a realistic and representative fashion. The protection afforded by various protection systems was investigated, including combining helmets with earmuffs and earplugs, a configuration that had not been investigated in the previous studies. As an effort to minimise experimental deviations inherent to explosive blast testing, the pressure waves from the present study were generated through a pressure-driven blast simulator.

II. METHODS

Blast Simulator

A blast simulator, i.e. modified shock tube, was used to generate blast waves. This blast simulator consists of a 304.8 mm diameter cylindrical driver that connects to a driven chamber comprised of a transition section and a square 1 m x 1 m open-ended tube (Fig. 1). A rarefaction wave eliminator was added to the muzzle of the shocktube after a 5.0 m long driven chamber section. The driver was pressurised with compressed air and frangible Mylar membranes were used as rupture diaphragms to create the shockwave. The large test cross-sectional area enables testing of relatively large targets within the blast simulator. Tests were conducted in the square driven section at a distance of 3.55 m away from the driver, allowing the shock front to be fully formed by the time it reached the test area.

Three overpressure side-on reference levels were tested throughout the trial series: 14 kPa, 28 kPa and 62 kPa. The 28 kPa value was chosen as it is commonly used to calculate the 4 PSI Minimum Safety Distance (MSD) used by Explosive Forced Entry (EFE) teams during their safety assessments [16]. The other two pressure levels were selected based on approximately representing half and double of the 28 kPa exposure level, within the constraint of the number of Mylar sheets required to achieve these levels.

Fig. 1. Blast Simulator located at the Canadian Explosive Research Laboratory (Ottawa, Canada).

Personal Protective Equipment

Seven different configurations of ear protection were investigated, involving three types of earplug, one set of earmuffs, and a large helmet faceshield. The three different types of earplug, shown in Fig. 2, were fabricated out of completely different materials and into different shapes. The 3M Standard (3M Canada, London, ON, Canada) foam earplugs are of a rounded, conical shape and made from a low-density polyethylene foam. The Ear Jelly (Ear Jellies, New York, NY, USA) are naturally spherical and made from an easily mouldable viscoelastic silicone rubber. The 3M Combat Arms are a “Multi-Flange” shape and made from an elastomeric polymer. All three types of earplug claim a similar noise reduction rating (NRR) of 25 dB. The 3M Peltor earmuffs (Fig. 3) claim an NRR of 27 dB and were chosen due to their lower width profile, which allowed them to be worn in conjunction with the Med-Eng VBS-250 Visor (Med-Eng, Ottawa, ON, Canada) and the 3M Mid-Cut military helmet (Fig. 4). A configuration referred to as "double protection" combined the 3M standard foam earplugs with the earmuffs, while the "triple protection" consisted of the double protection configuration with a visor added. It should be noted that all trials included the mid-cut military helmet. Table I lists the seven different protection variants used, in addition to the baseline.

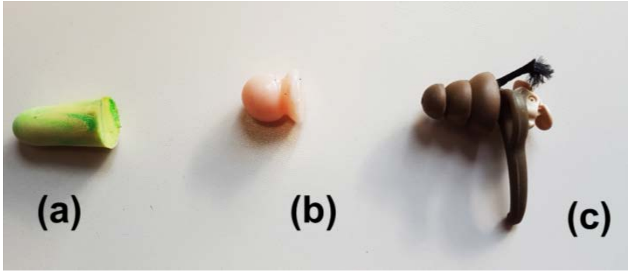

Fig. 2. Three different types of earplug used: (a) 3M Standard foam plugs, (b) Ear Jellies and (c) 3M Combat Arms.

Fig. 3. 3M Low-Profile, Peltor earmuffs.

Fig. 4. Med-Eng VBS-250 Visor mounted to a 3M mid-cut military helmet (unpainted).

TABLE I
DIFFERENT PROTECTION VARIANTS

Name	Ear Protection	Head Protection
Baseline	None	Helmet
Visor Alone	None	Helmet with Visor
Foam Plugs	3M Standard Foam	Helmet
Ear Jellies	Ear Jellies	Helmet
Combat Plugs	3M Combat	Helmet
Earmuffs	3M Peltor Ear Muffs	Helmet
Double Protection	3M Standard Foam & 3M Peltor Earmuffs	Helmet
Triple Protection	3M Standard Foam & 3M Peltor Earmuffs	Helmet with Visor

3D-Printed Headform

An EN960 size J headform [17] was scanned using an Artec Eva Lite handheld optical scanner driven by the Artec Studio application (Artec 3D, Santa Clara, CA) and 3D-printed using a Stratasys F370 fused deposition modelling printer (Stratasys, Eden Park, MN) in a Nylon-Chopped Carbon Fibre material. Additionally, a KEMAR anthropometric ear (G.R.A.S., Holte, Denmark), typically used in ANSI S3.36/ASA58-2012 headphone testing [18], was also scanned and 3D-printed in TPU 92A, a flexible polymer. The materials for the headform and the realistic ear were selected to ensure that they would resist multiple blasts and, eventually, full-scale explosive testing. The realistic ear mount includes a 5 mm deep ear canal, identical to the KEMAR ear, mounted to the headform's left side. In addition, a flush-mounted pressure sensor was incorporated into the headform (at the right ear), see Figs 5 and 6.

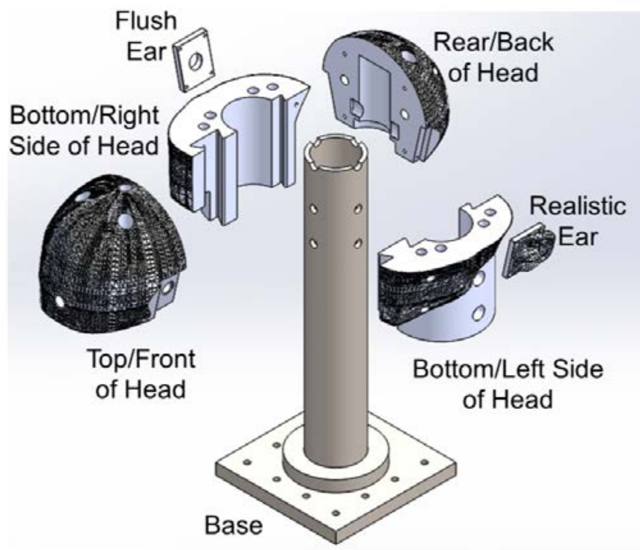

Fig. 5. Exploded CAD drawings of the 3D-printed headform and base plate.

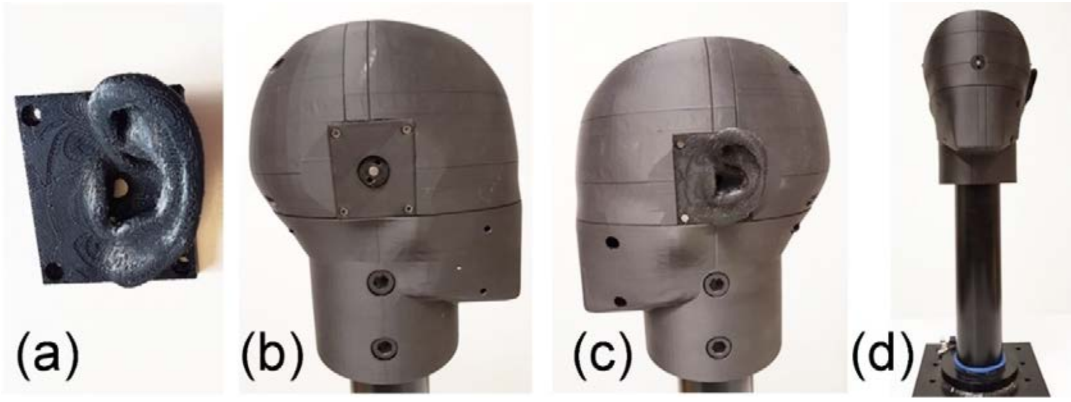

Fig. 6. 3D-printed headform: (a) realistic ear, (b) flush-mounted pressure sensor on headform, (c) realistic ear on headform, and (d) full test setup.

Instrumentation and Test Setup

A pressure sensor (PCB Piezotronics Model 113B24, Depew, NY) was located on the headform, flush-mounted at the ear location on the right, and another identical one was mounted within the realistic ear on the left. In addition, a pencil gauge (PCB Piezotronics Model 137A23, Depew, NY) was placed facing downwards, as a reference, directly above the headform (see Fig. 7), aligning the sensor with the ear gauges. The PCB sensor data were acquired at a rate of 200 kHz using a Yokogawa (SL1000, Newnan, GA) data acquisition system for a duration of 100 ms and post-processed using a two-pole, low-pass Butterworth filter set to attenuate signals above a 10 kHz cut-off frequency, following the methodology of Jetté *et al*. [13].

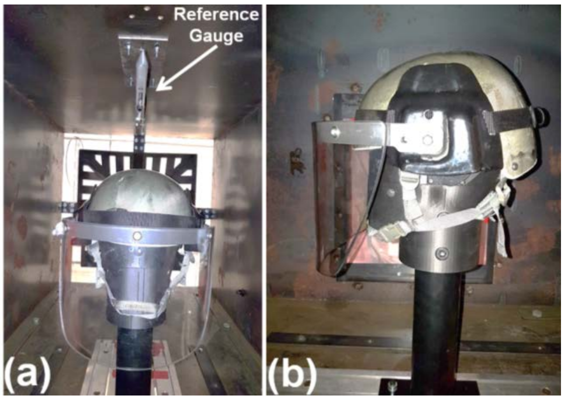

Fig. 7. Headform and reference pressure gauge within the blast simulator as seen from the (a) front and (b) side.

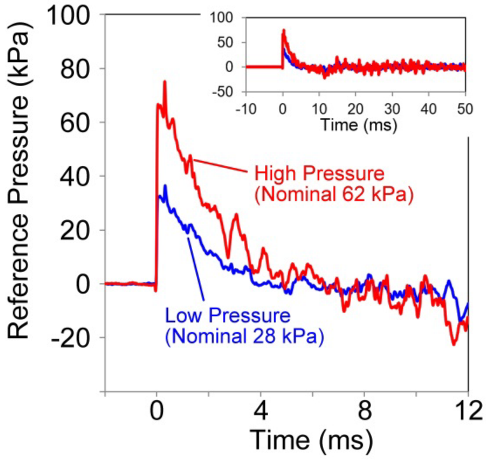

Fig. 8. Typical pressure profiles of low- and high-pressure trials (nominally 28 kPa and 62 kPa). The inset graph provides a zoomed-out view for 50 ms.

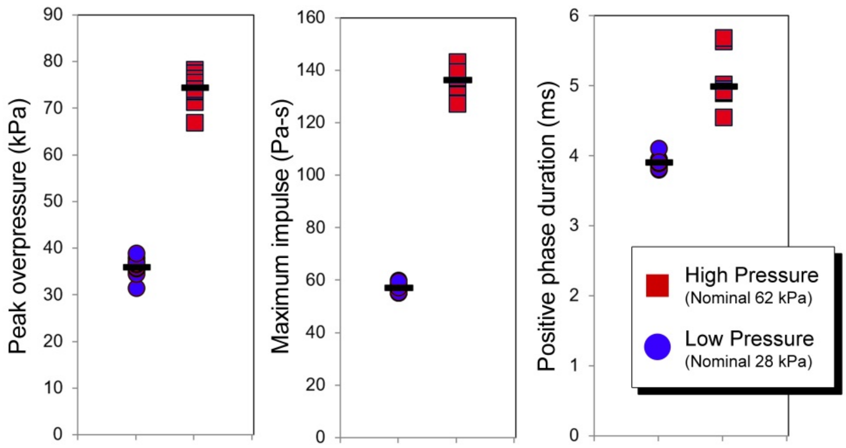

Fig. 9. (a) Reference peak pressure, (b) Maximum impulse and (c) Positive-phase duration obtained from the reference pressure gauge measurements.

III. RESULTS

Reference Pressure

Typical reference pressure profiles for both 28 kPa and 62 kPa used in this test series are provided in Fig. 8. It should be noted that the short spike roughly 1 ms after the initial peak is due the shock reflection off the backend of the blast simulators' driver section, and could not be eliminated. That said, the blast simulator was noted to have a high level of reproducibility and consistency as noted in the peak reference pressure, reference maximum impulse and reference positive-phase duration (Fig. 9). For each of the configurations tested, the range of reference pressure, impulse and duration data always stayed within 13% of the average value.

Effect of the ear canal

Figure 10 illustrates the unprotected ear pressure traces from a 28 kPa shock comparing the flush pressure sensor with that of the submerged pressure sensor within the realistic ear. A much higher peak pressure level is noted for the realistic ear. Given this divergence in trace shape, two additional shock tests were conducted at 14 kPa to extend this comparison, the results of which are presented with the two other pressure levels in Fig. 11. A strong linear correlation ($R^2 = 0.99$) was obtained between the peak realistic ear and flush-mounted pressures, whereby the realistic ear pressures are nearly three times greater than those of the flush-mounted sensor on average. The maximum impulses and positive-phase durations, by comparison, showed much less deviation between the two sensor-mounting methodologies. An amplification of the pressure due the presence of an ear canal was also noted by Anctil *et al*. [14]. Their results, conducted with a substantially larger blast threat (5.0 kg of C4 explosive at a horizontal standoff of 5.0 m), indicated an average pressure amplification of 4.1 due to the ear canal. The results of Gan *et al.* [15] showed lesser amplifications of only 1.6 at input pressure levels of 75 kPa, however these results may not be directly comparable as the location of the equivalent flush sensor was on the outer portion of the cadaver ear itself.

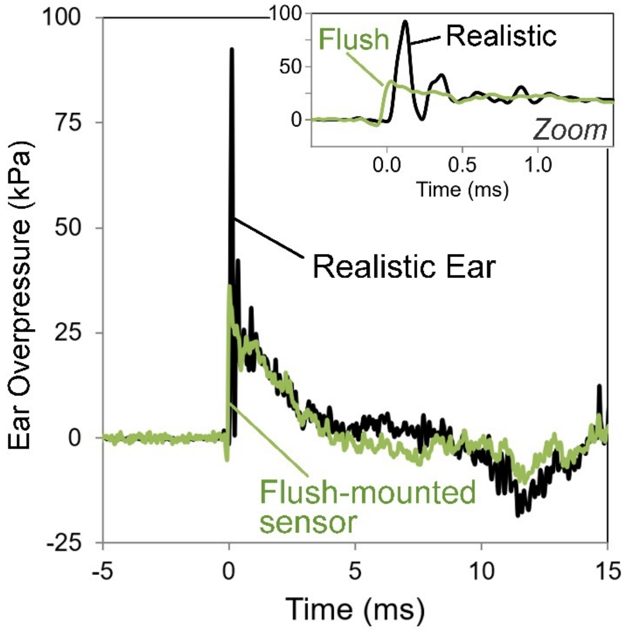

Fig. 10. Comparison of the pressure traces from the flush-mounted and realistic ear pressure sensors. The inset graph provides a zoomed-in view of the initial 1.5 ms.

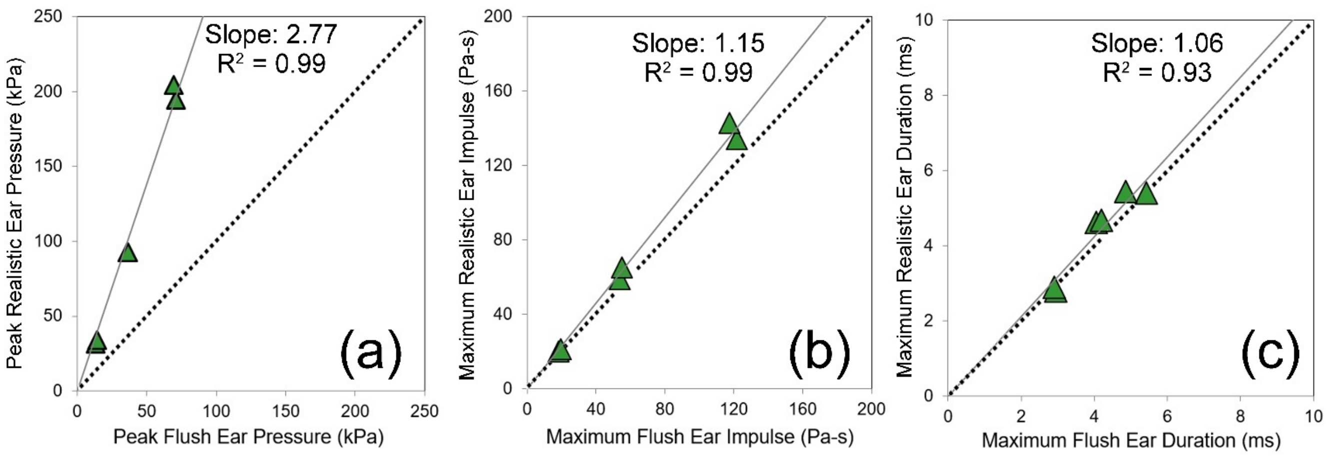

Fig. 11. Comparison of the (a) Peak pressures, (b) Maximum impulses and (c) Positive-phase durations obtained from the flush-mounted and realistic ear pressure gauges. Also noted are the linear best-fit correlation lines (solid) and an equivalency line (dashed) for reference.

Ear Protection Results

Figure 12 presents sample pressure traces from the realistic ear from all protection configurations, when shocked at the 28 kPa level. The addition of any type of protection was found to notably lower the peak pressure at the eardrum, while simultaneously slowing the pressure rise significantly. A high degree of similarity in the shape of the pressure traces was noted between the three different earplug options as well as between the double (3M Standard Foam & 3M Peltor Earmuffs) and triple protection (double protection plus visor) configurations. All three types of earplug, the earmuffs and the double and triple protection configurations displayed similar peak pressures (Fig. 13) for both the 28 kPa and 62 kPa shock loadings, respectively (the lower 14 kPa loading was not applied for the tests involving protective systems).

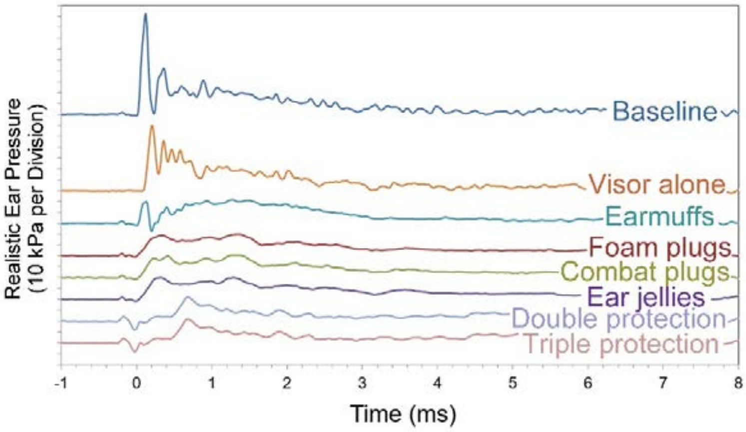

Fig. 12. Comparison of typical ear pressure traces for all eight different protection configurations conducted at a shock pressure level of 28 kPa.

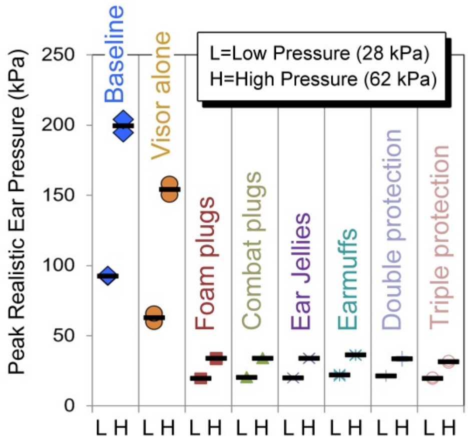

Fig. 13. Peak ear pressure for all protection configurations at both the lower 28 kPa (L) and higher 62 kPa (H) shock loadings.

IV. Discussion

Effect of the ear canal – No protection

So far, the realistic ear and the flush-mounted sensor results have been compared only in terms of pressure traces characteristics. The analysis is now expanded to apply three ear overpressure injury models to the measured data, namely the Auditory Hazard Assessment Algorithm for Humans (AHAAH) tool, developed by Price and Kalb [5, 6], the injury function developed by Richmond *et al*. [7, 8], based on the peak incident or reference pressure and positive phase duration, the injury criterion from James *et al*. [9], based on the peak pressure and maximum impulse.

First, the waveforms from both the realistic and flush-mounted ear trials were reformatted and input directly into the AHAAH software, assuming an eardrum and free-field sensor, respectively. Both sets of data indicated that the predicted ARU levels (Auditory Risk Units) for all the cases well exceeded the 500 ARUs, for even the highest levels of protection. Since 500 ARUs are considered barely safe [6], whereby there may be temporary shifts in hearing sensitivities, the AHAAH methodology may not have the necessary granularity at these levels to provide insightful predictions.

Next, the pressure data characteristics (i.e., peak pressures, maximum impulses and positive phase durations), are plotted on graphs corresponding to the two blast overpressure injury models in Fig. 14. Here, the results obtained from the realistic ear as well as those from the sensor flush-mounted to the head surface, at the three nominal pressure loading levels tested (14 kPa, 28 kPa and 62 kPa) are superimposed on a simplified version of their model. Based on the Richmond model, the injuries predicted from the realistic ear data are much more severe, to the point where the 28 kPa results with the realistic ear nearly line up with the more severe 62 kPa loading with the flush-mounted sensor, rendering a near identical 50% chance of a major rupture of the eardrum. Similarly, the 14 kPa results with the realistic ear and the 28 kPa results with the flush sensor predict a 1% chance of a major eardrum rupture. Major differences in injury predictions are similarly observed when comparing the realistic ear with the flush-mounted pressure sensor against the injury criterion set forth by James *et al*.

Strictly speaking, only the flush-mounted ear pressure results should be fed into the Richmond model, as flush-mounted ear data better represents an incident pressure measurement. Conversely, only the realistic ear results should be used in conjunction with the James model, as this model requires a peak eardrum pressure and impulse as inputs. Using only this subset of the data, the two models show moderate agreement in their injury predictions. The 62 kPa trials just eclipses a 50 % chance of major rupture from the Richmond Model, agreeing well with the James model's prediction. The 28 kPa trials predicts a 50 % chance of minor, moderate or major eardrum rupture in the Richmond model, when the James model suggests something less than 50 % chance of any rupture. And finally, the 14 kPa trials are just above the lower threshold for eardrum rupture in the Richmond Model, and predict no ruptures using the James Model.

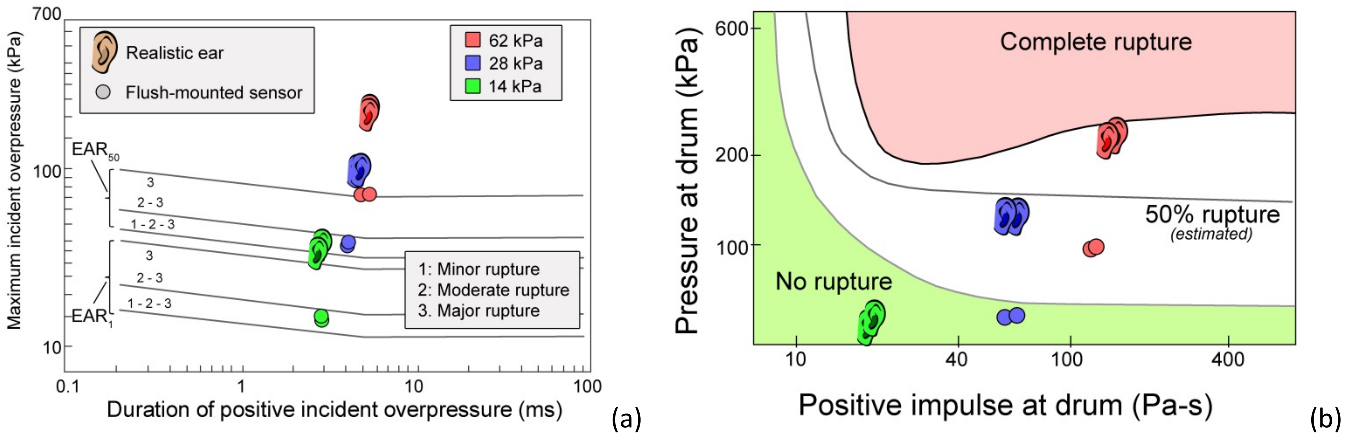

Fig. 14. Injury prediction for eardrum rupture modified from (a) Richmond *et al*. [7] and (b) James *et al*. [9] to include experimental results indicating both the realistic and flush ear. The same legend applies to both graphs.

Ear Protection Results – Realistic Ear only

While the realistic ear may not yield results directly comparable to external injury criteria, the test surrogate can still be used to rank different types of ear protection against each other. To that end, Fig. 15 provides a comparison between protection ratios of each of the seven tested protection configurations. The protection ratio is calculated as:

$$Protection\ Ratio = \frac{Unprotected\ \ Value}{Protected\ Value} \quad (1)$$

The "protection ratio" parameter is more effective than the percentage reduction when comparing systems that provide a high percentage reduction. By its nature, pressure percentage reduction asymptotes at 100%, thus providing little relative difference between solutions with reductions over 90%. The protection ratio, in contrast, flips the unprotected and protected values, moving the asymptote to 1, where the lowest and, more importantly, least interesting solutions typically reside.

The comparison of the protection ratios indicates three general trends. The first is that isolating the ear, whether through earplugs, earmuffs or a combination of both, is vastly superior to relying on a visor alone. Secondly, in all six of the isolated hearing protection concepts, greater protection was afforded to the ear when a higher threat was presented. This observation is in line with from the findings of Jetté *et al*. [13], where threats on the order of 126 kPa yielded even higher protection ratio values of 10 to 12. Finally, the type of isolating hearing protection made only a small difference. The three different types of earplug rendered nearly identical protection ratios, whereas adding the earmuffs (i.e. "double protection") and then the visor to the helmet (i.e. "triple protection") only marginally increased the protection ratio. This observation diverges from the results of Jetté *et al*. [13], whereby a similar double protection concept yielded a more pronounced increase in protection. This, however, is likely a function of the second stated trend, whereby the greater threat yielded greater effective protection.

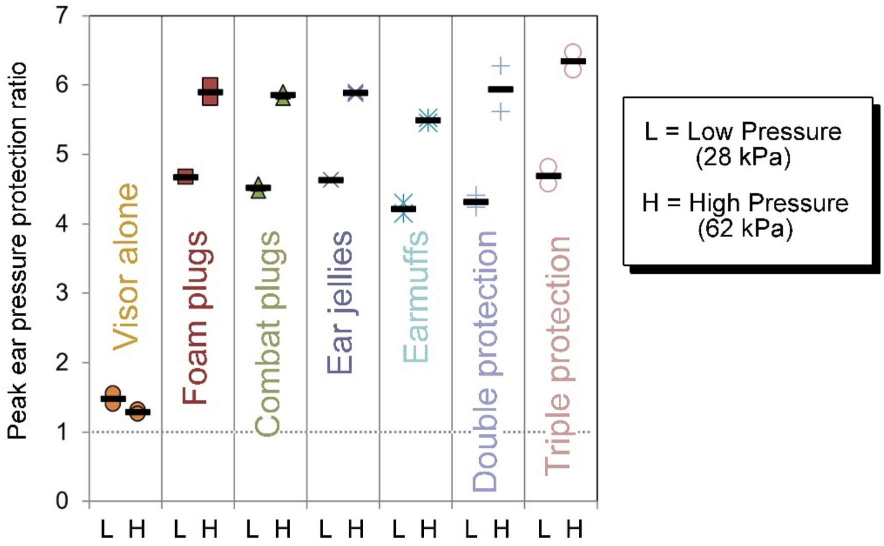

Fig. 15. Protection ratios for all seven different protection configurations at both the lower 28 kPa (L) and higher 62 kPa (H) shock pressures.

CONCLUSIONS

The presence of a simulated ear canal was investigated under low-level blast loading using a 3D-printed headform. This novel headform allowed for direct comparisons of blast exposure between a conventional flush-mounted pressure sensor with one embedded within a more realistic ear with an ear canal. Results for the bare head (unprotected) showed significantly divergent peak pressures, with the realistic ear yielding significant amplifications (factor of 2.77) over the flush-mounted sensor. Conversely, the maximum impulses and positive-phase durations remained strikingly similar, causing contradictory injury predictions from the established injury criteria based on which ear data were used.

Limiting the analysis to only the realistic ear case, specifically testing with earplugs, the different ear protection configurations were ranked. It was noted that the three types of earplug tested provided similar protection, while the addition of earmuffs ("double protection") and then a visor ("triple protection") yielded only marginally enhanced protection. Based on these observations, the results suggest that personnel regularly subjected to low-level blasts continue to don the ear isolating protective equipment of their choice. However, it should be noted that trials were only conducted with the surrogate facing the blast (i.e., side-on exposure of the ear), and as such, while differences in ear protection performance might differ in other orientations. Finally, as the current conclusion applies only to the low-level blast exposures tested (up to 62 kPa), further studies will be needed to expand to Explosive Ordnance Disposal (EOD) scenarios involving much higher pressures.

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