Blast load on operating personnel from shock grenade

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Abstract. When using heavy weapon systems or explosives in military operations and training, blast waves can cause collateral blast exposure to the operating personnel. To best mitigate the effect of such exposures it is of interest to know how the positioning of the personnel will affect the risk of injury, both in terms of distance from the blast and how interior details like walls and doors affect the pressure build up in semi-enclosed rooms. The use of personal protective equipment is also a factor that will affect the risk of injury. In this research, we performed pressure measurements at selected points of interest of blast waves caused by the detonation of a stun grenade. We measured the pressure in several experimental setups; measurement of a free field wave, behind cover, in a trench system and usage in connected semi-enclosed rooms. From these trials, we estimated the risk of injury to the brain, ear and lungs from single point injury predictions models using the pressure history. We discuss the mitigating effect of personnel position during the blast exposure and how using protective equipment can mitigate the effect of the exposure. The results show that such grenades can cause significant injury and that mitigating measures are important to reduce the risk of injury. We also compared the obtained pressure values with results from numerical calculations using the non-linear explicit finite element solver IMPETUS Afea. Based on this comparison we discuss using numerical calculations as a supplement to measurements of actual events to assess the risk of collateral blast injury, which is useful when creating training procedures and operating doctrine.

1. INTRODUCTION

Military personnel are prone to injury when exposed to blast waves. During the Operation Enduring Freedom in Afghanistan, explosions was one of the main causes of injuries to participating Norwegian soldiers [1]. This is in line with experiences from other nations [2]. The risk of injury from blast exposure depends on several factors such as peak pressure, impulse, frequency and number of exposures. Research on blast injury has been ongoing for a several decades and recently there has been an increased effort on the effect of low-level blasts [3]. Studies have shown that this type of sub-concussive blasts can cause injuries, which are not immediately recognized but manifests itself as neurological disorders at a later time [4]. Blast exposure of this magnitude can be encountered when personnel are operating weapon systems or explosives in training [5] and this can cause the number of exposures and frequency to be higher than exposure to operational blasts.

In this research, we will investigate the blast exposure on the operating personnel when using stun grenades in typical training situations and estimate the risk using single point (SP) injury predictions models. We will then examine the use of numerical calculations for risk assessment without having to perform experiments of all relevant geometry configurations. Finally we discuss mitigating factors such as protective equipment in operational training.

2. METHODOLOGY

To investigate the blast exposure on operating personnel from a shock grenade we detonated a stun grenade with a net explosive weight of 116 g Comp B and recorded the pressure history at points of interest. These pressure measurements were then used to assess the risk of injury by applying various SP injury prediction models for the lungs, ears and the brain to determine whether the activity could cause injury.

2.1 Pressure measurements

To get a representative overview of the blast load for the personnel in various settings it was decided to perform pressure measurements in four different situations,

- a free field wave
- behind cover
- in a trench system
- in connected semi-enclosed rooms

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2.1.1 Free field wave

Pressure measurements of the grenade as a free field wave are useful for verifying measurements when comparing to numerical calculations. The first step was therefore to measure the pressure in the case of a free field wave using piezoelectric pencil probes (PCB 137 A23). The pencil probes measured the pressure history at a distance of two, four and six meters from the grenade. The grenade and the pencil probes was placed on the same horizontal plane two meters above the ground with the pencil probes spaced out at 45 degrees to avoid interference with each other as shown in Figure 1. Using this setup and remotely detonating the grenade we could measure the passing pressure wave before reflections from the ground interfered with the wave pulse.

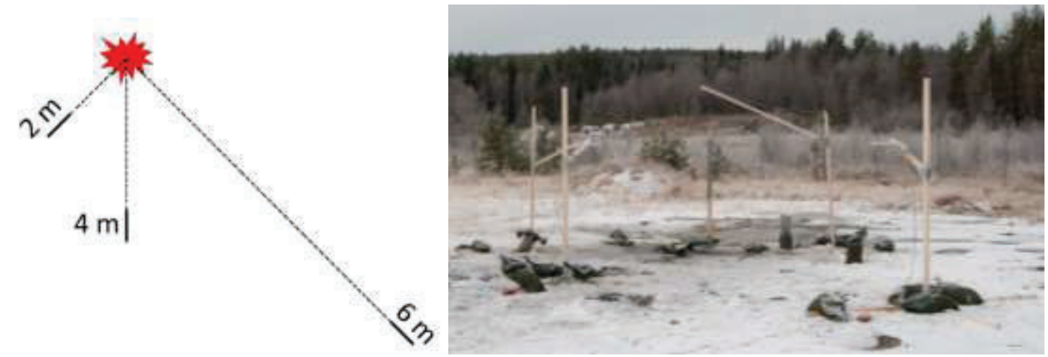

Figure 1. Experimental setup of the free field wave measurements

2.1.2 Behind cover

During throwing practice, the operating personnel takes cover from the blast wave by kneeling in a concrete booth after throwing the grenade at the training ground. It is thus of interest to measure the pressure history behind this cover to assess the risk of injury. In this experimental setup we switched to a piezoelectric sensor of the type PCB 102A05 which was fastened to the concrete wall in the booth, just below the ground level as illustrated in Figure 2. The membrane of the sensor was parallel to the ground to best record the side-on pressure. The ground from the booth have a slightly negative slope in the throwing direction and we measured grenades at a distance of two or four meters from the sensor. After remotely detonating the grenade we could record the passing blast exposure in the booth.

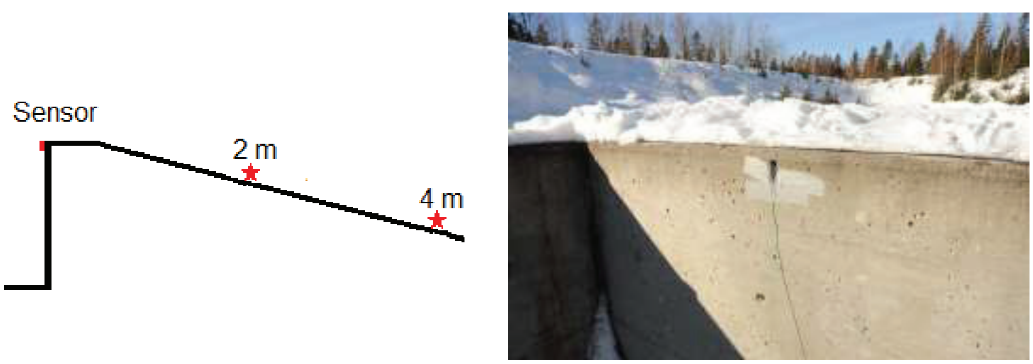

Figure 2. Experimental setup of the measurements behind cover

2.1.3 Trench system

Training with stun grenades in a trench system is another activity in which the operating personnel can experience blast wave exposure. The trench used consisted of concrete walls creating a canal with a width of one meter. At the time of the experiment, the height of the walls was around 115 cm, with the ground not being completely even due to a layer of snow. We put piezoelectric sensors (PCB 102A05) on the walls 40 cm from the top of the trench (approximately 75 cm above ground level) at positions shown in

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Figure 3 with the membrane of the sensor parallel to the ground. Using remote detonation the grenade detonated at a distance of 150 cm from the intersection. We put sensor 1 and 2 at a distance of 50 cm from the intersection, whereas the distance between sensor 2 and 3 was 303 cm + 50 cm along the wall.

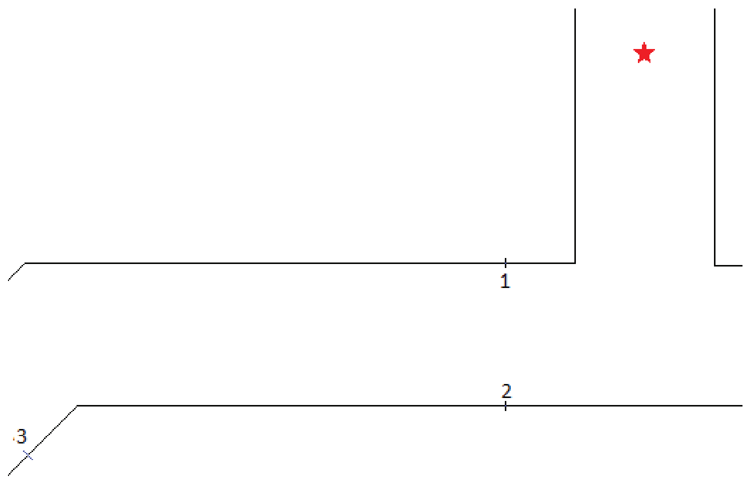

Figure 3. Experimental setup of the measurements in a trench system

2.1.4 Connected semi-enclosed rooms

The last setup was detonation of a grenade in connected semi-enclosed rooms. The position of the sensors and the grenade are as shown in Figure 4 with the measurements being in cm. The blue line indicates an open window and the open space is the door opening to the connected hallway. Sensors 1-3 are positioned 140 cm above the floor level in the hallway and sensor 4 is just below the window frame on the outside of the building. All sensor membranes were parallel to the ground. The height of the room was 238 cm with a total volume of 30.7 m^3.

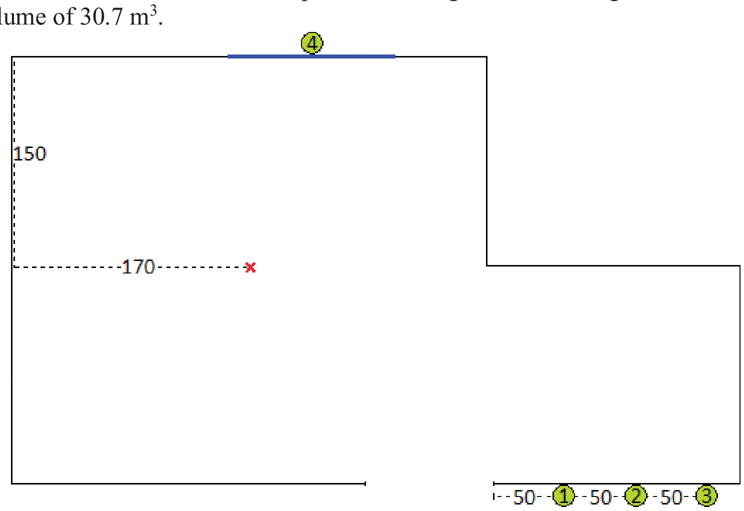

Figure 4. Sensor setup of the measurements in semi-enclosed rooms

2.2 Injury prediction models

After obtaining the pressure histories for the various experiments, we applied the collected data to different injury prediction models to assess the risk of injury for the operating personnel. The organs chosen were lungs, ears and the brain.

2.2.1 Lungs

When estimating the risk of injury to the lungs we used a modification of the blast injury model developed by Axelsson [6]. This model is a single degree of freedom (SDOF) system meant to describe the chest wall response of a human exposed to a given blast wave in a complex blast environment. It required pressure inputs from four gauges placed on a Blast Test Device (BTD) to calculate the chest wall velocities. Axelsson proposed that the average of the maximum of the four calculated velocities is a measure of injury called the Chest Wall Velocity Predictor (V). Based on experiments with sheep he created an Adjusted Severity of Injury Index (ASII) based on the level of injury. The correlation between injury level, ASII and V is shown in equation 1 and Table 1.

$$ASII = 0.124+0.117V^{1.205} \tag{1}$$

Table 1. Correlation between injury level, ASII and V

Injury level	ASII	V (m/s)
No injury	0.0-0.2	0.0-3.6
Trace to slight	0.2-1.0	3.6-7.5
Slight to moderate	0.3-1.9	4.3-9.8
Moderate to extensive	1.0-7.1	7.5-16.9
>50% Lethality	>3.6	>12.8

While the BTD-model requires data from four pressure gauges, a single point formula is defined by using the single point pressure in a given location as input to the Axelsson model. The value of V is then equal to the maximum chest velocity in the SP-model. The SP-model is much easier to work with numerically, as the ASII can be calculated in all locations with only one simulation. In contrast, with the BTD-model, the ASII can only be determined in one location at the time and a huge number of simulations (with different BTD locations) would have to be run to get an overview of the ASII as a function of position. The SP-model has earlier been shown to closely approximate the BTD-model for all kinds of scenarios, including short and long blast duration, free-field and near walls [7]. We will therefore be using the Axelsson SP-model as risk assessment for lung injury.

2.2.1 Ears

To evaluate the possibility of hearing injury we used the procedure for impulse noise defined in MIL-STD-1474D [8]. This procedure makes use of the peak sound pressure and B-duration calculated from the pressure history. The B-duration is the impulse duration to a point on the total blast wave where the rest of the exposure is at least 20 dB below the peak. The MIL-STD-1474D injury criterion for impulse noise is then a plot where the peak sound pressure (in dB) is plotted against the B-duration as shown in Figure 5. The three curves represent different amount of exposures a soldier can have during 24 hours.

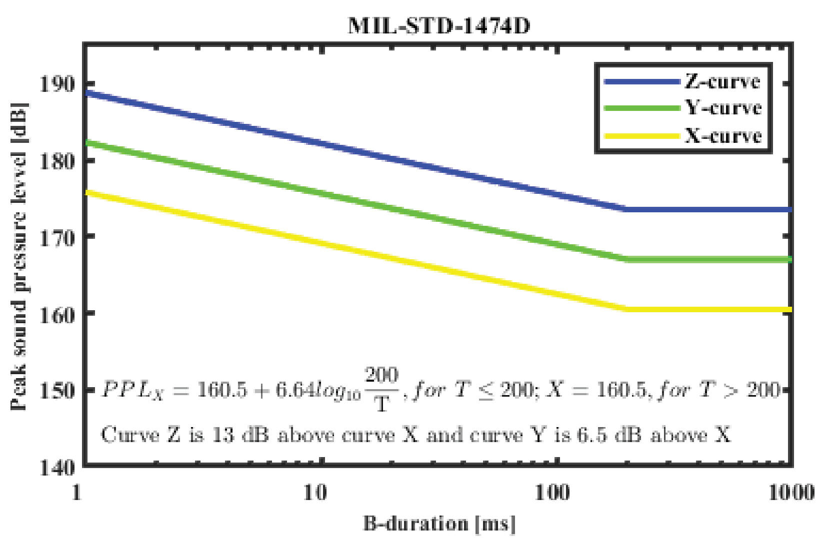

Figure 5. MIL-STD-1474D injury thresholds

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2.2.1 Brain

The effect of blast overpressure on the brain is an ongoing area of research. The complexity of the matter spans across several subjects and currently there is a NATO Research Task Group within the Human Factors and Medicine (HFM) Panel to develop exposure guidelines for blast overpressure (HFM-338). In our work, we decided to apply a peak pressure limit of 4 psi (27.8 kPa) as an injury criterion. The historic rationale for this threshold is the risk of eardrum rupture on unprotected human ears [9] and thus not based on damage to the brain per se. However, it is relevant in our context as the 4 psi threshold for brain damage is used in most studies on low-level blasts and used by various range officers to calculate the minimum safe distance for explosive breaching [10].

3. RESULTS

The sampling rate of the pressure measurements was 204 800 Hz and all collected data was low-pass filtered using an 8th order Bessel filter with a cut frequency of 40 kHz. With the processed measurements and the previously defined injury criterions, we could estimate the risk of injury to the operating personnel from the blast exposure.

3.1 Free field wave

For the free field wave experiment, we detonated six grenades and from the recorded measurements, we extracted the peak pressure and calculated the B-duration and ASII values at two, four and six meters from the blast. The average of these values are tabulated in Table 2 and in Figure 6 we have plotted the peak sound pressure (in dB) and B-duration as given in MIL-STD-1474D.

Table 2. Averaged results from the free field measurements

Distance [m]	Peak pressure [kPa]	B-duration [ms]	$ASII_{SP}$
2	54.7	10.9	0.018
4	16.4	15.3	0.009
6	10.0	16.9	0.007

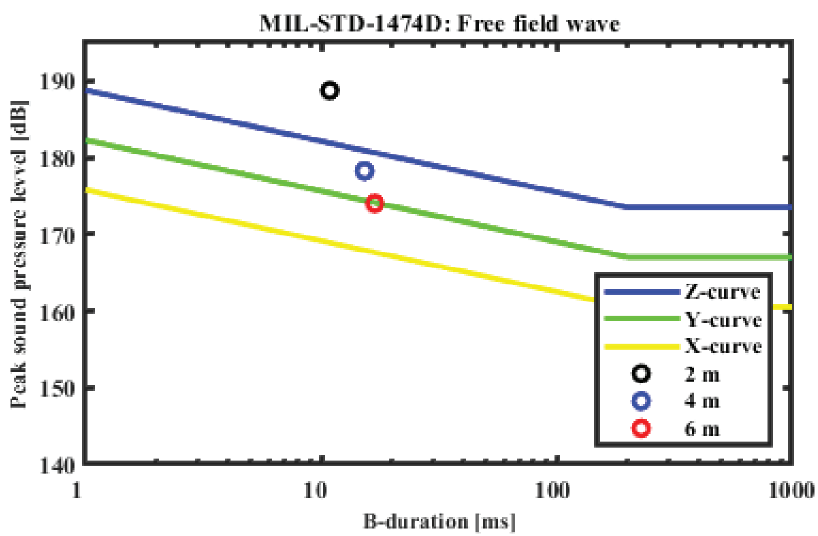

Figure 6. MIL-STD-1474D for 116g CompB in a free field wave

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As we can see from Table 2 and Figure 6, the risk of injury from the blast exposure a stun grenade creates in the free field decreases below our injury criterions with increasing distance to the grenade. The risk of lung injury is insignificant, whereas the risk to the ears and brain can be significant if close enough.

3.2 Behind cover

In the setup behind cover, we measured grenades at two and four meter from the detonation. The values of interest are given in Table 3. In Figure 7 we have plotted the peak sound pressure (in dB) and B-duration as given in MIL-STD-1474D.

Table 3. Averaged results behind cover measurements

Distance [m]	Peak pressure [kPa]	B-duration [ms]	$ASII_{SP}$
2	20.1	7.1	0.012
4	7.0	26.3	0.007

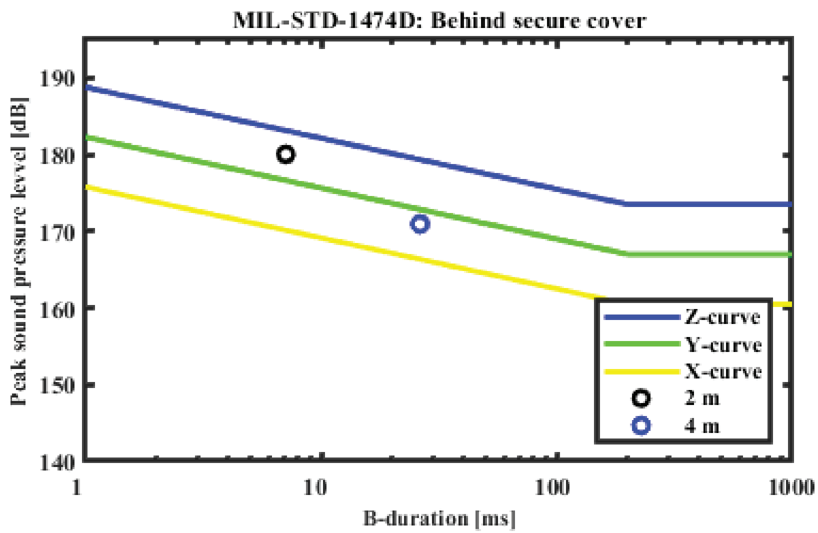

Figure 7. MIL-STD-1474D for 116g CompB behind cover

As we can see from the results, the risk of injury from the blast exposure when behind cover is insignificant when the distance to the grenade is at least 2 meters.

3.3 Trench system

In the trench system, we detonated three grenades and measured the pressures at the different positions outlined in Figure 3. The values of interest are tabulated in Table 4 and in Figure 8 we have plotted the peak sound pressure (in dB) and B-duration as given in MIL-STD-1474D.

Table 4. Averaged results in the trench system measurements

Sensor	Peak pressure [kPa]	B-duration [ms]	$ASII_{SP}$
1	19.5	33.9	0.012
2	80.8	9.1	0.018
3	4.7	87.2	0.008

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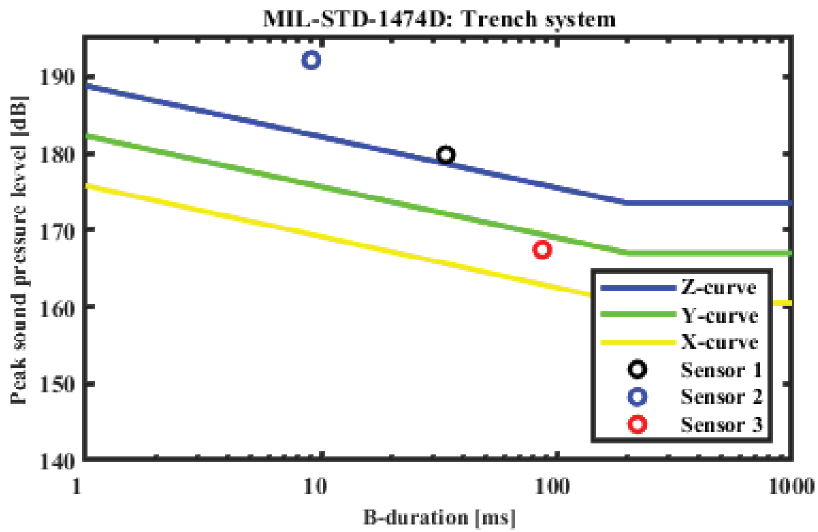

Figure 8. MIL-STD-1474D for 116g CompB in a trench system

As we can see from the results, the risk of injury from the blast exposure when operating a stun grenade in a trench can be significant. This comes due to the reflecting surfaces, which creates a peak pressure that can exceed the injury criterion for the brain. We also notice that the B-durations are quite long and will pose a risk to the soldiers hearing. It is thus of importance to ensure that the distance to the detonation is long enough both in terms of the distance in the channel in which the grenade resides and also the distance to the corner from the potential stacking position. The risk of lung injury is insignificant in this scenario.

3.4 Connected semi-enclosed rooms

In the setup of connected semi-enclosed rooms, we detonated three grenades. The averaged values of interest are tabulated in Table 5 and in Figure 9 we have plotted the peak sound pressure (in dB) and B-duration as given in MIL-STD-1474D.

Table 5. Averaged results in the trench system measurements

Sensor	Peak pressure [kPa]	B-duration [ms]	$ASII_{SP}$
0.5 m from door	24.7	373.4	0.009
1.0 m from door	19.0	491.6	0.009
1.5 m from door	16.0	469.1	0.009
Below window	37.6	114.0	0.014

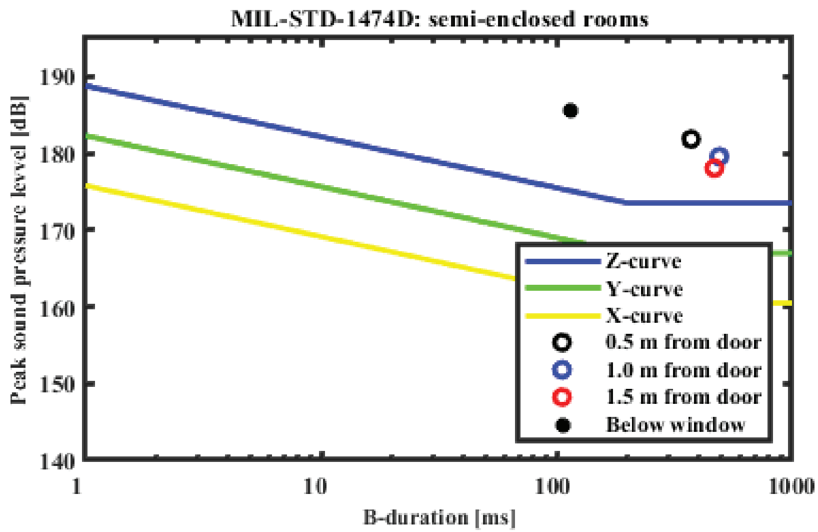

Figure 9. MIL-STD-1474D for 116g Comp B in connected semi-enclosed rooms

As we can see from the results, the risk of injury from the blast exposure when operating a stun grenade indoors can be significant. The reflecting surfaces in the geometry creates long B-durations will pose a risk to the hearing. The peak pressure outside the window is also exceeding the 4 psi threshold for the brain. It should also be stressed that the measurements done here is in the room connected to the room of detonation and the blast exposure inside the room of the grenade is even much higher. The risk of lung injury is insignificant in this scenario.

3.5 Summary

We have summarized the risk of injury in the various scenarios in Table 6. The risk of lung injury from a stun grenade is insignificant, but both hearing and the brain can be of risk to the operating personnel if close enough to the detonation. Especially when used in close proximity to reflecting surfaces that can cause buildup of the blast wave, which is the case when using the grenade in a trenches or indoors.

Table 6. Summary of the risk to operating personnel from stun grenades

Scenario	Lung	Ear	Brain
Free field	Insignificant	Yes (if close enough)	Yes (if close enough)
Behind cover	Insignificant	Insignificant (at 2 m)	Insignificant (at 2 m)
Trench system	Insignificant	Yes (caution required)	Yes (caution required)
Connected semi-Enclosed rooms	Insignificant	Yes (caution required)	Yes (caution required)

4. NUMERICAL CALCULATIONS

To create safe procedures for training it is of interest to know at which positions in a specific geometry that the blast exposure is at an acceptable risk level. Doing such experiments for each specific case is costly and if simulations can be employed this would be preferable. We used the numerical solver IMPETUS Afea to model the case of the free field wave and the semi-enclosed room and compared the simulation results to the measurements.

In the IMPETUS model the grenade is represented by a cylinder with height 5.94 cm, radius 1.97 cm and filled with Comp B using the IMPETUS particle model. We then defined output sensors as the same position as in the pressure measurements at two, four and six meters. Figure 10 shows the results of the Impetus simulation with cell sizes 0.02 m and 0.01 m compared to the measurements of the free

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field waves with largest and lowest peak pressure at a distance of 2 meters from the detonation. As we can see the IMPETUS model have a similar development as the measurements, but slightly underpredicts the peak at two meters.

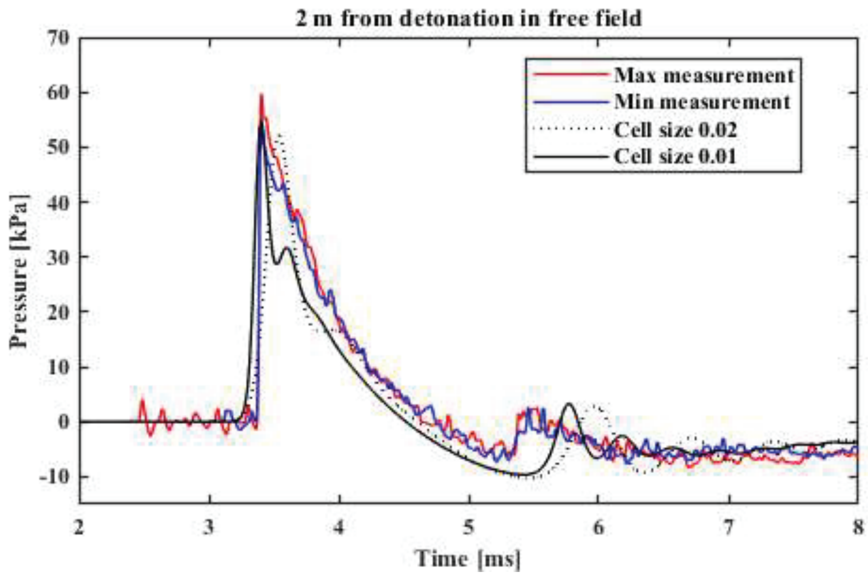

Figure 10. Comparison of IMPETUS and measurements of a free field wave

In the case of a detonation in a semi-enclosed room, we defined the roof, floor and walls using a rigid material and put this geometry inside an encompassing CFD domain filled with air. The total volume of the CFD-domain was 40 m^2. Again, we tried to simulate with cell sizes of 0.02 m and 0.01 m simulation with different cell size of the CFD domain to investigate the effect of the cell size.

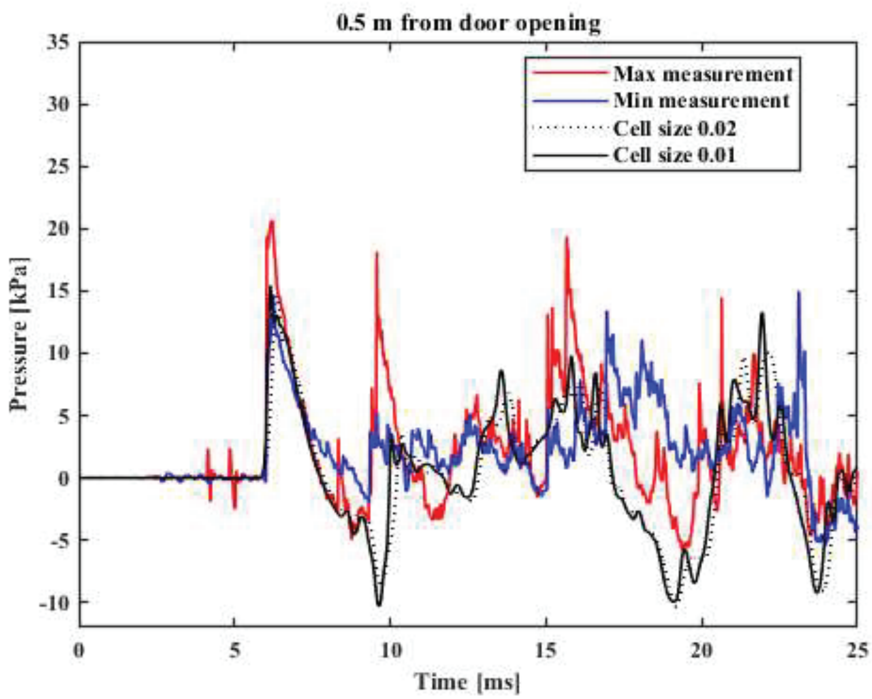

Figure 11. Comparison of IMPETUS and measurements in connected semi-enclosed room

Figure 11 shows the pressure history 0.5 meters from the door opening outside the room. As we can see, the simulation give a good estimate of the measurements. The small differences in measurements vs calculations can be due to several factors, such as inaccuracies in the measurement of the room, sensor positions, material properties, cell size or stochastic effects in measurements of detonation. In the case of cell size equal to 0.02 m the run time was just 4 minutes, whereas the cell size of 0.01 m gave a run time of 50 minutes. It is thus easy to obtain a good data foundation when developing training procedures that can maximize the training effect at an acceptable risk of injury.

5. DISCUSSION AND CONCLUSION

This work has shown that blast exposure from stun grenades can create a risk of injury for the operating personnel, especially when used in settings where there are surfaces that can reflect the blast wave. To mitigate this risk it is important to be aware of the blast exposure in the close proximity of the detonation. We have shown that employing a numerical tool as IMPETUS Alfea can provide calculations of the blast exposure to understand the risk of injury better, which is useful when creating training procedures for the personnel.

Another area of interest is the use of personal protective equipment (PPE) and how those can be designed to reduce the risk of injury from a given blast exposure. For instance, a review of the literature showed that wearing a helmet will, to some degree, protect against blast waves, given that the helmet is padded on the inside [11]. With the ability to use numerical calculations to get a good representation of the blast exposure of a given scenario, this data can in turn be used to assess the mitigating effect of varying PPE.

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