Test methodology for evaluating thoracic personal protective equipment against blast loading

J. Boutillier[1], S. De Mezzo[1], N. Prat[2], P. Magnan[1] and P. Naz[1]

[1]*French-German Research Institute of Saint-Louis (ISL), 5 rue du Général Cassagnou, Saint-Louis, 68301, France*
johanna.boutillier@isl.eu
[2]*Institut de Recherche Biomédicale des Armées, place Valérie André, Brétigny sur Orge, 91220, France*

Abstract. When designing new protective equipment for soldiers and law enforcement officers, the blast threat is not taken into account. The main focus is often on ballistic, stab and fragment protection. Primary blast injuries mainly concerned air-filled organs such as the lung and the gastrointestinal tract and studies have shown that some thoracic protective equipment (TPE) can worsen the level of injury.
An ISL anthropomorphic mannequin, called BOPMAN for Blast OverPressure MANnequin, was used to evaluate the efficiency of a soft ballistic TPE against blast threats of increasing intensities. Using the developed methodology, both qualitative (better or worse than) and quantitative (lung injury risk estimation) evaluations are possible.
Scenarios from 85g of C4 detonating at 3.8m from the mannequin to 4kg of C4 at 3m were performed unprotected and with a soft ballistic vest. Incident blast wave impulses from 17 kPa·ms to 237 kPa·ms were generated. Results show a near constant amplification factor of 1.35±0.20 on BOPMAN measurements with the vest compared to measurements unprotected. Estimated lung injury risks indicate that scenarios that should not generate lung injury when unprotected can be injurious with a soft thoracic protection. The percentage of increase of the lung weight ratio when equipped with a SBP are 0, 0.7, 2.7 and 18.7%. The augmentation of the ratio is due to pulmonary contusion and subsequent oedema. It was also noticed on high-speed videos that the TPE slaps the mannequin's chest when the shock wave arrived. The blast amplification observed could be the results of this slap caused by a small air-gap between the protection and the chest.

1. INTRODUCTION

The primary blast threat has not been considered in the development of protection systems to be used by soldiers and law enforcement personnel so far, mainly because no specification exists. The main focus is often on ballistic, stab and fragment protection. Nevertheless, air-filled organs such as the lung, ears and gastrointestinal tract are particularly susceptible to primary blast. So far, little is known about the efficiency of protective equipment against blast-induced thoracic damage. However, few studies have demonstrated that wearing low impedance thoracic protective equipment (TPE) worsens the level of blast-induced body injury, depending on the equipment used [1-5], although this finding seems to be inconsistent across studies [6-7]. However, placing a high density material (such as a ceramic plate) between the low impedance material and the incoming blast wave may help reducing blast-induced lung injury or mortality rate [2-3][8].

In order to correctly evaluate the performance of existing and future TPE against shock-waves produced by detonations of improvised explosive devices (IED), studies on thoracic models, especially mannequins, have recently emerged [9-13]. So far, the aim of these studies has been to demonstrate that the response of thoracic models is influenced by the TPE, although with this approach, one can only test if a protection system is better or worse than a reference system, without getting any information on the severity level of lung injury. Comparing the efficacy of different TPE using thoracic surrogates is a real progress in the process of designing optimal protections, but evaluating the level of protection they offer regarding the severity of lung injury would be more appropriate and informative. Indeed, such an evaluation could help find a good compromise between the weight of the systems and their ability to protect. More recently the ability of a new mannequin, called BOPMAN, to estimate the risk for lung injury in protected and unprotected soldiers was demonstrated [14]. The response of this mannequin was correlated with lung injury risk on 50kg swine.

In this study, the methodology developed with BOPMAN by Boutillier [14] for evaluating personal TPE against blast loading was applied to study the blast amplification behind a soft ballistic vest. The mannequin, unprotected and equipped with the vest was exposed to various short duration blast waves.

https://doi.org/10.52202/080042-0015

2. METHOD

2.1 Blast OverPressure MANnequin - BOPMAN

Figure 1 illustrates the anthropomorphic mannequin BOPMAN measuring 1.86 m for 78 kg. It is mostly made of solid polyethylene, with a specific instrumentation on the thoracic part, as shown in Figure 1C. The center of the thorax is not made of polyethylene but with a kind of drawer filled with silicone gel to represent the soft materials within the thorax. The thoracic part is equipped with:

- A pressure sensor (Kulite XT190M, 35 bar, USA) allowing the measurement of the reflected pressure on the thorax;
- A hydrophone (RESON TC4013, Denmark) placed in the silicone gel for the measurement of the internal pressure. It was located at the center of the gel block thanks to a thin plastic support, with the sensor tip located 1 cm behind the front wall of the thoracic part of the mannequin;
- A force sensor (B&K 8230, 22kN in compression and 2.2kN in traction, UK) at the rear part of the silicone gel block.

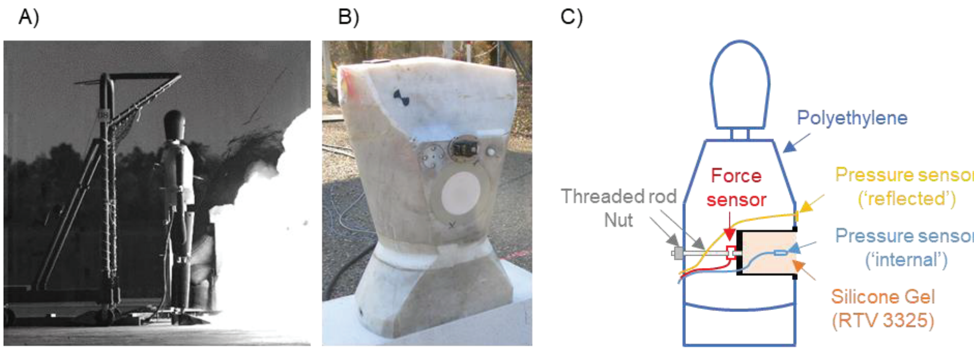

Figure 1. A) Illustration of BOPMAN exposed to a shock wave in standing position; B) Zoom view on the thorax; C) Schematic view of the thorax (side view) with details on the instrumentation

The response of this mannequin was previously correlated with lung injury risk on 50kg's swine [14]. The lung injury risk was estimated with the lung weight ratio RL/LL (RL for right lung, LL for left lung). In physiological condition, after exsanguination, this ratio is quite stable in swine. When this ratio changes, that means that fluid is trapped in or around the alveoli in one lung with the hypothesis that the exsanguination is equal between the 2 lungs, and that only one lung is damaged (that was verified during autopsy and previous unpublished histological data). The Axelsson Severity Score can also be determined, given a more descriptive aspect of the lung injury. All evaluations were done in a blinded manner (relatively to the experimental group). To fit with our animal model and experimental conditions, injury levels were determined as following, after macroscopic examination (both external and after slicing the lungs every centimeter): the lungs are graded ASS=0 for no injury, ASS = 1 for presence of surface petechiation, with no collection in the lung, ASS = 2 for presence of deep ecchymotic oedema with no "hematoma like" collection, ASS = 3 for large "hematoma like" involving less than 30% of the total volume or less than 50% of the surface on one of the slices, and ASS = 4 for large "hematoma like" involving more than 30% of the total volume or more than 50% of the surface on one of the slices. No medical imaging was available and used for the injury evaluation.

2.2 Tests with a soft ballistic thoracic protection

Four blast scenarios ranging from incident impulses of 17 kPa·ms to 237 kPa·ms were performed. For each scenario, BOPMAN thorax (27 kg with an height of 53 cm) is placed on a 15cm support at a given distance to a spherical explosive charge of C-4 suspended above the ground (height of burst around 20 cm). Quantity of C-4 and distance to the charge are determined to get the desired blast wave characteristics. Detail of the scenarios is given in Table 1. Results from exposing the whole BOPMAN or only its thorax are similar. For each scenario, reference tests were performed (thorax unprotected). Then, scenarios were reproduced while equipped with a soft ballistic thoracic protective vest. Three repetitions per scenarios and level of protection were performed for the reproducibility of the measurements. The experimental setup for the first three scenarios is illustrated in Figure 2. Experimental setup of scenario 4 is described in [14]. Exposing the standing BOPMAN to blast or only the thoracic

 https://doi.org/10.52202/080042-0015

part does not change the response data. The soft ballistic pack (SBP) is composed of aramid layers, UHMWPE UD layers as well as a thin foam layer. Its weight is 4.7 kg.

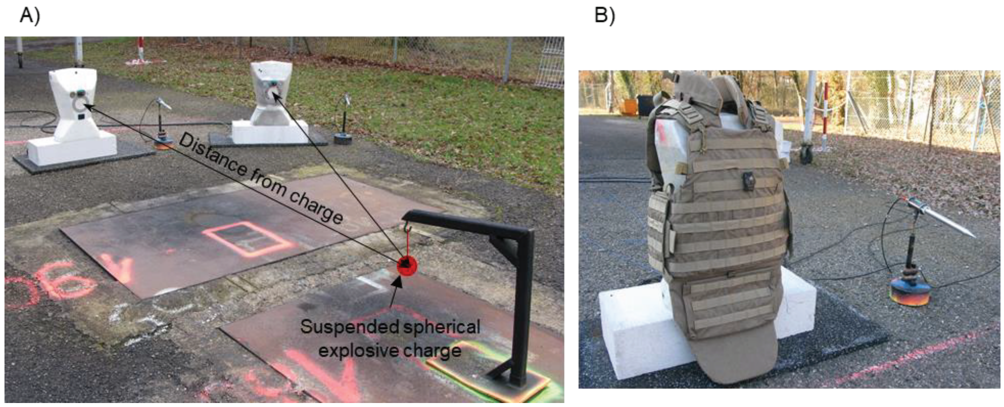

Figure 2. A) Experimental setup showing BOPMAN and pencil probe locations from the suspended explosive charge B) Illustration of BOPMAN thorax with the soft thoracic protective vest and the pelvis protection.

Table 1. Blast scenarios performed. The explosive charge was spherical and suspended 20cm above the ground.

Scenario	Mass of C-4, g	Distance from charge
1	85	3.8
2	500	3
3	800	2.3
4	4000	3

Every trial day begin with a test that serves to confirm the good response of BOPMAN by comparing the measurements with older data from a similar blast scenario. In addition to BOPMAN measurement, a pencil probe is placed near the mannequin at the same distance from the charge to measure the incident blast wave pressure profile. The height of the pencil probe sensitive part is 53 cm from the ground, similarly to the instrumented part of BOPMAN thorax. A FASTCAM Mini UX high speed camera at 10,000 frame per second was also used to visualize the vest movement under blast loading. This camera was placed at 25 m and orthogonally to the plane BOPMAN/explosive charge.

2.3 Data processing

All data were filtered with a 6th-order Bessel filter set at 90 kHz. Relevant metrics of interest were then computed for the pencil probe and BOPMAN (Table 2). The reflected and internal overpressure from BOPMAN are not presented as Boutillier [14] showed that those parameters are not relevant for protective system evaluation.

Table 2. Metrics of interest per sensor.

Sensor	**Metric of interest**
Pencil probe	Maximum positive incident pressure (ΔPi) Positive phase duration (T+) Maximum of incident impulse (ΔIi)
Reflected pressure sensor (BOPMAN)	Maximum of reflected impulse (ΔIr)
Internal pressure sensor (BOPMAN)	Maximum of internal impulse (ΔIint)
Force sensor (BOPMAN)	Maximum positive force (Force) Maximum of force impulse (ΔIforce)

2.4 Statistical analysis

Statistical analysis was done using Origin Pro software (OriginLab, United States). Metrics of interest were sorted based on thoracic protection level worn by BOPMAN and per scenario. If a normal distribution was observed, a one-way ANOVA test was performed to compare the mean values. Otherwise, a Kruskal-Wallis ANOVA test was performed. A $p < 0.05$ was considered significant.

3. RESULTS

3.1 Blast incident overpressure near the mannequin location

Blast incident characteristics for each scenario were comparable when the mannequin was unprotected or equipped with a soft ballistic protection, as indicated in Table 3. This table summarises mean and standard deviation (SD) of the metrics of interest from the pencil probe. P-values from paired student t-tests were also calculated. All p-values are above 0.05 (not statistically different), except for incident overpressure (ΔP_i)from scenario 2 (p= 0.03) and scenario 4 (0.01). For scenario 4, this can be explained by the proximity of the targets with the fireball that can lead to disturbances of the shock wave. Moreover, the pencil probe is 50 cm from BOPMAN with the sensitive part looking upward and slightly rotated in the opposite direction of BOPMAN to avoid reflection from the thorax. From high speed video, the wave speed are around 375, 470, 607 and 770 m/s for scenario 1 to 4, respectively. The reflection off BOPMAN should then arrived 1.3, 1.1, 0.8 and 0.6 ms after the incident wave passage, affecting slightly the incident impulse, but not the incident overpressure. Shock reflection off BOPMAN cannot explains p-value on ΔP_i from scenario 2. Nevertheless, data indicates that the blast pressure dose experienced by the mannequin and the vest were similar and, thus, allowed for a valid comparison across protection level tested.

Table 3. Incident pressure characteristics for the four blast scenarios. SBP: Soft Ballistic Pack

		ΔPi (kPa)	T+ (ms)	ΔIi (kPa ms)
Scenario 1	**Unprotected**	21.1 ± 0.6	1.89 ± 0.01	17.4 ± 0.0
	SBP	20.9 ± 0.3	1.89 ± 0.02	17.3 ± 0.2
Scenario 2	**Unprotected**	95.5 ± 8.0	2.33 ± 0.24	73.0 ± 3.2
	SBP	91.8 ± 2.4	2.24 ± 0.04	70.5 ± 1.8
Scenario 3	**Unprotected**	223.9 ± 14.9	1.72 ± 0.10	108.2 ± 2.6
	SBP	221.3 ± 11.6	1.67 ± 0.01	108.2 ± 2.2
Scenario 4	**Unprotected**	467.4 ± 48.6	2.28 ± 0.40	242.6 ± 22.6
	SBP	421.5 ± 37.6	2.28 ± 2.30	226.7 ± 7.8

Figure 3 illustrates an example of incident pressure and impulse profiles from unprotected and protected configurations for scenario 2 (500g at 3m).

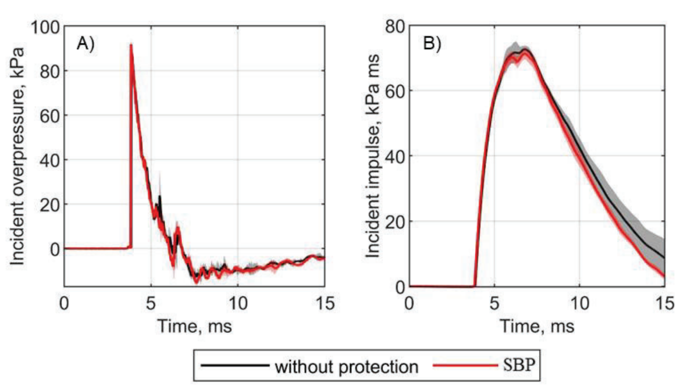

Figure 3. Example of incident pressure (A) and impulse (B) profiles from unprotected and protected (SBP) configurations (scenario 2, 500g at 3m)

https://doi.org/10.52202/080042-0015

3.2 Soft ballistic pack performance under blast loading

Figure 4 illustrates the force and the force impulse from BOPMAN unprotected and equipped with a SBP for scenario 2. An amplification of the maxima can be observed when equipped with the SBP compared to the unprotected scenario.

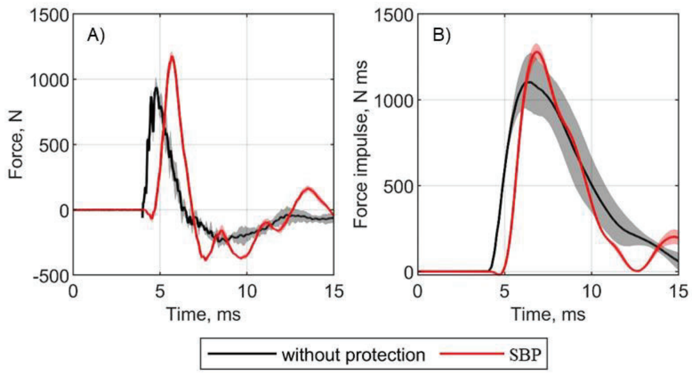

Figure 4. Example of force (A) and force impulse (B) profiles from unprotected (--) and protected (--) configurations (scenario 2, 500g at 3m)

The response of BOPMAN with the SBP differed significantly from the response unprotected for all tested scenarios (incident impulse up to 237kPa·ms, short duration wave). Figure 5 illustrates the comparison of the maximum values of the force and force impulse unprotected and with the ballistic vest for each scenario. BOPMAN lung injury threshold values are also plotted on the graph. It can be noticed that scenario 3 unprotected is close to/on the lung injury threshold while unprotected, which is in accordance with Bowen curves.

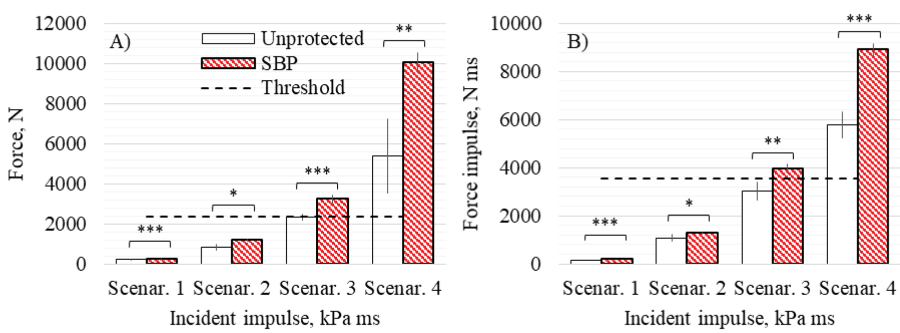

Figure 5. Comparison of the maximum values of the force and force impulse unprotected and with the ballistic vest for each scenario * $p<0.05$, ** $p<0.01$ and *** $p<0.001$

Figure 6 illustrates the mean and standard deviation of BOPMAN metrics ratio SBP/unprotected. The ratios SBP/unprotected from the force and the force impulse values were calculated. Then, mean values and standard deviation were calculated from previously obtained ratios. The mean ratio is statistically not different across scenarios ($p=0.587$). The amplification factor on BOPMAN metrics due to the wearing of a soft ballistic pack can be considered as constant for short duration blast wave of incident impulse up to 237 kPa·ms. The amplification factor is equal to 1.35 ± 0.20.

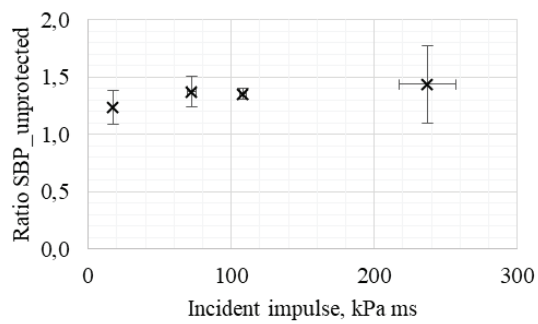

Figure 6. Mean and standard deviation of BOPMAN metrics ratio SBP/unprotected for each tested scenario. The ratio is plotted against the maximum of incident impulse.

It was also noticed with the high-speed video recorded that the SBP slaps the thorax when the shock wave hits it. Moreover, a double peak is seen on the internal pressure profiles when equipped with the protection. The more intense is the blast, the higher the inward movement of the protection will be. When the vest was positioned, there was (almost) no gap between the vest and the torso, but this small gap exists, leading to that displacement. SBP obeys to the successive compression and suction phases of the blast phenomenon. After this inward displacement, the negative phase of the incident blast wave led to the inflation of the protection with and without the pelvis protection attached to the vest. The movement of the SBP for the scenario 3 is illustrated in Figure 7.

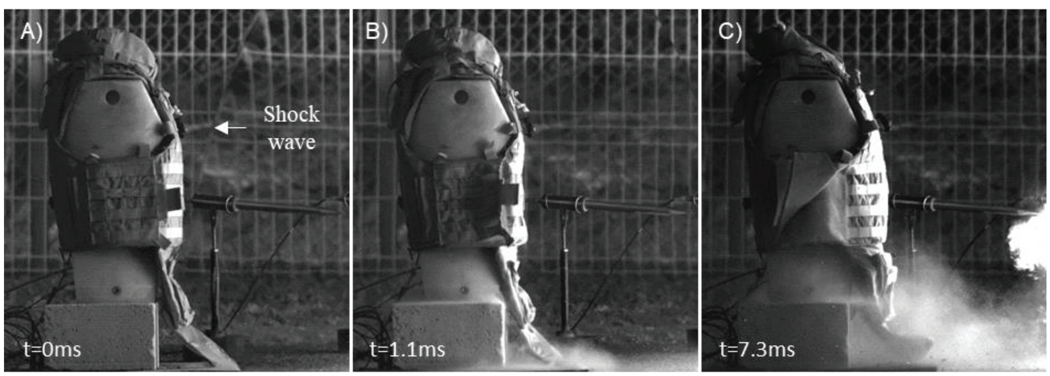

Figure 7. Movements of the SBP for the scenario 3. A) Vest before the arrival of the blast wave; B) Maximum compression of the vest; and C) Maximum expansion of the vest.

The addition of a ceramic plate was found to improve the performance of the TPE [14]. High-speed recording showed that the slap of the protection with a plate is slower than without it, which could be due to the addition of mass. Moreover, no expansion phase of this protection was visible, probably due to the rigidity of the protection with the ceramic plate.

3.3 Lung injury risk estimation

It was previously noticed a constant amplification factor on BOPMAN metrics while equipped with the SBP compared to unprotected scenarios. The constant amplification factor on BOPMAN metrics does not imply a constant amplification factor for lung injury level. As written in section 2.2, the ratio RL/LL was used to represent the extent of lung contusion. It can be calculated with equations (1) and (2) using the force or the force impulse measurement from BOPMAN. Those equations are slightly different from equations in [14] but are based on the same database. Only the chosen fitting equation is different.

$$\frac{RL}{LL} = 1.36 + 0.13 * e^{\frac{(Force-2348.2)}{4273.7}}, R^2 = 0.72 \quad (1)$$

$$\frac{RL}{LL} = 1.36 + 0.18 * e^{\frac{\left(\Delta I_{force}-3568.0\right)}{3653.7}}, R^2 = 0.77 \quad (2)$$

https://doi.org/10.52202/080042-0015

For information, during a blast event, lung injury was always on the lung facing the blast [14]. This can be proven by the left lung weight (LL) that was not statistically different across group (unprotected vs. equipped with a protection). The LL weight mean value is 158.6±34.0g.

Moreover, with RL/LL, the ASS (see section 2.2) can be calculated with the equation given in Fig 8. This metric give a more detailed description on the lung injury. Table 4 summarizes estimated RL/LL and ASS for each scenario and protection level. For the four tested scenarios, the percentage of increase of the ratio RL/LL when equipped with a SBP are 0, 0.7, 2.7 and 18.7%.

Table 4. Calculated RL/LL and ASS for all scenarios and protection level

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Unprotected	1.43 ± 0.01 ASS = 0	1.44 ± 0.01 ASS = 0	1.49 ± 0.02 ASS = 0	1.71 ± 0.09 ASS = 1
SBP	1.43 ± 0.01 ASS = 0	1.45 ± 0.01 ASS = 0	1.53 ± 0.02 ASS = 1	2.03 ± 0.14 ASS = 3

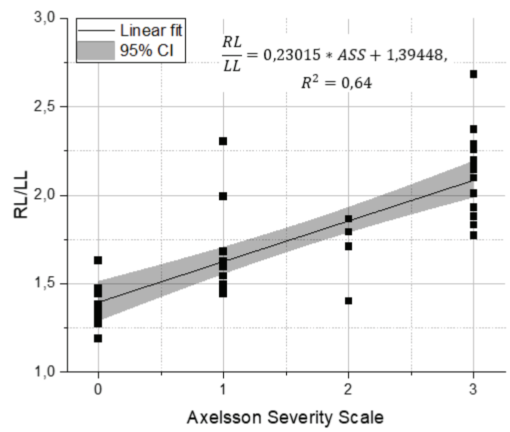

Figure 8. RL/LL as a function of the Axelsson Severity Score ASS from animal testing (data from [14]). The linear fit equation is written on the graph.

4. CONCLUSIONS

The aim of this study was to assess the feasibility of using an advanced surrogate system to evaluate blast amplification/attenuation behind a protective system. Therefore, the response of BOPMAN dummy is investigated while unprotected and equipped with a SBP. Incident blast wave impulses from 17 kPa·ms to 237 kPa·ms were generated by detonating spherical explosive charges of different masses at different distance from the target.

This study suggests that the test methodology used can detect relative differences in protection efficiency under blast loading. It was observed that for incident impulse up to 237 kPa·ms, the SBP amplifies the blast and so the lung injury risk. This latter was estimated with the RL/LL ratio and the ASS. BOPMAN metrics ratio (SBP over unprotected) was found to be roughly constant, at least over the incident impulse range tested, which does not imply a constant increase in lung injury level. This amplification factor is equal to 1.35 ± 0.20, while the percentage of increase of the ratio RL/LL when equipped with a SBP are 0, 0.7, 2.7 and 18.7%. It was also noticed with the high-speed video that the SBP slaps the thorax when the shock wave hits it. This movement is due to an inevitable small air gap between the vest and the thorax and the successive compression/suction phases as the shock front passed through it. The influence of the air gap on the amplification factor is unknown and should be studied.

While use of BOPMAN and the associated test methodology allowed for a comparison across different protection levels in terms of lung injury risk, some limitations were noted in this study. First, there is no standard to confirm the good positioning of the armor on the thorax. Nevertheless, a constant gap between the protection and the thorax was sought between the different experiments. Second, injury risk estimation is based on correlation performed at 237 kPa·ms with three levels of protection [14]. More data at other incident impulses are needed to increase the confidence on BOPMAN's ability to predict the lung injury risk in unprotected and protected configurations.

This study provides a first investigation of the use of BOPMAN to assess the effectiveness of TPE against blast loading based on lung injury risk. The results demonstrate that BOPMAN has potential to be used as a test mannequin to assess blast-induced lung injury risk. Additional works to investigate the sensitivity and reproducibility of BOPMAN to other blast exposures (e.g., severity levels, environments) and TPE are required to further validate this test device. Validation of a test device for the assessment of blast-induced lung injury is essential to properly evaluate protection systems for soldiers and law enforcement officers.

References

[1] Phillips Y.Y., Mundie T.G., Yelverton J.T. and Richmond D.R., Cloth Ballistic Vest Alters Response to Blast. J. Trauma, 1988; 28 (1); S149–S152.

[2] Cooper G.J. Townend D.J. Cater S.R. and Pearce B.P., The Role of Stress Waves in Thoracic Visceral Injury from Blast Loading: Modification of Stress Transmission by Foams and High-Density Materials. J. Biomech, 1991; 24 (5); 273–285.

[3] Cooper G.J., Protection of the Lung from Blast Overpressure by Thoracic Stress Wave Decouplers. J. Trauma, 1996; 40 (3); S105–S110.

[4] Gibson P.W., Amplification of Air Shock Waves by Textile Materials. J. Text Inst., 1994; 86 (1); 119–128.

[5] Prat N.J. Boutillier J. Cardona V. Monterspan F. Menini W. Mosnier J., et al., “Injury and Biomarkers from Pigs Following Isolated Open-Field Blast Exposure Depend on Ballistic protection Level”, in Poster from the Military Health System Reseach Symposium, Kissimmee, Florida. 2019

[6] Long J.B. Bentley T.L. Wessner K.A. Cerone C. Sweeney S. and Bauman R.A., Blast Overpressure in Rats: Recreating a Battlefield Injury in the Laboratory. J. Neurotrauma, 2009; 26 (6); 827–840.

[7] Wood G.W. Panzer M.B. Shridharani J.K. Matthews K.A. Capehart B.P. Myers B.S. et al., Attenuation of Blast Pressure behind Ballistic Protective Vests. Inj. Prev., 2013; 19(1); 19–25.

[8] Sekine Y. Saitoh D. Yoshimura Y. Fujita M. Araki Y. Kobayashi Y. et al., Efficacy of Body Armor in protection against Blast Injuries Using a Swine Model in a Confined Space with a Blast Tube. Ann. Biomed. Eng., 2021; 49(10); 2944–2956.

[9] Jetté F.X. Dionne J.P. Williams K. Anctil B. and Makris A., Development of a Mannequin for Assessment of Blast Injuries and Lethality – Assessment of Protective Systems, in Proceedings of the MABS 18th Conference, Schneizlreuth, Germany. 2004.

[10] Bass C.R. Davis M. Rafaels K., A methodology for assessing blast protection in explosive ordnance disposal bomb suits. Int. J. Occupat. Safety Ergonom., 2005; 11(4) ; 347–361.

[11] Ouellet S. and Williams K., Characterisation of Defence Research and Development Canada’s Mannequin for the Assessment of Blast Incapacitation and Lethality (DRDC MABIL), in Proceeding of the Personal Armour Systems Symposium, Brussels. 2008.

[12] Carboni M. DeCrisofano B. Segars R. and Maffeo M., Evaluation of a Blast Overpressure Test Device for Personal Protective Equipment, in Proceeding of the Personal Armour Systems Symposium, Quebec. 2010.

[13] Awoukeng-Goumtcha A. Thoral-Pierre K. Roth S., Toward a powerful tool for the prediction of human body trauma under extreme loadings through finite element simulations, in Proceeding of the Personal Armour Systems Symposium, Cambridge. 2014.

[14] Boutillier J. Cardona V. Magnan P. Ogier M. De Mezzo S. Montespan F. Menini W. Mosnier J. Naz P. and Prat N.J., A New Anthropomorphic Mannequin for Efficacy Evaluation of Thoracic Protective Equipment Against Blast Threats. Front. Bioeng. Biotechnol., 2022; 9:786881.

 https://doi.org/10.52202/080042-0015