Evaluation of test methods on personal protective equipment for blast overpressure

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Abstract. In recent conflicts, a major source of injury for military personnel are Improvised Explosive Devices (IEDs), which generate blast overpressure (BOP), fragments and heat. Personal Protective Equipment (PPE) of dismounted soldiers are primarily tested for protection against bullets, fragments, heat and stabbing using accepted formal standards. Until now there are no formalised standards specifying test methods to assess the PPE performance on protection against BOP. This study presents an overview of test methods for PPE BOP protection for the thorax and eyes which are published in open literature. A discussion of the features of the methods will be concluded by a proposal for an optimized method with indications of knowledge gaps or shortcomings to be filled out in the future.

1. INTRODUCTION

Explosions were the dominant mechanism of injury (72%) affecting NATO coalition forces operating in Iraq and Afghanistan during 2001 – 2011 [1]. Explosions include fragments, heat and blast overpressure, which all have their specific injury mechanism. Dismounted soldiers are likely to be protected by PPE (i.e. helmet, soft and/or hard body armour, eyewear, etc.), where ballistic and heat resistance properties are tested and certified using internationally accepted test standards [2-3]. However, accepted standards and test methods for evaluating PPE on BOP are not available. Although, such standards are relevant as the number of overpressure casualties cannot be neglected, as 3.6% of injured soldiers in Iraq/Afghanistan had evidence of thoracic BOP injury [4]. Ocular BOP injury is not specifically documented in epidemiology studies. The Birmingham Eye Trauma Terminology system (BETT) [5] definition of closed globe injuries could give an indication of ocular BOP injuries, since these injuries were found at blast-exposed patients with documented Traumatic Brain Injury (TBI) [6].
The goal of this research is to draft a test method for PPE BOP protection, including indication of knowledge gaps, based on a literature review of published methods for the thoracic and ocular region.

The following elements are considered to be essential for a test method:

- Relevant BOP
- Performance Criteria & Tolerances
- Test setups
    - Threat definition
    - Test device

2. LITERATURE REVIEW RESULTS

2.1 Scope

The selected body regions of interest are thoracic and ocular. The thorax seems to be the most investigated within the field of bodily BOP protection and the ocular area as an emerging topic. Both regions are likely to be protected for (dis)mounted soldier.
The literature review results are split into thoracic (2.2) and ocular (2.3). The assessment of literature was conducted through open access and journal papers, as well as conference proceedings from Personal Armour Systems Symposia (PASS) and Military Health System Research Symposium (MHSRS). Main keywords for identifying papers were: blast, protection, injury, overpressure, test, experiments. These were extended using thorax, thoracic, lung, ocular, eyes for analysing specific body parts.

2.2 Thoracic PPE BOP Test Methods

2.2.1 Relevant BOP

A relevant BOP testing regime is shown by the Bowen curves [7] describing the correlation between lethality and pressure wave characteristics incident overpressure and positive phase duration for an

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unprotected man. More specifically, lung injury risk curves to describe the probability of lung injury are described in [8], discriminating between slight, moderate and severe lung injury.
Investigated literature shows three loading scenarios, namely open field, shock tube and confined testing. Each of these loading environments has a specific impact on the effective blast wave characteristics. No standard blast loading definition could be found for testing thoracic PPE BOP performance [8-9].

2.2.2 Performance Criteria

The thoracic BOP protection is evaluated by measuring specific performance criteria. Specific tolerance values are used to classify the level of protection. Some are injury risk related others are not. Table 1 gives an overview of found criteria, tolerances, injury models and the corresponding references. The criteria are shown in the first column, commonly used names for injury models are given in the second column, references giving thoracic BOP injury tolerances are given in the third column and finally, references are listed in last column.

Table 1: an overview of performance criteria for the evaluation of thoracic PPE w.r.t. lung injury or lethality risk.

Criterion	Injury model	BOP injury tolerances	References
Product of chest velocity (V) and the normalized compression (C) (VC) [m/s]	Viscous Criterion [10]	Lung injury risk [8]	[8-13]. [8],[10-14]
Lung mass [kg]	Fluid in lungs	x	[15]
Chest wall acceleration (a_{cw}) [m/s^2] Sternum acceleration (a_{st}) [m/s^2]	x	Lung injury risk [8] [15]	[8] [15]
		Indirect correlation with lethality risk [16]	[16]
Chest wall velocity (v_{cw}) [m/s]	x	Lung injury risk [8]	[8]
	Axelsson Injury Model (AIM) [21]	Adjusted Severity of Injury Index (ASII) [22]	[17-22]
	Stuhmiller Injury Model (SIM) [23]	Lung injury risk Lethality risk	[23]
Chest wall displacement (d_{cw}) [m]		Lung injury risk [8]	[8]
Incident pressure (p_i)[kPa]	Bowen curves [7]	Lethality [7]	[7],[24-25]
Incident pressure impulse m(i_i) [kPa*ms]		Lung injury risk [8]	[8]

2.2.3 Test setups

The thoracic BOP protection is evaluated through performing simulated BOP tests. The test setups are evaluated by threat definition and test device.

- The threat definition of test setups is described by the loading environment: shock tube, free field and confined space. Also, the characteristics of the blast wave are given.
- The test devices are described and mentioned by their abbreviation.

Table 2 gives an overview of test devices, measured parameters, mention of injury model, threat definition. The tested protective system and effect on the measured parameter are also included.
This table is an update and extension of an overview published earlier [26]

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Table-2: an overview of test setups for evaluating thoracic BOP PPE.

TD	Test device	Measured parameters	Injury model	Armour config.	Results & remarks	Ref
S[1]	Animals & Thoracic Rig	Lung mass & a_{cw}	x	(1) Textile (2) Plate	Comparison of performance between armour config (2) and (1): decreased lung injury, lung mass and peak a_{cw}	[15]
S[10]	Animals	Lung mass, Fatality	x	(1) None (2) Vest	Comparison of vest versus no vest: severe lung injury increased and a higher average fatality of test animals	[27]
F[2]	MABIL, (BTD not used for results)	a_{cw} Incident pressure Lethality risk	Bowen curves [7]	(1) Textile (2) Vest (3) Vest+Plate	Config (2) versus (1): similar lethality probability, (2) has increased peak a_{cw} Config (3) versus(1): lower lethality probability and decreased peak a_{cw}	[16]
C[3]	BTD MBTD	Surface pressure, v_{cw}, w_e	SIM	(1) None (2) Materials	Config (2) versus (1): decreased severity of injury, overpressure, v_{cw} and W_e	[28]
F[4]	HSTM	Pressure in organs a_{cw} Compression	X	(1) Textile (2) Vest+Plate	Comparison of performance between armour config (2) and (1): maximum pressure decreased in left lung, increased in left lobe of liver. Pressure impulse increased in stomach and liver.	[29]
C[5]				1) Textile (2) Vest (3) Vest+Plate	Config (2) versus (1):max. pressure increased in liver right lobe, decreased in liver left lobe. Pressure impulse increased in stomach, liver right lobe, decreased in liver left lobe. Config. (3) versus (2): peak pressure increased in left lung, decreased in liver left lobe. Pressure impulse increased in stomach, liver right lobe, decreased in liver left lobe.	
S[6]	Steel pipe	Surface pressure	Bowen curves [7] + other	(1) None (2) Vest (3) Vest+Plate	Config (2) versus (1):peak pressure decreased and pulse duration increased, lung injury probability increased or remained within the same regime Config (3) versus (1): Peak pressure and lung injury probability decreased	[30]
C[7]	Flat plate	Surface pressure	x	(1) None (2) Plate	Config (2) versus. (1): transmitted pressure and impulse decreased.	[31]
	MABIL	a_{cw}			Config (2) versus. (1) a_{cw} decreased	

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Table 2 (continued)

C[8]	CS	Surface pressure	Bowen	(1) None (2) Vest (3) Vest+Rigid Material	Comparison of performance between config (2) and (1):pressure and lethality probability increased. Config(3) versus (1): peak pressure and lethality probability decreased. Positive phase duration increased.	[32]
F[9]	Hybrid II	a_{cw} p_{cw}			Comparison of performance between config (2) and (1) maximum a_{cw} and lethality probability increased. Config (3) versus. (1) maximum a_{cw}, overpressure and lethality probability decreased.	
F[11] C[12]	Hybrid III MBTD BTD	Pressure profiles a_{cw}	SIM VC	(1) Vest (2) Plate+Vest	Comparison of config (2) versus (1): Average We and maximum v_{cw} decreased, no VC change	[33]

Threat Definition (TD): Shock tube (S), Free field (F), Confined space (C) loading conditions.
Where a_{cw}, v_{cw} and d_{cw} are chest wall acceleration, velocity and displacement respectively,
1 = unknown; 2 =20 kg C4 at 6.25 m and 10 kg C4 at 4 m; 3 = unknown; 4 = 1.4 kg C4; 1.8 kg C4 and 2.3 kg C4 at 2.3 m on 1 m height; 5 = 0.7 kg; 0.9 kg and 1.2 kg thermobaric charge; 6 = incident overpressure peaks ranging between 83 – 640 kPa; 7 = 0.25 C4 at 1 m; 8 = 0.12 or 0.25 kg C4 at 0.65-0.55-0.45 m distance; 9 = 0.05-0.1-0.2 kg C4 at 0.66-0.68 m distance;10 = 115, 230, 295 and 420 kPa ;11 = 0.7, 0.9, 1.2, 1.4, 1.8 kg; 12 = 0.7, 0.9, 1.2 kg

Three categories in used test devices can be distinguished:

- Non anthropomorphic: measuring behind armour pressure test devices CS, BTD, MBTD;
- Lower complexity anthropomorphic thoracic chest wall motion test device MABIL;
- Higher complexity anthropomorphic test devices HYBRID III and HSTM;

The devices listed in Table 2 are described below.

- Thoracic Rig: A rig replicating the peak acceleration response of the thoracic pig wall [15].
- Blast Test Device (BTD): a rigid vertical instrumented cylinder based on thoracic dimensions of sheep [19]. Pressure transducers are mounted flush with the cylindrical surface.
- Modified Blast Testing Device (MBTD): is very similar to the BTD but modified to handle protective materials [28],[34-35]. The MBTD collects pressure data using many pressure sensors to map out the pressure contour around the entire protective material.
- Mannequin for the Assessment of Blast Incapacitation and Lethality (MABIL) [36] is a anthropomorphic test device. Accelerometer measurements are performed mid-torso, sternum and abdomen.
- Hybrid III originated from the automotive industry and is an anthropomorphic test device with acceleration, force and displacement sensors in the different body parts [37]. Extra sensors are sometimes added for a specific study purposes [38].
- Human Surrogate Torso Model (HSTM) is a high fidelity anthropomorphic test device developed to for armour blunt trauma [29]. High fidelity due to a detailed skeletal structure, major thoracic and abdominal organs, mediastinum, flesh and skin and the number of varying materials used. Instrumentation consists of pressure sensors, within different organs, sternum accelerometers, displacement sensor to measure chest displacement and load cell.
- Chest Simulator (CS) [32]: curved aluminium plate (12.7mm) thick bolted on a flat aluminium base plate. The curved plate is roughly similar to the human torso and pressure sensors are mounted flush at the surface.

2.3 Ocular PPE BOP Test Methods

2.3.1 Relevant BOP

Living rodents have been used to investigate short and long term injuries after single and repetitive BOP [39-47]. The BOP leading to ocular injures provide an estimate for the relevant BOP regime. Using

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animals with human size eyes (larger than rodent eyes) better emulates effects for the human eye [48]. Two studies are highlighted here:

- Living rabbits, revealing relevant ocular trauma (corneal thickness, retinal thickness) caused by survivable pressure levels: 120-132 kPa peak overpressure, 96-104 Pa*s impulse [49].
- *In vivo* porcupine eyes also sustain primary blast ocular trauma caused by survivable pressure levels: 113 kPa peak overpressure, positive phase duration of 2.4 ms, impulse 128 Pa*s [50].

2.3.2 Performance Criteria

The ocular PPE protection performance for BOP is evaluated by use of injury criteria and tolerances [51-52] or by making a relative comparison between PPE [53-55]. Table 3 gives an overview of available ocular injury criteria, -models and -tolerances shown in the first, second and third column respectively.

Table-3: ocular injury criteria

Injury criterion	Injury model	Injury Tolerances
Incident peak pressure [kPa]	risk of vision loss calculator [51]	risk function [51]
Reflective peak pressure [kPa]	injury risk prediction [52]	risk function (IOP) [52], [56]
Intra-Ocular Pressure (IOP) [kPa]		

2.3.3 Test Setups

The test setups are characterized by the threat definition and test device.

- The laboratory threat simulation is defined by the blast overpressure parameters: peak overpressure, positive phase, impulse, complex waves and the threat source: shock tube or free field.
- The test devices used in each test setup are described by head form and PPE.

The setups are listed in Table 4.

- Three configurations can be distinguished, namely the bare head form, open eyewear and closed eyewear configurations. Open eyewear implies gaps between the head form facial region and the eyewear and closed eyewear implies that the gaps between head form facial region and eyewear are closed by material.
- Head forms: Most studies used a custom anthropomorphic head form, one study a standardized FOCUS head form and one included a porcine eye surrogate.
- Combat helmet: Most studies include a combat helmet placed upon the head form.
- Important varying parameters are described by Remarks (Rm) in Table 4.

Table 4 gives an overview of threat definition, test devices, measured parameters, mention of injury model, threat definition. Mention of tested protective system, effect on the measured parameter and remarks regarding important variations are also included.

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Table-4: an overview of test setups for evaluating ocular BOP PPE.

TD	Test device	Measured parameters	Injury model	PPE	Results (Rs) & Remarks (Rm)	Ref
S[1]	Small and large head form + combat helmet + ocular PPE	Reflective pressure at corneal surface	x	(1) Bare (2) Open eyewear (3) Closed eyewear	Rm: Varying head form size and orientations. Rs: Config (2) versus (1): decreased reflective peak pressure for a few orientations and increased reflective pressure for most orientations. Config (3) versus (1): decreased reflective peak pressure for most orientations and increased reflective pressure for a few orientations.	[53]
S[2]	Head form + combat helmet	Reflective pressure at corneal surface	x	(1) Bare (2) Open eyewear (3) Closed eyewear	Rm: Varying head form orientations & loading. Rs: Config (2)&(3) versus (1) decreased reflective peak pressure for most orientations and increased reflective peak pressure for a few orientations (3) versus (2)&(1) increased reflective pressure impulse for some orientations	[54]
S[3]	Head form + combat helmet	Reflective pressure at corneal surface	risk of vision loss calculator	(1) Bare (2) Open eyewear (3) Closed eyewear	Rm: Varying headform orientations & loading Rs: Config (3)&(2) versus (1) decrease in “risk of vision loss” for an orientation (2) versus. (1) increase in “risk of vision loss” for an orientation	[51]
S[4]	Head form + porcine eye	IOP Facial pressure sensors	(1) eye dissection (2) eye injury risk calculation	(1) Bare (2) Open eyewear (3) Closed eyewear	Rm: Varying loading Rs: Config (2) versus (1) decreased IOP for 2/3 loading scenarios and an increased IOP, IOP impulse and reflective pressure impulse for 1/3 loading scenarios (3) versus (1) decreased IOP, IOP impulse and reflective impulse for all loading scenarios	[52]

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Table 4 (continued)

F5	Head form (FOCUS)	Reflective pressure at corneal surface	x	(1) Bare (2) Open eyewear (3) Closed eyewear	Rm: varying loading Rs: (2) w.r.t (1) decreased reflective peak pressure for both loading scenarios (3) w.r.t (2) decreased reflective peak pressure for both loading scenarios	[56] [55]

1 = Using a Friedlander blast wave characterised by; a measured peak overpressure of ~11 kPa, a positive phase duration of ~1.5 ms); 2 = Using Friedlander blast waves characterised by incident overpressure levels of 70, 140 and 210 kPa 70, 140 and 210 kPa; 3 = Incident pressures varying between 78 and 306 kPa with a positive phase duration between 2.97 – 5.32 ms; 4 = 69 kPa, 138 kPa, 207 kPa static overpressure with a positive duration around 2.5 ms;5 = free-field incident overpressures of ~46 and ~190 kPa (0.5 kg C4 at 3m and 5 kg C4 at 3.8m).

3. DISCUSSION

3.1 Threat Simulation

Blast testing using shock tubes, free field or confined spaces loading conditions have their own characteristics. Shock tubes enable blast research in laboratory conditions. The desired pressure at the specimen can be carefully designed using the driver's length, drivers gas and specimen location. However, special attention should be given to for instance, the rarefaction effects of the open end of the tube, the tube cross section-specimen size ratio and the dynamic pressure component because they all have a significant impact on the loading experienced by the target [56]. Free field blast experiments are convenient due to increased fidelity: inclusion of acoustic, thermal, optical and electromagnetic components found in actual blasts and excluding the boundary effects of a shock tube for instance [58].

3.2 Thoracic PPE BOP Test Methods

BOP and PPE body interaction and on top indicating injurious consequences requires multidisciplinary expertise, which indicates the complexity of assessing thoracic PPE BOP protection performance [29]. However, based on thoracic PPE BOP animal studies, a hard armour material combined with a specific backing could decrease lung injury and peak a_{cw} [15], whilst standalone soft armour is able to increase severe lung injury and average fatality [27].

Non animal studies show that protection using only soft material is able to increase a_{cw} [7], [28] and that hard/plate material combinations were able to decrease the lethality probability and peak a_{cw} [16],[31]. Similar effects observed for behind armour surface pressure as performance measurement [28],[30], [32]. However, the behind armour surface pressure shows significant inconsistencies between different test devices. The physics of behind armour pressure is a topic of discussion.

Therefore, measuring a_{cw} seems as a promising performance parameter able to distinguish between different armour configurations.

The MABIL, HSTM, Hybrid III test devices are equipped for measuring a_{cw}. The MABIL test device appears to be less complex than the HSTM and Hybrid III. The HSTM and Hybrid III measure more performance parameters but the added value for a Thoracic PPE BOP test method remains to be determined.

The following results of acceleration based test devices were found:

- The Hybrid III measuring acceleration based parameters: $a_{cw,}$ v_{cw} w_e showed to be repeatable and discernible between charge levels. [33]
- The MABIL showed a correlation between peak a_{cw} and the peak incident overpressure [36].

Other testing devices found in literature but not included in Table-2 are the Swedish torso surrogate amino [59] and South African Torso Surrogate [60].

There are test methods which do not provide consistent results and are therefore questionable to be used for a standard PPE BOP performance assessment:

https://doi.org/10.52202/078352-0044

- The BTD provided inconsistent and contradictory results during the evaluation of different protective materials [38].
- The BTD, MBTD calculated W_e without armour system were inconsistent [33].
- The Hybrid III anthropomorphic test device, obtained an inconsistent measurement between a_{cw}, peak v_{cw} and W_e. [33]
- The Hybrid III with the criterion VC_{max} was not usable [33].
- The HSTM anthropomorphic test device, an increased impulse was measured within the surrogate stomach and liver but not the lungs when PPE was present [29].
- The influence of a complex pressure time history on performance parameters measured by test devices is investigated in [61-62]

The correlation between BOP and injury risk to assess the protective performance needs further elaboration [13], [60], [63-64]. Especially development of severity risk scales for non-lethal or low lethal injurious consequences [61]. Also the influence of armour materials, e.g. mass and cushioning, on the chest kinematics is not fully understood [28],[33].

3.3 Ocular PPE BOP Test Methods

Ocular BOP injury could be expected from Friedlander blast wave characterised by 113-132 kPa incident peak overpressure or 96-128 Pa*s incident pressure impulse. The usage of ballistic eyewear was not related to reducing closed eye injury [6] but is correlated with decreasing eye injuries (26% to 17%) [22] possibly only mitigating secondary fragments. If closed eye injuries are caused by BOP, this could imply that the used eyewear is not protecting against BOP.
The repeatability and reproducibility of measured reflective pressure at the corneal surface, different types of eyewear or the effect of open and closed eyewear for multiple head form orientations is investigated by all studies. One study included measuring the IOP. Further investigation is required to determine the deviation of these parameters.

Ocular PPE BOP Test methods appear to be in a premature phase. However there is serious potential if to merge available information and methods as a basis for a formal standard. E.g. the FOCUS head form is fit to be used for PPE BOP evaluation according to [65].
Further research and elaboration of published research is required . Relevant publications and associated knowledge gaps are listed below for respectively Injury criteria, performance parameters and choice of test configuration:

Injury criteria:

- The injury risk predictions are based on animal test data and their applicability to humans needs to be determined;
- Risk of vision loss calculator [51]. An ocular injury criterion was formulated for the applied pressure. However, specifics to this injury criterion and tolerances were not available.
- Intra Ocular Pressure (IOP) [52]. IOP and reflective pressure were measured at a similar position. The measurements were correlated with injury by assessing the affected eyes for injuries and through using injury risk curves for projectile impacts [56]. The calculated risks are <2% for all eye injuries when protection was worn but are only calculated for the head-on situation;
- Protective eyewear is mainly evaluated using reflective pressure at the corneal surface. However, other parameters such as positive phase duration, corresponding impulse or IOP could also be important [53], [52];
- The reliability of ocular injury curves in relation to post-mortem [52].

Performance parameters:

- Repeatability/reproducibility cannot be assessed based on available publications;.
- Using injury risk as performance parameter;
- The variety of head forms, combat helmets and the influence onto the performance parameter;
- Head-form rotations up- and downward has not been found within the available studies.

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4. CONCEPT TEST METHOD

The prementioned performance criteria and test setups for testing thoracic and ocular PPE against BOP help to specify the first elements for a concept test method.

4.1 Thoracic PPE BOP Test Methods

- BOP regime: the lung injury criteria and tolerances in [8], discriminating between none, light, severe lung injury seems promising to determine desired blast loading.
- Performance parameter(s):
  Measuring a_{cw} for evaluating the performance of PPE seems a good starting point, able to distinguish between relevant loading levels, correlated to lung injury and incident overpressure.
- Test device
  A relatively simple test device designed and constructed for evaluating PPE against the effects of BOP and able to measure a_{cw} is preferred. For instance the MABIL or the thoracic rig.

4.2 Ocular PPE BOP Test Methods

- BOP regime: a Friedlander blast wave characterised by 113-132 kPa incident peak overpressure or 96-128 Pa*s incident pressure impulse produces ocular injury at animals and can be used as starting point.
- Performance parameter: measuring reflective pressure at the corneal surface.
- Test device: an anthropomorphic head form equipped with pressure sensors plus eyewear.

5. CONCLUSION

A standard test methodology for evaluating thoracic or ocular PPE performance against the effects of BOP is not available. The available custom test methodologies show variability in both measured parameters and test devices.
BOP regimes for testing thoracic and ocular PPE have been found in literature, some based on animal test data. Some BOP injury criteria and test devices for both body regions were found throughout literature.

- Thoracic hard armour material seems able to decrease lung injury, peak a_{cw} [15] and lethality [16], [31-32]. While soft armour seems able to increase severe lung injury, average fatality [27] and a_{cw} [16], [32] This effect is also shown by the studies using transmissive pressure as performance measurement [28], [30-31].
- Open and closed eyewear seem able to decrease and increase measured reflective pressure at the corneal surface, corresponding impulse and IOP depending on head form orientation.

The results of experimental testing has shown that ocular and thoracic PPE are able to improve and worsen the performance parameter in question.

A basis for concept methods are formulated for both, thoracic and ocular PPE. This needs further elaboration to create preferable international homologation of a performance standard.

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