Chest wall velocity and intra-thoracic pressure impulse as relevant parameters in predicting thoracic injury for short-duration blast wave

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Abstract. Blast pulmonary trauma are common consequences of modern war and terrorism actions. To better protect soldiers from that threat, the injury risk level when protected and unprotected must be assessed. Knowing that the lung injury risk level when unprotected is correlated with the maximum of incident impulse for shock wave duration below 6 ms, the objective is to correlate parameters related to large animal chest response under blast loading with a pulmonary risk level. It implies to determine parameters which are themselves correlated with the incident impulse for short-duration waves. Twelve post-mortem swine (PMS), lying on the ground, were exposed to shock wave of increasing intensity. Two groups of 6 PMS were set-up and exposed to shock waves of constant positive phase duration. Group 1 and 2 were respectively exposed to shock waves of duration 1.0 ms and 1.8 ms. Their thorax were instrumented with a piezo-resistive pressure sensor, an hydrophone placed into the esophagus and an accelerometer, screwed onto a mid-torso rib, directly exposed to the shock wave. Combining those scenarios with others performed at a duration 1.4 ms allowed to show that two parameters were correlated with incident impulse ranging from 35 kPa ms to 160 kPa ms: the maximum chest wall velocity (V_{MAX}) and intra-thoracic pressure impulse ($\Delta Ieso$). Lung injury tolerance limits from no injury to severe ones (hemorrhage involving up to 60% of the lung) were redefined with those parameters. The lung injury threshold for near wall scenarios in terms of incident impulse is 58.3 kPa ms, corresponding to a V_{MAX} of 2.78 m/s and a $\Delta Ieso$ of 137.8 kPa ms. This study allowed the definition of injury criteria for the evaluation of lung injury risk when unprotected, which is a first step toward the proposition of tolerance limits to evaluate thoracic protective system regarding injury outcomes.

1. INTRODUCTION

Until now the design of a new thoracic protective equipment for soldier and law enforcement did not considered the risk of blast injury. Indeed, focus is made on ballistic, knives and fragments protection, leaving the uncertainty for protection against explosive devices. However, studies have proven that some thoracic protections can induce an amplification of the blast threat behind the protection, which increase the risk of chest and abdominal injuries (lungs and gastrointestinal injuries) [1-5]. Understanding the reason of such amplification of the injury risk (or reduction) is important, but being able to predict the risk level when a person is unprotected or protected is also a challenge for the development of future thoracic protective systems.

In order to evaluate a thoracic protection as regard to injury risk level, an adapted injury criterion is needed and should be measurable on a dummy to reduce the use of animal model. Different injury criteria were defined regarding blast wave characteristics [6-9], maximum chest wall velocity [10-11] or the irreversible work [12]. However, those models are not directly usable to estimate the lung injury risk under a thoracic protection [13]. Nevertheless, they can be used as a basis for the development of adapted criteria able to estimate lung injury risk level when protected/unprotected. Indeed, Boutillier *et al.* [9] demonstrated that the lung injury risk level (from no injury to severe ones) is correlated with shock wave incident impulse (ΔI_I) of duration below 6 ms. A good injury criterion for thoracic protective system evaluation regarding lung injury risk could then have these properties:

- Be correlated with the incident impulse;
- Be able to discriminate thoracic protective systems and estimate the correct injury risk with a thoracic protection.

Data measured on instrumented anthropomorphic manikins or on animal models can be examined to check those two conditions. Magnan *et al.* [14], Bass *et al.* [15] and Bouamoul *et al.* [16] respectively exposed the "U"-shape membrane, the Hybrid III and the MABIL (Mannequin for Blast Incapacitation and Lethality) to blast with and without thoracic protective equipment. Regarding animal models, thoracic response of post-mortem swine (PMS) exposed to blast threats of increasing intensity at a constant positive phase duration have been analyzed by Boutillier *et al.* [17]. Moreover, thoracic

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response and injury outcomes on living swine exposed to a specific blast threat for three levels of protection (none, soft ballistic pack and hard ballistic pack) have been shown by Prat *et al.* [5].

The aim of this study is to propose relevant parameters for the definition of a good lung injury criterion related to large animals' chest response. Three datasets were used, corresponding to post-mortem swine exposed near a wall to shock waves of different short positive phase durations. Data obtained from new experiments from shock wave of duration 1.0 ms and 1.8 ms were compared to data previously obtained with shock waves of duration 1.4 ms [17]. This strategy allowed the evaluation of parameters related to large animal chest response that correlated with ΔI_I for short-duration blast waves. After selecting such parameters, lung injury tolerance limits related to these latter were defined. For that purpose, lung injury thresholds related to the maximum of incident impulse from Boutillier *et al.* [9] were used. In this latter study, lung injury thresholds were defined for 50 kg large animals exposed near a wall to short-duration Friedlander blast waves. The threshold from no injury to trace/slight injury (superficial petechial or ecchymotic hemorrhages involving less than 10% of the lung surface) was defined at a ΔI_I of 58.3 kPa ms. A ΔI_I of 119.1 kPa ms led to moderate injuries (subpleural ecchymotic hemorrhage with superficial involvement of 11–30% of the lung surface) and above 232.8 kPa ms, severe injuries (diffuse ecchymotic hemorrhage extending into parenchyma involving 31–60% of the lung) were observed. The hypothesis underlying this study is that the chest response of a post-mortem or a living animal model can reasonably be considered identical in the field of high-speed loadings [18] (even if this statement needs to be verified).

2. METHODS

The animals used in our study were purchased from a recognized source producing high quality animals for experimental testing. They were sacrificed for the specific purpose of testing under the European directive (2010/63/EU), adopted in February 2013 in France.

2.1 Animals

Experiments were carried out on twelve post-mortem swine (53.1 ± 5.3 kg) at a rate of one per day. Due to the absence of gastrointestinal tract, the abdominal cavity, before being sutured, was filled with natural sponges placed on a plastic bag to ensure the morphology necessary for the tests.

A uniaxial accelerometer (PCB 3501A12, 60 kG) was screwed with a small rigid target (on top of it for displacement tracking purpose) on the 8th-9th rib, counting from top of the thorax. The sensor was fixed at the highest point of the rib (compared to ground level) when the post-mortem swine is lying on its left flank. In addition, two pressure sensors were used:

- A piezo-resistive pressure sensor (Kulite XCQ 093, 35 bar) was placed near the accelerometer, sutured on the skin. It measures the pressure experienced by the PMS thorax;
- A hydrophone (RESON TC4013) was placed inside the esophagus to measure the intra thoracic pressure. Its sensitive part was located underneath the accelerometer (8th-9th rib).

The instrumentation cables were tunneled under the skin for protection and to avoid interferences related to their shake.

2.1 Near wall blast experiments

Figure 1 illustrates the experimental setup. Animals were placed on the ground, lying on the left flank. Spherical charges of Composition-4 (C-4) were hanging over the animal at two different heights of burst (HoB). In addition to the animal instrumentation, two Free-Field ICP® pencil probes (type 137B22, PCB piezotronics) were used to measure the threat characteristics at the same distance from the explosive charge that the animal.

Two high-speed camera were installed on the proving ground at 30 m from the charge to delay the video instability during the passage of the shock wave:

- A Photron SA-Z (color, 40,000 fps) filmed the whole setup. Sphericity and homogeneity of the fireball can then be checked after the detonation;
- A Phantom V1610 (black and white, 40,000 fps) provided a zoomed view of the animal thorax (instrumented part) in order to record the chest displacement during the interaction with the shock wave. The optical center of the camera was at the same height from ground than the target fixed on the accelerometer.

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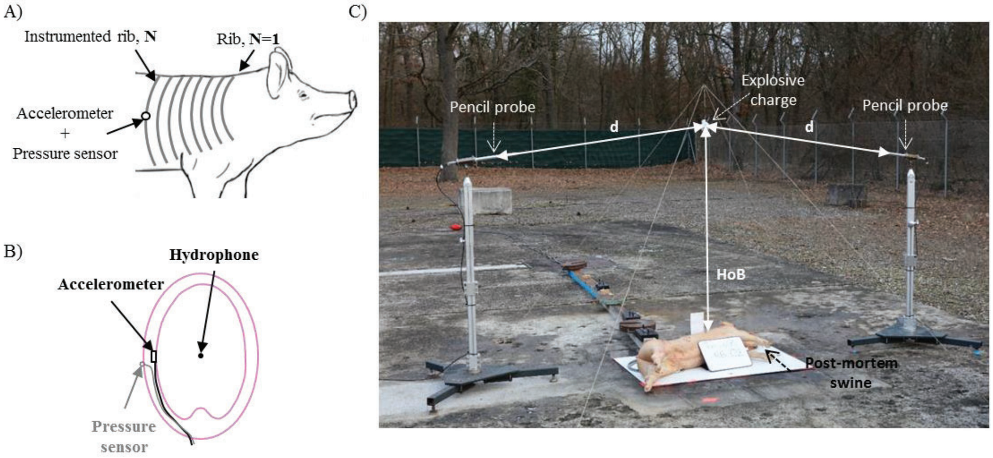

Figure 1. A) and B) Animal instrumentation setup; C) Experimental setup. d: distance explosive charge / pencil probe sensitive part. Illustration of the configuration with HoB = 140 cm

Post-mortem swine were exposed to Friedlander shock waves of increasing intensity with two different positive phase durations. Two animal groups were built:

- Group 1: N=6. Exposed to 1.0 ms shock waves duration;
- Group 2: N=6. Exposed to 1.8 ms shock waves duration.

Table 1 summarized the test matrix performed. Five scenarios were performed per group and distributed to check the reproducibility of the measurement on different animals. Around forty experiments per group were performed.

Table 1: Test matrix

Group 1 (T+=1.0 ms)			Group 2 (T+=1.8 ms)		
C-4 (kg)	HoB and d (cm)	Nb test	C-4 (kg)	HoB and d (cm)	Nb test
0.13	140	12	0.40	270	10
0.35	140	7	0.75	270	7
0.50	140	6	1.80	270	7
0.80	140	8	2.30	270	7
1.00	140	5	3.50	270	6

3. RESULTS

The acquisition was made by a high-speed range data acquisition system (MF instruments), with a sampling rate of 1 MHz. Data were then filtered with a 6th order Bessel at 100 kHz for the pencil probes and at 60 kHz for the other sensors.

Due to slight differences on animals' weight, scaling laws of Baker *et al.* [19] were used. The scaled factor was calculated to scale measured data to a 50 kg animal. Several parameters were analyzed:

- The incident/reflected pressures and corresponding impulses (which are defined as the time integration of pressure profiles);
- The intra thoracic (esophageal) pressure and corresponding impulse;
- The swine chest wall kinematic through acceleration, velocity and displacement of the instrumented rib. Chest wall acceleration was obtained from the accelerometer while both displacement and velocity were obtained through video tracking of the small rigid target fixed on the accelerometer.

3.1 Pressure measurements

Figure 2-A and 2-B summarized the average pressure measurement characteristics in terms of overpressure (ΔP) and maximum of impulse (ΔI) for all scenarios tested for group 1 and 2, respectively. Group 1 were exposed to Friedlander waveform of ΔP_I ranging from 101 kPa to 475 kPa, with an average positive phase duration of 1.02 ± 0.06 ms. It induces ΔI_I from 36 kPa ms to 117 kPa ms. Group 2 faced similar threat, with higher positive phase duration. Indeed, they faced threats of ΔP_I from 60 to 301 kPa with an average positive phase duration of 1.78 ± 0.11 ms, corresponding to ΔI_I from 39 kPa ms to 145 kPa ms.

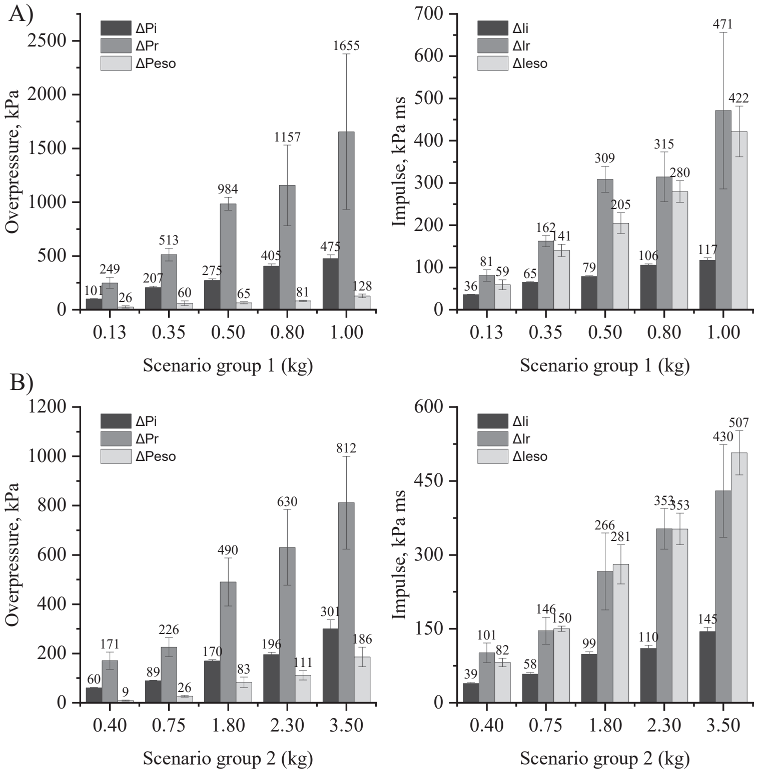

Figure 2. Characteristics of the pressure measurements for tested scenarios in (A) group 1 and (B) group 2. The subscripts 'I', 'R' and 'eso' correspond to the incident, reflected and esophageal pressure measurement characteristics.

Incident pressure and impulse profiles from the detonation of 0.50 kg of C-4 (group 1) and 1.80 kg of C-4 (group 2) are illustrated in Figure 3-A and 3-B respectively (graphs on the left side). Reflected pressure measurements, illustrated in Figure 3-A and 3-B for same scenarios (graphs in the middle) are more disturbed than the incident pressure. This is noticeable on Figure 2, where the pressure characteristics are plotted. This is partially due to the difficulty to correctly place the sensor on the post-mortem swine skin regarding the explosive charge but bad weather conditions during some tests (rain) could have affect measurements because of the sensor used. Two intra thoracic (esophageal) pressure measurements are also illustrated on Figure 3-A and 3-B (on the right side). Due to filtering effect of the chest wall, the rise time is much longer than the two previous pressure measurements. Moreover, as illustrated in Figure 2, the esophageal overpressure (ΔPeso) is 1.6 to 5 times lower than the incident overpressure while the reflected overpressure (ΔI_R) is 2.5 to 3.5 times higher than this latter. Indeed, for Group 1, the overpressure ranged from 101 to 475 kPa, from 249 to 1655 kPa and from 26 to 128 kPa, respectively for ΔP_I, ΔP_R and ΔPeso. This is different for the maximum impulse, where both the reflected (ΔI_R) and the esophageal impulses (ΔIeso) are in the same order of magnitude and are higher than ΔI_I.

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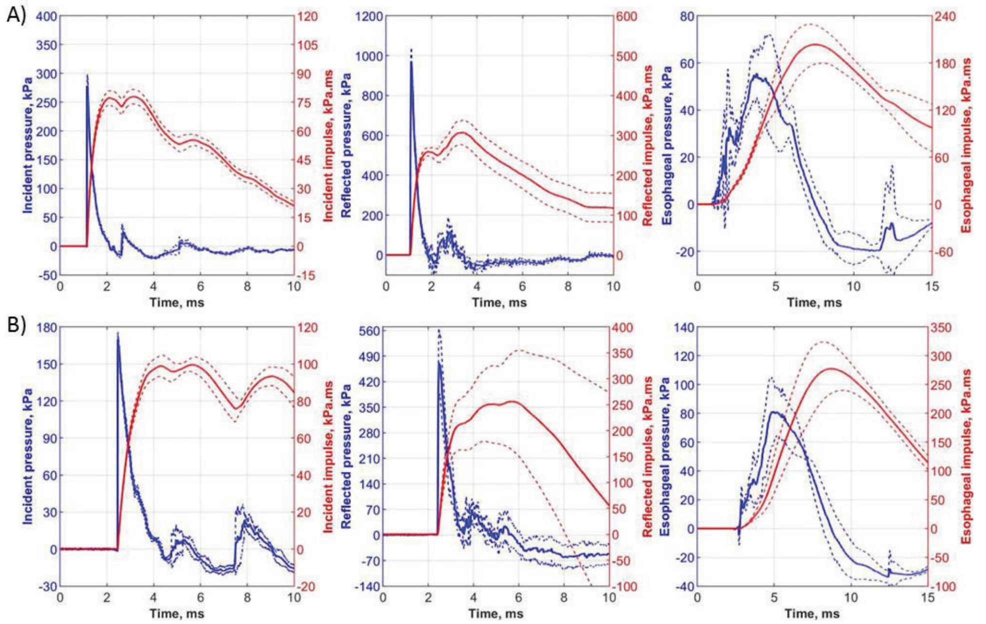

Figure 3. Pressure time histories from the pencil probe (incident pressure, left), the Kulite sensor (pressure on the chest skin, middle) and the hydrophone (intra thoracic pressure, right). Data from scenarios 0.50 kg at 140 cm ((A), group 1) and 1.80 kg at 270 cm ((B), group 2) are plotted

3.2 Chest wall motion

Figure 4-A and 4-B illustrate measured and calculated chest acceleration, velocity and displacement for the detonation of 0.50 kg of C-4 (group 1) and 1.80 kg of C-4 (group 2), respectively.

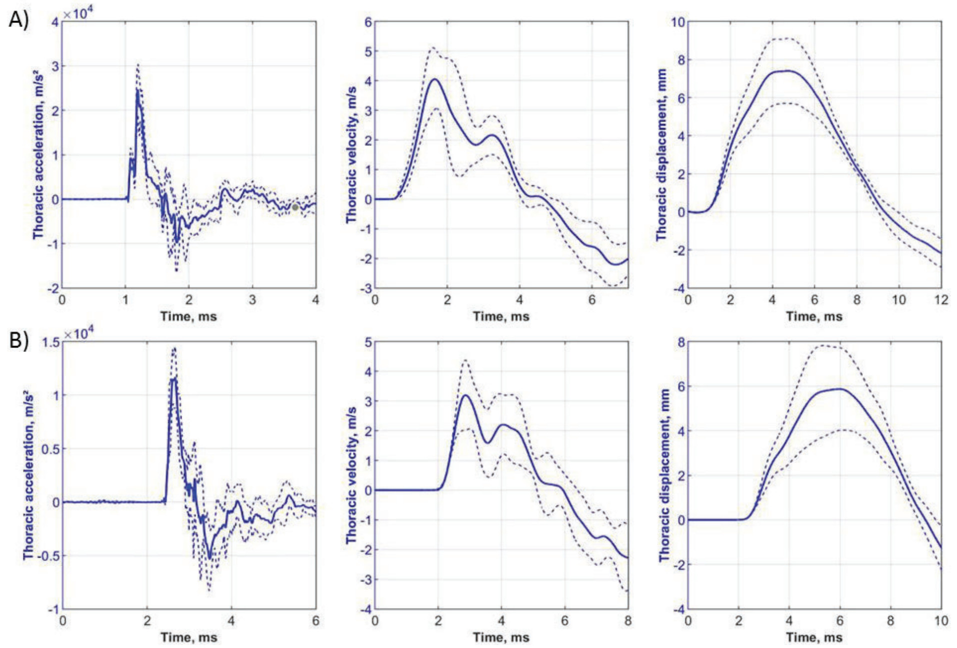

Figure 4. Chest wall motion response from scenarios 0.50 kg at 140 cm ((A), group 1) and 1.80 kg at 270 cm ((B), group 2). Chest wall acceleration (left side), velocity (middle) and displacement (right side) time histories are illustrated

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Characteristics of these profiles are summarized on Figure 5, where standard deviations are around 20% for the maximum chest wall acceleration (Γmax), velocity (Vmax) and displacement (Dmax). For Group 1, with ΔI_I ranging from 36 kPa ms to 117 kPa ms:

- Γmax from 6413 ± 1346 m/s^2 to 45610 ± 12767 m/s^2 were measured;
- Vmax from 1.6 to 6.6 m/s were calculated (tracking was not possible for 1.00 kg of C-4);
- Dmax from 2.6 mm to 11.1 mm were calculated (tracking was not possible for 1.00 kg of C-4).

For Group 2, with ΔI_I ranging from 39 kPa ms to 145 kPa ms:

- Γmax from 4063 ± 607 m/s^2 to 30932 ± 5887 m/s^2 were measured;
- Vmax from 1.5 to 6.9 m/s were calculated;
- Dmax from 2.3 mm to 11.6 mm were calculated.

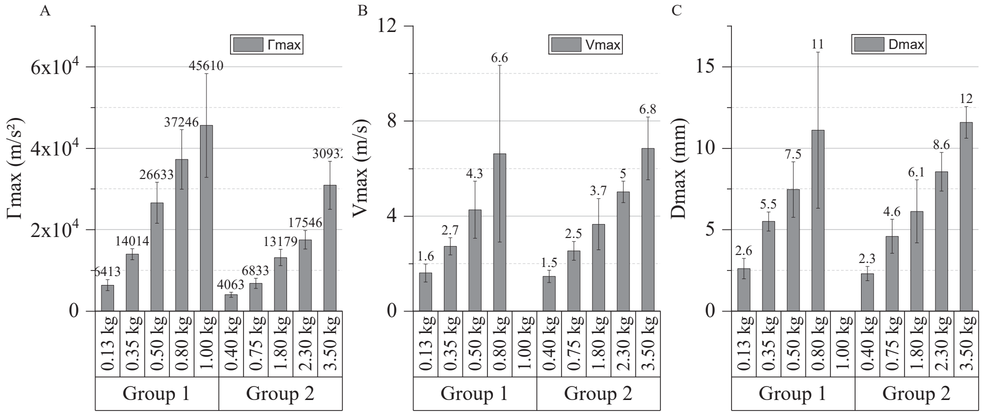

Figure 5. Characteristics of the chest wall motion for all tested scenarios. Maximum of: A) chest wall acceleration (Γmax), B) velocity (Vmax) and C) displacement (Dmax) are plotted.

4. DISCUSSION

Lung injury risk level was found to be correlated with shock waves incident impulse of duration below 6 ms [9]. For near wall exposition, the threshold from no injury to trace/slight injury was defined at a ΔI_I of 58.3 kPa ms. A ΔI_I of 119.1 kPa ms leads to moderate injuries and above 232.8 kPa ms, severe injuries are observed. However, this parameter is not sufficient to evaluate the injury risk variation when wearing a thoracic protective system. The parameter that could be used as a lung injury criterion for thoracic protective system evaluation could then be correlated with incident impulse and be able to discriminate thoracic protective system by a correct estimation of the injury risk under the protection.

Figure 6 illustrates the chest wall motion parameter and the intra thoracic pressure and impulse against the maximum incident impulse for PMS expositions to three different shock wave durations: 1.0 ms and 1.8 ms from current study and 1.4 ms from Boutillier *et al.* [17]. It can be noticed that only the maximum chest wall velocity and intra thoracic impulse are well correlated with the incident impulse for short duration waves. Vmax and ΔIeso are then good candidate parameters for injury criteria definition for short duration shock waves, at least for unprotected scenario.

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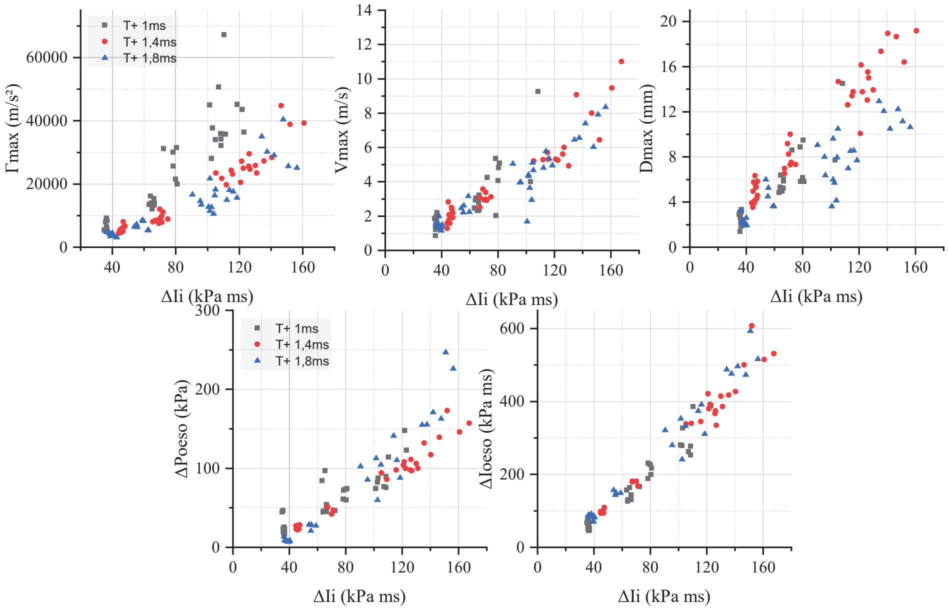

Figure 6. Comparison of the measured parameters on PMS exposed to shock waves of three different positive phase durations: 1.0 ms (black square), 1.4 ms (red circle) and 1.8 ms (blue triangle). Chest motion parameters and intra thoracic pressure and impulse are plotted against ΔI_I.

Figure 7 shows fitted curves for ΔIeso and Vmax plotted against ΔI_I in addition to 95% confidence intervals (CI). The obtained correlations are the following, with R^2 values of 0.99 (2nr order polynomial fit) and 0.95 (linear fit), respectively (p-value<0.001):

$$\Delta I_{eso} = 1.68906\Delta I_I + 0.01156\Delta I_I^2 \quad (1)$$

$$V_{MAX} = 0.04776\Delta I_I \quad (2)$$

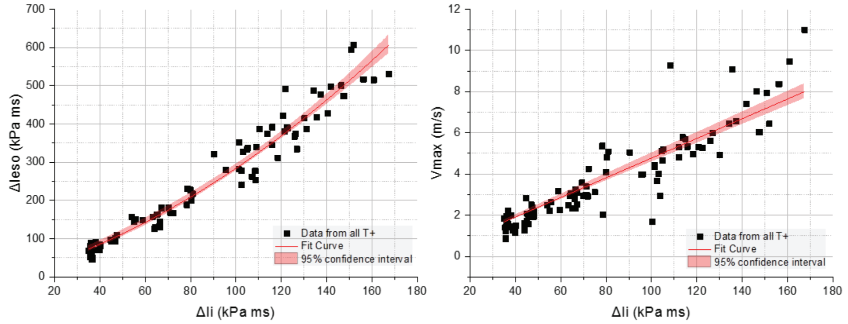

Figure 7. Fitted curves for ΔIeso (left) and Vmax (right) plotted against ΔI_I, in addition to 95% confidence intervals. Data from all positive phase durations are plotted.

Using lung injury risk level thresholds defined by Boutillier *et al.* [9], for near wall experiments, threshold values in terms of maximum chest wall velocity (Vmax) and intra thoracic pressure impulse (ΔIeso) have been defined. Table 2 summarized the defined thresholds, valid for an unprotected 50 kg animal exposed to short-duration Friedlander waveform against a wall. Thresholds in terms of Vmax for near wall scenarios are of the same order of magnitude then the ones proposed by Axelsson *et al.* [10]. Those latter were defined using a one degree of freedom mathematical model whose aimed was to reproduce the human thorax response exposed to shock wave (Friedlander or complex), while lung injury risk were obtained from sheep experiments. The trace/slight+, moderate+ and severe+ lung injury thresholds defined by Axelsson *et al.* are respectively 3.6-7.5 m/s, 4.3-9.8 m/s and 7.5-16.9 m/s, while the proposed 50% risk values are respectively 2.7-2.9 m/s, 5.4-6.0 m/s and 10.6-11.6 m/s.

Both types of measurement (velocity and internal pressure impulse) could be measured on an adapted dummy and under a thoracic protection. In order to be used as injury criteria on such dummy (unprotected), correlations between dummy chest response and swine chest response must be evaluated (Vmax or ΔIeso). A validated finite element model (FEM) of the dummy could be a good alternative to experimentation. Because of ethical reasons and costs, a swine FEM could also be validated regarding the large database available on swine chest response to blast. Such model could allowed the definition of tolerance limits regarding biomechanical parameters to be defined.

To check if Vmax and ΔIeso can discriminate thoracic protective system and estimate the correct lung injury risk with thoracic protection, data on living animals are needed. Such data were presented by Prat *et al.* [5], where anesthetized swine (unprotected and protected) were exposed to a high-intensity blast in free-field. Both parameters seemed able to discriminate thoracic protective system, with higher value when lung injury were more severe, and inversely. Nevertheless, data with several shock wave characteristics, in free-field and in near wall configuration, are needed.

Table 2. 50% risk of a given lung injury level for an unprotected 50 kg animal model exposed to Friedlander waveform against a wall. Threshold values in terms of ΔI_I, Vmax and ΔIeso are presented

Lung injury risk level	ΔI_I, kPa ms	Vmax, m/s	ΔIeso, kPa ms
None	< 58.3	< 2.78 (95% CI [2.66 2.91])	< 137.8 (95% CI [128.4 147.1])
Trace/Slight+	> 58.3	> 2.78 (95% CI [2.66 2.91])	> 137.8 (95% CI [128.4 147.1])
Moderate+	> 119.1	> 5.69 (95% CI [5.43 5.95])	> 365.1 (95% CI [355.9 374.4])
Severe+	> 232.8	> 11.12 (95% CI [10.62 11.62])	> 1019.7 (95% CI [952.6 1086.7])

5. CONCLUSION

In order to evaluate the efficiency of thoracic protection against the blast threat, adapted injury criteria must be developed. Two angles are considered: the chosen criterion must be correlated with shock wave incident impulse and be able to predict injury level for both unprotected and protected thorax. This study investigated the first angle.

Combining published [17] and new experimental data obtained on post-mortem swine exposed to short-duration blast waves against a wall pointed out two physical parameters that respect the first angle: the maximum chest wall velocity (Vmax) and the maximum esophageal impulse (ΔIeso). Those two parameters can be considered as adapted criteria for the estimation of lung injury risk when unprotected and exposed to Friedlander wave (near wall). Data on living animal response to blast wave with different thoracic protection are needed to verify the second angle.

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