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## Lung injury risk assessment during blast exposure

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## ABSTRACT

Blast pulmonary trauma are common consequences of modern war and terrorism action. To better protect soldiers from that threat, the injury risk level when protected and unprotected must be assessed. Knowing from the literature that a possible amplification of the blast threat would be provided by some thoracic protective systems, the objective is to propose an original approach to correlate a measurable parameter on a manikin with a pulmonary risk level. Using a manikin whose response is correlated with the proposed tolerance limits should help in the evaluation of thoracic protective system regarding injury outcomes.

A database including lung injury data from large mammals have been created, allowing the definition of iso-impulse tolerance limits from no lung injury to severe ones (~60% of ecchymosis). As the use of this metric is not sufficient to evaluate the performance of protective systems on a manikin, the iso-impulse tolerance limits were associated with the thoracic response of post-mortem swine under blast loading. It was found that the lung injury threshold in terms of incident impulse is 58.3 kPa·ms, corresponding to a chest wall peak of acceleration/velocity/displacement of 7350 m/s<sup>2</sup>, 3.7 m/s and 6.4 mm respectively. Lung injuries are considered as severe (30–60% of ecchymosis) when the incident impulse exceed 232.8 kPa·ms, leading to a chest wall peak of acceleration/velocity/displacement of 79.7 km/s<sup>2</sup>, 14.7 m/s and 30.1 mm respectively.

The defined lung tolerance limits are valid for a 50 kg swine (unprotected) exposed side-on to the blast threat and against a wall.

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## 1. Introduction

The thorax is the body part that offers the largest surface to the blast threat and it contains three main components: the heart, the lungs and the major arterial and venous vessels (aorta, pulmonary veins and vena cava). The protection of this body part from the blast threat have a double interest. First, air-filled organs, such as the lung, are the most sensitive to shock wave. Second, the mitigation of brain damages following the exposure to a shock wave. Indeed, recent studies on the understanding of blast-head interactions indicate that part of the functional and morphological alterations of the brain may be due to the blast wave entering the thorax (Cernak, 2010; Courtney and Courtney, 2011).

In recent years, a special effort has been made to improve personal protection against bullets, fragments and knives, leaving protection against blast nearly unchanged, except for specific demining protections. A part of the scientific community is aware that a possible amplification of the blast threat (reinforcing the loading behind the protection) would be provided by certain protective clothing or equipment (Cooper et al., 1991; Jetté et al., 2004; Phillips et al., 1988; Thom et al., 2007). Since thoracic protection systems are not all equal in terms of efficiency against the blast threat, an evaluation of the performance with respect to injuries outcomes must be performed. Several manikins, such as the 'U'-shape membrane, the Hybrid-III and the MABIL ('Mannequin for Blast Incapacitation and Lethality'), have already been used under blast loading for the evaluation of the thoracic response with or without personal protective equipment (Bass et al., 2005; Bouamoul, 2008; Magnan et al., 2012). When those manikins were equipped with such an equipment, the performance was evaluated by comparing metrics such as the peak thoracic acceleration or the

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reflected pressure with and without the protection. Nevertheless, an injury severity based assessment of protection level of body armour for blast should be developed, in addition to a manikin adapted to that threat.

Regarding the existing injury criteria, several were developed since 1960. The first criterion developed was the Bowen curves (Bowen et al., 1968) to know the percentage of lethality of a 70 kg man exposed to an ideal shock wave. Those curves were derived from experimental campaigns on small and large mammals exposed to blast against a wall, and results were extrapolated for free-field interactions. This model was later revised by Richmond and Cooper (2002) and Bass et al. (2008), but the tolerance limits remain similar. The Axelsson and the Stuhmiller models (Axelsson and Yelverton, 1996; Stuhmiller et al., 1996) were then developed to fill the gaps of the previous criteria, namely the restriction to a simple shock wave, the hypothesis of similarity between species, the use of non-validated extrapolations hypotheses or the lack of knowledge on specific body part injury level. Those models allows, using a 1 degree of freedom mathematical model and a Blast Test Device, to know the thoracic injury level in terms of AIS (Abbreviated Injury Scale) of humans, whatever the environment. Simplified versions of the Axelsson model have been proposed by Teland (2012). Among the limitations of those models (Boutillier et al., 2016) can be cited the fact that they are not well adapted for the evaluation of protective systems. Indeed, the Bowen curves (and all the revisions) give the percentage of lethality for unprotected persons using the side-on (referred here as incident) pressure wave characteristics and the Axelsson model uses the Blast Test Device (and therefore pressure signals recorded on each of these facets) but it is still a challenge to measure a pressure under a protection.

In order to allow researchers to evaluate thoracic protective systems against the blast threat with respect to possible injury outcomes, a new methodology is proposed to correlate lung injury level with global kinematic parameters related to unprotected swine thoracic response. Lung tolerance limits, valid for a 50 kg swine exposed side-on to the blast threat and against a wall, are proposed and are presented hereafter. Using a manikin whose response is correlated with the developed tolerance limits could be the methodology for evaluating protective thoracic system and to propose future protective solution.

## 2. Methods

### 2.1. Brief description

Experimental data from 50 kg swine exposed to shock wave against a wall showed that simple relations exists between global kinematic parameters related to swine thoracic response and the blast wave characteristics, such as the maximum of incident impulse ( $\Delta I_i$ ) (Boutillier et al., 2017). Knowing, from White et al. (1971), that for short-duration waves the primary blast effects are sensitive to  $\Delta I_i$ , the idea is first to defined lung injury tolerance limits in terms of  $\Delta I_i$  using injury data from the literature. When those limits are defined, the second step is to use the thoracic response data coming from the experiments of Boutillier et al. (2017) and to associate global kinematic parameters related to the post-mortem swine thoracic response to lung injury level, using the incident impulse limits previously defined. The proposed methodology is summarized on Fig. 1. The following chest motion parameters will be considered as metrics for lung injury level: the viscous criterion and the peak values for the chest acceleration, velocity and displacement. This former parameter is an injury prediction criterion, coming from the automotive field and developed by Lau and Viano (1986), which asses the risk of soft tissue injury

by a rate-dependent viscous injury mechanism. It is defined as the maximum of the product of the chest wall velocity and the thorax compression, which is the division between the chest wall displacement and the undeformed depth of the thorax.

Analogies exist between the swine and the human being, such as the size and organisation of its internal organs. Even if the conformation of the ribcage differs somewhat, the assumptions underlying this research are the following:

- The lateral chest response of a swine is similar to the frontal chest response of a human for blast loading.
- The lung injury outcomes are similar between the swine and the human.
- The chest response of a post-mortem and a living swine is similar for blast loading.

### 2.2. Data from literature

Very few studies indicating the degree of lung injury for a blast threat are available in the literature. Richmond et al. (1968) performed tests in both shock tubes on dogs (~15.7 kg) and with explosive charges on sheep (~50 kg). Their objectives was, for constant positive phase durations (5.7 and 400 ms), to observe the degree of lung injury as a function of the reflected overpressure. Free-field trials were carried out on pigs and sheep of about 30 kg and 50 kg exposed to different explosive charges (Vassout, 1985; Vassout et al., 1995; Prat et al., 2015; Magnan, 2016). In each of these studies, pulmonary lesions are categorized into five groups: none, trace/slight, moderate, severe and extensive. Table 1 gives a description of these injury levels. Dodd et al. (1989) studied the injury threshold for repeated free-field exposures on 40–70 kg sheep. Only cases resulting in no injury were included.

As this database is made of data from experiments performed against a wall or in free-field, the Bowen 'pressure dose' concept was used. This concept was developed to extend the Bowen curves (near wall configuration) to a person in prone position and a standing person in free-field. The assumption, illustrated in Fig. 2 is that a similar lethality risk is provided for these three configurations if the corresponding 'pressure dose' are equals (the duration of the wave is not changed):

- For near wall configurations, the pressure dose is the reflected pressure.
- For a standing person in a free-field configuration, the pressure dose is the incident pressure plus the dynamic pressure  $q = \frac{5P_i^2}{2P_i + 14P_0}$  ( $P_i$  and  $P_0$  are respectively the incident and the ambient pressure).
- For a prone person in free-field, the pressure dose is the incident pressure.

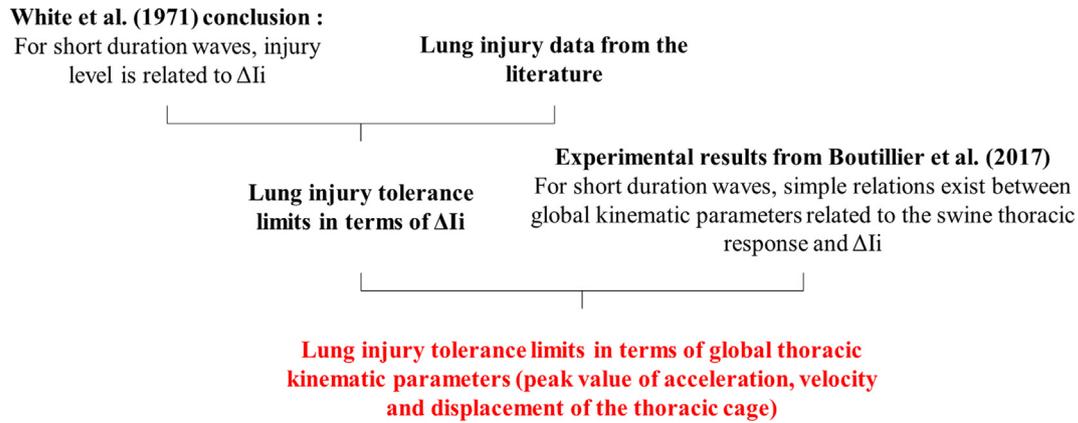
The data previously cited are first scaled to a 50 kg animal using Bowen's Law, written in Eqs. (1) and (2).

$$\Delta P_{R_{scaled}} = \Delta P_R \left( \frac{424 \text{ kPa}}{P_{SW}} \right) \left( \frac{101.35 \text{ kPa}}{P_0} \right), \text{ kPa} \quad (1)$$

$$T_{scaled}^+ = T^+ \sqrt[3]{\frac{m_{scaled}}{m}} \sqrt{\frac{P_0}{101.35 \text{ kPa}}}, \text{ ms} \quad (2)$$

where  $m$  is the animal mass in kg,  $\Delta P_R$  is the maximum reflected overpressure,  $P_{SW}$  is the long-duration overpressure in kPa resulting in 50% mortality (see Bowen et al., 1968).  $T^+$  is the positive phase duration in ms.

Although working with reflected pressure/impulse would have at least two benefits (less translation error and measurable parameters on a manikin), it was decided to work with the incident



**Fig. 1.** Proposed methodology to define injury criteria in terms of global kinematic parameters related to the swine thoracic response (near wall scenarios).

**Table 1**  
Description of the lung injury levels.

Injury level	Description
None	No injury
Trace/slight	Superficial petechial or ecchymotic hemorrhages involving less than 10% of the lung surface
Moderate	Subpleural ecchymotic hemorrhage with superficial involvement of 11–30% of the lung surface
Severe	Diffuse ecchymotic hemorrhage extending into parenchyma involving 31–60% of the lung
Extensive	Confluent transparenchymal hemorrhage involving 60–100% of the lung

pressure/impulse. When experimental tests were performed against a wall, the given blast wave characteristics was the reflected pressure ( $P_R$ ) and  $T^*$ .  $P_R$  was then transformed into incident pressure using the Eq. (3) (Teland, 2012). Regarding the configuration where a person stand in free-field, the Bowen pressure dose concept was used as previously stated. In these free-field tests, only the incident pressure was given. To use the Bowen concept and transcribe the scenarios into near wall scenarios, the dynamic pressure must be calculated and added to the incident pressure given in the studies. This total pressure is then considered, using the Bowen concept, to be equal to the reflected pressure of a scenario against a wall, leading to similar injuries. It is finally this reflected pressure that is transformed into incident pressure using the Eq. (3).

$$P_R = \frac{8P_i^2 + 14P_iP_0}{P_i + 7P_0} \quad (3)$$

In addition to the previously cited data, which will be used to propose lung injury tolerance limits in terms of  $\Delta I_i$ , the post-mortem swine thoracic response from Boutillier et al. (2017) is

used to propose lung injury tolerance limits in terms of global kinematic parameters. In those experiments, post-mortem swine (50 kg) placed side-on to the threat and against the ground were exposed to five scenarios of increasing intensities.

Fig. 3 illustrates the overlaying of the Bowen curves (near wall scenario, 50 kg animal) and the lung injury data from the literature. Configurations tested on post-mortem swine have also been graphed (black x-mark symbols). It seems clear from this graph that there is a lack of data available in the literature in terms of lung injury. Only 229 cases are available for duration waves below 6 ms, most of them are without lung injury (184), and 94 cases for long-duration ones (>20 ms).

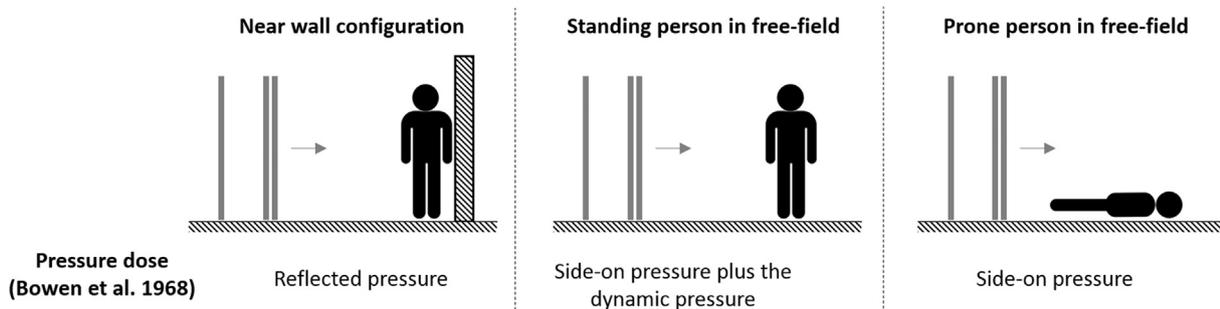
### 2.3. Statistical analysis

In order to define the best suitable values to derive lung injury tolerance limits in terms of maximum of incident impulse (short-duration wave, < 6 ms) regarding existing data, binary logistic regression was used and carried out with XLSTAT. With this method, the probability of lung injury risk is defined as in Eq. (4).

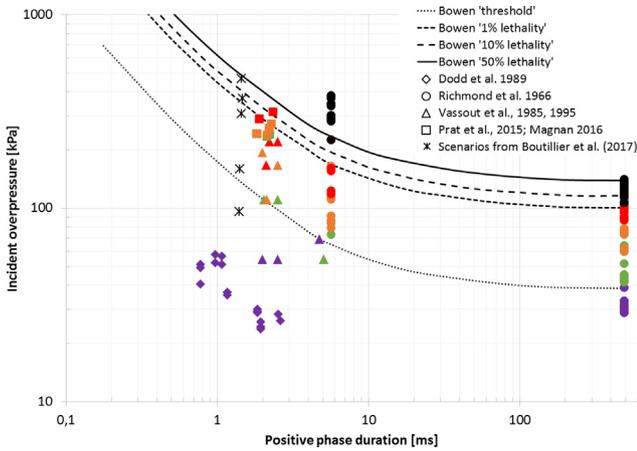
$$P(X) = \frac{1}{1 + e^{-(a+bX)}} \quad (4)$$

where a and b are two parameters calculated by regression. The  $R^2$  values (Nagelkerke) were calculated and used to determine the quality of the fit (a value of 0 for a poor fit, and 1 for a good fit). The  $R^2$  criterion is enriched by the Akaike and Schwarz Information Criteria (AIC and SIC). Those parameters deal with a trade-off between model fit and complexity of the model. A lower AIC or SIC values indicates a better fit.

Tolerance limits in terms of incident impulse for short-duration wave are proposed for different lung injury level.



**Fig. 2.** Illustration of the Bowen pressure dose concept.



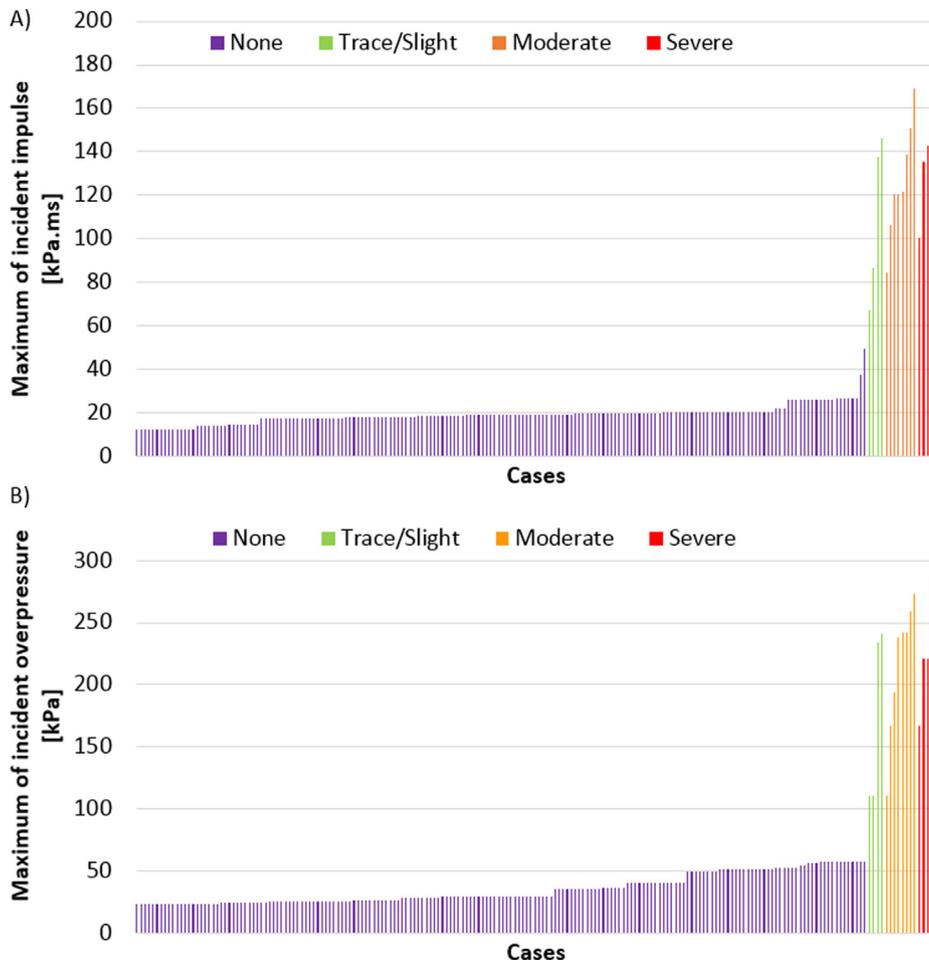
**Fig. 3.** overlaying of the Bowen curves (near wall scenario, 50 kg animal), the data from the literature and the scenarios performed in the experiments of Boutillier et al. (2017) on swine (near wall scenario, 50 kg animal). The colors correspond to different lung injury levels: purple = 'none'; green = 'trace/slight'; orange = 'moderate', red = 'severe' and black = 'extensive'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3. Development of new lung tolerance limits

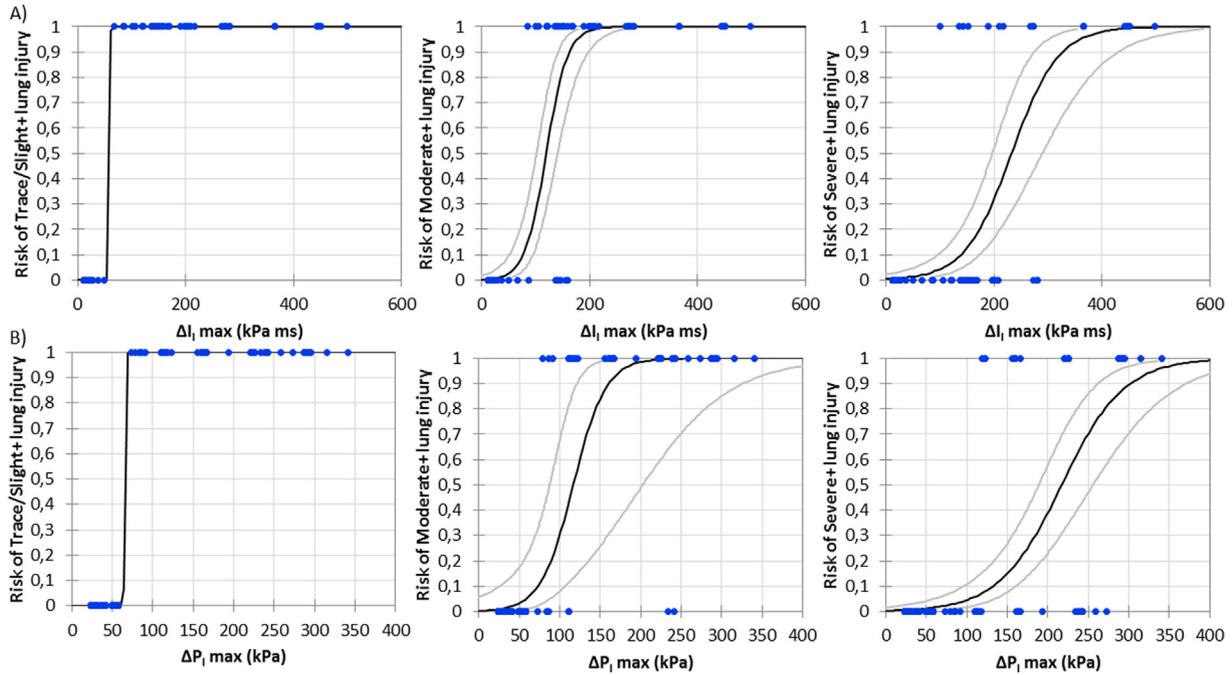
#### 3.1. Limits in terms of shock wave parameters

The 229 available data (unprotected) for short-duration waves are shown in Fig. 4a and b, data respectively represented by the maximum of incident impulse and overpressure, distributed according to the injury level. Data for long duration cases are exposed in supplementary material. Each column represents an injury level: purple-none, green-trace/slight, orange-moderate and red-severe. The range of maximum of incident impulse ( $\Delta I_1$ ) and overpressure ( $\Delta P_1$ ) for short-duration cases is respectively 12.00–498.4 kPa.ms and 23.8–340.7 kPa. It appears from Fig. 4 that both  $\Delta I_1$  and  $\Delta P_1$  present a quite smooth histogram with smaller discontinuity between lung injury levels. It is then not clear which parameter should be used for injury criterion definition. This will be examined with the logistic regression analysis.

The injury risk curves for short-duration waves, with respected 95% confidence interval, are plotted in Fig. 5. For each fit, the  $R^2$  (Nagelkerke) value and the AIC/SIC were calculated and listed in Table 2. It appears that the  $R^2$  value decrease when the injury severity increase, going for example from 1.0 for the trace/slight



**Fig. 4.** Blast wave duration cases below 6 ms: (A) maximum of incident impulse displayed for different lung injury levels; (B) maximum of incident overpressure displayed for different lung injury levels.



**Fig. 5.** Injury risk curves to predict probability of lung injury for short-duration waves according to: (A) the maximum of incident impulse; (B) the maximum of incident overpressure. From left to right: Trace/Slight+ lung injury; Moderate+ injury and Severe+ injury.

**Table 2**

Fit parameters of the logistic regressions.

	Trace/Slight+		Moderate+		Severe+	
	R <sup>2</sup> (Nagelkerke)	AIC/SIC	R <sup>2</sup> (Nagelkerke)	AIC/SIC	R <sup>2</sup> (Nagelkerke)	AIC/SIC
Incident overpressure data	1.0	4.0/10.8	0.80	61.3/68.1	0.64	59.4/66.3
Incident impulse data	1.0	4.0/10.8	0.88	39.8/46.7	0.71	50.1/56.9

+ tolerance limit to 0.71 for the severe+ one for the analysis with the impulse data. It can also be noted that the R<sup>2</sup> values for the logistic regression with  $\Delta P_1$  are slightly less than the one obtained with  $\Delta I_1$ , with the exception of the 'trace/slight+' fit. Despite the lack of lung injury data, the R<sup>2</sup> and the AIC/SIC values indicate that the fits with  $\Delta I_1$  are of better quality than the ones with  $\Delta P_1$ . Indeed, lower values have been obtained for the logistic regression on the impulse data, i.e. an AIC of 39.0 for the analysis with the impulse (moderate+ injury risk) compared with 71.8 for the analysis with the incident overpressure. The maximum of incident impulse is then the best suitable parameter to derive lung injury tolerance limits for short-duration waves. From the logistic regression analysis, maximum incident impulse values for a 50% risk of trace/slight+, moderate+ and severe+ are obtained and listed in Table 3. The 50% risk values are 58.3 kPa-ms, 119.1 kPa-ms and 232.8 kPa-ms respectively.

**Table 3**

50% risk of a given lung injury level obtained with the logistic regression (impulse data). NaN: Not a Number.

Injury level	Impulse threshold (50% risk) Short-duration cases	R <sup>2</sup>	AIC/SIC
Trace/slight+	58.3 kPa-ms	1.00	4.0/10.8
Moderate+	119.1 kPa-ms	0.88	39.8/46.7
Severe+	232.8 kPa-ms	0.71	50.1/56.9
Extensive+	NaN	NaN	NaN

### 3.2. Limits in terms of global kinematic parameters related to swine thoracic response

New tolerance limits in terms of maximum of incident impulse have been proposed to predict lung injury risk for short-duration waves. However, those limits are not usable to predict lung injury risk when protected. A correlation between those impulse limits with kinematic parameters of the thoracic wall is then made using data obtained for short-duration wave of incident impulses from 40 to 160 kPa-ms against a wall. The following relations between the thoracic wall motion and  $\Delta I_1$  (in kPa-ms) were obtained (Boutillier et al., 2017):

$$\Gamma_{MAX}(\Delta I_1) = 1.241 * \Delta I_1^2 + 53.611 * \Delta I_1 \quad (5)$$

$$V_{MAX}(\Delta I_1) = 0.063254 * \Delta I_1 \quad (6)$$

$$D_{MAX}(\Delta I_1) = 1.168 * 10^{-4} * \Delta I_1^2 + 0.1023 * \Delta I_1 \quad (7)$$

$$VC_{MAX}(\Delta I_1) = -8.732 * 10^{-9} * \Delta I_1^3 + 1.689 * 10^{-5} * \Delta I_1^2 + 2.630 * 10^{-4} * \Delta I_1 \quad (8)$$

where  $\Gamma_{MAX}$ ,  $V_{MAX}$  and  $D_{MAX}$  are respectively the maximum of chest wall acceleration in m/s<sup>2</sup>, velocity in m/s and displacement in mm.  $VC_{MAX}$  is the viscous criterion in m/s.

Table 4 summarized the tolerance limits in terms of  $\Gamma_{MAX}$ ,  $V_{MAX}$ ,  $D_{MAX}$  and  $VC_{MAX}$  using the previously mentioned equations and the proposed injury tolerance limits in terms of  $\Delta I_1$ . The parameter val-

**Table 4**

Predicted lung injury tolerance limits (50% risk) in terms of global kinematic parameters related to swine thoracic response.  $\Gamma_{max}$ ,  $V_{max}$  and  $D_{max}$  are respectively the peak of chest wall acceleration, velocity and displacement.  $VC_{max}$  is the viscous criterion. NaN = Not a Number.

	Trace/Slight+	Moderate+	Severe+	Extensive
$\Gamma_{max}$ (m/s <sup>2</sup> )	7336	23,981	79,738	NaN
$V_{max}$ (m/s)	3.7	7.5	14.7	NaN
$D_{max}$ (mm)	6.4	13.8	30.1	NaN
$VC_{max}$ (m/s)	0.07	0.26	0.87	NaN

ues for 50% risk of lung injury (threshold) are 7,336 m/s<sup>2</sup>, 3.7 m/s, 6.4 mm, 0.07 m/s, respectively in terms of  $\Gamma_{MAX}$ ,  $V_{MAX}$ ,  $D_{MAX}$  and  $VC_{MAX}$ .

**4. Discussion**

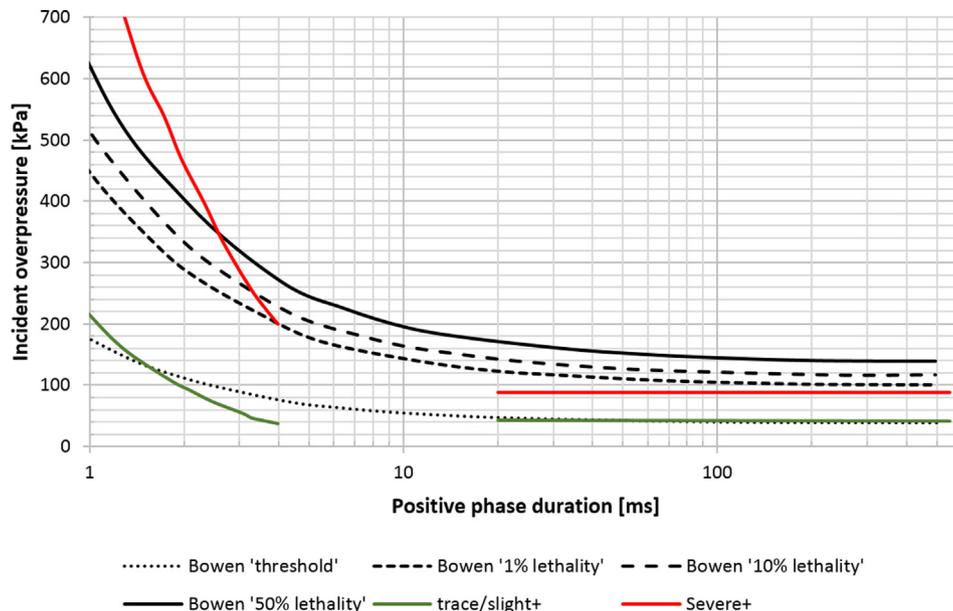
A new methodology was proposed and used to define lung injury tolerance limits. Using lung injury data from the literature and the thoracic response obtained in post-mortem swine experiments, lung tolerance limits were obtained in terms of  $\Delta I_1$ ,  $\Gamma_{MAX}$ ,  $V_{MAX}$ ,  $D_{MAX}$  and  $VC_{MAX}$  (short-duration waves, <6 ms) for each of the four following lung injury levels: None, Trace/Slight ( $\leq 10\%$  of affected lungs), Moderate (11–30%) and Severe (31–60%). These limits are valid for a 50 kg animal exposed side-on to Friedlander waves and against a wall. The assumptions made in this study (similarity of chest response and injury outcomes for blast loading between swine and human) are not explicitly proven but are the best approximations at this moment. Further research are needed to validate them. Regarding the hypothesis made which stated that the chest response of a post-mortem and a living swine is similar for blast loading, part of the response can be found in the literature. The main problem is the lack of muscle tone, but while it would have an influence on low-speed loadings, high-speed impact studies, such as ballistics or blast, do not allow muscle tension to develop within the time of the chest wall displacement (Bir et al., 2004). The chest response of a post-mortem or a living animal model could reasonably be considered identical in the field of high-speed loadings, even if this statement need to be verified.

As previously stated, working with the reflected blast wave characteristics would have several benefits: less translation error and measurable parameters on a manikin. However, the reflected pressures reported on the database correspond to the pressure

measurements on the animal support (a plane and large surface), and the relations from Boutillier et al. (2017) relate the pressure experienced by the animal to the thoracic swine chest motion. This latter pressure profile is different from the one measured on a large and plane surface, principally because of rarefaction waves that will have the effect of reducing the duration of the wave and so the impulse. Hence, the incident blast wave characteristics were used.

The proposed tolerance limit for a 50% risk of lung injury (trace/slight+) is 58.3 kPa.ms for short-duration wave. This critical limit can be compared with the Bowen ‘threshold of lung injury’ curve. Fig. 6 superimposes the Bowen curves and the proposed tolerance limits for a 50% risk of trace/slight+ and severe+ injury (short and long-duration waves (e.g. supplementary materials)). This illustration shows that the proposed thresholds for trace/slight+ lung injury are in accordance with the Bowen curve. However, it also shows that the 50% risk of severe+ lung injury tolerance limit is between the Bowen threshold and the 1% of lethality curves for long-duration wave, and crosses the 1% and 50% risk of lethality for short-duration wave. It can suggest that for short-duration wave, the animal death is not only dependent on lung injuries, but that other injuries, such as gastrointestinal haemorrhages, play an important role. Moreover, Fig. 6 seems to illustrate that the lung injury risk thresholds between short and long-duration is dependent on both the incident impulse and the overpressure. But data are needed to evaluate this observation.

The tolerance limits defined in terms of  $\Delta I_1$  for different lung injury levels were then used to correlate the swine chest motion (from Boutillier et al., 2017) to lung injury risk. When a blast wave impacts the body, direct pressure and shear waves are generated (Cooper et al., 1991). The pattern of lung injury in blast would suggest that direct pressure wave contribute to the injury and that direct shear or chest compression are not the principal injury mech-



**Fig. 6.** Comparison of the Bowen curves with the proposed 50% risk of trace/slight+ and severe+ lung injury.

anisms (Clemedson and Jönsson, 1964; Cooper et al., 1991; Cooper, 1996; Fung et al., 1988; Stuhmiller et al., 1996). The direct pressure wave is governed by impedance mismatched, and its characteristics are dependent upon  $\Gamma_{\max}$  and  $V_{\max}$  (Cooper et al., 1991; Cooper, 1996). It would then be more interesting to correlate  $\Gamma_{\max}$ ,  $V_{\max}$  or  $VC_{\max}$  to lung injury level rather than  $D_{\max}$ . The proposed tolerance limit for a 50% risk of lung injury (trace/slight+) in terms of  $\Gamma_{\max}$  is 7336 m/s<sup>2</sup>. This value is not in accordance with the threshold proposed by Cooper (1996), i.e. 10,000 m/s<sup>2</sup>, and corresponds to a 27% difference. This can be due to the lack of injured data (only 45 cases) or to a difference in animal position and mass considered (not given in Cooper, 1996). However, the lung injury tolerance limits proposed in terms of  $V_{\max}$  are within the range proposed by Axelsson and Yelverton (1996). Indeed, 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, where the proposed 50% risk are respectively 3.7 m/s, 7.5 m/s and 14.7 m/s. Nevertheless, it can be noticed that the viscous criterion threshold values are 0.07 m/s, 0.26 m/s and 0.87 m/s for trace/slight+, moderate+ and severe+ injuries respectively, whereas the limits defined in the automotive field and for non-lethal weapons impacts are respectively 1 m/s (for an AIS3+) and 0.8 m/s (for rib fractures, Bir, 2000). This shows that, with the exception of the Axelsson model that predict similar  $V_{\max}$  injury thresholds, the existing values are not suitable for blast interaction with a biological model and that the proposed limits should be more acceptable even if more data are needed.

In order to help in the determination of a good candidate parameter for injury criteria definition, which must be constant on an iso-impulse according to the presented analysis and to White's conclusion (1971), the swine chest response under blast waves of different, short, positive phase duration should be assessed. The new data should be used to refine the proposed tolerance limits and the found candidate parameter or parameters should be correlated to injury level using the proposed methodology. Nevertheless, more lung injury data are needed to refine the proposed lung tolerance limits and it is still unknown whether  $\Gamma_{\max}$ ,  $V_{\max}$  or  $VC_{\max}$  are good parameters to evaluate the performance of a thoracic protection against the blast threat. A study of Ouellet and Williams (2008) exposed the MABIL manikin, unprotected and protected, to different blast threats and found that  $\Gamma_{\max}$  could be a good candidate parameter to differentiate the performances of thoracic protections, contrary to  $V_{\max}$ . However, the thoracic response of this manikin is not correlated with injury tolerance limits, which leaves the question of the good candidate parameter for an assessment regarding possible injury outcomes unresolved. Another possibility for an injury risk criterion would be to measure the pressure transmitted into the lung, but measuring the intra-pulmonary pressure is difficult without being invasive and usually not measurable on a manikin. More study are needed to determine the efficient parameter, but this study is a first step toward that aim and proposed a methodology and first lung tolerance limits in terms of global kinematic parameter related to swine thoracic response.

### Conflict of interest statement

The authors have nothing to disclose.

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### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.02.011>.

### References

- Axelsson, H., Yelverton, J.T., 1996. Chest wall velocity as a predictor of nonauditory blast injury in a complex wave environment. *J Trauma*. 40 (3), 31–37.
- Bass, C.R., Davis, M., Rafaels, K., 2005. A methodology for assessing blast protection in explosive ordnance disposal bomb suits. *Int. J. Occupat. Safety Ergonom.* 11 (4), 347–361.
- Bass, C.R., Rafaels, K.A., Salzar, R.S., 2008. Pulmonary injury risk assessment for short-duration blasts. *J Trauma*. 65, 604–615.
- Bir, C., 2000. The Evaluation of Blunt Ballistic Impacts of the Thorax PhD. Thesis. Wayne State University, Detroit.
- Bir, C., Viano, D., King, A., 2004. Development of biomechanical response corridors of the thorax to blunt ballistic impacts. *J. Biomech.* 37, 73–79.
- Bouamoul, A., 2008. Numerical Calculation of Blast Effect on Human and on the Mannequin for the Assessment of Blast Incapacitation and Lethality. Technical memorandum. DRDC Valcartier TM 2008-285, Defense R&D Canada.
- Boutillier, J., Deck, C., Magnan, P., Naz, P., Willinger, R., 2016. A critical review on primary blast thorax injury and their outcomes. *J. Trauma Acute Care Surg.* 81 (2), 371–379.
- Boutillier, J., De Mezzo, S., Deck, C., Magnan, P., Naz, P., Willinger, R., 2017. Chest response assessment of post-mortem swine under blast loadings. *J. Biomech.* 65, 169–175.
- Bowen, I.G., Fletcher, E.R., Richmond, D.R., 1968. Estimate of Man's Tolerance to the Direct Effects of Air Blast. Technical Progress Report, DASA-2113. Defense Atomic Support Agency, Department of Defense, Washington, DC.
- Cernak, I., 2010. The importance of systemic response in the pathobiology of blast-induced neurotrauma. *Front. Neurol.* 1 (art.151), 1–9.
- Clemedson, C.J., Jönsson, A., 1964. Dynamic response of chest wall and lung injuries in rabbits exposed to air shock waves of short duration. *Acta Physiol. Scand.* 62 (233), 3–31.
- Cooper, G.J., Townend, D.J., Cater, S.R., Pearce, B.P., 1991. The role of stress waves in thoracic visceral injury from blast loading: modification of stress transmission by foams and high-density materials. *J. Biomech.* 24 (5), 273–285.
- Cooper, G.J., 1996. Protection of the lung from blast overpressure by thoracic stress wave decouplers. *J. Trauma* 40 (3), 105–110.
- Courtney, M.W., Courtney, A.C., 2011. Working toward exposure thresholds for blast-induced traumatic brain injury: thoracic and acceleration mechanisms. *NeuroImage*. 54, S55–S61.
- Dodd, K.T., Yelverton, J.T., Richmond, D.R., Morris, J.R., Ripple, G.R., 1989. Nonauditory Injury Threshold for Repeated Intense Freefield Impulse Noise. Walter Reed Army Institute of Research, Washington, DC.
- Fung, Y.C., Yen, R.T., Tao, Z.L., Liu, S.Q., 1988. A hypothesis on the mechanism of trauma of lung tissue subjected to impact load. *J. Biomech. Engng.* 110, 50–56.
- Jetté, F.X., Dionne, J.P., Williams, K., Ancil, B., Makris, A., 2004. Development of a mannequin for assessment of blast injuries and lethality – assessment of protective systems. Proceedings of the MABS 18th Conference. Schneizlreuth, Germany.
- Lau, I.V., Viano, D.C., 1986. The viscous criterion – bases and applications of an injury severity index for soft tissues. In: Proceedings of the Thirtieth Stapp Car Crash Conference. San Diego, pp. 123–142. SAE Paper No. 861882.
- Magnan, P., De Mezzo, S., Heck, S., Boehrer, Y., 2012. Approche métrologique du chargement par le blast de cibles anthropomorphiques instrumentées – Essais ISL/DGA Tt. Report S-R 108/2012 of the French-German Research Institute of Saint Louis, France.
- Magnan, P., 2016. Private communication.
- Ouellet, S., Williams, K., 2008. Characterisation of Defence Research and Development Canada's Mannequin for the Assessment of Blast Incapacitation and Lethality (DRDC MABIL). Presented at the Personal Armour Systems Symposium Brussels, Belgium.
- Phillips, Y.Y., Mundie, T.G., Yelverton, J.T., Richmond, D.R., 1988. Cloth ballistics vest alters response to blast. *J. Trauma* 28 (1), S149–S152.
- Prat, N.J., Montgomery, R., Cap, A.P., Dubrick, M.A., Sarron, J.C., Destombe, C., May, P., Magnan, P., 2015. Comprehensive evaluation of coagulation in swine subjected to isolated primary blast injury. *Shock* 43 (6), 598–603.
- Richmond, D.R., Damon, E.G., Fletcher, E.R., Bowen, I.G., White, C.S., 1968. The relationship between selected blast-wave parameters and the response of mammals exposed to air blast. *Ann N Y Acad Sci.* 152, 103–121.
- Richmond, D.R., Cooper, P.W., 2002. Evaluation of Bowen's curves. Unpublished manuscript.
- Stuhmiller, J.H., Ho, K.-H.H., Vander Vorst, M.J., Dodd, K.T., Fitzpatrick, T., Mayorga, M., 1996. A model of blast overpressure injury to the lung. *J. Biomech.* 29 (2), 227–234.

- Teland, J.A., 2012. Review of blast injury prediction models. FFI-rapport 2012/00539.
- Thom, C., Cronin, D., Ouellet, S., Makris, A., 2007. Numerical simulation of primary blast injury amplification by fabrics. *J. Biomech.* 40 (S2), 56–57.
- Vassout, P., 1985. Effets biologiques des ondes de choc aériennes: synthèse des travaux réalisés à ce jour. Report NB 402/85 of the French-German Research Institute of Saint-Louis, France.
- Vassout, P., Mayorga, M.A., Argyros, G., Topper, M., 1995. Biological effect of blast on sheep: a comparison of shock tube exposure to free-field exposure. Proceeding of the MABS 14th conference, Las Cruces, New Mexico, USA.
- White, C.S., Jones, R.K., Damon, E.G., Fletcher, E.R., Richmond, D.R., 1971. The biodynamics of airblast Technical Report DNA2738T. Defense Nuclear Agency, Washington, DC.