Thoracic response of post-mortem swine under blast loadings

J. Boutillier, S. De Mezzo, C. Deck, P. Magnan, P. Naz, R. Willinger

Abstract To better protect soldiers from blast threat, it is necessary to develop an adapted injury criterion and, prior to this, to evaluate the response of a biological model against that threat. The objective of this study is to provide some robust data to quantify the thoracic response of post-mortem swine under five different blast loadings.

A total of 47 experiments were performed on seven female post-mortem swine (54.5±2.6 kg), placed side-on to the threat and against the ground. Their thorax were instrumented with a piezo-resistive pressure sensor and an accelerometer directly exposed to the shock-wave, and a target was mounted on the latter in order to track the ribcage displacement.

For incident impulses ranging from 47 kPa.ms ± 2% to 173 kPa.ms ± 6%, the measured maximum of linear thoracic acceleration (Γmax) goes from 5,800 m/s ± 16% to 41,000 m/s ± 8%, with a duration of 0.8ms. Ribcage displacement ranging from 5 mm ± 20% to 20 mm ± 15%, with a duration of 9 ms, are reached. These reproducible data were used to find simple relations (linear, 2nd and 3rd order polynomials) between the kinematic parameters (plus the viscous criterion) and the incident impulses.

Correlating the new experimental data with the prediction from the Bowen curves showed a lung injury threshold in terms of Γmax similar that of by Cooper (10,000 m/s²). However, the limits defined for the viscous criterion in the automobile field (1 m/s for AIS3+) and for non-lethal weapons (0.8 m/s) seems not adapted for the blast threat.

Keywords Biological model, Blast, Experimentations, Lung injury limits, Thoracic response.

I. 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 those vital organs is a real challenge, and it is necessary to identify the critical points and the key parameters to take into account for the development and the improvement of individual protective equipment. The individual's tolerance to impacts has mainly been studied in the automotive industry, which provides the main injury criteria. In addition to problems related to road safety, another aspect to take into account in this regard is the military arena, which has not been much studied. The long-term interest is to evaluate thoracic protection systems, since they are not all equal in terms of efficiency against the blast threat [1-4]. For that specific aim dummies are used, with an appropriate instrumentation, such as the "U"-shape membrane, the Hybrid-III or the MABIL ("Mannequin for Blast Incapacitation and Lethality") [5-7]. It is not yet possible, with current knowledge, to quantify the variation in lung injury level resulting from the wearing of a thoracic protection. Indeed, this can only be achieved with an injury criterion and a biofidelic mannequin adapted to this threat, but neither of these two conditions is fulfilled to date.

To obtain those two conditions and enable researchers to quantitatively evaluate the efficiency of thoracic protective systems against the blast threat, an experimental campaign has been performed in order to investigate the thoracic response of a post-mortem biological model widely used in blast studies. The biological model used is a 50 kg swine, used in particular by the French Military Health Service to evaluate the

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pathophysiological thoracic response to “behind armor blunt trauma” (BABT) or non-lethal weapons and, more recently, the effects of blast [8-16]. In those studies, animals were exposed side-on to the threat.

The swine has a number of analogies with the human being, including the size and organisation of its internal organs. Although the conformation of the ribcage differs somewhat, the biomechanical behaviour and the relationship with the cardio-respiratory system is the same. A 50 kg swine has the corpulence of a young adult man.

In the current study, 50 kg post-mortem swine were exposed side-on and against the ground to shock-waves of increasing intensities in order to reproduce threat of varying levels, from inducing no injury to 50% of lethality, according to the Bowen curves (near wall scenario) [17]. Working on post-mortem subjects implies that lung injuries could not be assessed. They were instrumented with a piezo-resistive pressure sensor and an accelerometer directly exposed to the shock-wave, and a target was mounted on the latter in order to track the ribcage displacement. The objective is to evaluate the reproducibility of the measurement intra and inter animals, and to know the thoracic response of post-mortem swine for a large range of incident impulses. This study reports reproducible data of the thoracic response of swine under blast loadings, data which are not available in the literature.

II. METHODS

This section describes the post-mortem swine used in the present study and exposed to several shock-waves, as well as their instrumentation. In addition, it provides a description of the set-up and the performed scenarios.

Animal preparation

A total of seven post-mortem female swine (54.7 ± 2.4 kg) were procured, at the rate of one per day. The first task was to refill the abdominal cavity with a flexible material, ensuring the morphology and the support necessary for the tests. Four natural sponges, previously moistened, were placed in a plastic bag and introduced into the abdomen, which was then sutured. An illustration of the swine #7 and of the bag filled with natural sponges is shown in Fig. 1.

Fig. 1. A) Global view of swine #7; B) replacement of the abdominal viscera with four natural sponges previously placed in a plastic bag.

The main body measurements of the swine are presented in Table I. These seven biological models, six females and one male, were the subject of a seven-day experimental campaign. Each was exposed to a series of explosions of different intensities.

TABLE I
CHARACTERISTIC DIMENSIONS OF THE SEVEN SWINE USED IN THIS STUDY. SD IS THE STANDARD DEVIATION

	Swine #1	**Swine #2**	**Swine #3**	**Swine #4**	**Swine #5**	**Swine #6**	**Swine #7**	**Mean values**	**SD**
Weight (kg)	56	50	54	55	57	57	54	54.7	2.4
Length (cm)	114	112	108	108	112	110	110	110.6	2.2
Thoracic perimeter (cm)	81.5	79	83	79	86	83	80	81.6	2.6
Abdominal perimeter (cm)	85	79	84	85	89	90	84	85.1	3.6
Skin thickness (cm)	2	1.7	2.2	2	2.5	2.5	2	2.1	0.3
Thoracic width (cm)	20.7	18.8	20.8	20.5	21	20.8	21	20.5	0.8

Instrumentation used

Each biological model was instrumented with the following sensors (Fig. 2).

- A uniaxial accelerometer (PCB 3501A12), screwed with two self-drilling screws on the 8th-9th rib from the top of the thorax (Fig. 2). It was placed so that it directly faced the incident threat. A rigid target, based on thin steel plates (1 mm) where 5 mm side square elements (black and white) were glued, was fixed on the accelerometer in order to track the displacement of the thoracic wall. Its width is 1 cm, for a height of at least 3 cm, so that when the instrumentation is fixed and the sutures are made, about 2 cm of the plate protrudes from the skin. A detailed picture of the dimensions of the accelerometer and the target is provided in Fig. 3.
- A piezo-resistive pressure sensor (Kulite XCQ 093) to measure the reflected pressure received by the exposed surface (Fig. 2). It was first placed in a flexible tube in order to protect it and then sutured to the skin near the accelerometer to keep it in contact with the skin.

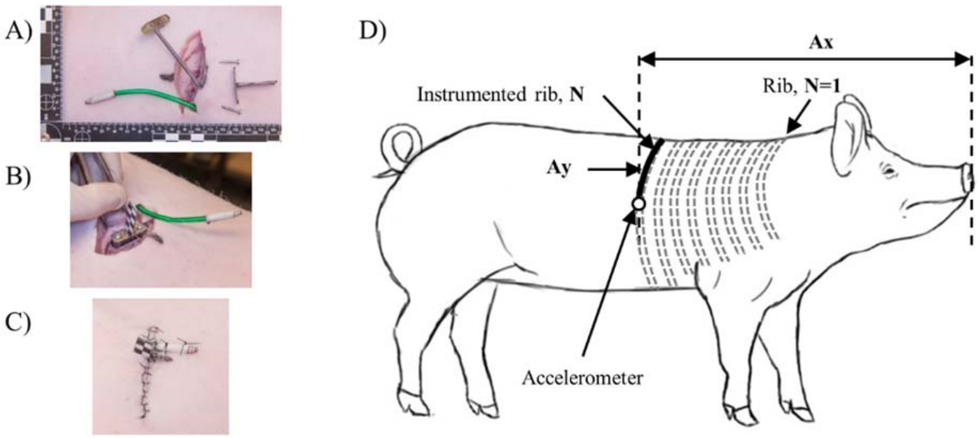

Fig. 2. A) View of the instrumentation; B) the accelerometer and the target are fixed to the rib; C) suture of the skin around the accelerometer and target, and fixation of the pressure sensor on the skin near the accelerometer; D) schematic view of the sensor position on the animal.

In order to protect the instrumentation cables and to avoid the interferences related to the whiplash of the latter, they are tunneled under the skin and come out at the level of the animal spine. Table II summarises the position of the instrumentation on the different swine. It can be seen that the number of ribs per animal may differ. This is due to the fact that the pairs of ribs are 12 to 16 in the swine, usually with 14 or 15 pairs.

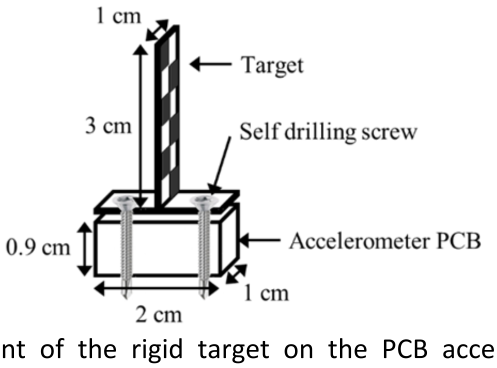

Fig. 3. Illustration of the placement of the rigid target on the PCB accelerometer for video-tracking. The dimensions are also displayed.

TABLE II
SENSOR POSITIONS ON EACH ANIMAL, ACCORDING TO THE ILLUSTRATION IN FIG. 2D

	Swine #1	Swine #2	Swine #3	Swine #4	Swine #5	Swine #6	Swine #7
Snout – Accelerometer (cm)	?	60	57	59	61	59.5	57.5
Ay: Spine – Accelerometer (cm)	23	18	20.5	19.9	20	20	19.5
N: Instrumented rib (from top)	9	9	8	9	9	9	9
Total number of pairs of ribs	15	14	14	14	15	15	15

In addition to the instrumentation on the biological model, two Free-Field Blast ICP pressure probes, type 137B22 from PCB Piezotronics, were used to measure the side-on pressure at the same distance from the charge as the swine.

The acquisition was made by a high-speed range data acquisition system (MF instruments), with a sampling rate of 1 MHz. The data were then filtered with a 6th order Bessel at 80 kHz.

High-speed cameras were installed in the experimental field:

- one Photron RS color (5,000 fps) is a view of the whole scene, to check the homogeneity and the sphericity of the fireball;
- one Phantom V1610 (black & white) (20,000 fps) is used to visualise the shock-wave interaction with the animal. This camera is located at a height of 20 cm (distance between the ground and the centre of the camera optics), corresponding to the average thoracic width of the swine. It allowed the tracking of the ribcage displacement using the target fixed on the accelerometer.

Both cameras are placed 30 m from the charge in order to delay the video instability during the passage of the shock-wave on the camera. Their recording window is shown in Fig. 4.

From those instrumentation, several parameters can be extracted: the incident/reflected pressures and corresponding impulses; the acceleration of the swine ribcage; the chest wall velocity, obtained by time integration of the acceleration; and the ribcage displacement, obtained from video-tracking. In addition to those kinematic parameters, the Viscous Criterion is calculated for each scenario. This injury prediction criterion, coming from the automotive field and developed by Lau *et al.* [18], is defined as the maximum of the product of the thorax deformation speed and the thorax compression. The maximum of this curve (VCmax) is related to a level of injury (the AIS scoring system), a VCmax of 1 m/s will induce a 25% risk of AIS3+. The limit for non-lethal weapons is lower: 0.8 m/s for rib fracture.

As meteorological conditions affect the blast propagation, a weather station (VAISALA WXT520) was used during the experiments. It recorded the ambient pressure, temperature, wind direction and speed, humidity and rainfall.

Fig. 4. Recording window on the two high-speed cameras.

Experimental testing

The biological model is put on a 1.5 x 1 x 0.02 m steel plate placed on the ground, lying on the left flank (side-on exposure). This plate is used so as not to damage the proving ground and to avoid any projections of ground fragments that can disturb the analysis of the videos. Accordingly, the shooting area was systematically swept before each test.

The explosive used is the Composition-4 (C-4). The spherical charges (hand-modeled) are hanging over the animal, so that the distance between the accelerometer and the bottom of the charge is 2 m. As shown in Fig. 5, depicting the experimental set-up, a rope system is used to minimise rocking of the explosive charge. The explosive charge is ignited at the centre of the sphere with an SA4003 MI detonator (Davey Bickford).

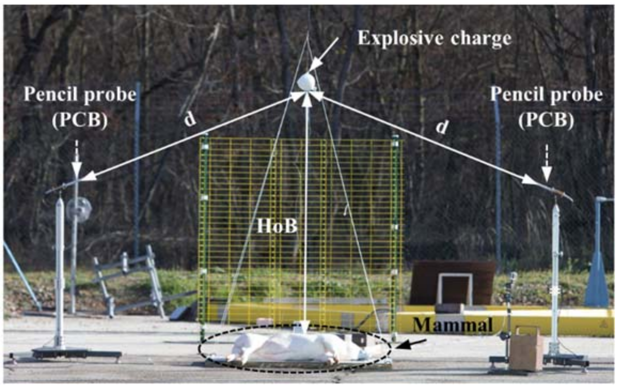

Fig. 5. Experimental set-up showing the position of the animal and of the pencil probes according to the threat. The distances “bottom of the explosive charge to Accelerometer” and “bottom of the explosive charge to sensor of the pencil probes” are identical.

Using a home-made software, called Blast-ISL, it is possible to know the mass of C-4 required for a given distance to reach a certain level of injury based on the Bowen curves (near wall scenario), scaled for a 50 kg animal [17]. Five scenarios were chosen, allowing for blast impacts from inducing no injury to 50% of lethality:

- 0.3 kg: induce no injury according to the Bowen curves;
- 0.6 kg: lung injury threshold;
- 1.5 kg: 1% of lethality;
- 1.8 kg: 10% of lethality;
- 2.5 kg: 50% of lethality.

As summarised in Table III, a total of 47 experiments were performed on seven post-mortem swine, experiments which were distributed to check the intra and inter individual’s reproducibility of the measurements. Each day of testing started with a 0.3 kg detonation on the swine procured the same day, to ensure the reproducibility of the measurements compared with the results of the previous days, and also to ensure the sensors’ proper functioning.

TABLE III

SUMMARY OF THE EXPERIMENTAL TESTS PERFORMED

	0.3 kg	**0.6 kg**	**1.5 kg**	**1.8 kg**	**2.5 kg**	**Total number of tests**
Swine 1	3	3	-	-	-	**6**
Swine 2	3	3	1	-	-	**7**
Swine 3	3	3	-	1	-	**7**
Swine 4	1	-	2	2	1	**6**
Swine 5	3	-	2	3	1	**9**
Swine 6	3	-	2	2	1	**8**
Swine 7	1	2	-	-	1	**4**
Total number of tests	**17**	**11**	**7**	**8**	**4**	**47**

III. RESULTS

Fig. 6 shows the mean of the incident pressures and impulses measured with the pencil probes for the five scenarios tested and the associated standard deviations. The biological models faced Friedlander threat of maximum overpressure ranging from 96 kPa ± 7% to 468 kPa ± 2%, with positive phase durations between 1.39 ms ± 2.7% and 1.44 ms ± 3.2%. Those waves generate maximum of incident impulses from 47 kPa.ms ± 2% to 173 kPa.ms ± 6%.

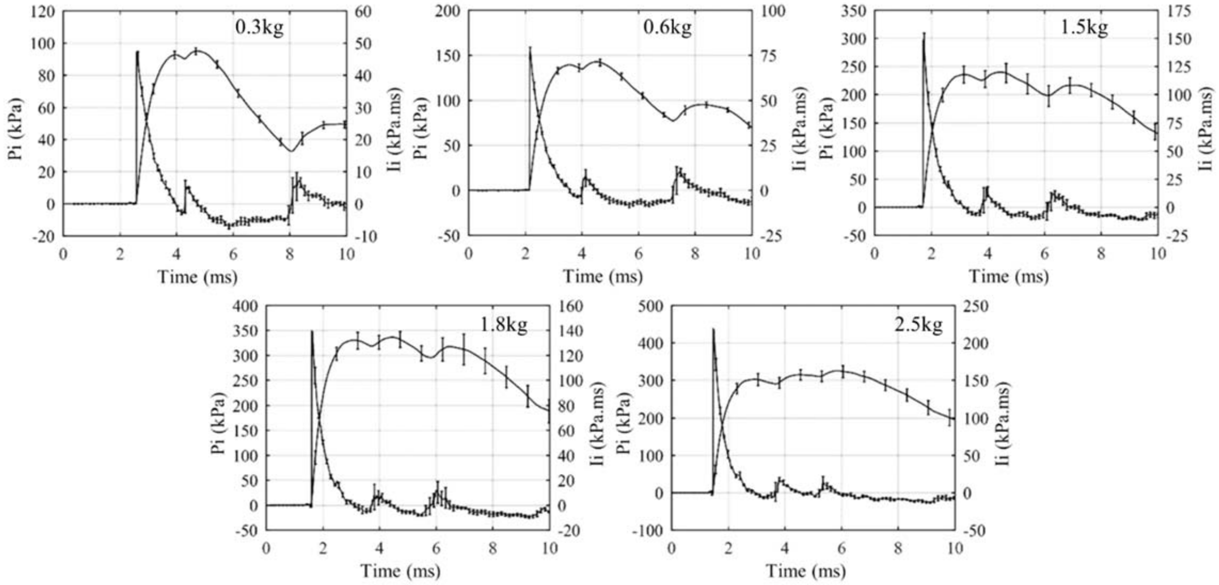

Fig. 6. Side-on pressure and impulse profiles for the different threats that faced the swine. These profiles are the mean recorded values with the standard deviations.

When this Friedlander wave interacts with the swine, a reflected wave is formed that moves partly in the opposite direction of the incident wave. This pressure is measured on the swine near the accelerometer that directly faces the threat. Fig. 7 shows the reflected pressures and impulses measured by the Kulite XCQ-093 sensor.

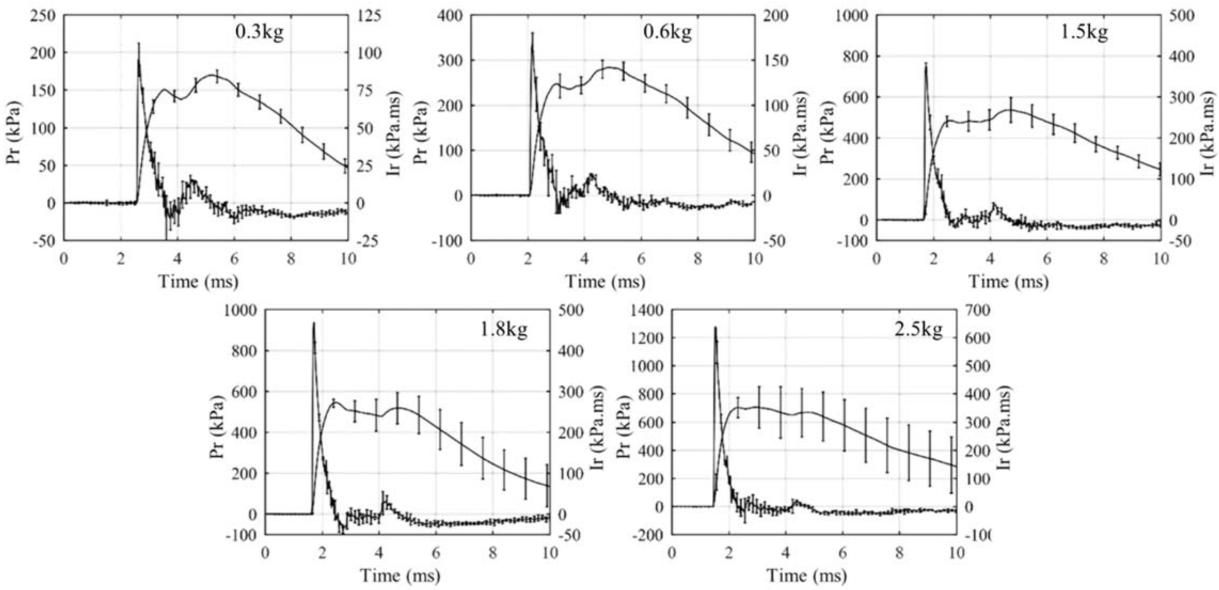

Fig. 7. Reflected pressure and impulse profiles for the different threats that faced the swine. These profiles are the mean recorded values with the standard deviations.

The reflected overpressures reached ranged from 196 kPa ± 9% to 1299 kPa ± 11%, which correspond to maximum of impulses ranging from 85 kPa.ms ± 4% to 375 kPa.ms ± 16%, respectively. The positive phase duration of the reflected pressure was between 0.77 ms and 0.93 ms, while the one for the incident pressure wave was about 1.41 ms.

In contrast to the incident pressure measured by the pencil probes, the inter-individual standard deviations of the wave characteristics are slightly higher. While the standard deviations calculated on the incident pressures were lower than 9.5% in all scenarios, it reached, for the reflected pressures, 20.7% for the 0.6 kg scenarios and between 8.9% and 13.5% for the others. This observation is similar for the intra-individual reproducibility of the pressure measurements. The reproducibility of these measurements is, therefore, not perfect but it is sufficiently reasonable to consider them in the rest of this study, given the difficulty of placing this sensor on a biological model facing blast threats.

Measured linear accelerations and displacements of the swine ribcage under blast loadings

In order to compare the ribcage response from swine of slightly different weights (54.7 ± 2.4 kg), all the data obtained were scaled to a 50 kg animal using the scaling laws of Baker *et al.* [*19*].

The set of scaled mean acceleration profiles obtained per scenario is given in Fig. 8 (left). The range of maximum linear acceleration (Γmax) recorded is between 5,800 m/s² ± 16% and 41,000 m/s² ± 8%, for duration between 0.7 ms and 0.9 ms. The main characteristics of the acceleration profiles are reproducible regarding the results per and between swine, with standard deviations below 16%.

The evolution of the thoracic wall over the first 15 milliseconds, obtained by video-tracking, is illustrated in Fig. 8 (right). Displacements ranging from 5 mm ± 20% to 20 mm ± 16% for duration between 8.1 ms and 10 ms are reached.

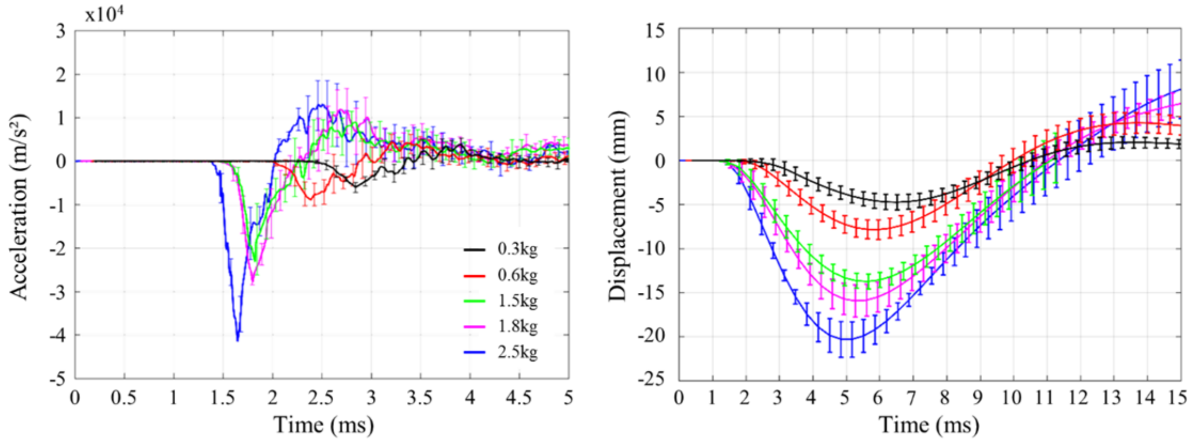

Fig. 8. Acceleration-time histories (*left*) and displacement of the ribcage (*right*) for the scenarios tested (scaled for 50 kg animals). These profiles are the mean recorded values with the standard deviations.

By analysing the intra-individual results, standard deviations on the displacement are less than 10%, with the exception of results from swine #2 and #3 exposed to 0.3 kg of C-4, where the errors are respectively 12.1% and 22.8%. This may be due to the difficulty of video-tracking related to the resolution of the video. Indeed, a too wide field was chosen for the high-speed camera, at 20,000 ips, leading to pixels measuring 1.25 mm x 1.25 mm. As a result, large errors can be introduced when manually tracking on a 20 mm x 10 mm grid pattern with 5 mm elements. The positive phase duration is also reproducible, with errors of less than 11% on all configurations.

Despite small intra-individual standard deviations, the inter-individual ones are higher regarding the maximum of displacement (Dmax). Indeed, the statistics show standard deviations between 14.6% and 19.6% on Dmax. Only the experiments with 1.5 kg of C-4 have a very good inter-individual reproducibility, with a standard deviation of 6.8%. However, considering the difficulties of working on a biological model under blast loadings and the video-tracking resolution, the data obtained are considered reproducible and can now be used for further in-depth analyses.

Relations between the maximum of incident impulses and the response of the swine ribcage

Fig. 9 shows the obtained evolution of Γmax, Vmax (maximum of chest wall velocity, obtained by time-integration of the acceleration) and Dmax against the incident overpressure (ΔPi) (Fig. 9A) and the maximum of incident impulse (ΔIi) (Fig. 9B). As the thoracic acceleration is proportional to the applied force to the chest wall, a linear trend is observed (R^2=0.92) between the maximum of acceleration and the incident pressure, which is itself proportional to the applied force (Fig. 9A). The same observation is true for the chest wall velocity as a function of the incident impulse, where a linear relationship is applied (R^2=0.92).

In order to find the right trend curve to apply to each of the parameters, the procedure is to use the known relationships, namely proportional relations between Γmax and ΔPi, and between Vmax and ΔIi. Thus, to find the relation between Vmax and ΔPi, the relation between Γmax and ΔPi is integrated (since the velocity is obtained by time-integration of the acceleration). Thus, a 2nd order polynomial will be applied. The procedure is repeated for the other parameters obtained by integration. For all trend curves, the parameters are constrained to zero. It seems relevant that no acceleration, velocity or ribcage displacement take place without applied constraint on the swine. Simple relationships (linear, 2nd and 3rd order polynomials) with coefficients of determination R^2> 0.85 are obtained for all parameters.

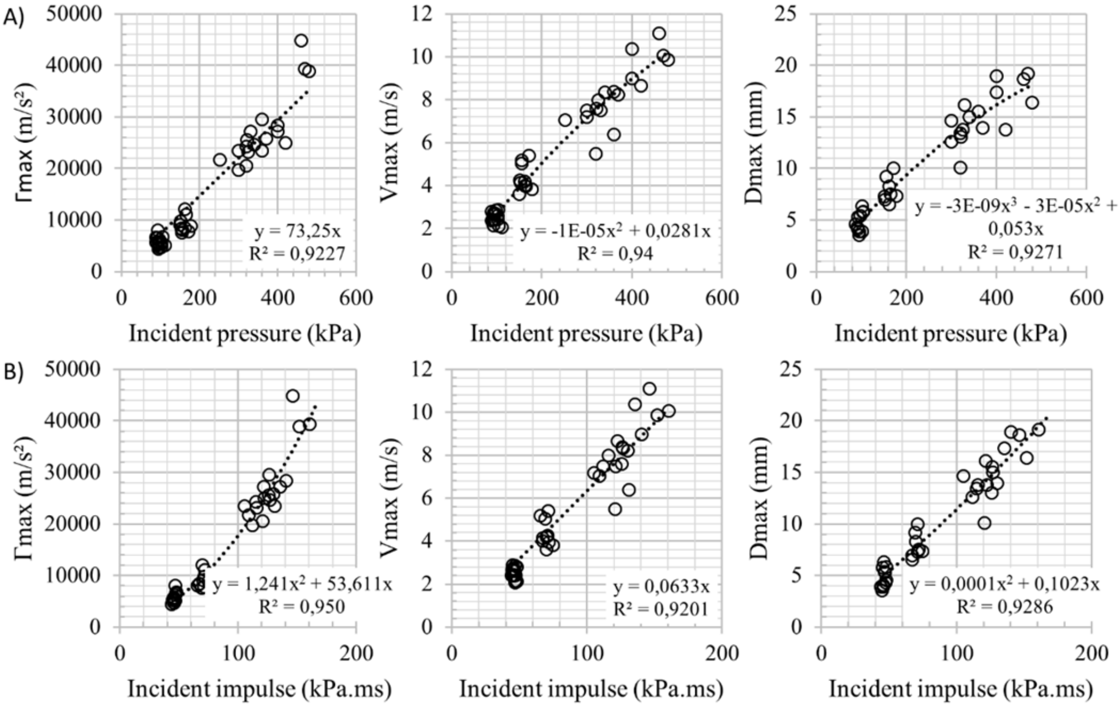

Fig. 9. Evolution of the different kinematic parameters (Γmax, Vmax (maximum of chest wall velocity), Dmax) against: A) the incident overpressure; B) the maximum of incident impulse. The equation of the tendency curves and their associated R^2 are written on each graph.

The response of the post-mortem swine ribcage under blast loadings is therefore known for maximum incident and reflected impulses until 160 kPa.ms and 430 kPa.ms, respectively.

The viscous criterion calculated from the obtained data on swine

The viscous criterion (VC) is a thoracic injury criterion developed by Lau *et al*. [18] and used in the automotive field. As a reminder, it is defined as the maximum value of the product of the thoracic wall velocity by the chest compression (VCmax).

In our analysis, this criterion is calculated by using the thoracic thickness of the swine measured during the experimental campaign (Table I). The thoracic compression is then defined as the ratio of the measured ribcage displacement to the thoracic thickness. Fig. 9A shows the calculated average time evolution of the viscous criterion for biological models exposed to 0.6 kg C-4 charges. Fig. 9B illustrates the evolution of the VCmax as a function of the maximum incident impulse. It can be seen that the value of VCmax increases from 0.025 m/s for the biological models exposed to 0.3 kg of C-4, to 0.343 m/s for the worst scenario tested (50% of lethality).

On the same biological model, the standard deviations measured on VCmax are less than 15%, except for swine #2 and #3, where it reaches 33.11% and 27.25%, respectively, for the 0.3 kg configurations. However, since this criterion is defined as the maximum value of the product of the velocity by the thoracic compression, the standard deviations on each of these parameters are reflected in VCmax. It has been seen previously that the displacement standard deviations calculated for these same configurations were 12.1% and 22.8%, respectively, and that the standard deviation on Vmax for swine #2 exposed to 0.3 kg of C-4 was 16.1%. This explains the larger errors on the VCmax.

Like the maximum of chest wall displacement, the inter-individual standard deviations are greater than the intra-individual ones: between 21.17% and 35.52%. The data obtained are nevertheless considered reproducible, given the values of this criterion, which are very close to zero. The regression obtained between

VCmax and the incident impulse is of good quality, with a R^2 equal to 0.89 (3^{rd} order polynomial).

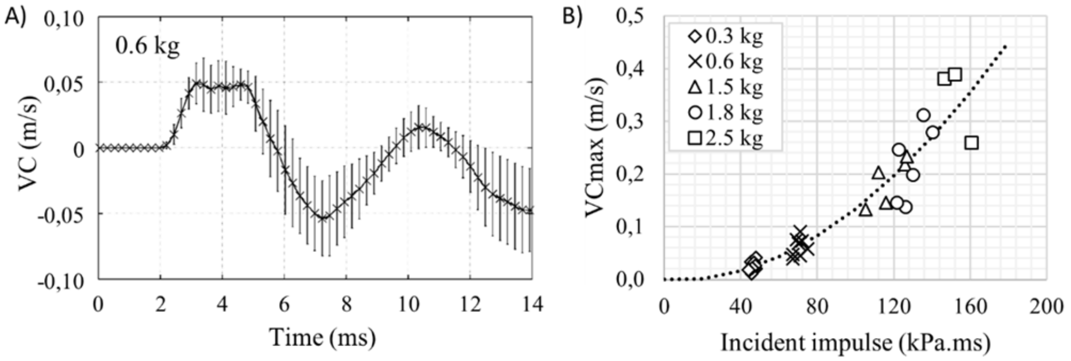

Fig. 9. A) Temporal evolution of the viscous criterion of swine exposed to 0.6 kg of C-4. The profile is the mean recorded values with the standard deviations; B) evolution of VCmax as a function of the maximum of incident impulse. The trend curve obtained is $VCmax = -8{,}733.10^{-9}\Delta I^3 + 1{,}689.10^{-5}\Delta I^2 - 2{,}63.10^{-4}\Delta I$ (R^2=0.8922).

IV. DISCUSSION

The experimental campaign performed on post-mortem swine allowed the knowledge of the swine thoracic cage response under blast loadings for incident impulses until 160 kPa.ms, which corresponds to a 50% of lethality scenario according to the Bowen curves.

Although post-mortem human subjects (PMHS) and animals have been widely used as a substitute for the thorax of a living human being, the relationship between the thoracic behaviour of these three "models" has been little studied. A study of Prat et al. [11] showed that the motion of the pig's chest is greater than that of the PMHS under lateral ballistic blunt impact. This difference could be attenuated if comparing the frontal thoracic response of PMHS to its lateral thoracic response in the automotive domain. Indeed, some studies have shown that the frontal or oblique impact results in a greater deflection and a lower force than a lateral impact [20-21]. Nevertheless, experiments should be performed at high rate in order to evaluate how similar is the frontal thoracic compliance of the human to the lateral thoracic compliance of the swine. Furthermore, questions were raised about the approximation of the thoracic response of a PMHS to that of a living human being, the main problem being the lack of muscle tone. But while this lack of muscle tone would have an impact 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 thoracic displacement [22]. The thoracic cage response of a post-mortem or a living biological model could reasonably be considered as identical in the field of high-speed loadings such as blast, even if this statement need to be verified.

Reproducible data of the swine thoracic motion have been obtained, allowing to show patterns between blast intensity and thoracic motion. However, working on post-mortem biological model does not allowed to do it between blast intensity and lung injury. In order to highlight the order of magnitude of the ribcage motion that would induce a certain level of injury, the obtained data were coupled with the prediction from the Bowen curves. It revealed that the lung injury threshold in terms of maximum of linear acceleration is 10,062 m/s², which is in accordance with the threshold proposed by Cooper *et al.* [23], i.e. 10,000 m/s². Moreover, it seems that the viscous criterion limits defined in the automotive field, i.e. 1 m/s for AIS3+, and for non-lethal weapon impacts, i.e. 0.8 m/s for rib fractures, are not suitable for the interaction of a shock-wave with a biological model. Indeed, Bowen *et al.* [17] predicted the lung injury threshold for an exposure to a Friedlander shock-wave generated by the detonation of 0.6 kg C-4 at 2 m (against a wall scenario). However, the VCmax obtained for that scenario induces risks for an AIS3+ of 0% (VCmax=0.06 m/s). Looking at the scenario inducing 50% of lethality according to the Bowen curves (2.5 kg at 2 m), the VCmax obtained induces risks for an AIS3+ of barely 4% (VCmax=0.34 m/s). This shows that the viscous criterion needs to be redefined to predict thoracic injuries due to the primary blast.

With the aim of qualitatively or quantitatively evaluating the changes in injury achieved through the use in of protective clothing on a biological model, an adapted injury criterion is needed. For Friedlander waveforms, this criterion must be constant on an iso-impulse as the impulse governs the injury level [24]. In order to help in the determination of a good candidate parameter for injury criteria definition, one step would be to study the swine response under blast waves of different, short, positive phase duration than the one tested in that experimental campaign (T+ around 1.41 ms). Another step would be to correlate blast intensity (impulse) and injury level, and the combination of both findings will bring helpful tools for the evaluation of protective system under such a threat.

Moreover, the obtained thoracic response of post-mortem swine under different blast loadings could be used to validate a finite element model of a swine. That could help in the understanding of blast interaction with a biological model and in the determination of injury tolerance limits at tissue level.

V. CONCLUSIONS

The thoracic responses of seven post-mortem swine (around 54 kg) under blast loadings from inducing no injury to 50% of lethality were studied. The biological models were exposed side-on to the threat and against the ground, with the C-4 explosive charge 2 m above them. With an adapted instrumentation, the thoracic responses have been obtained until incident impulses of 160 kPa.ms, data which are not available in the literature. The data obtained showed a good intra and inter biological models reproducibility, which allowed the identification of simple relations between the ribcage response in terms of Γmax, Vmax, Dmax and VCmax as a function of the maximum of incident impulses.

Using those relations, it has been found that the maximum of linear acceleration obtained for the scenario inducing "lung injury threshold", according to Bowen, is in accordance with the threshold defined by Cooper *et al.* [23] and that the viscous criterion limits must be redefined to be used on blast studies.

VI. ACKNOWLEDGEMENT

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