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Chest response assessment of post-mortem swine under blast loadings ☆

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ABSTRACT

To better protect soldiers from blast threat, that principally affect air-filled organs such a lung, 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 chest response of post-mortem swine under blast loadings.

7 post-mortem swine (54.5 ± 2.6 kg), placed side-on to the threat and against the ground, were exposed to 5 shock-waves of increasing intensities. Their thorax were instrumented with a piezo-resistive pressure sensor, an accelerometer directly exposed to the shock-wave and a target was mounted on the latter in order to track the chest wall displacement.

For incident impulses ranging from 47 kPa ms ± 2% to 173 kPa ms ± 6%, the measured maximum of linear chest wall acceleration (Γmax) goes from 5800 m/s^2 ± 16% to 41,000 m/s^2 ± 8%, with a duration of 0.8 ms. Chest wall displacements 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 and reflected impulses.

Correlating the new reproducible data with the prediction from the Bowen curves showed a lung injury threshold in terms of Γmax similar to that of Cooper (10,000 m/s^2). However, the limits defined for the viscous criterion in the automobile field and for non-lethal weapons seems not adapted for the blast threat.

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 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 (Boutillier et al., 2016).

Any impact to the body will generate direct pressure and shear waves (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 mechanisms (Clemedson and Jönsson, 1964; Cooper et al., 1991, Cooper, 1996; Fung et al., 1988; Stuhmiller et al., 1996). The direct pressure wave transferred from an incident shock wave will be governed by impedance mismatched, and its characteristics are dependent upon the peak velocity (Vmax) and the peak acceleration (Γmax) of the chest wall (Cooper et al., 1991; Cooper, 1996). When this pressure wave propagates through the lung, haemorrhage will occur if the pressure differential across the capillary/alveolar interface reaches a critical failure level of unknown magnitude. Moreover, the stress waves will also reflect and reinforce within the chest cavity to result in stress concentration and injury at sites distant from the chest wall (Cooper, 1996). The individual's tolerance to impacts has mainly been studied in the automotive industry, which provides the main injury criteria, but 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 (Cooper et al., 1991; Jetté et al., 2004; Phillips et al., 1988; Thom et al., 2007). For that specific aim dummies are used, such as the "U"-shape membrane, the Hybrid-III or the MABIL ("Mannequin for Blast Incapacitation and Lethality") (Bass et al., 2005; Bouamoul, 2008; Magnan et al., 2012). However, an adapted injury criterion is needed in order to quantitatively evaluate the efficiency of a

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thoracic protection, in addition to a biofidelic mannequin adapted to that threat. Unfortunately, neither of these two conditions is fulfilled to date.

To obtain those two conditions and enable researchers to better protect soldiers against the blast threat, an experimental campaign has been performed to investigate the chest response of a post-mortem biological model widely used in blast studies: a 50 kg swine. This model is particularly used by the French Military Health Service to evaluate the pathophysiological chest response to behind armor blunt trauma or non-lethal weapons and, more recently, the effects of blast (Couret et al., 2013; Magnan et al., 2014; 2015; Moomey et al., 1998; Pavier et al., 2015; Prat et al., 2010, 2012, 2015; Vassout et al., 1986). 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.

The objective of the current study is to assess the chest response of 50 kg post-mortem swine for a large range of incident impulses and to evaluate the reproducibility of the measurement intra and inter animals.

2. Methods

The European directive (2010/63/EU), adopted in February 2013 in France, concerns only living animals. There are no regulations regarding animal's carcasses obtained in a slaughterhouse.

The animals used in our study were not sacrificed for the specific purpose of testing, but were intended for food. The carcasses were then obtained from the slaughterhouse. We have ensured their conservation and destruction.

2.1. Animal preparation

A total of seven post-mortem 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.

The main body measurements of the swine are presented in Table 1. 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.

2.2. Instrumentation used

Each biological model was instrumented with the following sensors (Fig. 1).

- A piezo-resistive pressure sensor (Kulite XCQ 093) to measure the reflected pressure received by the exposed surface (Fig. 1A). It was first placed in a flexible tube in order to protect it and then sutured to the skin near the accelerometer.
- A uniaxial accelerometer (PCB 3501A12) screwed on the 8–9th rib from the top of the thorax (Fig. 1B). 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 chest wall displacement. Its width was 1 cm, for a height of at least 3 cm, so that when the instrumentation was fixed and the sutures were made, about 2 cm of the plate protruded from the skin. A detailed picture of the dimensions of the accelerometer and the target is provided in Fig. 1C.

In order to protect the instrumentation cables and to avoid the interferences related to the whiplash of the latter, they were tunneled under the skin and came out at the level of the animal spine. During the experimental campaign, the post-mortem swine had 14–15 pairs of ribs. The number of ribs per animal may differ, due to the fact that the pairs of ribs are 12–16 in the swine, usually with 14 or 15 pairs. The accelerometer was at a distance of the swine nose (Ax) of 59.0 ± 1.5 cm (cf. Fig. 1B) and the spine-accelerometer distance (Ay) was 20.1 ± 1.5 cm.

In addition, 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 (5000 fps) was used to visualise the whole scene, to check the homogeneity and the sphericity of the fireball;
- one Phantom V1610 (black & white) (20,000 fps) was used to visualise the shock-wave interaction with the animal. This camera was located at a height of 20 cm (distance ground/centre of the camera optics), corresponding to the average chest width of the swine. It allowed the tracking of the chest wall displacement using the target fixed on the accelerometer.

Both cameras were placed 30 m from the charge in order to delay the video instability during the passage of the shock-wave on the camera.

From those instrumentation, several parameters were extracted: the incident/reflected pressures and corresponding impulses; the swine chest wall acceleration; the chest wall velocity, obtained by time integration of the acceleration; and the chest wall displacement, obtained from video-tracking. In addition, the Viscous Criterion was calculated for each scenario. This injury prediction criterion, coming from the automotive field and developed by Lau and Viano (1986), 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 +. For non-lethal weapons, a VCmax equal to 0.8 m/s represents a 50% risk of rib fracture (Bir, 2000).

Table 1
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
Mass (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