Primary blast injury on thorax: a critical review of the studies and their outcomes

Johanna Boutillier, Caroline Deck, Pascal Magnan, Rémy Willinger, Pierre Naz

Abstract Since World War II, researchers have been interested in exploring the injury mechanisms involved in primary blast on the thorax by using animal models and surrogates. These studies were mostly concerned with the finding of the lung injury threshold and the relationship between the physical components of the air blast-wave and the biological response. Studies have also been conducted to investigate the effect of repeated blast exposures on the injury outcomes and threshold. This has led to several injury criteria, such as the Bowen's Curves or the Axelsson's Chest Wall Velocity Predictor. This paper aims at doing a critical literature review of this specific topic.

Keywords Primary blast, thorax, literature review, injury criteria.

I. INTRODUCTION

The detonation of an explosive charge is one of the first causes of injuries on the battlefield [1]. The use of improvised explosive devices (IED) has become important and was responsible for up to 60% of the US forces deaths in Operation Enduring Freedom in Afghanistan [2]. The injured person generally suffers from multi-trauma [3]. There are the wounds coming from the sudden increase of ambient air pressure resulting from the detonation and directly impinge upon the body, which is called primary blast injuries. Such injuries principally affect gas-containing organs, such as lungs, middle ear and gastrointestinal tract [4-5]. These victims could also sustain injuries from flying fragments coming either from the ammunition itself or from the environment (secondary blast), from the displacement of the body, thrown against surrounding obstacles (tertiary blast) and, finally, from miscellaneous types of injury, such as thermal effects, dust, pathogens (quaternary blast).

The focus is on understanding the interaction between the air blast and the thorax. Since World War II, several studies have been conducted all around the world to better understand this interaction. Works have been carried out on the influence of blast-wave parameters on the outcomes on living mammals, which can be the percentage of survivability, the maximum mid-sternum acceleration, velocity and so on [6]-[9]. From these studies, different injury criteria have emerged, such as the Bowen's curves [10], the Axelsson's Blast Test Device (BTD) model [11] and the Stuhmiller BTD model [12]. Moreover, during recent years, the uses of numerical approaches, to better understand physical phenomena that could lead to injury criteria and to an improvement of the protective solutions, has increased [13]-[24][5]. Most of the time, these numerical tools are used to complete experimental studies or parametric testing while saving cost and time. In addition, they provide an interesting alternative to animal experimentation, for ethical reasons. Greer et al. [13] managed to correlate the pressure in the lung with injury risk using the Bowen's curves and a quasi two-dimensional finite element model (FEM) of the human thorax. Each of these injury criteria has its own limitations and a contradiction has been seen by Bouamoul et al. [25] between the different parameters used for injury prediction. For these reasons, an ANR ASTRID project was built, which we call BLASTHOR, which stands for blast interaction with a thorax. The aim is to give insight into parameter(s) that can be linked to injury risk. This information will be used to instrument a test dummy for mitigation evaluation. For that purpose, a step-by-step approach has been chosen, with a simultaneous use of experimental and numerical studies.

This paper aims at doing the state-of-the-art on primary blast interaction with a thorax. To do so, a summary is carried out on the physics of blast and the findings from animal and dummy studies, which leads to the

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existing injury criteria and their limits.

II. METHODS

Physics of Blast

The change in the air pressure after the detonation of a spherical explosive charge is caused by the quasi instantaneous conversion of a solid or liquid into gasses. For a moment, these gasses occupy the same volume as the initial explosive charge, but the pressure and the temperature are extremely high. It will then expand rapidly and compress the surrounding air, causing the blast overpressure. In a free-field environment, the pressure-time history that results from the blast has a well-known shape, called the Friedlander profile. This blast is characterised by an initial quasi instantaneous rise in pressure, and is followed by an exponential decay, leading to the under-pressure phase, before recovering ambient level of pressure a few milliseconds later (Fig. 1(a)). The blast-wave parameters, such as peak overpressure, positive phase duration, impulse that is mathematically described as the time integration of the pressure signal, or its velocity, are strongly dependent on various factors, including the size and the type of explosive used and the distance from this charge. This idealised blast-wave can increase in complexity when the charge detonates with an initial height of burst or when it is located in a complex environment, such as a street with walls, a bunker, etc. Reflected waves can be magnified locally and cause substantially greater injuries (Fig. 1(b)).

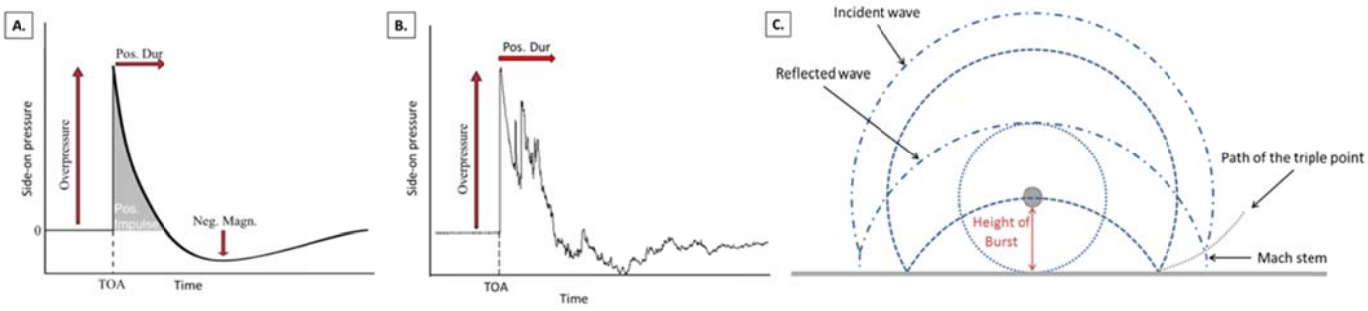


Fig. 1. (a) Friedlander waveform. TOA=Time of Arrival. Pos. Dur=Positive Phase Duration. Neg. Magn=Negative magnitude. (b) Example of a complex blast-wave. (c) Illustration of the wave propagation during a blast.

When the detonation of the spherical explosive charge occurs above a ground, it creates a reflected wave that will travel through a pre-shocked air. As the air was already shocked by the incident wave, the gases are pre-compressed and hot, which enables the reflected wave to travel faster than the incident one. As it travels faster, the reflected wave will catch and join the incident wave, producing the Mach stem (Fig. 1(c)). The intersection between the incident wave, the reflected wave and the Mach stem is called the triple point. The path of this point depends on the size of the explosive charge and its height of burst (HoB). Above this point, the target will face two consecutive shocks, i.e. the incident wave and the reflected wave. Under the triple point, only one shock with an increased pressure will be seen.

Studies on animals

Since World War II, researches have been carried out on small and large mammals to better understand the mechanisms of thoracic injuries related to an air blast [26]-[31][9]. Studies were also made to find injury criteria by making correlation between physical parameters with the probability of survivability or the level of injury [10][10]-[12][32][33].

Effect of a single blast exposure

When dealing with the understanding of single blast interaction with mammals, most of the researches have focused on the Friedlander waveform to better understand the influence of the pressure-time history parameters on the mammal response. First, studies performed on the effect of the overpressure and the positive phase duration are exposed. Then, the effect of the time of rise is discussed and, finally, the effects of repeated exposure and their outcomes are presented.

Effect of the overpressure and the positive phase duration on the mammals' outcomes

The first study to figure out the effect of the overpressure and the positive phase duration on mammal's response was conducted in 1966 by Richmond et al. [26]. The experiments consisted in performing side-on reflected exposures on mammals with shock tube and high explosive. From the 204 dogs and 115 goats exposed

to an overpressure of 350 kPa with durations from 15 ms to 400 ms, they were able to find the 50% survivability curves for both animals, which were quite similar. For the 60 dogs exposed in the case where the duration was fixed at 400 ms and the pressure varied from 60 to 250 kPa, the lung threshold was found. In cases of Friedlander profile, the pressure and the positive phase duration, which also define the impulse, seem naturally to be parameters of choice linked with survivability. It appears that for the same level of injury, a higher pressure is needed for short duration (below 10 ms) than for long duration. This tendency was also observed by Vassout et al. [34] with their works on sheep exposed to high explosive charge (duration: 2 ms, overpressure: 100, 200, 300 and 400 kPa) and by Dodd et al. [31] on shock tube experiments, also with sheep. It means that the criterion for injury is the impulse for short-duration wave and the overpressure for long-duration wave [35]. However, looking at the pressure profiles from high explosive and shock tube, it appears differences. There is a constant pressure level over several milliseconds for shock tube experiments with long duration, which makes the pressure profiles not similar to a Friedlander shape. Moreover, when dealing with closed shock tube experiments, the animal at the end of the shock tube will face the incident wave, but as the shock tube is closed, this wave will be reflected on the other side of the tube to finally shock again the mammals. This can lead to higher injury than the same configuration in an open shock tube. Richmond et al. [7] did the summary of experiments with high explosive and shock tube on small and large mammals and found that the survivability curves for both mammal sizes are not the same (Fig. 2). Indeed, they found the 50% survivability for 2 ms duration to be 240 kPa for small mammals, like mice, and 1380 kPa for large mammals, such as sheep. Small mammals seem to be injured faster than larger ones for the same threat. These differences between species can be the results of differences in the shape, anatomy organisation and material properties. Bass et al. [33] report that large animals tend to have thicker visceral pleura than small mammals, which can potentially increase their lung blast tolerance. The experiments on large mammals were then used by Bowen to extrapolate these results to humans by the use of a mathematical model [10], leading to the well-known Bowen's curves (Fig. 3).

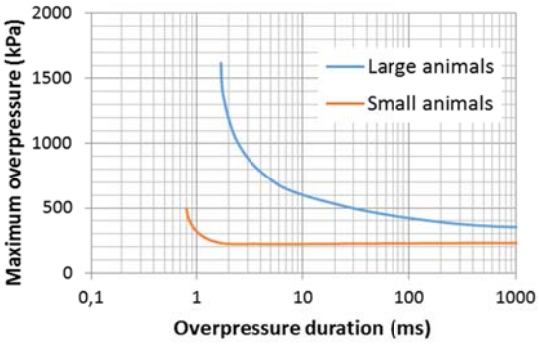


Fig. 2: Lethality curves for small and large mammals.[33]

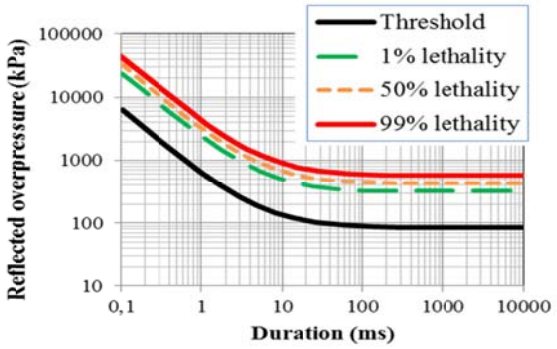


Fig. 3. Bowen's curves for various percentages of lethality – Person standing near a wall.

Other studies have aimed to understand the effect in changing one parameter on the idealised pressure-time history on the animal response. Instead of checking the survivability, the aim was to investigate the internal pressure and the measure of the acceleration of the chest wall. This was done by Vassout et al. [8] on swine in free-field, with pressure duration of 2 ms and an overpressure from 26 kPa to 380 kPa coming from high explosive detonation. They noticed whatever the overpressure in free-field, no amplification is seen on the interfaces of chest wall/lung parenchyma or lung parenchyma/heart, which is in accordance with the findings of their previous study [30]. This observation seems to invalidate the theory of diphasic environment, which forecast an increase in pressure in the interface diphasic environment/dense environment [36]. In the same study [30], the hypothesis of pulmonary wounds caused by an echo of the lung volume was invalidated by checking the influence of the pulmonary volume on the pulmonary injury on rats, and the result is in accordance with that of Jaegger et al. [28], on sheep, where the experimental set-up was identical. Indeed, no significant changes are observed in lung injuries in both studies. From the hydrophone measurements, it was shown that there was an increase in the time of rise when it is placed in a deeper position on the swine thorax [8], due to the filtering effect of the tissues. Regarding the acceleration, it increases with the reflected pressure on the instrumented rib, leading to the thought that the displacement of the chest wall could be the cause of the

superficial pulmonary wound. The acceleration has also been considered in experiments on pigs performed by Cooper [9], where the lung injury was found to be proportional to the peak acceleration of the lateral thoracic wall. He found that over 10,000 m/s², injury to the lung can occur. Nonetheless, the rib cage of pigs is different from the one of a man in terms of shape, and these mammals where exposed side-on to the threat. The extrapolation to human does not seems then obvious. Plus, there is no information in his paper about how they measured the acceleration. Because looking at the measured acceleration from Vassout et al. [8], discrepancies are observed. From the same configuration, the acceleration can go from 10,800 m/s² to 24,400 m/s. The reproducibility of such parameter on living mammals seems tricky, and care must be taken on the set-up of the study.

Effect of the rise time and of a step-by-step rise

Biological response to "slow"-rising blast pressures have been investigated and biological systems are more tolerant to pressure pulses that rise "slowly", without the presence of a shock front [7]. It was also found that blast waves that rise in two steps are less lethal. It was investigated with high explosive in open field by Froböse [37] on rats, where the tolerance increases by moving them away from the reflecting plate. It was also shown by Richmond et al. [7], with shock tube experiments on several species, that the longer the time between the two shocks is, the higher the tolerance of the species will be. For example, for a rat in the near-wall scenario, there is 100% mortality; by taking the animal away from the wall so that the reflected overpressure arrived 0.4 ms after the incident one, the percentage of mortality is 0%. It seems that the incident pressure may protect the animal from the reflected overpressure by providing a new and higher ambient pressure as well as inside the thorax. Indeed, Damon et al. [6] have shown with shock tube studies that an increase in ambient pressure provides a higher resistance for mammals. When looking at the mortality versus time between shocks from Richmond et al. [7], the response of small and large mammals looks different. For small mammals, an increase in the time between shocks results in a decrease in mortality. Whereas for large mammals, such as dog, the mortality stays constant until several milliseconds between shocks to finally rapidly decrease.

Effect of repeated blast exposure

In 1943, Desaga [38] observed an increase in the pulmonary injury severity by exposing dogs to consecutive shocks. For a constant positive phase duration, Vassout et al. [29] have shown that the mortality rate of the rat and the pulmonary injuries for high explosive exposure are directly dependent on the overpressure and the number of exposures. When doubling the number of exposures, a division by four of the overpressure is needed to get the same pulmonary injury. For the mortality rate, a division by two of the overpressure is compensated by a multiplication of 20 of the number of exposure. From these results, several studies have been conducted.

Long-duration shock-wave

The study of Richmond et al. [27] on the effect of repeated long-duration blast-wave on mammals focused on two things. First, the influence of the number of repetitions for a given pressure-time history and second, the interval between shocks are evaluated. Sheep were placed at the endplate of a shock tube, with 30 minutes interval between the three repetitions of a blast wave of 100 ms duration and overpressures of 179 and 241 kPa. By measuring the ratio of the lung weight over the body weight, they have clearly seen the extent of lung haemorrhage when going from one shock to three shocks, even an increase in the number of deaths. Secondly, an examination of the effect of the time between shocks was carried out. A blast that produced 5% lethality on rats for a single shock was produced and repeated up to three times with four different intervals. An increase in time between shocks seems to increase the tolerance. Going from an interval of 30 minutes to 24 hours leads to a decrease in the mortality rate from 36.27% to 7%, respectively.

Short-duration shock-wave

Vassout et al [39] have studied the effect of repeated air blast from high explosive (overpressure of 100, 200, 300 and 400 kPa at 2 ms) on swine up to 64 repetitions with an interval of 5 minutes. They noticed that the tendency is not the same as that observed with the rat in 1978 [29]. As previously mentioned, the lung injury threshold found for swine is 200 kPa for a 2 ms duration. When dealing with 8 repetitions, this threshold dropped to 150 kPa. Richmond et al. [40] did the same experiments in shock tube with swine and sheep and with overpressure from 100 kPa to 415 kPa and a duration of 10 ms. The interval between shock was 1 minute, the results are then not comparable. They evaluated the mortality rate, as well as the injuries to the gastrointestinal tract, the laryngeal tract and the injuries to the lung. It appears that a repetition of sub-lethal blast overpressure results in early mortality and that with an overpressure below the one needed to have lung

haemorrhages, the increase in the number of exposures will increase the incidence and the severity of the gastrointestinal and upper respiratory tracts. The sensitivity of the last two parts of the body has also been seen in experiments on swine and sheep for explosive charge [41][42]. Laryngeal injury appears to be a good indicator of other organ involvement. Indeed, these injuries are present before the appearance of other injuries, or at the same time as injuries to the gastrointestinal tract and to the lung. For that reason, Phillips et al. [43] uses the results of several experiments to imagine a non-auditory injury for Friedlander waves by creating a 3D graph with the number of exposures, the pressure and the impulse.

Dood et al. [42] affirm that sheep and swine can be a reasonable "human surrogate" for the prediction of non-auditory injury location, type and severity. But because of differences between species, such as the posture and the upper respiratory tract (a relatively short and protected extra thoracic course for man, but in sheep it is a long, ventrally located extra thoracic trachea), the use of mammals to estimate human consequences is always subject to uncertainty. Consequently, man should be less likely to get upper respiratory tract injury compared to sheep. Moreover, all these studies were done for a Friedlander waveform where *P* and *I* define both the delivered energy and the duration of the wave. Consequently, the use of either impulse or duration is equivalent when dealing with Friedlander profile. This relation breaks down, however, when considering complex blast-wave.

Blast injury prediction models

For primary blast, several injury criteria have been developed for free-field and complex scenarios focusing on different parameters, either from the Friedlander pressure-time history [10][32][33] or changes on the body, like the chest wall velocity [11][12].

Bowen's curves and revisions

The Bowen's curves relate the percentage of survivability for a man according to the peak pressure and the positive phase duration. These curves are based on a pool of animal experiments involving a total of 2,097 animals of 13 different species. It was initially realised for near-wall scenarios, and was then extended to open-field scenarios with assumptions. Using a lung model [10] and the technique of dimensional analysis, scaling equations related to the mass of the mammal and theirs square wave pressure (Psw) have been developed (Eq. (1) and (2)). The square wave pressure is the "long duration" pressure that gives 50% of mortality. The assumption of similarity of mammalian species, i.e. similarity of shape of the body structure and equivalent distributions of tissue mass and elasticity was made. For human, the Psw was taken as the mean value of the large species, i.e. 424 kPa. Indeed, from a study of Crosfill and Widdicombe that put forward differences between "small" and "large" animals, men seem to be in the large species category when looking at the average density of lungs and the ratio of the average gaseous volume of lungs over the body mass. To extrapolate to human, Bowen used the 50% survivability curve (LD50) from large animals to go to a 70 kg animal and made the assumption that the percentage of mortality is not dependant of the mass of the animal. Richmond [44] used a different approach: the Psw for a 70 kg's animal was measured using an extrapolation of the curve Psw versus average body mass for several blast durations. The question whether animals are divided in two groups seems to have no importance for long duration pulse, but it has for small duration as it can be seen in Fig. 4. Using estimate of lethal limit for man by Desaga and Fisher, Krohn and Zuckerman, it seems that the extrapolation of Bowen pass through these limits (Fig. 4).

$$P = P_r\left(\frac{424}{P_{sw}}\right)\left(\frac{101.35}{P_0}\right), kPa \quad (1)$$

$$T = T_t\sqrt[3]{\frac{70}{m}}\sqrt[2]{\frac{P_0}{101.35}}, ms \quad (2)$$

where m is measured in kg and P in kPa.

Richmond et al. [32] made the evaluation of the Bowen's curves for a standing man position by plotting the results of nine new experiments on the Bowen's curves (Fig. 5). Like Bowen et al. [10], when pressure-time history was not available or when the measurement of the positive phase duration was not easy, tabulated values were used instead. They used the empirical formula by Goodman and Richmond used the ConWep program. Most of the new data are in agreement with the Bowen's curves, especially at duration greater than 10 ms. For duration less than 10 ms, the Bowen predictions seem to be too high.

Recently, Bass et al. [33] and Rafaels et al. [47] updated the survivability curves of Bowen by including more data, even in free-field. Bass et al. used 1,129 animal experiments taken from 13 studies for a blast duration less than 30 ms. Using that data, they found no difference in short-duration cases between the cases against a reflecting wall and the cases in free-field standing perpendicular to the direction of the shock wave. This observation goes against the hypothesis of pressure dose from Bowen, which postulates different injury for those cases. There is not, however, sufficient data to statistically discriminate between the observation of Bass and the original Bowen "dose", so further research is required. For the prone position, Bowen et al. [10] and Bass et al. [33] postulate the same hypothesis: injury is equivalent if the incident pressure is equal to the reflected pressure in case of a near wall scenario. Still no data are available to validate this extension. Finally, the experimental data added by Bass et al. has not made many differences for the survivability prediction, but it reminds that there is a need of experimental investigation on that purpose.

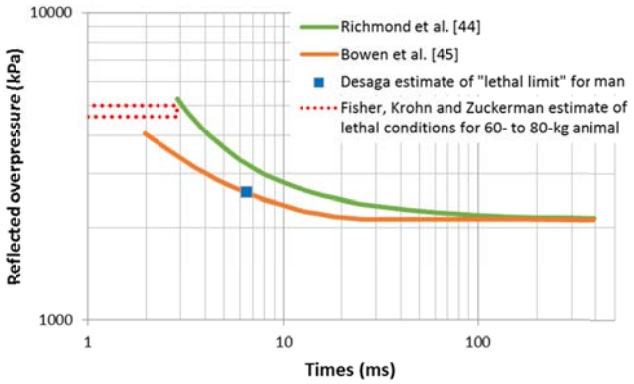


Fig. 4: A comparison of various estimates of man's tolerance to air blast [45]

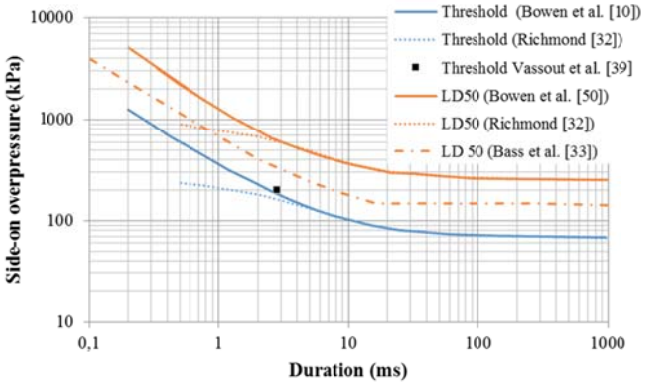


Fig. 5: Various versions of the Bowen's curves LD50 (50% survivability) and threshold for a standing position. If not specified, the curves come from large mammals. They are all scaled to a 70 kg mammal.

The limitation of these injury criteria is that they are only valid for free-field blast scenario with questionable blast duration measurement using tabulated value. Indeed, plotting together the results in terms of positive phase duration shown discrepancies between these tabulated values. It is then difficult to state in the reliability of such data. Furthermore, assuming identical material properties for each category of species with the same shape of the body structure can leads to errors. Plus, even the internal organisation of the organs is different for species in the same group, which can lead to another level of injury. The assumptions for the open field extension are not yet validated, and differ between criteria. Finally, they only consider the lethality and not injury risk.

The Axelsson's model

The Axelsson's model was developed to fulfil the limitation previously mentioned of the Bowen's/Bass curves [11]. It was addressed by using a mathematical model (single degree of freedom (DOF)) whose aim is to describe the chest wall response of a human exposed to any blast-wave, either a Friedlander one or a complex blast-wave (Fig. 6). Axelsson used the pressure output from the Blast Test Device (BTD), which is a rigid cylinder with pressure gauge every 90 degrees interval at mid-height. The mathematical equations of the Axelsson's model are expressed by four independent differential equations, corresponding to the four pressure gauges of the BTD:

$$M.\frac{d^2x_i}{dt^2} + J.\frac{dx_i}{dt} + K.x_i = A.\left(p_i(t) - p_{i.lung}(t)\right) \; i = 1,2,3,4 \tag{1}$$

$$p_{i.lung}(t) = p_0\left(\frac{V_0}{V_0 - A.x_i}\right)^g \tag{2}$$

With the pressure from the BTD, the chest wall positions x_i *(t)* are obtained, as well as the chest wall velocities and the lung pressures. Using the Bowen's curves for the case where the body is parallel to the blast-wave propagation, they found that the maximum chest wall velocity was constant for several pressure-duration

points on the same Bowen's curve. With this observation, they decided to use this parameter as an injury risk predictor: the Chest Wall Velocity Predictor.

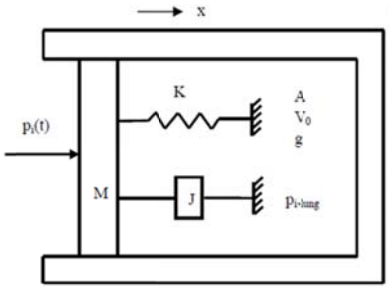
From the four pressure gauges on the BTD, Axelsson et al. [11] get four maximum inward chest wall velocities. He proposed the following parameter as a measure of injury:

$$V = \frac{1}{4}\sum_{i=1}^{4} \max(v_i(t)) \tag{3}$$

Using the experiments of Johnson [48] on sheep in a confined environment, the model is finally calibrated and a correlation is made between the measured Adjusted Severity of Injury Index (ASII) and the chest wall velocity V (Table 1).

TABLE 1: CORRELATION BETWEEN ASII AND V

Injury level	ASII	V (m/s)
No injury	0.0–0.2	0.0–3.6
Trace to slight	0.2–1.0	3.6–7.5
Slight to moderate	0.3–1.9	4.3–9.8
Moderate to extensive	1.0–7.1	7.5–16.9
>50% lethality	> 3.6	> 12.8



Name	Explanation
A	Effective area
M	Effective mass
V_0	Lung gas volume at x=0
J	Damping factor
K	Spring constant
p_0	Ambient pressure
$p_i(t)$	External (blast) loading pressure
$p_{lung}(t)$	Lung pressure
g	Polytropic exponent for gas in lungs
x	Chest wall displacement

Fig. 6: Thoracic model according to Axelsson [11].

Even if the Axelsson's model solves the problem of the Bowen's/Bass curves mentioned in the previous section, there are still some problems with this model. Indeed, it can be seen in the paper of Teland [49], which detailed the existing injury criteria, that Axelsson used surprising pressure measurement from the BTD for the calibration of his model. First, the two side gauges differ despite the symmetrical situation. Further, the rear gauge for 227 g of C-4 is higher than in case of 454g. As these pressures are the base of his injury criteria, it can lead to different prediction of V, and so to a different relation between ASII and V. Moreover, closer inspection of the data in the Axelsson report shows that one chest wall velocity can predict either trace to slight injuries or more than 50% lethality. It remains uncertain whether the calculated velocity is a good estimation of the one in mammals.

The Stuhmiller's model

A similar approach of Axelsson et al. [11] was taken by Stuhmiller et al. [12]. Instead of considering a spring/mass system for the model of a thorax, they used a model that considers the forces on the chest wall due the external blast load, the internal pressure arising from the bulk compression of the lung, and the compression wave generated by the chest motion. As with the Axelsson's model, the Stuhmiller's model is a single DOF model that requires the four pressure-time histories from the BTD to calculate the four chest wall velocities. Using these velocities, they defined a parameter called normalised work, which defines the "total work done to produce the wave divided by the volume of the lung and the ambient pressure", and a relationship was found between this parameter and the lung injury (Fig. 7). It can be noticed that in his next paper [50], Stuhmiller found that the compressive wave strength in his model is proportional to the chest wall velocity, which is consistent with the correlation made by Axelsson et al. [11].

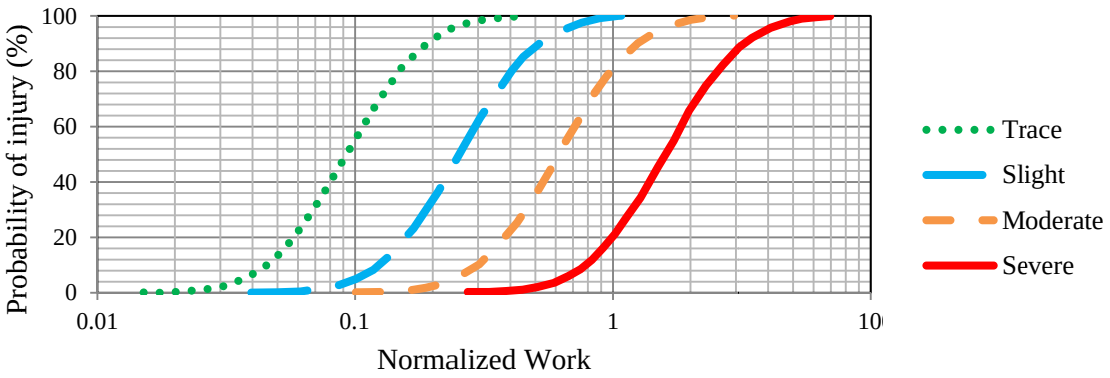


Fig. 7: Probability of injury vs. normalised work [12].

From his pleural dynamics model and experimental data used by Bowen, Stuhmiller found different values of compute normalized work for small and large animals for conditions producing 50% lethality. However, if the biomechanical structures of the different species were similar, these values much have been the same. Taking into account the viscoelastic forces, the results should be unified.

Studies on dummy

The use of dummy for blast experiments for both the prediction of injury and the characterisation of the efficiency of protective systems becomes important as there are many difficulties in conducting experiments on living animals, including ethical reasons and the costs of such studies.

Blast test device

The Blast Test Device is a hollow cylinder with four pressure gauges mounted every 90 degrees interval at mid-height (Fig. 8). This surrogate has been used to provide input to some injury prediction models, such as the Axelsson's and Stuhmiller's models. The limitation of such a dummy is related to his composition. Indeed, due to the fact that the BTD is rigid, the reflected pressure measured by the pressure gauges is over-predicted compared to the one that would be measured in case of a deformable structure. The more deformation there is, the more attenuation in the pressure measurements there are. Although the material used is not viscoelastic, and because the deflection of the thorax during a blast exposition is of few millimetres, the measured pressure on the BTD should be a good approximation of what would have seen a human thorax.

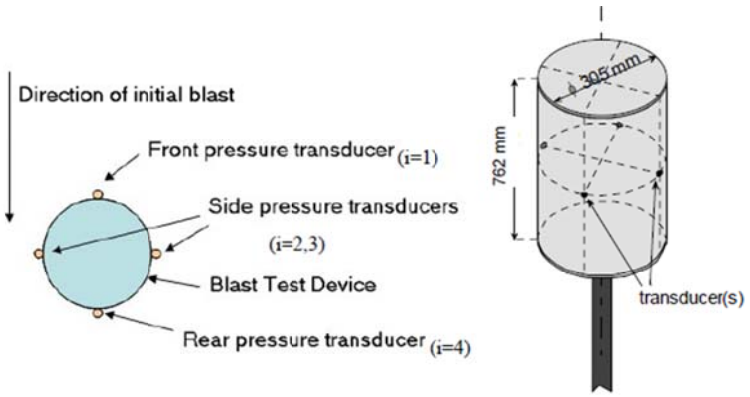


Fig. 8: Blast test device [49].

Fig. 9: DRDC MABIL surrogate [51].

The Mannequin for the Assessment of Blast Incapacitation and Lethality

The Mannequin for the Assessment of Blast Incapacitation and Lethality (MABIL) was developed in Canada at Defense Research and Development Canada (DRDC) – Valcartier (Fig. 9). The aim of this 50th percentile male torso dummy is to evaluate protective systems. To do so, the surrogate is instrumented with accelerometers at mid-torso, at the height of the sternum, and another in the abdomen.

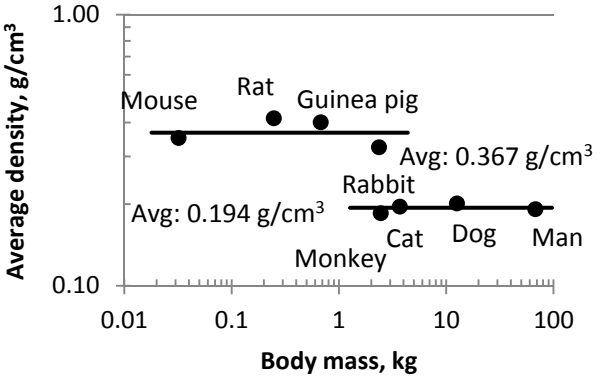
As for Cooper [9], who found the acceleration to be proportional to the lung injury on pigs, the acceleration of MABIL was found to be a good parameter for the prediction of the efficiency of a protection system [51]. Indeed, tests on unprotected MABIL as well as with soft and hard body armour have been performed and the

obtained results went to the same direction than the one found in the literature on animals using the acceleration as evaluation parameter. With the MABIL surrogate, the velocity was also investigated, but this metric did not seem to be appropriate. Even if the results obtained with this human surrogate are in accordance with the results from the literature on animals, there is yet no way to quantify the amplification or the decrease in terms of injury to the lung. It seems to be usable only for qualitative assessment of the protective system.
Thanks to this surrogate, a problem was highlighted. Indeed, Bouamoul et al. [25] tested different Bowen's injury level (Lung threshold, LD1 and LD50) with two durations for each one, and evaluated the acceleration and the velocity using the MABIL numerical surrogate. They noticed that the mid-sternum acceleration is higher for blast with short duration than for those with longer duration for the same injury level. According to the observation of Cooper, it means that the short blast duration should induce more injuries compared to the long duration results. However, the Axelsson's model correlates ASII to chest wall velocity. Regarding the results from the MABIL numerical surrogate, it appears that blast with long duration should induce more injuries than the one with short duration as they induce higher velocity. From these observations, it seems hard to state which parameter that is currently used for injury prediction and for the design of protective system is correct.

III. DISCUSSION

Over the last 40 years, studies have been performed to better understand the mechanisms of thoracic injuries related to an air blast (primary blast). As an output of all the experimental studies on animals during this period, four injury criteria were proposed (Table 2). But as in every experiment, there are strengths and weaknesses:

- Richmond et al. [26] found the LD50 for goats and dogs using shock tube and high explosive experiments. However, the shape of the pressure profiles coming for both ways to generate a shockwave can be different, with a constant pressure level over several milliseconds for long duration blast. Bowen used these results to found the Bowen's curves injury criteria, but the effect on mammals of such pressure profiles can be different from a Friedlander profile.
- Experiments in shock tube are generally realised with closed tube. The mammals faced then the incident shock, plus the reflections from the other side of the tube. It can lead to higher injury than if the animals only faced the incident wave.
- Several studies have been performed on swine to evaluate the influence of the Friedlander blast wave on the rib cage acceleration. Cooper [9] found this acceleration to be proportional to lung injury, with a threshold of 10,000 m/s². As mammals were exposed side-on to the threat and because the shape does not look like the human thorax, extrapolation to human does not seem obvious.
- Small and large animals have not the same tolerance to blast. Two ways to extrapolate results to human have been used. Bowen separate small from large animal, and took the Psw as the mean values of the Psw from large mammals. Richmond made a regression equation on the Psw versus body man graph to find the Psw of a 70 kg man. The hypothesis of Bowen seems more credible when knowing the difference in structure of both categories as shown Fig. 10 [45]. Plus, Bass et al. [33] report that large animals tend to have thicker visceral pleura than small mammals, which can potentially increase their lung blast tolerance.



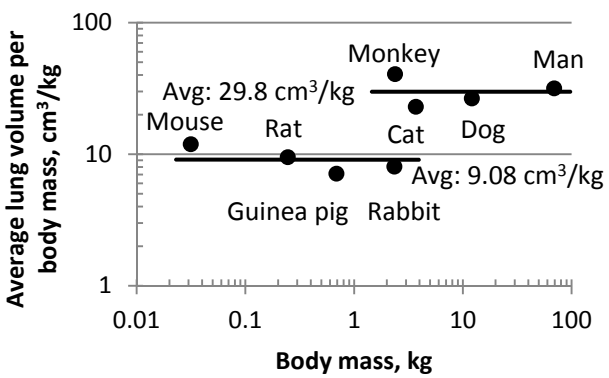


Fig. 10: Average lung volume per body mass and average lung density as functions of body mass. [45]

Most of the injury criteria were found using studies not in free-field. Indeed, Bowen et al. realised their lethality curves using near wall animal expositions, and used assumptions to go to a criterion available in free-field. Bass et al. made another assumption claiming that experimental data suggested no differences between standing near a wall and in an open field. However:

- This hypothesis seems wrong as the pressure on the side or on the rear of the body will be significantly different for these two configurations. It means for Bass that only the front pressure on the body matters to the injury. In that sense, the concept of pressure dose for the Bowen's criteria, while having little experimental evidence, looks more correct.
- Another discrepancy between both models is the way to measure the positive phase duration for short-duration Friedlander blast wave. Bowen et al. used the tabulated values of Goodman while Bass et al. used the ConWep data. Nonetheless, these abacuses give different values for the positive phase duration. One or both curves model should have been shifted, leading to new injury curves.

The foundation of the Axelsson's and Stuhmiller's theories is that measurement on a BTD is similar to a human. It seems that both criteria were calibrated with the same experimental data on sheep in confined space. But in his publication [12], Stuhmiller included at least two errors in the differential equation for the model, making it impossible to apply. For that reason, this model will not be discussed hereafter. Telan [49] made a comparison of the Axelsson's model with the Bowen's/Bass curves for 50% lethality. He found out that these three models are in good agreement for long duration wave for near wall scenarios, while discrepancies are observed for short duration. In that latter case, Axelsson predicts significantly less injury than Bowen and Bass. It can be the result of the use of tabulated values for the positive phase duration.

TABLE 2

SUMMARY OF BLAST INJURY PREDICTION MODELS

Injury model	Type of shock wave	Scenarios	Input	Output	Advantages	Disadvantages
Bowen [10]	Ideal (Friedlander)	Near wall Open field Prone position	P and T	% of survivability	Based on a big set of experimental data on animals. Requires only P and T. Easy to use.	Only for idealized waves. Based on near wall scenario, the others are assumptions. Use of doubtful tabulated values when the positive phase duration was not measured.
Bass [33]	Ideal (Friedlander)	Near wall Open field Prone position	P and T	% of survivability	Based on a big set of experimental data on animals. Requires only P and T. Easy to use.	Only for idealized waves. Use of doubtful tabulated values when the positive phase duration was not measured. Debatable assumptions for open field scenario.
Axelsson [11]	Any	Any	Four pressure measurements from the BTD	ASIII (degree of injury)	It works for any type of shock wave.	Requires four pressure histories from the BTD. Debatable pressure measurement from Johnson experiments were used for the calibration of the model. Based on experiments with small quantities of explosive.
Stuhmiller [12]	Any	Any	Four pressure measurements from the BTD	Probability of injury to the lung (%)	It works for any type of shock wave.	Requires four pressure histories from the BTD. Mistakes in the differential equation in the original paper.

Though, to overcome the limitations of the Bowen's/Bass curves only usable for Friedlander waveform, it is better to go to criteria such as the Axelsson's or the Stuhmiller's models as there are not limited to the idealised pressure-shape, and take into account the pressure all around the body. But closer inspection of the data in the

Axelsson's report shows that one chest wall velocity can predict either trace to slight injuries or more than 50% lethality. It remains uncertain whether the calculated velocity alone is a good estimation of injuries in mammals. Moreover, it has been shown with the MABIL dummy that the velocity is not a good metric for the evaluation of protective system, but the acceleration is. It means that to quantify the efficiency of such system, an injury criteria based on the acceleration peak must be helpful. Cooper already shown correlation between injury to the lung and the peak acceleration on pigs' thorax, but the extrapolation to human does not seem evident and more data would be needed.

IV. CONCLUSIONS

To gain a better understanding of the interaction of a blast-wave with the thorax, a critical review is proposed. The aim would be to adapt a human surrogate for injury prediction and for the characterisation of the efficiency of protective systems. It is emphasised that damages observed in humans following blast exposure depend on several parameters coming from the target itself (human, animals or dummies), but also from the conditions under which the detonation occurs. Particular attention is paid to the impulse (especially for short duration waves). Plenty of studies have been conducted, leading to injury criteria such as the Bowen's curves or the Axelsson's model. This latter one is also convenient for enclosed spaces or more generally for complex pressure-time histories. This led to the use of specific surrogates for injury assessment.

Thorax surrogates with specific instrumentation represent an interesting alternative to the animal experimentation for investigating loading criteria. However, the use of biological specimen is inescapable to achieve a clinical ranking of the injuries (such as AIS: Abbreviate Injury Scale scoring system) to correlate with a physical parameter. Two problems emerge: how to scale injury to the lung from pigs or sheep to human, and how to get reproducible acceleration data on living mammals? The first question is still unresolved, but the second one can be a question of minutia during the experimental tries. Researcher must be sure to put the instrumentation at the same location on the body and according to the threat. Findings coming from the use of these surrogates will contribute to validate the ability of numerical codes used, to catch the physics at play and finally improve their accuracy. Among the aimed objectives, a better prediction of the risk of blast-related injury in humans and provision of guidelines to address efficiency and reliability of personal protective equipment are expected.

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