

Effect of human and sheep lung orientation on primary blast injury induced by single blast

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Abstract. The intensity and type of trauma inflicted on a body by blast overpressure are related to many factors. Among them, body orientation. In order to study the effect of body orientation, detailed models of 2D horizontal slices of human and sheep thoraces have been developed and validated with the limited data available in the open literature. The main goal of this study is to verify if the injuries observed in the animal are truly representative of human lung injuries for simple blast loadings at different orientations to the blast. In total, twelve blast directions were simulated for three different blast injury levels based on the Bowen curves. The sheep and the human torsos were rotated according to their vertical axis in increments of 30 degree starting from 0 degree through to 330 degree. From this study, it is predicted that the greatest reduction in lung primary blast injuries may be come from focusing on protecting the torso from -60 deg to +60 deg. Results showed also, that sheep are more dependent to the blast wave duration and orientation.

1. INTRODUCTION

Explosions have the potential to cause life-threatening injuries (e.g. blunt, penetrating wounds and blast overpressure injuries). Most blast injuries traditionally are divided into three major categories: primary, secondary, and tertiary injuries. A person may be injured by more than one of these mechanisms in any given event. Primary blast injuries (PBI) are exclusively caused by the blast overpressure. A PBI usually affects air-containing organs such as the lung, ears and gastrointestinal tract. Secondary blast injuries are caused by fragments that impact the body. Tertiary blast injuries include traumatic amputation and injuries sustained due to whole body displacement including impact (e.g. being thrown against another object) [Ref. 1].

There is a need to understand and predict this type of injury in order to improve, develop and optimise protection. In this optic, a numerical finite element (FE) model was built to predict blast injury from simple blast overpressures [Ref. 2]. Using an advanced non-linear FE method, arbitrary Lagrangian-Eulerian formulation (ALE), two-dimensional models of the human and sheep torsos were constructed. The main goal of this study was to find a correlation between the prediction of lung injury in sheep and human, particularly as a function of orientation with respect to the blast wave, and to verify if the injuries observed in the sheep are truly representative of human lung injuries for a given blast loading condition.

2. BLAST WAVE IN AIR

Major conventional high explosives release, in a relatively short amount of time, a large quantity of energy through expansion of the gaseous detonation products. This results in an overpressure wave that also commonly called blast wave. The passage of the blast wave through a particular position away from the detonation can be characterized as simple or complex depending on the time history of the overpressure observed at that position. A simple blast-wave pressure disturbance resulting from an ideal explosion in free field has the shape of a Friedlander curve. In the Friedlander curve, the pressure is comprised of a positive phase characterized by an instantaneous rise to the peak overpressure followed by a rapid decay of the overpressure. This is followed by a longer but low magnitude negative pressure phase before a return to ambient conditions as shown in Figure 1. Complex blast waves can be described as any loading that does not fall under the description of a simple blast wave and is typically characterized by multiple peaks and a complex waveform. This type of waveform is characteristic of all but the most idealized real world loading and is the result of multiple wave reflections off objects in the environment such as the ground,

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buildings, the walls of an enclosure, etc. Figure 1 shows also a comparison between a real blast wave for a free field test with an elevated cylindrical charge and the idealized Friedlander approximation.

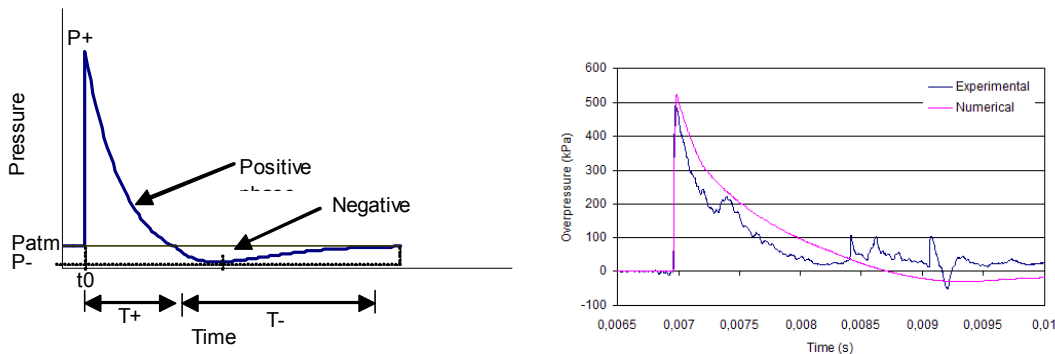


Figure 1. Typical Friedlander pressure curve (left), comparison between a real blast wave and a Friedlander approximation, case: 5 kg C4 at 2.5m (right).

For simplicity of the modeling approach at this stage of the blast injury study, the blast loading considered has been assumed to follow a Friedlander pressure curve as a reasonable idealization of free field blast loading.

3. BOWEN CURVES

The Bowen curves [Ref. 3] were generated from a wealth of data, primarily from shock tube testing of two groups of animals: small animals (e.g. mice, pigs and rabbits) and large animals (e.g. monkeys, sheep and swine). Scaling rules were applied to generate injury thresholds and predictions of lethality for a human. The Bowen curves are often used as a simple model to estimate primary injuries from a simple (Friedlander) blast loading. Figure 2 shows the Bowen curves for a man oriented perpendicular to the blast direction. In this figure, two versions of curves are given: The original curves [Ref. 3] and a new set of survivability curves by Bass *et al.* [Ref. 4] based on a complete reanalysis of the original data supplemented by additional data from more recent sources. This study was performed using the revised curves by Bass *et al.*

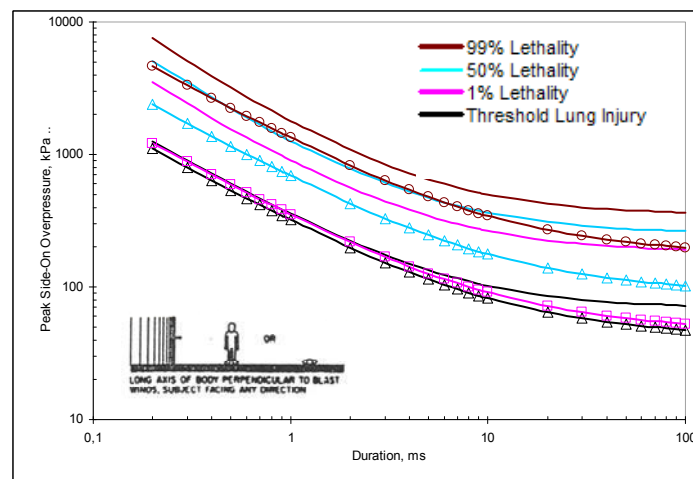


Figure 2. Original (dashed lines [Ref. 3]) and new Bowen curves (dashed lines with symbols [Ref. 4]) for a man oriented perpendicular to the blast direction

Three Friedlander (simple blast) curves that represent the threshold level (TH), 1% and 50% probability of lethality (LD_1 and LD_{50}) for durations equal to 2 ms on the revised Bowen curves were selected. These curves and their characteristic peak pressures and durations are listed in Table 1. An abbreviation for these curves is used throughout the article. For example, TH-T₂-P₂₀₀ refers to a threshold blast wave with duration equal to 2 ms and a peak overpressure of 200 kPa. LD_1 -T₂-P₅₀₀ refers to an LD_1 blast wave with duration equal to 2 ms and a peak overpressure of 500 kPa.

Table 1. Characteristics of the blast waves using during the simulations

TH		LD_1	LD_{50}
Peak overpressure, kPa	200	500	700
Positive phase duration, ms	2	2	2

From the work done by O'Brien *et al.* and Cooper *et al.* [Refs. 5, 6], pressure within the lung, exposure time and the rise time of the pressure are proposed as indicators of lung trauma. Experimental tests involving measurements of the intra-thoracic peak pressure suggested a threshold between 70 kPa and 110 kPa for human lungs [Ref. 7]. Lacking any direction from the open literature on similar sheep-lung injury thresholds, the 70 kPa threshold was also used to quantify the sheep lung injuries in this study.

4. FINITE ELEMENT MODEL OF THE HUMAN AND SHEEP MODELS

The human and sheep models described in this section were initially generated by The University of Waterloo under a contract from DRDC Valcartier [Ref. 2] and based on the work done by O'Brien *et al.* and Cooper *et al.* [Refs. 5, 6]. Figure 3 shows a top view of the numerical and CT-scanned human and sheep torso components. The human model was created from images from the Visible Human Project, National Library of Medicine [Ref. 8]. As such, the model is representative of an 82 kilogram, 1.8 meter high man with the slice taken at the fifth and sixth thoracic vertebrae. The sheep model was created using pictures from an atlas of x-ray anatomy of sheep [Ref. 9] and is therefore representative of the two-year old 56.6-kilogram ewe used to generate the atlas. The model represents a slice at the fifth and sixth thoracic vertebrae level.

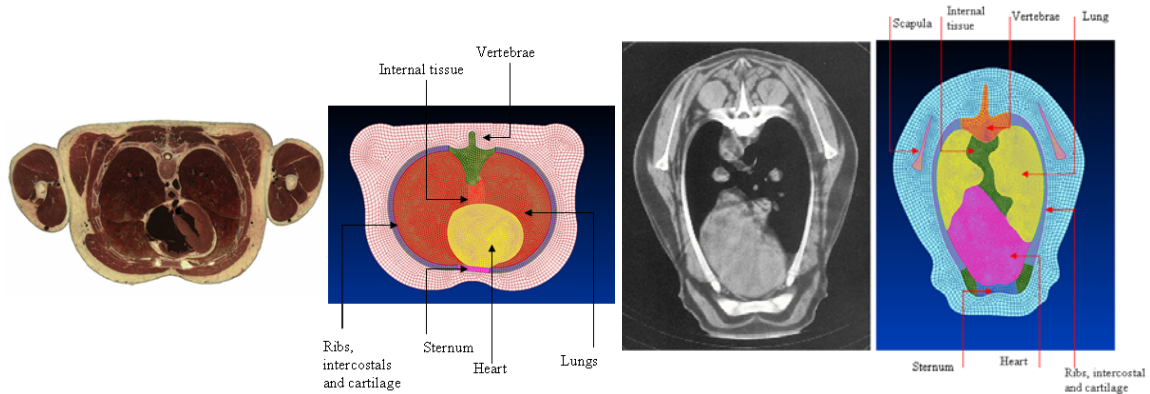


Figure 3. A top view of the numerical and actual human (left) and sheep (right) torso components [Ref. 2]

The LS-Dyna hydrocode was used to simulate the coupled human/sheep torso and blast wave [Ref. 10]. Several methods for creating blast overpressure loading on solids in LS-Dyna were investigated. Among them, is modeling the detonation of an ideal explosive using *LOAD_BLAST card implemented in LS-Dyna. In this method, a pressure-time history is applied on each element of the torso. This method was not used since coupling between the blast flow and the torso is significant in accurately predicting the

energy transfer to the tissue. The other method is an Arbitrary-Lagrangian-Eulerian (ALE) formulation [Ref. 10]. This method was chosen for its flexibility as it allows the desired overpressure and pulse duration to be generated with a more realistic representation of coupling between the blast wave and resulting flow and the thorax. In order to maintain the ALE coupling, the sizes of the sheep and human elements were kept equal or smaller than the size of the air elements surrounding the torso. The size of the sheep and human elements varies from 2.5 mm to 5 mm. The human and the sheep models were modeled in a way that they can move with the blast. Their boundaries were not fixed in x and y directions.

The human and sheep model featured four layers of elements through the thickness of the quasi 2D slice. Because of the three-dimensional nature of the rib cage, the model was divided into two components (2 elements through the thickness per component): a bone-level where the rib cage is represented by bone and an intercostal-level where the structure of the rib cage is captured by modeling the intercostal muscle tissue. The different characteristics of bone (e.g. the ribs) and muscle have an influence on wave propagation and hence on the injury that develops behind the rib cage. Finally, an extensive literature review focused on human and animal tissue material properties was performed by University of Waterloo to determine the relevant inputs for the constitutive models used to represent each material [Ref. 2].

4. EFFECT OF BODY ORIENTATION ON THE BLAST INJURY

The intensity and type of trauma inflicted on a body by blast overpressure are related to many factors. Among them, body orientation. In order to study this factor, the sheep and human models were exposed to blast waves from different sides. In total, twelve orientations were simulated at three different blast injury levels that correspond to the 2 ms overpressure duration (TH-T₂-P₂₀₀, LD₁-T₂-P₅₀₀ and LD₅₀-T₂-P₇₀₀). The sheep and the human torsos were rotated around their vertical axes in 30 degree increments starting from 0 through to 330 degrees in the clockwise direction. The position corresponding to 0 deg orientation is shown in Figure 4 and it's corresponding to a man facing the blast wave. The position of the sheep is the one that was used in the experimental tests done by Bowen [Ref. 3].

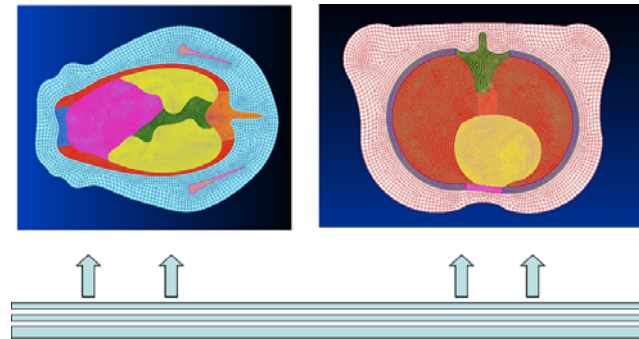
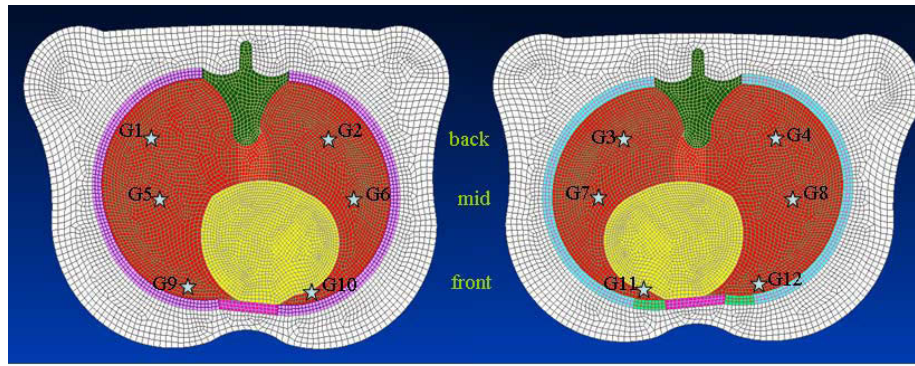


Figure 4. Blast wave direction, 0 deg orientation

The average of the maximum overpressure of twelve elements located in the human torso lung model and six elements located in the sheep-lung model, as shown in Figures 5 and 6 respectively were generated from the FEM. These pressures were averaged from virtual gauges in both the intercostal and rib layers of the mesh.

Polar plots of the average maximum overpressure give a qualitative assessment of the effect of the blast orientation on the human and sheep torso injuries. In the human model, the average of the G1 to G4 virtual gauge maximum overpressures is referred to as the *back* curve. The curve labelled *mid* corresponds to the average of the G5 to G8 virtual gauge maximum overpressures and the curve labelled *front* is the average of the G9 to G12 virtual gauge maximum overpressures. In the sheep thorax, the curve labelled *left* represents the average of virtual gauges G1 and G2 maximum overpressures. The curve labelled *right* is the average of G3 and G4 gauges maximum overpressure data and the curve labelled *up* corresponds to the average of the G5 and G6 virtual gauge maximum overpressures.



Lower side, intercostal Upper side, bone
Figure 5: Gauge locations for body orientation inputs, human

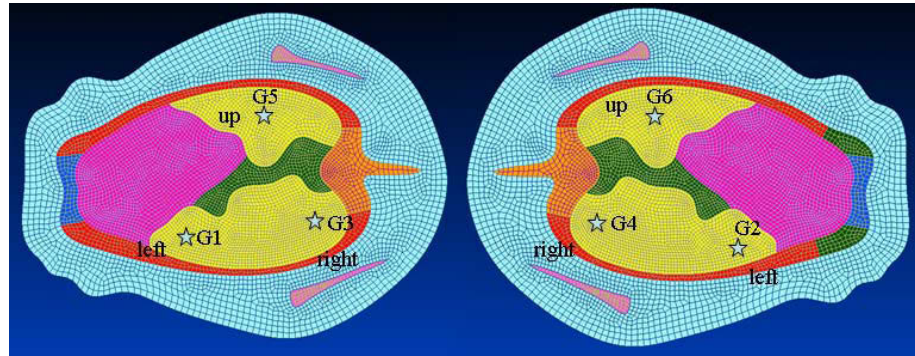


Figure 6: Gauge locations for body orientation inputs, sheep

4. RESULTS AND DISCUSSION

Figure 7 shows a polar plot of the maximum human and sheep lung pressures as a function of orientation of the blast loading. From the TH-T₂-P₂₀₀ figures, when the blast impacts a human torso at angles varying between 330 deg to 30 deg in the clockwise direction, the blast is predicted to induce significant lung injuries. In the sheep, the TH-T₂-P₂₀₀ blast is predicted to be below the threshold for injury irrespective of the orientation.

The same trend observed from the LD₁-T₂-P₅₀₀ loading (Figure 9) is also noted when using the LD₅₀-T₂-P₇₀₀ loading history. The LD₅₀-T₂-P₇₀₀ blast is predicted to have slight effects on the human lungs in the case where the torso is in the 120 deg to 240 deg positions (clockwise direction). If this reduced sensitivity to blast in these orientations can be proven in humans, it could be a significant driver when designing future protection systems. For example, the blast protection for the torso could cover the arc from 300 to 60 deg in the clockwise direction. In the sheep case, only the 180 deg case induces slight blast injuries in the lungs with significant injuries being predicted in at least one lung in all other cases.

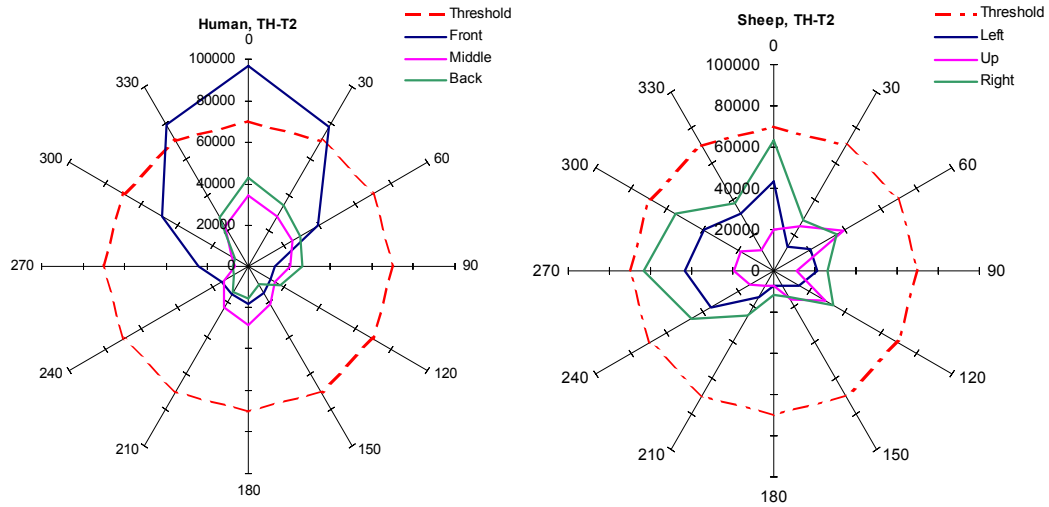


Figure 7: Maximum human (left) and sheep (right) lung overpressure for different orientations with respect to the blast origin, TH-T₂-P₂₀₀

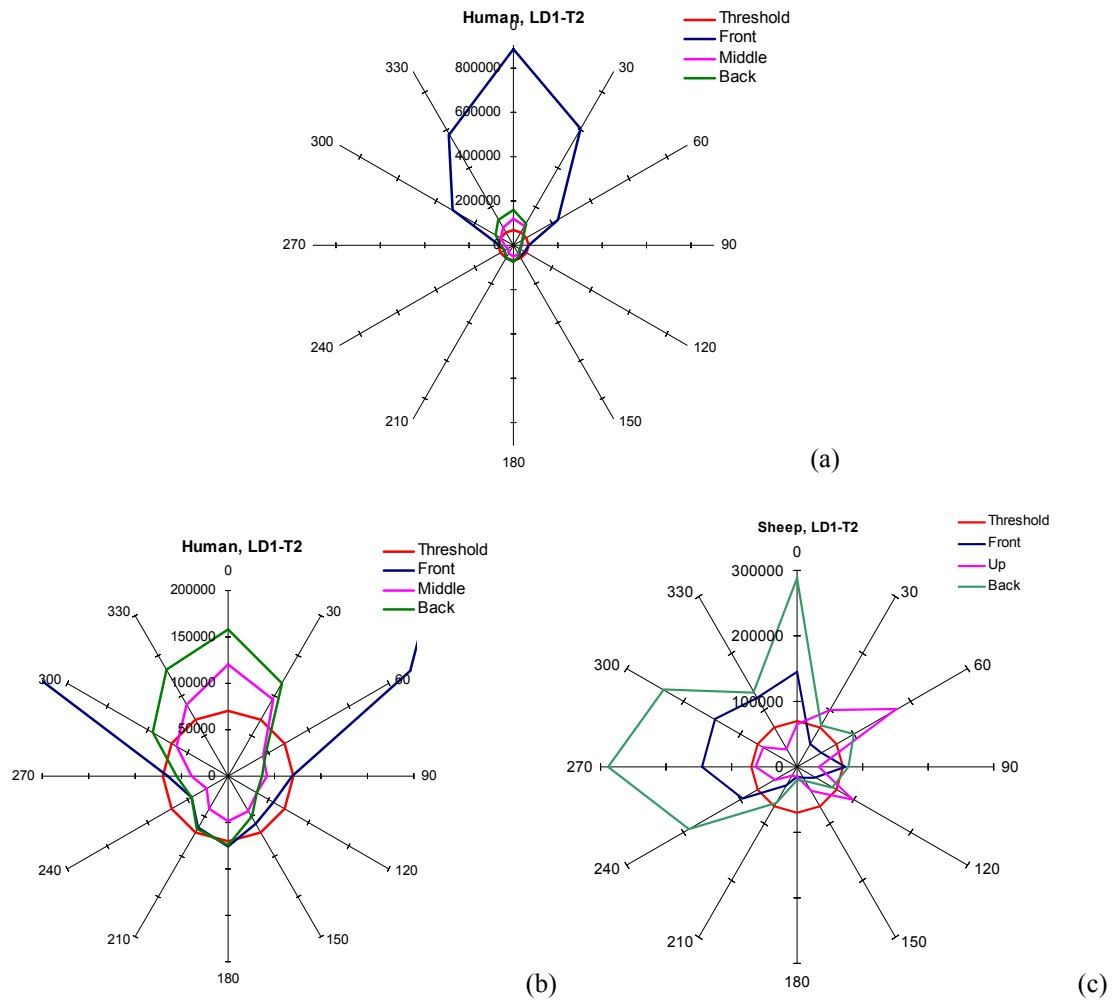


Figure 8: Maximum human (a, b) and sheep (c) lung overpressure (in Pa) for different orientations with respect to the blast origin, LD₁-T₂-P₅₀₀

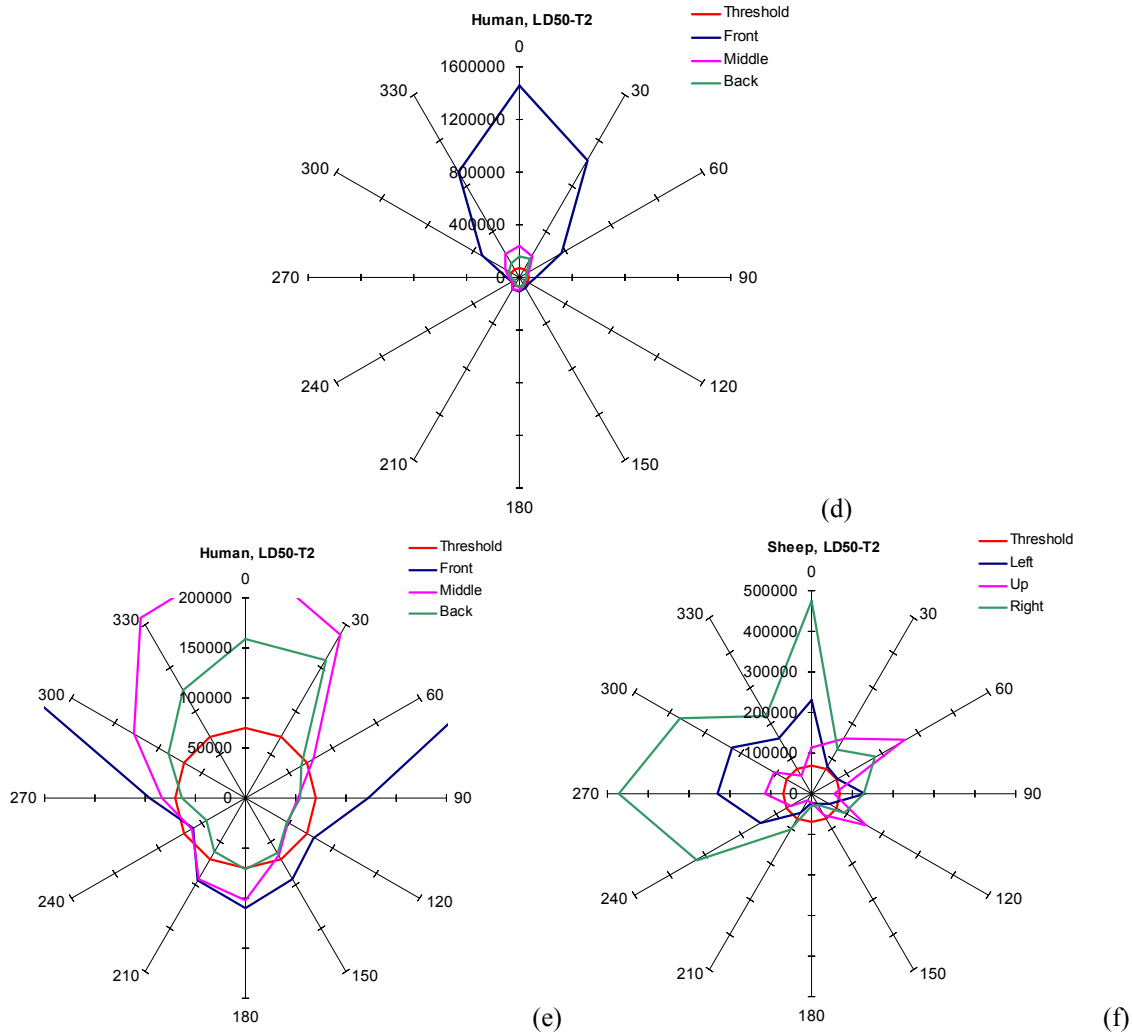


Figure 9: Maximum human (d, e) and sheep (f) lung overpressure (in Pa) for different orientations with respect to the blast origin, $LD_{50}-T_2-P_{700}$

CONCLUSION

Quasi two-dimensional FE models of a human and sheep thorax were developed using the non-linear arbitrary Lagrangian-Eulerian formulation in LS-Dyna. The FE models were applied to studies of the effect of body orientation to the blast wave. The parametric study showed that there is an effect of body orientation on blast injuries predicted in human and sheep models. From this study, it is predicted that the greatest reduction in lung PBI may be come from focusing on protecting the torso from -60 deg to +60 deg measured in the horizontal plane relative to the long axis of the body. Further enhancements can be made to the torso model. First, other two-dimensional slices taken at different levels in the human and sheep thoraces, or indeed a full three-dimensional human and sheep torso model, should be modelled since only injuries between the fifth and sixth vertebrae level were studied and generalized as predictors of overall lung injury. Second, the model developed in the present study does not allow wave propagation in the vertical direction (principle axis of the body). Also, material properties and constitutive model specially for lung tissues need to be investigated in order to increase the accuracy of the numerical results. Finally, the next step of this study is to investigate different thoracic blast protection concepts.

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