



HAL
open science

Thorax Injury Criteria Assessment Through Non-Lethal Impact Using An Enhanced Biomechanical Model

Michèle Bodo, Anthony Bracq, Rémi Delille, Christophe Maréchal, Sébastien Roth

► **To cite this version:**

Michèle Bodo, Anthony Bracq, Rémi Delille, Christophe Maréchal, Sébastien Roth. Thorax Injury Criteria Assessment Through Non-Lethal Impact Using An Enhanced Biomechanical Model. *Journal of Mechanics in Medicine and Biology*, 2017, 17 (07), pp.1740027. 10.1142/S0219519417400279 . hal-03451435

HAL Id: hal-03451435

<https://uphf.hal.science/hal-03451435v1>

Submitted on 30 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

THORAX INJURY CRITERIA ASSESSMENT THROUGH NON-LETHAL IMPACT USING AN ENHANCED BIOMECHANICAL MODEL

MICHÈLE BODO

*Laboratoire Interdisciplinaire Carnot de Bourgogne
University Bourgogne Franche-Comté, UTBM
UMR CNRS 6303/Univ. Bourgogne Franche Comté (UBFC)
F-90010 Belfort, France*

ANTHONY BRACQ, REMI DELILLE and CHRISTOPHE MARECHAL

*University of Valenciennes, LAMIH UMR CNRS/UVHC 8201
F-59313 Valenciennes, France*

SÉBASTIEN ROTH*

*Laboratoire Interdisciplinaire Carnot de Bourgogne
University Bourgogne Franche-Comté, UTBM
UMR CNRS 6303/Univ. Bourgogne Franche Comté (UBFC)
F-90010 Belfort, France
sebastien.roth@utbm.fr*

Ballistic injury refers to the interaction of a projectile and the human body, resulting in penetration or blunt trauma. In order to consider both consequences, a hydrodynamic elastoplastic constitutive law was implemented in a numerical FE model of the human torso to simulate soft tissues behavior and to evaluate their injury risk. This law, derived from 20% ballistic gelatin, was proven to be very efficient and biofidelic for penetrating ballistic simulation in soft tissues at very high velocity. In this study, the ability of the hydrodynamic law to simulate blunt ballistic trauma is evaluated by the replication of Bir *et al.*'s (2004) experiments, which is a reference test of the literature for nonpenetrating ballistic impact. Lung injury criteria were also investigated through the Bir *et al.*'s experiments numerical replication. Human responses were evaluated in terms of mechanical parameters, which can be global (acceleration of the body, viscous criteria and impact force) or local (stress, pressure and displacement). Output results were found to be in experimental corridors developed by Bir *et al.*, and the maximum pressure combined with the duration of the peak of pressure in the lungs seems to be a good predictor for lung injury.

Keywords: Nonpenetrating ballistic impact; biomechanics; soft tissues; FE method; numerical simulation; lung injury.

*Corresponding author.

1. Introduction

Exposure to ballistic threats is frequently encountered today and can occur both in defense and civilian environment.¹ Ballistic threat investigations have interests in various fields: in the military and civil context, for the protection against ballistic attacks and in forensics, to understand damage mechanisms and body tissue behavior.²

Several studies have been conducted concerning the terminal ballistics (interaction of the projectile with the target) and for wound ballistic, which refers to the interaction between a projectile and the human body.³ In the past, post-mortem human subjects (PMHSs) and animals were used to investigate the terminal effects of projectiles, but to overcome ethical issues and to have high fidelity, from the 1960s, the effects of projectiles are often investigated using tissue surrogate materials such as ballistic gelatin (BG) or ballistic soap.^{1,4-9} The use of BG has been proven by many experimental studies of the literature, which highlight its role as human soft tissue surrogate, taking into account the high strain rate response of human soft tissues.^{7,10-13} Thus, results derived from these experiments were used for numerical simulations. However, numerical models need material properties able to reproduce the high degree of strain-rate sensitivity of the human soft tissues,¹⁴ based on these experiment results. In this way, a study was first conducted by Awoukeng-Goumicha *et al.*,⁸ who use the 20% BG material to simulate ballistic impacts in soft tissues, using finite elements (FE) method. This model was modified by Taddei *et al.*⁹ who replicated impacts of steel spheres into soft tissues, represented by 20% BG, using hybrid FE-smooth particle hydrodynamics analysis. In both cases, a hydrodynamic material law was used to model gelatin behavior, and the numerical results were in good agreement with experimental results. Hydrodynamic constitutive law is interesting to explore how soft tissues can be affected by high velocity impacts and thus to understand the mechanism of injuries to find criteria for the risk of injury appearance, such as lung injuries.

As Bir *et al.*² related, limited data on human blunt ballistic impact involving an impactor of 20–200 g and impact velocity of 20–250 m/s are available in the literature. These impact conditions can occur both in sports such as baseball, hockey and lacrosse leading to injuries and death¹⁵ and in the use of less-lethal weapon projectiles.¹⁶⁻¹⁸ Generally, less-lethal weapon projectiles are characterized by mass going from a few grams up to 100–200 g and by muzzle velocities going up to 150–200 m/s. Indeed, during these last decades, the exponential increasing use of less-lethal kinetic weapon projectiles in individual or riot control is designed to cause enough physical pain to incapacitate or repel the target while minimizing the risk of severe injuries.¹⁸ However, the literature reports that the most targeted zone of the body, the thorax, can sometimes sustain severe injuries.¹⁹⁻²³ So, the less-lethal kinetic weapon projectiles raise the question of their dangerousness and how blunt projectile ballistic impact can lead to injuries.

Focussing on the thoracic impact, the present study is a numerical investigation of blunt trauma based on the replication of Bir *et al.*'s experiments.² These

experiments were replicated using a thoracic FE model with enhanced tissue constitutive law. The projectiles used are noncompressible PVC baton of different masses. Shots were made on the sternum to investigate the response in the impacted area location: classical mechanical parameters generally used in the literature were evaluated and comparison between numerical and experimental data was conducted. Lung responses were also investigated to derive injury criteria and injury severity.

This paper will first describe the material law used to model soft tissues, the FE model used and the experiments of Bir *et al.* Then, the next section deals with the investigation of the computer surrogate biomechanical response and the evaluation of thoracic injury criteria.

2. Materials and Methods

2.1. Hydrodynamic law for soft tissues

The mechanical properties of BG are known to be dependent on strain rate, time and temperature.¹² As illustrated in the literatures,^{7,13} the BG is a better simulant for human tissue than other materials such as soap, lard and Sylgard. Although some studies^{12,24,25} highlight the hyperelastic and hyperviscoelastic properties of BG to describe its strain rate compressive response under specific test conditions, other studies underlined the hydrodynamic aspect of the gelatin.^{13,26,27} This last type of behavior is of interest, allowing to model the gelatin in shock configurations (penetrating impacts, blunt impact and blast loading effects on soft tissues). To simulate soft tissues, an elastoplastic hydrodynamic material was used according to Refs. 8 and 9. To model this behavior, the Mie–Grüneisen equation of state (Eq. (3)) is used to define the nonlinear pressure evolution. For numerical implementation, the polynomial form of the EOS is used (Eq. (1)). Moreover, the elastoplastic behavior of the gelatin is simulated by the Hollomon hardening law (Eq. (5)).

The pressure is computed using a polynomial expression:

$$P = C_0 + C_1 * \mu + C_2 * \mu^2 + C_3 * \mu^3 + (C_4 + C_5 * \mu) * E_{v0}, \quad (1)$$

where $\mu = 1 - \frac{\rho}{\rho_0}$ and E_{v0} is the internal energy per initial volume unit. The coefficients C_i were determined from the Hugoniot and the equation of state. The cubic form of Hugoniot (Eq. (2)), the Mie–Grüneisen equation of state (Eq. (3)) and the energy conservation equation ((Eq. (4)) were used:

$$P_H = k_1 * \mu + k_2 * \mu^2 + k_3 * \mu^3, \quad (2)$$

$$P - P_H = \Gamma_0 * (E - E_H), \quad (3)$$

$$E_H - E_0 = \frac{1}{2} (P_H + P_0) * (V_0 - V_H). \quad (4)$$

By replacing Eqs. (2) and (4) in the equation of Mie–Grüneisen Eq. (3), the C_i coefficients can be obtained like this:

$$C_0 = P_0;$$

$$\begin{aligned}
c_1 &= k_1 - \frac{\Gamma_0}{2} * P_0 = \rho_0 * C_0^2 - \frac{\Gamma_0}{2} * P_0; \\
c_2 &= k_2 - \frac{\Gamma_0}{2} k_1 = \rho_0 * C_0^2 * (2s - 1) - \frac{\Gamma_0}{2} \rho_0 C_0^2; \\
c_3 &= k_3 - \frac{\Gamma_0}{2} k_2 = \rho_0 * C_0^2 * (s - 1)(3s - 1) - \frac{\Gamma_0}{2} \rho_0 C_0^2 (2s - 1); \\
c_4 &= C_5 = \Gamma_0.
\end{aligned}$$

Therefore, the pressure state depends on the five parameters ρ_0, C_0, s, Γ_0 and E_{v0} , which are, respectively, the initial density, the initial material sound of speed, the slope of the linear shock Hugoniot function, the Gruneisen parameter and the initial volumetric internal energy.

To summarize, soft tissues behavior for numerical implementation in the FE code (RADIOSS) is described as follows:

- the hydrodynamic character is represented by Eq. (1) involving the C_i coefficients;
- the elasticity is described with Hooke's law using the Young's modulus E ;
- Poisson's coefficient ν as long as the equivalent stress of Von Mises remains lower than the plastic yield stress A .

Plasticity is modeled with the hardening Hollomon law (Eq. (5)):

$$\sigma = A + B\varepsilon_p^n. \quad (5)$$

With ε_p the plastic strain, B is the hardening parameter and n is the hardening exponent. The law can be bounded in stress (σ_{\max}) and strain (ε_{\max}).

Mechanical parameters used for soft tissue simulation, derived from Refs. 8 and 9, are given in Tables 1 and 2. The unit systems used are mm, g, ms.

2.2. HUByx FE modeling

The FE model of the human torso named HUByx (Hermaphrodite Universal Bio-mechanics yx-model) was developed based on 3D reconstruction from medical scans and can be considered as 50th percentile male model. This numerical surrogate

Table 1. Elastoplastic parameters for soft tissues.

ρ_0 (g/mm ³)	E (MPa)	ν	A (MPa)	σ_{\max} (MPa)	ε_{\max}
1.06×10^{-3}	50	0.499	3	3.1	0.2

Table 2. Hydrodynamic parameters for soft tissues.

E_{v0}	C_1	C_2	C_3	Γ_0	P_0
0.5882	2449	6502.2	9251.9	0.17	-0.1

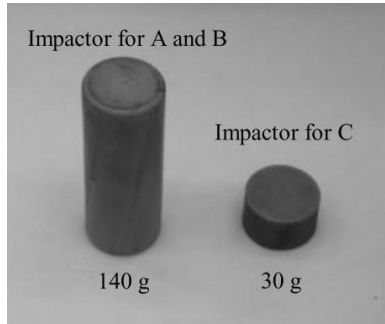


Fig. 1. Impactors used by Bir to determine human response to blunt ballistic impacts, extracted from Bir's thesis.

includes the main organs: heart, lungs, kidneys, liver, spleen, stomach, intestines, muscles, skin and the skeleton. The development of the HUByx model can be found in Ref. 28. This model was already validated against available data from the literature in various fields: automobile and nonpenetrating ballistic,²⁸ blast²⁹ and some civil loadings.^{30,31} Until now, soft tissues were modeled using a viscoelastic model, based on the Boltzmann model; however, the literature reports the nonlinear behavior of soft tissues material (by studying liver and kidney tissue behavior)³² with a high influence of the impact velocities. Therefore, the present study used the elastoplastic hydrodynamic law (Sec. 2.1) to model soft tissues behavior (lungs, heart, liver, spleen, kidneys and stomach). Material laws have been implemented in the dynamic FE code (Radioss, Altair Hyperworks 14). Impactors used by Bir are noncompressible PVC baton of different masses (Fig. 1). These impactors were numerically modeled and simulations were conducted in accordance with the three impact conditions of experiments of Bir *et al.*²

Global and transversal views of HUByx can be found in Figs. 2 and 3. Except the soft tissues material parameters (Tables 1 and 2), material properties implemented in the numerical model are listed in Table 3.

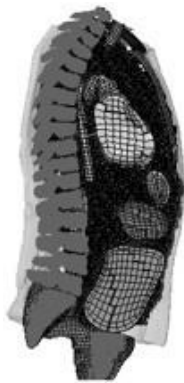


Fig. 2. Global front view of the HUByx model.

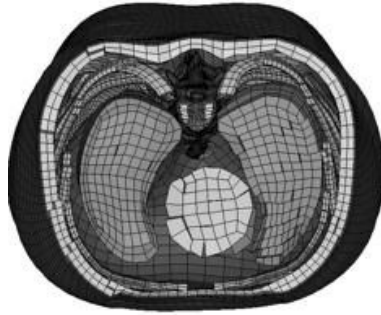


Fig. 3. Global transverse view of the HUByx model.

The HUByx numerical model was used to reproduce the experiments of Bir *et al.* A first validation of the model had already been done by implementing a viscoelastic behavior law of Boltzmann type for the soft tissues. This second series of validation consists in replacing the viscoelastic law by a hydrodynamic law in order to be able to use the HUByx model for both nonpenetrating ballistic impacts and penetrating impacts (when the projectile crosses human tissues) and to evaluate lung injury criteria.

The impactors used in the BIR tests were numerically reproduced with the same dimensions and mass (Fig. 4).

2.3. Bir's validation test

The biomechanical responses of the human body to impacts are of crucial importance in the evaluation of protective equipment. Thus, Bir *et al.*² developed thoracic response corridors subjected to three different impact conditions for speed ranging from 20 m/s to 60 m/s. These corridors were obtained from experiments on

Table 3. Material laws implemented in the biomechanical FE model HUByx.

Tissues	Material model	Density (g/mm ³)	Young's modulus (MPa)	Poisson ratio	Yield stress (MPa)	References
Aorta	Elastic	0.001	25	0.3		34, 35
Trachea	Elastic	0.001	25	0.3		34, 35
Diaphragm	Elastic	0.001	3	0.3		34, 35
Muscles	Elastic	0.001	1–10	0.3		35
Skin	Elastic	0.001	31.5	0.45		35
Inter-organs space/fat	Elastic	0.001	0.5	0.45		34–36
Abdomen/intestine	Elastic	0.001	0.5	0.45		34
Spongy bone	Elastic	0.001	50	0.4		35
Cortical bone	Elastic-plastic Johnson-Cook	0.001	14,000	0.3	70	35, 37
Cartilage	Elastic	0.001	50	0.3		36
Intervertebral disc	Elastic	0.00125	5	0.3		34



Fig. 4. HUByx model with impactor C (lateral and frontal views).

13 PMHSs and are a fundamental source of data in the assessment of nonpenetrating impacts.

Repeated impacts were performed as long as the rib cage and sternum showed no fractures. The PMHSs have different physical characteristics, emphasized by the variability of their anthropometric data. The 13 PMHSs were exposed to three different types of nonpenetrating ballistic impact on the thorax to determine the mechanical response of the thorax based on changes in the impact force versus time, deflection of the thorax versus time and the evolution of the force as a function of deflection. The three ballistic impact conditions gave different results. Bir's corridors were used to validate HUByx biomechanical responses under the same impact conditions.

Bir's experiment tests are described in Table 4. The impactors used by Bir *et al.* (2004) are illustrated in Fig. 1.

2.4. Description of injury criteria

The literature lists a series of studies providing information on mechanical parameters: pressure^{38,39} and more global parameters such as VC_{max} , to study their

Table 4. Ballistic impact conditions.

	Projectile type	Length (mm)	Diameter (mm)	Mass of projectile (g)	Impact velocity (m/s)
A	Noncompressible PVC baton	100	37	140	20
B	Noncompressible PVC baton	100	37	140	40
C	Noncompressible PVC baton	28.5	37	30	60

Specimen ID	Impact condition	VC _{max}	AIS
NIJ10	A	.51	0
NIJ11	A	.24	0
NIJ12	A	.46	0
NIJ13	A	.24	0
NIJ8	A	.26	0
NIJ7	B	1.97	2
NIJ8	B	2.35	2
NIJ10	B	2.18	2
NIJ11	B	1.01	3
NIJ13	B	.65	2
NIJ9	C	.14	0
NIJ10	C	.59	0
NIJ11	C	.24	0
NIJ12	C	.60	2
NIJ13	C	.30	0

Fig. 5. AIS and VC_{max} for the 13 PMHS used by Bir.³³

abilities to predict body injuries. These parameters were evaluated to assess thoracic injuries.

2.4.1. The viscous criterion

The viscous criterion (VC) is one of the criteria developed for the thoracic part to evaluate the risk of injury.⁴⁰ The VC_{max} is defined as “the peak of the product between compression [$C(t)$] and the velocity of compression [$V(t)$]”. The compression $C(t)$ is a normalized thorax compression relative to the normal depth of the thorax of 236 mm. This criterion is used by Bir to predict costal and sternal injuries. The curve of the chest deflection as a function of time allowed the calculation of VC_{max} for each test condition. The VC_{max} values obtained were associated with the injury data. All cases without rib or sternum fractures revealed by an X-ray test were considered AIS 0 (abbreviated injury scale). AIS values were assigned to all cases in which there were injuries according to autopsy revelations. Thus, Fig. 5 extracted from the work of Bir³³ lists the AIS and the VC_{max} obtained for the different specimens subjected to the three test conditions (A, B and C).

Table 5 summarizes the VC_{max} and AIS (Fig. 5) for each impact condition.

Table 5. VC_{max} and AIS derived from Bir’s experiments for each impact condition.

	VC _{max}		AIS	
	Min	Max	Min	Max
Impact condition A	0.24	0.51	0	0
Impact condition B	0.65	2.35	2	3
Impact condition C	0.14	0.60	0	2

2.4.2. Lung pressure

Pressure is a mechanical parameter used in several studies for the risk of lung injury assessment.^{38,41} Indeed in the 1960s, Bowen *et al.*³⁸ performed experiments over 2097 animals of 13 different species to establish injury risk curves related to human in the context of blast. These curves called “Bowen curves” aim to estimate the tolerance of human to the primary effect of blast overpressure. As lungs being the most affected organs and a contributing factor to the rates of mortality due to blast, lung injuries were examined on the Bowen curves in terms of lung damage threshold. Maximum overpressures were plotted against durations, and the curves give the threshold of lung damage and the lethality which represents various survival probabilities (1%, 10%, 50%, 90% and 99%).

This methodology is therefore used to evaluate the risk of lung damage for Bir’s nonpenetrating impacts.

3. Results

Results on the human thoracic part were evaluated for each impact condition by plotting force–time, chest deflection–time and force as a function of thoracic deflection.

3.1. HUByx mechanical responses — global criteria

3.1.1. Force–time, deflection–time and force–deflection responses

The different curves shown in Figs. 6–8, constitute the numerical results obtained through the replication of Bir’s experiments. In black continuous line are the corridors obtained with different specimens.

These responses in terms of force/time, deflection/time and force/deflection are globally within the corridors defined by Bir. These curves thus validate the use of the hydrodynamic law for soft tissues and confirm the biofidelic response of the HUByx model for nonpenetrating ballistic impacts.

3.1.2. VC response

Numerical VC_{\max} was evaluated in our simulation by using the maximum value of the product of the relative compression of the node of maximum deflection in the impacted area of the thorax and the velocity of the node of maximum deflection. The initial thickness of the thorax was taken to be equal to 236 mm.

VC_{\max} values obtained from the numerical simulation are given in Table 6

The numerical values of VC_{\max} are included between the Min and Max values obtained by Bir (Table 5).

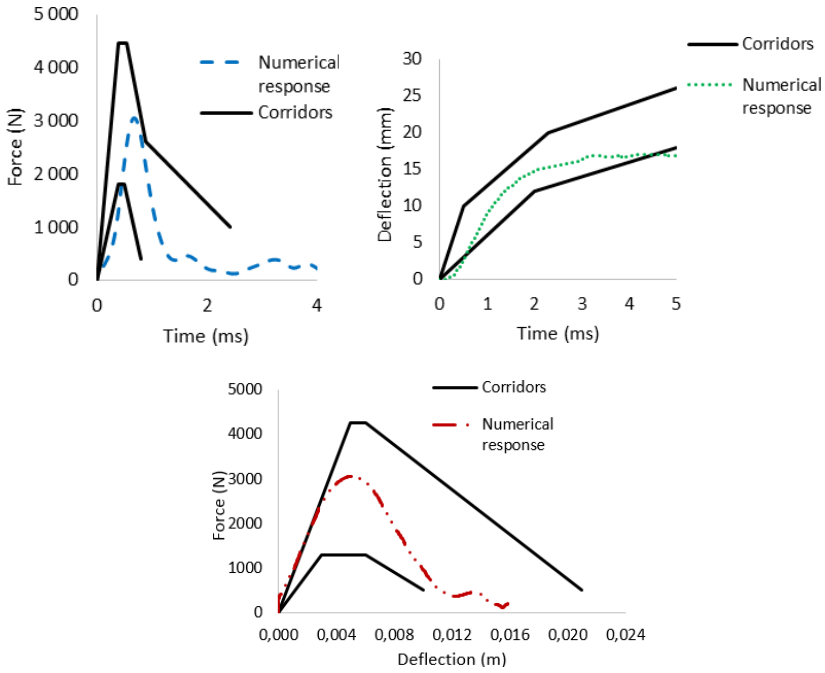


Fig. 6. Numerical response compared with Bir's experimental results for impact condition A.

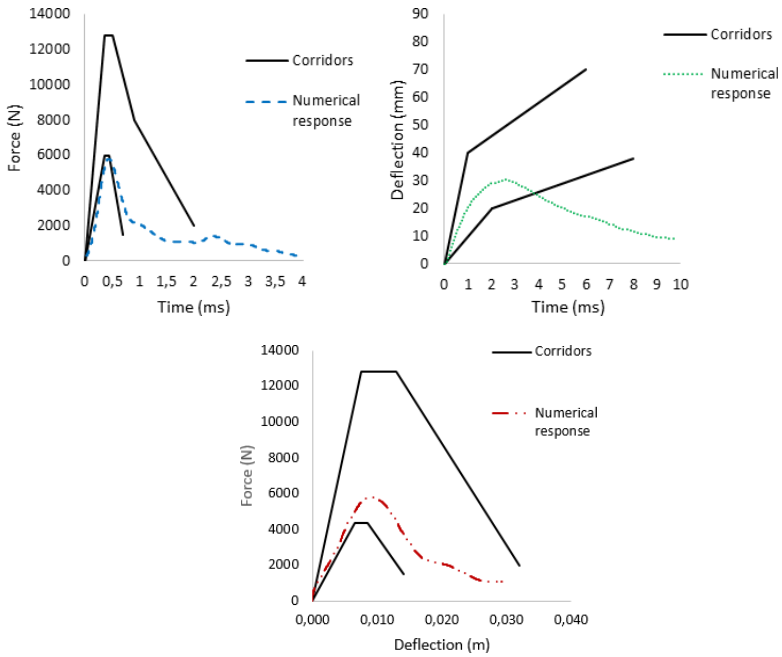


Fig. 7. Numerical response compared with Bir's experimental results for impact condition B.

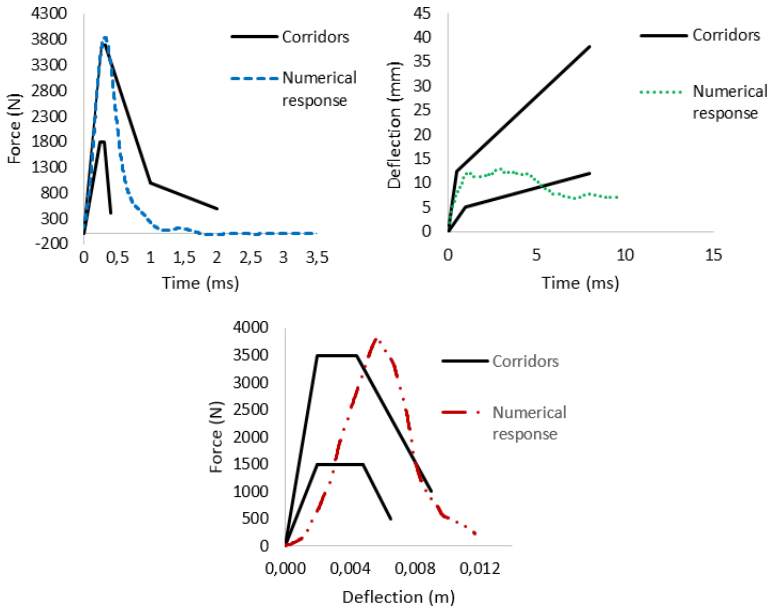


Fig. 8. Numerical response compared with Bir's experimental results for impact condition C.

Table 6. VC_{max} derived from numerical simulation.

	VC_{max}		
	Min	Max	Numerical values
Impact condition A	0.24	0.51	0.36
Impact condition B	0.65	2.35	1.33
Impact condition C	0.14	0.60	0.27

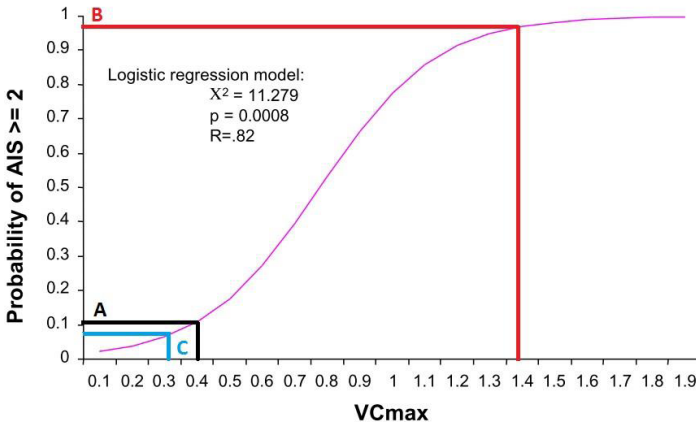


Fig. 9. Plotting of numerical VC_{max} on the injury risk curve of $AIS \geq 2$ versus VC_{max} . This curve was determined by logistic regression analysis from experimental cadaver data (Bir).³³

Table 7. Lung pressure resulted from numerical simulation.

	P_{\max} (MPa)	Duration of the pic (ms)	P_{\max} (psi)
Impact condition A	0.118	1.5	17.1
Impact condition B	0.552	1.5	80.0
Impact condition C	0.102	1	14.8

By plotting the numerical VC_{\max} values obtained with the FE simulations, in the injury risk curve of $AIS \geq 2$ versus VC_{\max} , and determined by the logistic regression analysis from experimental cadaver data,³³ it should be noted that:

- concerning impact condition A, the probability of having an $AIS \geq 2$ is about 11%;
- concerning impact condition B, the probability of having an $AIS \geq 2$ is about 98%;
- concerning impact condition C, the probability of having an $AIS \geq 2$ is about 8%.

These results are in agreement with Fig. 5, which gives the experimental values of AIS and VC_{\max} .

3.2. *HUByx mechanical responses — local criteria*

In addition to the investigation of global criteria, this study goes further to assess the risk of lung injury. Therefore, mechanical parameters in the lungs (pressure), resulted from numerical simulation, were analyzed (see Fig. 10).

The maximum pressure considered in this study case is an average value over the maximum pressure zone.

The results obtained in terms of peak pressure (mean value of the maximum pressure zone) and the duration of the peak pressure are given in Table 7, for three impact conditions (P_{\max} is the mean of pressure value in the maximum pressure area).

Bir's experiments were carried out on PMHSs; lung injuries are, therefore, difficult or even impossible to observe and characterize. This is the main limit of Bir's testing for the study of human tissues. Bowen tests carried out on animals then become interesting in the study of lung injuries because the lungs are alive and therefore filled with air. Knowing that the AIS describes the severity of injuries, it seems interesting to establish a link between the pulmonary damage of the Bowen curve and the AIS values obtained in Bir's experiments. AIS 3 corresponds to four or more rib fractures on one side and two to three rib fractures with hemothorax or pneumothorax from a skeletal injury point of view and also corresponds to lung contusion and minor heart contusion from a soft tissue injury point of view.¹ Thus, using comparison between the Bowen lung damage curve and AIS 3 is really interesting and allows characterizing the lung injury which could correspond to the Bir impact condition B.

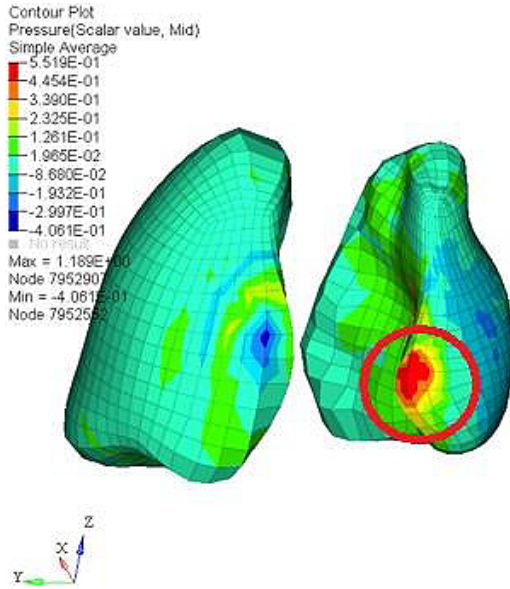


Fig. 10. Pressure peak area (impact condition B).

By plotting the points obtained for each impact case on the Bowen curves, it can be observed that impacts A and C are below the lung threshold damage. Impact B, on the other hand, is above the limit of pulmonary lesion, suggesting a risk of pulmonary contusion. The latter hypothesis is supported by the fact that in the soft tissue AIS scale, a pulmonary contusion corresponds to an AIS 3,¹ which is consistent with the AIS obtained by BIR for the impact condition B (Fig. 5). Figure 11 shows the three cases of impacts plotted on the Bowen curves.

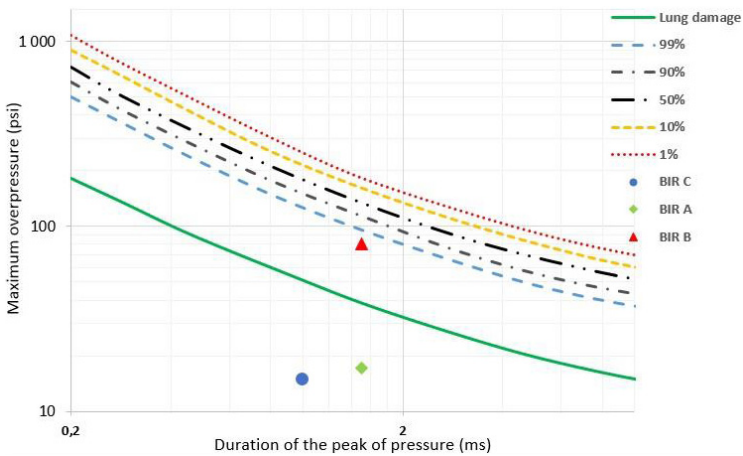


Fig. 11. Use of Bowen's lethality curves (1%, 10%, 50%, 90%, 99% are survival probabilities).

4. Discussion

The numerical replication of Bir's experiments is a convenient starting point to study the human thoracic responses under blunt ballistic trauma. The conducted numerical replication of Bir's tests used specific soft tissue modeling, based on 20% BG which is considered as a reliable human tissue surrogate.^{10,12,13} However, as stated by Nicholas and Welsch¹⁰ "although gelatin can simulate the density and viscosity of living human tissue, it lacks the structure of tissue. Gelatin does not bleed or have nerves or vessels". Thus, gelatin cannot simulate entire biological components. Nevertheless, from a numerical point of view and at a macroscopic level, the results obtained in terms of force–time and deflection–time histories and force versus deflection curves were in accordance with Bir's experimental corridors. Although Bir's corridors of force versus time have been criticized for possible measurement errors related to the nonconservation of momentum and energy,⁴² the Bir corridors remain a reference in the field of nonpenetrating ballistic impact.

By changing the soft tissues behavior law, roughly the same results were obtained both in the case of the use of a viscoelastic law (previous study²⁸) and in the case of the hydrodynamic law (current study). However, it should be noted that the most influential material properties with regard to these ballistic validation cases are certainly the mechanical properties of bone materials, particularly sternum. Since the objective was to investigate the lung injuries, material properties of the lung were of particular attention. In order to go further in the exploration of bone fracture appearance, more analyses are needed focussing on bones constitutive law.

It has been shown that for impact velocities above 3 m/s, the tolerance to injury becomes rate-sensitive.³³ Therefore, for these impact cases, VC_{\max} has proven to be the best predictor for injuries.⁴⁰ This confirms the idea of using the injury curve of AIS versus VC_{\max} to evaluate the probability to sustain skeletal AIS ≥ 2 (Fig. 9).

Moreover, as Bir³³ stated that "for impacts with a velocity of deformation above 30 m/s, blast injuries are common in the lungs"; it, therefore, seemed interesting to assess the probability of lung injury appearance from blunt ballistic impacts, based on blast criteria. Bowen curves³⁸ then appear as a good way to assess lung injuries. Thus, when the peak pressure in the lungs as a function of the duration of the peak was plotted on the Bowen curves, it was found that impact case B is above the limit of pulmonary damage unlike the cases A and C. These results are consistent with those obtained experimentally by Bir. Indeed, for the impact case B, an AIS 3 had been raised and AIS 3 can refer to at least three rib fractures with hemothorax or pneumothorax,¹ which can lead to pulmonary contusion. Our initial aim is to assess lung injuries, and it appears essential to include bone fracture in our investigation. This step is under progress.

To summarize, these results contribute to numerically validate the Bir experiments with an elastoplastic hydrodynamic law for soft tissues. Indeed, the material

properties used in the literature to model penetrating impact⁸ can be used for nonlethal impact, as Bir replications' tests give satisfactory results. In addition to Bir's numerical replication and the classical force and displacement time history, investigation on more local mechanical parameters was conducted, leading to very interesting conclusion about the correlation between AIS and pressure versus time parameters. The three cases of Bir were significantly plotted on Bowen curves.

Nonlethal impacts are specific loadings and still raise the question about their dangerousness for the human body and the choice of projectiles to reduce the risk of injuries. Several studies of the literature have investigated these issues, attempting to explore their impacts on different surfaces at different velocities.^{16,18,43} At a numerical level, the modeling process used in the present study can be extended to several other projectiles, even deformable ones (Bir's projectile being rigid), in order to assess their potential dangerousness and the risk of injury for the human body when impacted by such projectiles.

5. Conclusion

Numerical replication of Bir's reference case is an important step in the validation of the thoracic numerical model, in terms of mechanical response under blunt ballistic impacts. The use of an elastoplastic hydrodynamic law, already validated for soft tissues in the case of penetrating ballistic, was found to be interesting for non-penetrating ballistic impacts. Indeed, biofidelic response of the numerical model was obtained, in agreement with Bir's experimental corridors. Assessment of these three reference impacts was also conducted using other mechanical numerical parameters such as VC_{\max} and pressure time history and was found to be very interesting to evaluate the dangerousness of these impacts. Indeed, the values obtained and compared with the AIS scale give encouraging results in the investigation of thoracic injury criteria. The validation process used in this study could be applied to other types of projectiles, such as nonlethal ones, to assess the risk of blunt impact injuries.

Acknowledgments

The authors would like to acknowledge the Region Bourgogne Franche-Comté (France) for their financial support.

References

1. Schmitt K-U, Niederer PF, Cronin DS, Muser MH, Walz F, *Trauma Biomechanics*, Springer, Berlin Heidelberg, 2014.
2. Bir C, Viano D, King A, Development of biomechanical response corridors of the thorax to blunt ballistic impacts, *J Biomech* **37**(1):73–79, 2004.
3. Sellier KG, Kneubuehl BP, *Wound Ballistics and the Scientific Background*, Elsevier, Amsterdam, 1994.

4. Fackler ML, Malinowski JL, The wound profile: A visual method for quantifying gunshot wound components, *J Trauma* **25**(6):522–529, 1985.
5. Dyckmans G, Ndompetelo N, Chabotier A, Numerical and experimental study of the impact of small caliber projectiles on ballistic soap, *J Phys IV (Proc)* **110**:627–632, 2003.
6. Nsiampa N, Dyckmans G, Chabotier A, Numerical simulation of the tumbling effect of small caliber projectiles into ballistic soap, *8th World Congress on Computational Mechanics (WCCM8)*, Venice, 2008.
7. Appleby-Thomas GJ, Hazell P, Shepherd CJ, Wood DC, Roberts A, On the dynamic behavior of three readily available soft tissue simulants, *J Appl Phys* **109**:1–6, 2011.
8. Awoukeng-Goumtcha A, Taddei L, Tostain F, Roth S, Investigations of impact biomechanics for penetrating ballistic cases, *Biomed Mater Eng* **24**(6):2331–2339, 2014.
9. Taddei L, Goumtcha A, Roth S, Smoothed particle hydrodynamics formulation for penetrating impacts on ballistic gelatine, *Mech Res Commun* **70**:94–101, 2015.
10. Nicholas NC, Welsch JR, Ballistic Gelatin, Technical Report, Institute for Non-Lethal Defense Technologies Applied Research, The Pennsylvania State University, 2004.
11. Jussila J, Leppaniemi A, Paronen M, Kulomaki E, Ballistic skin simulant, *Forensic Sci Int* **150**(1):63–71, 2005.
12. Cronin DS, Falzon C, Dynamic characterization and simulation of ballistic gelatin, in *Proc SEM Annual Conf*, Albuquerque, New Mexico, USA, 2009.
13. Appleby-Thomas GJ, Hazell PJ, Sheldon RP, Stennett C, Hameed A, Wilgeroth JM, The high strain-rate behaviour of selected tissue analogues, *J Mech Behav Biomed Mater* **33**:124–135, 2014.
14. McElhaney JH, Dynamic response of bone and muscle tissue, *J Appl Physiol* **21**(4):1231–1236, 1966.
15. Maron BJ, Poliac LC, Kaplan JA, Mueller FO, Blunt impact to the chest leading to sudden death from cardiac arrest during sports activities, *N Engl J Med* **333**(6):337–342, 1995.
16. Robbe C, Nsiampa N, Papy A, Oukara A, A new thoracic surrogate for assessing the impact of kinetic energy non-lethal projectiles, *Proc Personal Armour System Symposium (PASS)*, Cambridge, UK, 2014.
17. Pavier J, Langlet A, Eches N, Prat N, Bailly P, Jacquet JF, Experimental study of the coupling parameters influencing the terminal effects of thoracic blunt ballistic impacts, *Forensic Sci Int* **252**:39–51, 2015.
18. Nsiampa N, Numerical assessment of non-lethal projectile thoracic impacts, Ph.D. Thesis, Université de Liège, 2016.
19. Ritchie AJ, Plastic bullets: Significant risk of serious injury above the diaphragm, *Injury* **23**(4):265–266, 1992.
20. Mahajna A, Aboud N, Harbaji I, Agbaria A, Lankovsky Z, Michaelson M, Fisher D, Krausz MM, Blunt and penetrating injuries caused by rubber bullets during the Israeli-Arab conflict in October, 2000: A retrospective study, *The Lancet* **359**(9320):1795–1800, 2002.
21. Suyama J, Panagos PD, Sztajnkrzyer MD, FitzGerald DJ, Barnes D, Injury patterns related to use of less-lethal weapons during a period of civil unrest, *J Emerg Med* **25**(2):219–227, 2003.
22. Hubbs K, Klinger D, Impact Munitions Data Base of Use and Effects, *Technical Report*, U.S. Department of Justice, National Institute of Justice, 2004.
23. Rezende-Neto J, Silva FD, Porto LB, Teixeira LC, Tien H, Rizoli SB, Penetrating injury to the chest by an attenuated energy projectile: A case report and literature review of thoracic injuries caused by “less-lethal” munitions, *World J Emerg Surg* **4**:26, 2009.

24. Cronin D, Salisbury C, Horst C, High rate characterization of low impedance materials using a polymeric split Hopkinson pressure bar, *Proc Soc Experimental Mechanics (SEM) Annual Conf and Exposition on Experimental and Applied Mechanics*, pp. 314–322, 2006.
25. Cronin DS, Falzon C, Characterization of 10% ballistic gelatin to evaluate temperature, aging and strain rate effects, *Exp Mech* **51**(7):1197–1206, 2011.
26. Nagayama K, Mori Y, Motegi Y, Nakahara M, Shock Hugoniot for biological materials, *Shock Waves* **15**(3):267–275, 2006.
27. Shepherd CJ, Appleby-Thomas G, Hazell PJ, Allsop DF, The dynamic behaviour of ballistic gelatin, *AIP Conf Proc*, Nashville, United States, Vol. 1195, pp. 1399–1402, 2009.
28. Roth S, Torres F, Feuerstein P, Thorax-Pierre K, Anthropometric dependence of the response of a thorax FE model under high speed loading: Validation and real world accident replication, *Comput Methods Programs Biomed* **110**(2):160–170, 2013.
29. Awoukeng-Goumtcha A, Thorax-Pierre K, Roth S, Toward a powerful tool for the prediction of human body trauma under extreme loadings through finite element simulations, *Proc Personal Armour System Symp (PASS)*, Cambridge, UK, 2014.
30. Awoukeng-Goumtcha A, Bodo M, Taddei L, Roth S, From military to civil loadings: Preliminary numerical-based thorax injury criteria investigations, *Int J Numer Method Biomed Eng* **32**(3):e02738, 2016.
31. Bodo M, Roth S, Uncertainties of impact configuration for numerical replications of real-world trauma: A FE analysis, *J Mech Med Biol* **16**(08):1640018, 2016.
32. Nicolle S, Vezin P, Palierne J-F, A strain-hardening bi-power law for the nonlinear behaviour of biological soft tissues, *J Biomech* **43**(5):927–932, 2010.
33. Bir C, The evaluation of blunt ballistic impacts of thorax, Ph.D. Thesis, Wayne State University, 2000.
34. Zhao JZ, Narwani G, Development of a human body finite element model for restraint system R & D applications, *The 19th Int Tech Conf Enhanced Safety of Vehicles (ESV)*, Paper No. 05-0399, 2005.
35. Shigeta K, Kitagawa Y, Yasuki T, Development of next generation human FE model capable of organ injury prediction (Paper number 09-0111), *21st Int Tech Conf Enhanced Safety of Vehicles*, Stuttgart, Germany, 2009.
36. Roberts JC, Merkle AC, Biermann PJ, Ward EE, Carkhuff BG, Cain RP, O'Connor JV, Computational and experimental models of the human torso for non-penetrating ballistic impact, *J Biomech* **40**:125–136, 2007.
37. Yamada H, *Strength of Biological Materials*, Williams & Wilkins, Baltimore, 1970.
38. Bowen IG, Fletcher ER, Richmond DR, Estimate of man's tolerance to the direct effects of air blast, Technical Report, Lovelace Foundation for Medical Education and Research Albuquerque, New Mexico, 1968.
39. Van der Voort M, Holm KB, Kummer PO, Teland JA, Van Doormaal JCAM, Dijkers HPA, A new standard for predicting lung injury in inflicted by Friedlander blast waves, *J Loss Prevent Process Ind* **40**:396–405, 2016.
40. Lau IV, Viano DC, The viscous criterion — A new index of injury induced by high speed impact, *J Biomech* **19**(6):485, 1986.
41. Teland JA, Van Doormaal JCAM, Blast wave injury prediction models for complex scenarios, *22nd MABS-Military Aspects of Blast and Shock*, Bourges, France, 2012.
42. Courtney MW, Courtney AC, Apparent measurement errors in “Development of biomechanical response corridors of the thorax to blunt ballistic impacts”, *J Biomech* **41**:486–487, 2008.
43. Robbe C, Evaluation expérimentale de l' impact thoracique des projectiles non-létaux, Ph.D. Thesis, Ecole Royale Militaire, Université de Liège, 2013.