NUMERICAL SIMULATION ON DYNAMIC RESPONSE OF THE CHEST WALL LOADED BY THE BLAST WAVE

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Abstract:

In this paper, a three-dimensional finite element model of the human thorax was constructed using Mimics software and Icem CFD software. This model was loaded with a 100-kPa blast wave and constructed to analyze the dynamic response of the chest wall. The simulation results have shown that a blast wave can cause stress concentration on the ribs and ribs inward movement. The third, fourth, and fifth ribs have the maximum inward moving velocity of 1.6 m / s without any injury for the human body. The three-dimensional finite element model can realistically reflect the characteristic mechanical response of the chest wall to blast wave loadings and can be used for further studies on blast injury mechanism, i.e., injury prediction.

1 Introduction

The blast injury is an injury common in explosion accidents during modern wars and at ordinary times. The scholars at home and abroad have made much systematic research into the blast injury, with abundant achievements in the mechanism causing the blast injury. This research indicates that the fast inward displacement of the chest wall after being hit by the blast wave is one of the major reasons causing the blast injury, and fast displacement of the chest wall may create a localized pressure wave on the lung tissues, while it fails to quickly release the energy, causing thus lung hemorrhage and edema lesions [1]. 177 test sheep were placed at different positions in four sealed steel vessels of different sizes, and then the spherical C-4 plastic explosives were ignited to injure the test sheep. Injury assessment reference values based on each test sheep with the digital pathological injury scoring system after injuring the sheep were performed to obtain the ASII (Adjusted Severity of Injury Index). The test results indicated that the ASII score, the animal injury and the maximum inward chest wall speed were well pertinent [2, 3]. The view that the maximum inward chest wall speed could be used as a judgment index for judging non-hearing impairment under the complex blast wave was put forward and the mathematical model between the maximum inward chest wall speed and the ASII score was established [4,5]. With the development of computer technology, the High-fidelity FEM model was applied to the research of blast injuries. At first, an anatomy-based 3D FEM model of a sheep thorax was constructed and then a modeling study of thorax biomechanics in response

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to blast events was conducted. Due to computer limitations, the FEM sheep model used a small number of elements that were insufficient to capture steep pressure waves inside the lungs [6, 7].

Stuhmiller et al used the 3D human thorax/lungs FEM model and Ls-Dyna FEM software tools to study biomechanics of thorax and lung responses to blast wave loadings. [8, 9] The model had sufficient resolution to simulate the dynamics of pressure waves within the lung and against the heart. In a recent study, a fully coupled CFD-FEM FSI model capable of simulating blast wave interaction with a thorax has been developed. In this model, a pressure wave can penetrate into the tissue and propagate in the lung. This model solves the fluid-structures interaction problems needed to model blast wave lung injury. Also, the two-dimension chest finite element model was established to study the spread of blast wave in lung tissues of the human body [10]. The size, shape and internal structure of the two-dimension chest model referred to the human body model in the VHP of the United States, and the space between the 5th and the 6th breastbone was chosen as the cross section of the two-dimension model; the chest size of 210 mm × 310 mm, the thickness of 1.4cm, and 4 layers of 2-D shell element types were established. The aforementioned mathematical models and animal experiments showed a good correlation between the animal injury and the maximum inward chest wall speed.

These models above were simplified during establishing the chest finite element model so that there were less geometric similarity and less dynamic similarity between these models and the real models, and it restricted the research of the mechanism causing blast injury.

Therefore, the modeling method based on the real Chinese standard human body was adopted in the paper to establish a finite element model loaded by blast waves, which could not only present the changing mechanical process of the chest wall after being impacted but also forecast the occurrence of injury. The model employing the real geometrical shape of a human body was thus true and very accurate, and of more practical significance.

2 Principles and Methods

2.1 Calculation Principle

When a blast wave encounters the human chest with higher density, it will both reflect off the object and diffract around it. The magnitude of the reflected pressure is related to both the incident shock strength and to the angle of incidence of the blast wave. The incident wave will also penetrate the chest wall and generate shear and compression stress waves within the human chest [11].

The total pressure (the peak reflected pressure, p_r) on the chest wall is the sum of the dynamic pressure, q , and the static pressure, p_s :

$$p_r = 2p_s + (\gamma - 1)q , \quad (1)$$

where γ is the ratio of specific heats.

The Lobdell-Viano model used in thoracic injury biomechanics during a blast wave impact [1] can also be expressed in a general Newton's second law form:

$$p_r = m\frac{dv}{dt} + Dv + k\Delta u , \quad (2)$$

where m is the mass of the chest wall, v is the velocity of the chest wall, D is the damping coefficient, k is the spring constant, Δu is the chest deformation.

Consider the lungs as the compressed objects, and further deduce to get the mathematical model of chest wall movement:

$$\frac{mdv}{dt} = (p_r(t) - p_0(1 + 0.5(\gamma - 1)\frac{v}{c_0})^{\frac{2\gamma}{\gamma-1}} - \frac{p_0 mx}{\rho_1 h}) \quad (3)$$

In the formula, p_0 , ρ_0 and c_0 are respectively the initial pressure, density and sound velocity inside the lungs, v is the moving speed of the chest wall, γ is the heat capacity ratio, x is the movement distance of the chest wall, ρ_1 is the density of the chest wall, and h is the thickness of the chest wall.

If the chest wall velocity is very small compared with the speed of sound, then the equation can be expanded to give the linear form:

$$mdv = (p_r(t) - \rho_0 c_0 v - \frac{p_0 mx}{\rho_1 h})dt\,, \qquad (4)$$

Solve the first order constant coefficient differential equation to get the relation between the chest wall moving speed and the load of external blast wave:

$$v(t) = \exp(-\frac{\rho_0 c_0 t}{m}) + \frac{p_0 xt}{\rho_1 h} + \int \frac{p_r(t)}{m} dt\,, \qquad (5)$$

The model indicates that the chest wall moving speed is mainly determined by three factors, the first one is the size of external blast wave loadings, the second one is the pressure wave caused by movements of the chest wall, and the third is the internal pressure required by compression of the lungs and other organs. Among them, the size and duration of external blast wave loadings are playing a decisive role [12].

The blast wave of explosion impacts the human body through the fluid substance, i.e., the air and solid substance, and this process is a process of interaction between the fluid substance and solid substance. The pressure of the fluid substance will cause deformation to the solid substance, and the deformation of the solid substance will change the periphery of the fluid substance. The full fluid-structure interaction algorithm in Ansys Ls-Dyna is adopted in the paper to solve this problem.

In the analysis of explosion issues, the blast waves caused in the medium will cause the periodic interruptions of various physical quantities and will do problems to the solution, therefore, the artificial volume viscosity should be added to the pressure items in calculation so as to convert strong interruptions of the blast wave into circumstances of violent but continuous changes in a very narrow area, and this method is adopted in all prior /earlier studies of hydrodynamic forces by differential response programs and finite element programs in calculating the wave induced hydrodynamic forces, and only the specific algorithms are slightly different [13,14].

The standard algorithm is:

$$q = \rho l (C_0 l |\varepsilon_{kk}|^2 - C_1 a |\varepsilon_{kk}|)\,,\ \varepsilon_{kk} < 0\,;$$

$$q = 0,\ \varepsilon_{kk} > 0. \qquad (6)$$

In it: l is the characteristic length, a is local sound velocity, ρ is current mass density, $|\varepsilon_{kk}|$ is the trace of strain rate tensor, C_0 and C_1 are dimensionless constants.

After introducing the artificial volume viscosity q, the stress calculation formula is amended into:

$$\sigma_{ij} = s_{ij} + (p+q)\delta_{ij}\,. \qquad (7)$$

In the formula, p is pressure, s_{ij} is deviator stress tensor.

2.2 Modeling

The 3D model was constructed on the basis of the CT image data of normal adult Chinese males (170 cm tall, 65 kg weight, 35 years old). The gray-scale resolution of the CT image was 512 × 512 × 8 bits and scanning interval for the image sequence was 0.625 mm(Figure 1). Then input the CT image into Mimics13.0 software for reconstruction of the 3D model of the human thorax (Figure 2) and the 3D model including 5 parts that is, the lungs, heart, chest rib, soft tissues of the body and the shoulder blade. The 3D model constructed was represented in Figure 3.

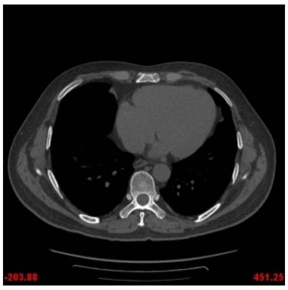


Figure 1. CT scan pictures.

Finally input the model file into the Ansys Icem CFD software for classification of tetrahedral mesh and establishing of air field, the air field is a cube with the size of 1000×1000×1500mm, the unit quantity of hexahedral element is 75204, and the quantity of various chest units and nodes are listed in Table 1 below.

Finally input the model file k into Ls-Dyna used for loading and solving of the blast wave.

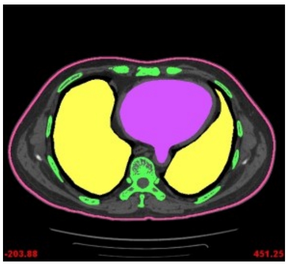


Figure 2. Different organs recognized in mimics software.

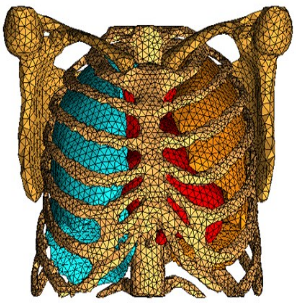


Figure 3. 3D Finite Element Model of thoracic bones and internal organs.

2.3 Loading and Solving of the Blast Wave

Loading and solving of the blast wave is completed by Ls-Dyna software, cm-g-μs units are developed FEM in Ls-Dyna, Material parameters for muscle and organs of the human thorax are listed in Table 2, the 3D solid element SOLID164 is adopted for presenting the chest model of the human body and air field, thereinto, the ALE algorithm of SOLID164 Unit is chosen for the air field because the structures of human organ model are very complicated, so the single-point integral algorithm of SOLID164 Unit is chosen, and the hourglass control is performed. In order to simplify the calculations, the elasticity constructive *MAT_ELASTIC is adopted for descriptions of the muscles, bones and organs.
As it is difficult to forecast the changes of contact circumstances of organs inside a human body, contact may happen between various organs impacted by the blast wave. Therefore, the automatic contact calculation method model offered by Ls-Dyna is adopted in this simulation research. In order to facilitate loading, the preset pressure-time curve is adopted in the research to simulate the impacts from the blast wave on the human body, the preset peak overpressure is 660kPa (Figure 4), peak overpressure becomes 100 kPa because of attenuation when it reaches the chest wall.

Table 1. Quantity for various organs of the chest

	Breastbone Rib	Shoulder Blade	Muscle Tissues	Heart	Lungs
Tetrahedron Element	30377	8110	38691	12568	39797
Node	9788	2321	9361	2645	8152

Table 2. Material parameters for muscle and organs of the human thorax

Materials	Density	Elasticity Module	Poisson’s Ratio
	(g/cm^3)	(GPa)	
Lung	0.21	1e-6	0.3
Shoulder Blade	1.25	2.18 e-4	0.3
Chest Rib	1.56	8 e-3	0.4
muscle	1.00	1.3 e-3	0.4
Heart	1.00	1.4 e-3	0.4

After performing the solving settings, the calculation time is 4000µs, 0.9 is chosen as the time step control factor, and export one result file every 20µs results binary data intervals is 0.5µs.

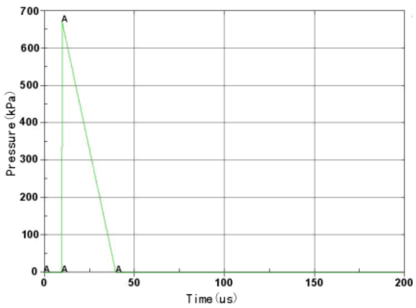


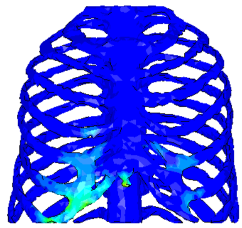
Figure 4. Load curve of blast wave

3 Experimental results

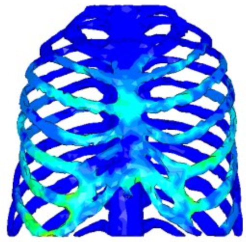
After loading the pressure from 100kPa blast wave on the chest, first a forward spreading blast wave is formed at 0.179ms; the blast wave arrives at the surface of the chest at about 0.279 ms, due to the differences of human body resistance, some blast waves spread inside the body while some other waves form reflected waves and the blast waves entering the body are impacting the chest wall and compressing the breastbones. The blast waves continue to move at 0.579ms, the diffraction phenomenon occurs around the chest, the roughly same pressures are formed on both sides; the pressure rapidly functions on back from both sides of the body at 1.079ms, the entire chest is surrounded by the pressure field; the blast waves continue to spread ahead from the chest at 1.639ms, and complete the loading process from the blast waves on the chest.

3.1 Stress Changes after Impacts on Chest Wall

As indicated in Figure 5, first the 6th and 7th right soft ribs begin to move inward at 0.280 ms after the chest wall is impacted, and the stress received at that time is the largest compared to other parts of the chest wall. At 0.339ms, with the further loading of blast waves, the color indicator bar of the 3rd and 4th soft ribs and the 6th and 7th ribs starts to darken. At 0.460ms, the color indicator bar of the whole frontal breastbone ribs starts to darken, and the color indicator bar of the 4th and 5th ribs behind the chest starts to darken. At 0.939ms, the color indicator bar of the entire thorax starts to darken.



t = 2800 µs



t = 4600 µs

Figure 5. Stress Diagram for the Thorax after Being Loaded with Blast Waves

3.2 Changes of Chest Wall Displacements

As indicated in Figure 6, the thorax starts to move inward after the blast wave loading on the chest wall, the color of the color indicator bar of the 5th and 6th soft ribs is the darkest at 0.359ms, the color of the color indicator bar of the connection between the 3rd, 4th and 5th soft ribs and the ribs is the darkest at 0.459ms, the color of the color indicator bar of the connection between the 4th and the 5th ribs is the darkest at 0.579ms, and the color of the color indicator bar of the manubrium and the mesosternum is the darkest at 1.079ms.

3.3 Changes of Chest Wall Speed

As indicated in Figure 7, the speed of moving inward of the ribs is evidently different after the blast waves loading on the chest wall, the color of the color indicator bar of the 5th soft rib is the darkest at 0.319ms, the color of the color indicator bar of the connection between the 3rd, 4th, 5th soft ribs and the ribs is the darkest at 0.419ms, the color of the color indicator bar of the 4th, 5th ribs and the manubrium is the darkest at 0.579ms, the color of

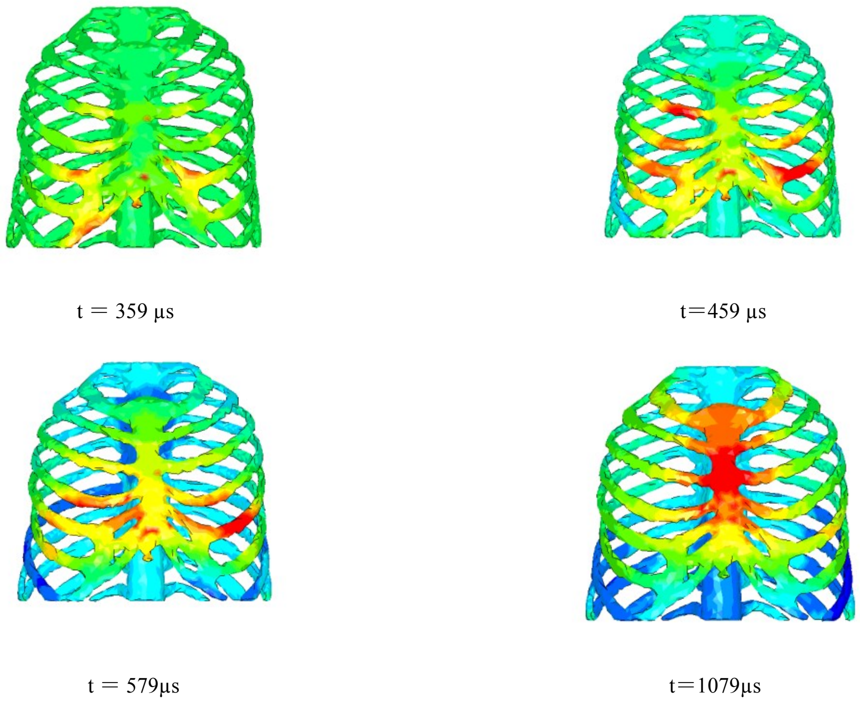


Figure 6. Displacement Diagram for the Chest Wall after Being Loaded with Blast Waves

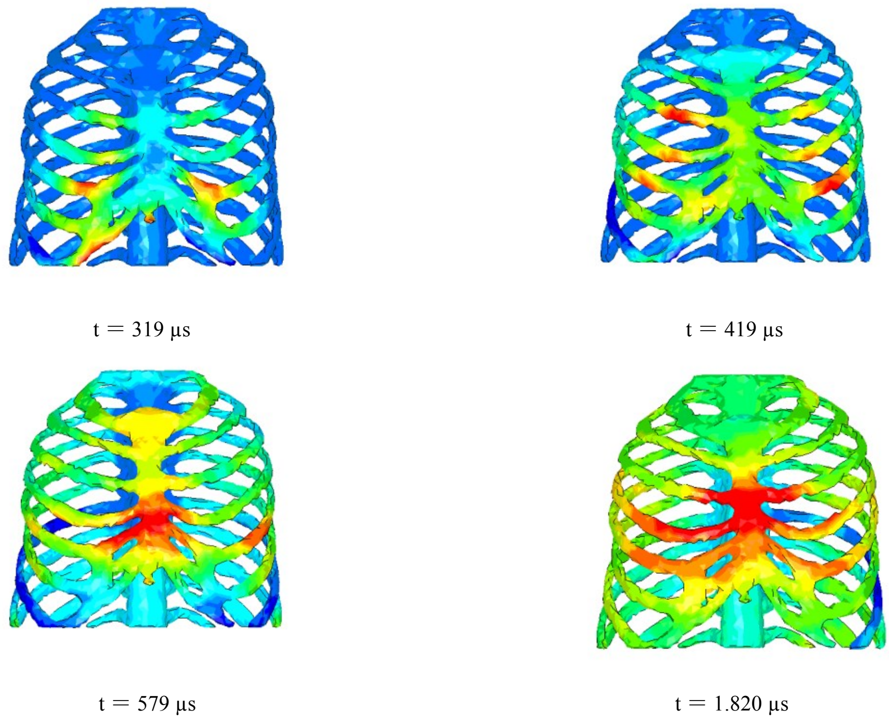


Figure 7. Moving Speed Diagram for the Thorax after Being Loaded with the Blast Waves

the color indicator bar of the 3rd, 4th, 5th ribs and the corresponding manubriums is the darkest at 1.820ms. It shows that the 3rd, 4th, 5th ribs have the maximum inward moving velocity.

The point of the 5th rib which is 2cm away from breastbone is chosen as the rib movement position in the paper, and the maximum inward moving speed of the rib obtained at t = 0.58ms is 1.6m/s, and the moving speed change curves of the ribs is illustrated in Figure 8.

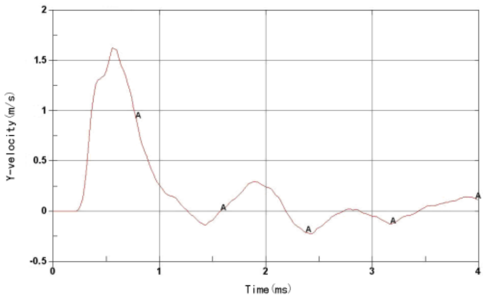


Figure 8. The 5th rib velocity curve loaded by blast wave of 100kPa peak overpressure

4 Discussions and Conclusion

Alexander D.Greer et al. forecast the primary blast injury of the blast wave through establishing a two-dimensional chest finite element simplified model, the 5th rib is chosen as the cross section of the two-dimensional model [15], it offers a new thought for forecasting the blast injury with finite element. In addition, according to Bass curve, the human body is not injured after loading the blast wave at pressure 100kPa. Hakan Axelsson et al consider that there is a sound correlation between the ASII injury score, animal injury and the maximum inward chest wall speed in the biologic effect research of complex blast waves [5]. The people are not injured when the maximum inward chest wall speed is less than 3.6 m/s, the injury is slight to minor when the chest wall speed is 3.6 – 7.5 m/s, the injury is minor to medium when the chest wall speed is 4.3–9.8m/s, and the injury is medium to serious when the chest wall speed is 7.5-16.9 m/s. The simulation research shows that the maximum inward moving speed of the 5th rib of the chest wall is 1.6m/s after loading the blast wave at the pressure of 100 kPa, the human body is not injured, and this is consistent with the injury data forecast by Bass curve and the forecast injury of the maximum inward chest wall speed.

Mimics is adopted in the paper to construct the 3D finite element model of the human body, the Ls-Dyna finite element software is adopted to analyze the stress and movement changes of the human chest wall after being loaded with the blast wave, the research results indicate: the rib stress changes, inward movement displacements and speeds are different on different occasions; the inward moving speed of the 3rd, 4th and 5th ribs is the highest, among them the maximum inward moving speed of the 5th rib of chest wall reaches 1.6m/s after being loaded with the blast wave at peak overpressure 100kPa for 1ms, the human body is not injured, this mutually verifies with the research achievements from other scholars, and the results show they are consistent.

Therefore, three-dimensional finite element model of the human thorax constructed in the paper is appropriate, the numerical simulation results are reliable, they basically reflect the loading process of the blast wave, and also explore another method for the research into blast injury mechanism.

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