Finite element analysis of the dynamic response of the cardiovascular system to the blunt ballistic impact

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Abstract

On the basis of the Chinese Visible Human Dataset (CVHD), a three-dimensional human finite element model that includes skin, muscle, bone, the lungs, the heart and the vascular trunk was developed. In the LS-DYNA software environment, a numerical simulation of the blunt ballistic impact, which was caused by a 5.56-mm rifle bullet moving with the speed of 910 m/s toward a human torso wearing a composite body armor vest, was performed, and the stress and pressure response of the cardiovascular system were calculated. The simulation results demonstrated that the blunt ballistic impact introduced a high-frequency pressure response on the chambers of heart, which was characterized by a high amplitude and short duration. The peak values of the pressure waves, measured at the ascending aorta and superior vena cava ports, were 659.3 kPa and 542.8 kPa respectively, which suggested that the blunt ballistic impact on the chest would result in injury to distant target organs through the cardiovascular system. The computational results of this model can provide a basis for predictions of heart injuries, in-depth studies of the mechanical mechanism of cardiovascular injuries to blunt ballistic impacts and further improvements in protective equipment.

Key words: blunt ballistic impact, cardiovascular system, dynamic response, finite element analysis

1 Introduction

In regional conflicts and violent terrorist attacks, gunshot wounds are one of the main threats. Use of body armor can effectively reduce the occurrence of penetrating wounds, but the blunt ballistic impact generated from body armor after it is hit by a bullet can still possibly cause damage to human tissues and organs [1]. The cardiovascular system is often an important target of blunt impacts. In an accident investigation in 2001, Siegel discovered that whether cardiac trauma occurred after the blunt impact to the chest was an important determinant of survival [2]. The cardiovascular system injuries caused by the blunt ballistic impact are very frequent in various types of military activities, but the injury mechanism, especially as to the biomechanical mechanism, is still unclear. Currently, physical models [3], animal experiments [4, 5], corpse tests [6, 7] and digital simulation models [8,9] are used for studying the dynamic response of blunt impact to the chest. Some researchers have performed finite element analyses of aortic rupture caused by blunt impacts [8]. However, the heart is treated as a single homogeneous medium in most studies, and this treatment is not sufficient for calculating the actual dynamic response of the cardiovascular system to the blunt ballistic impact. Until now, a general finite element simulation of the cardiovascular system's response to the blunt ballistic impact has not been reported. In this paper, a human torso finite element model, based on CVHD, to perform the numerical simulation of the dynamic response to the impact of a 5.56-mm rifle bullet on body armor was constructed. Through the analysis of the stress and pressure distribution rules of cardiovascular system, the characteristics and mechanisms of cardiovascular injuries caused by the blunt ballistic impact would be discussed. The research can provide in-depth studies of the mechanical mechanism of the cardiovascular injuries caused by the blunt ballistic impact and further improvements in protective equipment.

2 Principles of cardiovascular system's response to the blunt ballistic impact

The response of cardiovascular system to the blunt ballistic impact is a complex mechanical problem related to the processes such as how bullets penetrate body armor, the collision between the armor and the human body, and the propagation of pressure waves in the human body.

When bullets penetrate body armor, if the contact stress σ is greater than dynamic yield limit of σ_r^D, plastic deformation of the bullets or body armor occurs. According to the basic formula of stress waves, the backward speeds after the bullets and body armor impact v_1, v_2 are shown as follows respectively,

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$$v_1 = \frac{\sigma}{\rho_p c_{ep}}, \quad (1)$$

$$v_2 = \frac{\sigma}{\rho_t c_{et}}. \quad (2)$$

At this time, the relative speed VEA is the bullet-impact speed limit, which is also known as H-K speed limit:

$$v_{EA} = \sigma_r^D \left(\frac{1}{\rho_p c_{ep}} + \frac{1}{\rho_t c_{et}} \right), \quad (3)$$

where ρ_p is the density of the bullet material, c_{ep} is the elastic wave velocity of the bullet material, ρ_t is the density of the protective material, and c_{et} is the elastic wave velocity of the protective material.

When the relative speed is increased, the relative compressibility of the solid is reduced. Consequently, a pressure wave forms in the solid. The relative speed at this time, VHA, is known as the speed limit of fluid deformation.

$$v_{HA} = \sqrt{\frac{K_t}{\rho_t}}, \quad (4)$$

where Kt is the volume compression modulus of the protective material.

After instantaneous deformation of the body armor, a collision with the body surface occurs, and the remaining energy is transmitted to the body in the form of pressure wave. According to the classical theory of biomechanics, the vast majority of human tissues are nonlinear viscoelastic materials, and their response depends on the loading conditions. According to Ogden's [10] nonlinear elastic material theory and Christensen's [11] viscoelasticity theory, the stress-strain relationship is as follows:

$$\sigma = \mu * \lambda_x^{\alpha-1} + \int_0^t G * e^{-\beta(1-\tau)} \frac{\partial \varepsilon}{\partial \tau} d\tau, \quad (5)$$

where α is the Ogden model material parameter, μ is super elastic modulus of human tissue, β is the Christensen model parameter, and G is viscoelastic modulus of human tissue.

3 The mechanical mechanism of cardiovascular injuries to the blunt ballistic impact

Two mechanisms are suspected to explain cardiovascular injuries to the blunt ballistic impact: First, compression and shear force of the sternum and ribs acts on the intermediate organs, which causes structural damage to the heart and surrounding tissue; Second, transmission of pressure wave in the cardiovascular system causes damage to the distant parts of the body. The cardiovascular system is a pressure circulation loop, and the blood is an incompressible continuous fluid medium; therefore, pressure wave attenuation is less in the cardiovascular system than in other tissue. The transmission of pressure wave in blood vessels may cause injury to distant target organs (such as the brain). Such injury effects are called remote effects. Bir confirmed that the blunt ballistic impact can cause structural damage to the heart, lungs and other organs [7]. An animal study on behind-armor blunt trauma demonstrated that exposed animals exhibited decreased cardiac capacity [12]. Cripps et al claimed that the in vivo pressure wave that are generated by the blunt ballistic impactsare the main cause of damage to internal organs [13]. Cernak found that the pressure wave caused by explosion are transmitted to the distant parts through the cardiovascular system [14]. Courtney argued that the blunt ballistic impact may cause similar injuries to the human body [15]. These results suggest that the increase in blood vessels pressure during the blunt ballistic impact may be significant enough to cause the cardiovascular injuries.

4 Numerical simulation

The dataset was obtained from CVHD provided by the Digital Medicine Institute of the Third Military Medical University at http://cvh.tmmu.edu.cn/cvhstore/index.asp. This resource was freely available. The original specimen for the digitized human dataset was the dead body of a 35-year-old Chinese male with a height of 170 cm and weight of 65 kg. After frozen embedding, milling was performed using an industrial milling drill, and the cross-sections were then photographed. The dataset included 2518 cross-sectional images with a section spacing of 1.0 mm and a horizontal pixel size of 0.167 mm. The continuous images of the layers 1405-1709 were selected for reconstruction of a three-dimensional model of the human chest.

The human images were imported into the Mimics version 16.0 software. In the segmentation module, three-dimensional geometric model was established. The generated geometrical model was saved in STL (standard triangle language) files. The STL format of the geometric model was imported to HyperHesh version 10.0, which was used to generate the corresponding shell and solid elements. The chest model was composed of 15 parts and included 91,339 nodes, 527,020 tetrahedral elements and 9,612 shell elements. The skin was constructed from shell elements, whereas the muscle equivalents, bone, the lungs, the heart, blood vessels and blood were constructed from solid elements. The complete chest finite element model is shown in Figure 1. The cardiovascular system includes cardiac muscle, the left ventricle, the left atrium, the right ventricle, the right atrium, the ascending aorta, the superior vena cava, the inferior vena cava and blood. The details of the cardiovascular model are shown in FIGURE 2. Linear elastic properties were used for bone and viscoelastic properties were used for other tissues and organs. The material parameters and constitutive relations are described in the references [8, 16, 17, 18]. The material parameters of various tissues are presented in Table 1.

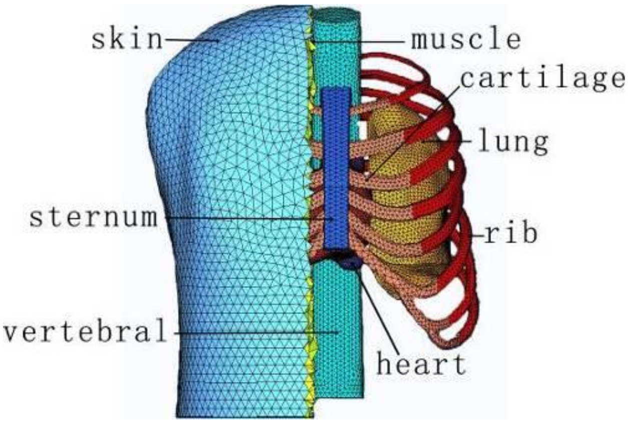

FIGURE 1 Complete finite element model of the chest

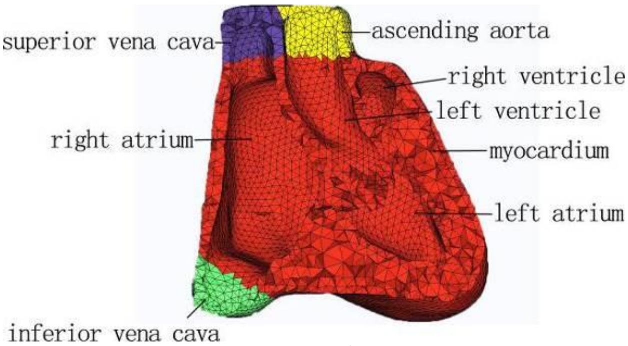

FIGURE 2 Finite element model of the cardiovascular system

A 5.56-mm rifle bullet, which was composed of the bullet core and the shell case, was used. The MAT_JOHNSON_COOK elastic-plastic material model in the GRUNEISEN state equation was adopted. The body armor was a composite structure that was composed of a panel of alumina ceramic and a backboard of high-density polyethylene fibre. For the ceramic material, the MAT_JOHNSON_HOLMQUIST-CERAMICS damage material model was used. For the high-density polyethylene fibre plate, the MAT_COMPOSITE_DAMAGE composite material model was used. A face-intrusive contact between the bullet and body armor was used to simulate the penetration of a bullet into the body armor. The bullet impact point was located in the middle of the sternum, and the bullet's initial speed was 910 m/s. The bullet was shot along the horizontal direction. A detailed model chart is presented in FIGURE 3. After a K file was generated in HyperMesh, it was imported to the finite element software package ANSYS/LS-DYNA version 11.0 to perform the computation.

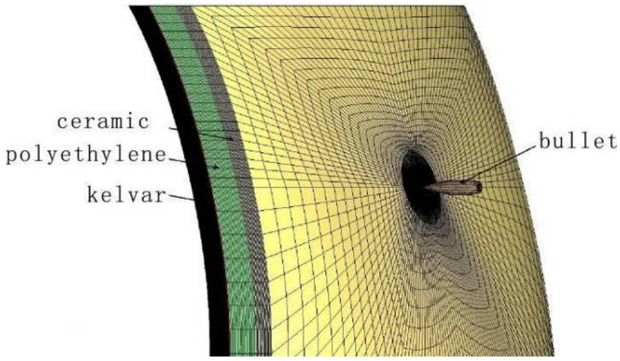

FIGURE 3 The finite element model of bullets and composite body armor

TABLE 1 The material parameters of the various tissues in the human finite element model

Tissues	ρ/(kg/m^3)	K/GPa	G_0/KPa	G_∞/KPa	β	E/GPa	υ
Skin	1200	2.9	200	195	0.1		
Muscle equivalents	1120	1.03	200	195	0.1		
Sternum	1250					9.5	0.25
Cartilage	1170					0.0025	0.4
Ribs	1180					9.5	0.2
Spine	1330					0.355	0.26
Cardiac muscle	1120	0.744	67	65	0.1		
Lung	600	0.744	67	65	0.1		
Artery	1120	0.744	67	65	0.1		
Blood	1060			2000		1×10^{-10}	0.5

Note: β- attenuation coefficient; G_0-short-term elastic shear modulus; G_∞- long-term elastic shear modulus; K - elastic bulk modulus; E - modulus of elasticity; υ- Poisson's ratio

5 Results and analysis of numerical simulation

After the LS-DYNA computation was finished, the post-processing program prepost was used to determine the stress distribution at different times and the pressure response at different locations.

When the bullet hit the body armor, the stress was transmitted to the heart and other internal organs in the form of wave. At t=48 μs, the stress wave reached the surface of the heart. Over time, the stress fields expanded to the surroundings. At t = 2000 μs, the stress wave covered all areas of the heart surface and transferred to the inferior vena cava. FIGURE 4 shows the Von Mises equivalent stress distribution on the surface of the heart at different times. Figure 5 presents the Von Mises equivalent stress distribution of cross-section of the heart, which shows the distribution of the stress wave in the chambers of the heart at different times.

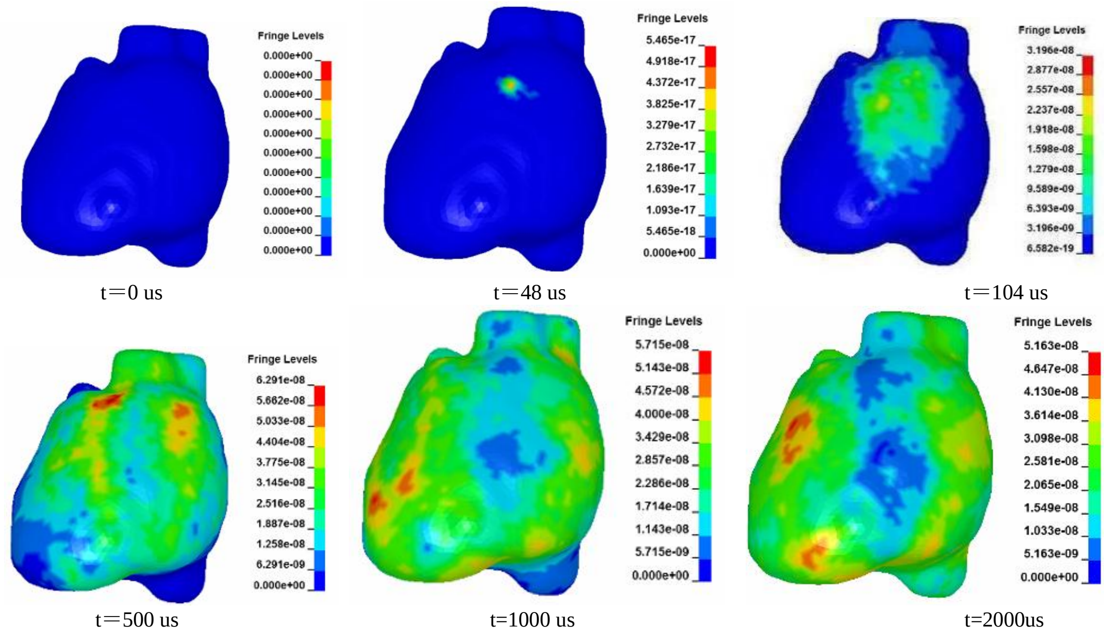

FIGURE 4 Equivalent stress distribution on the surface of the heart at different times

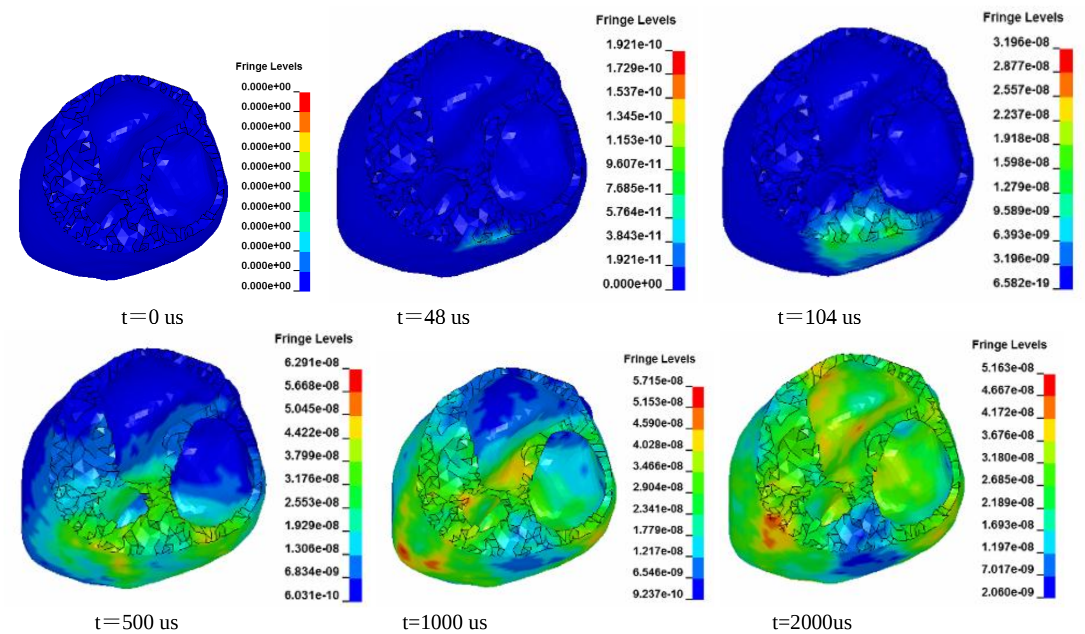

FIGURE 5 Equivalent stress distribution in the chambers of the heart at different times

The blunt ballistic impact introduced a high-frequency pressure response in the human cardiovascular system, which was characterized by a high amplitude and short duration. The pressure curves for the ventricles and atria are shown in Figure 6. The peak of the instantaneous pressure in the left ventricle was the greatest, with a value of approximately 0.8012 MPa, and the peak of the instantaneous pressure in the left atrium was the lowest, with a value of approximately 0.3167 MPa. Figure 7 shows the pressure curves in the ascending aorta and superior vena cava.

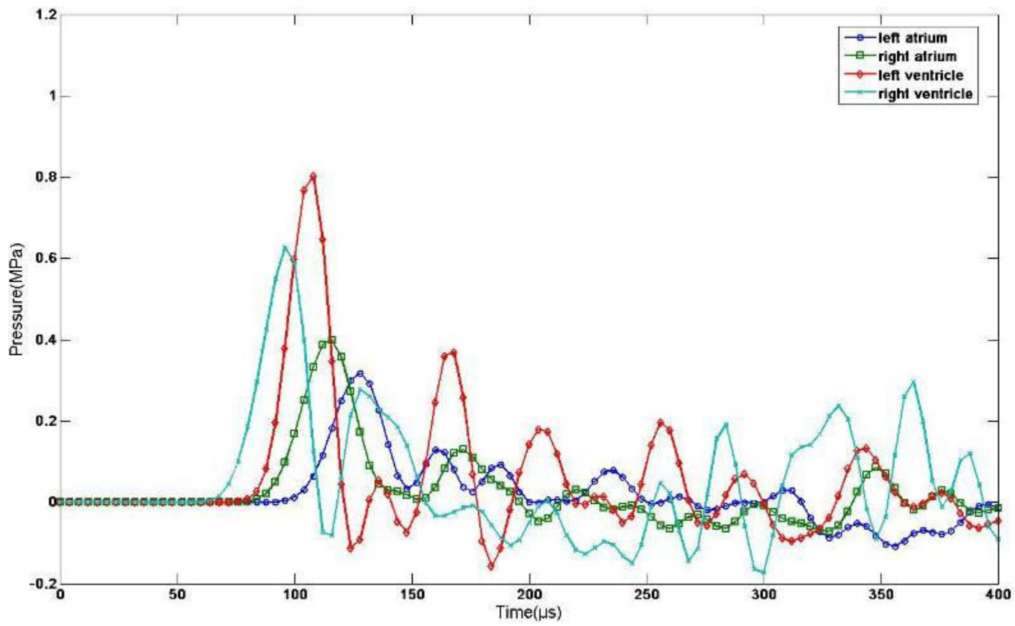

FIGURE 6 The pressure curves for the atria and ventricles

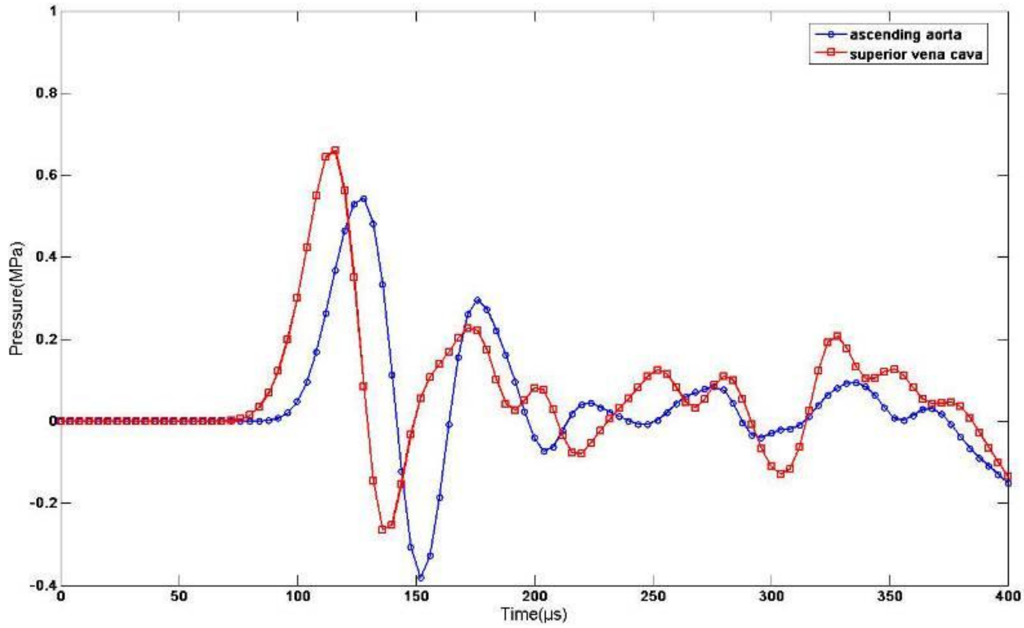

FIGURE 7 The pressure curves for the ascending aorta and superior vena cava

In this model, the maximum Von Mises stress of the heart appeared at the left ventricle, and the sites of the peak values of pressure waves were the left ventricle, right ventricle, right atrium, and left atrium, in descending order; the pressure peak in the ventricle was 2-3 times that in the atria. The results suggested that the ventricle is easier to rupture than the atria, which was consistent with the results of an accident investigation from Siegel [2]. When the intracranial pressure reaches 100-300 kPa, it can cause mild-to-moderate brain injuries [19]. The peak values of high-frequency pressure waves measured in the ascending aorta and superior vena cava port were 659.3 kPa and 542.8 kPa respectively, that suggested the pressure wave generated from the blunt ballistic impact might be transmitted from the cardiovascular system to the brain. Currently, the rules of transmission of high-frequency pressure wave in the cardiovascular system are still unclear, and they should be further studied in the future.

6 Conclusions

The present study proposes a computer-based simulation approach to investigate the response of cardiovascular system to blunt ballistic impacts. A three-dimensional finite element model, which includes human cardiovascular organs is developed. By using this model, the numerical computation of the stress distribution and pressure response of cardiovascular system under the blunt ballistic impact are implemented. The human injury results predicted by the model are found to agree with the injury effects observed in animal experiments and reported in the literatures. The model accurately reflects the morphological structure of the heart cardiovascular system, that will be helpful in the design of impact protection systems.

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