Brain Injury Caused by Rifle Bullet Impacting Bulletproof Plate: Experiment and Simulation

Xingyuan Huang

Hunan University of Science and Technology

Xiaoping Hu

Hunan University of Science and Technology

Zhihua Cai (✉ caizhihua003@163.com)

Hunan University of Science and Technology

Research

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1 **Brain injury caused by rifle bullet impacting** 2 **bulletproof plate: Experiment and Simulation**

3 Xingyuan Huang, Hunan University of Science and Technology, Xiangtan, China,
4 411201, hxyuan97@163.com.

5 Xiaoping Hu, Hunan University of Science and Technology, Xiangtan, China, 411201,
6 hxp210@163.com.

7 Zhihua Cai, Hunan University of Science and Technology, Xiangtan, China, 411201,
8 caizhihua003@163.com. **The corresponding author of this paper.**

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10 **Abstract**

11 **Background:** In wars, when bullets impact the bullet-proof helmet, kinetic energy
12 will be transferred from the skull to brain tissue, resulting in the rapid deformation,
13 stretching, shearing and final destruction of the soft tissue. In recent years, with the
14 continuous upgrading of protective equipment, the penetration ability of bullets into
15 protective equipment has gradually decreased, but the problem of head injuries caused
16 by deformation of the back of the helmet has become increasingly prominent. It is of
17 great significance and value to study the brain trauma caused by the bullet impact of
18 the bullet-proof helmet.

19 **Methods:** First proceeded the rifle bullet impact physical brain model experiment and
20 the results were used to verify the simulation process of high-speed bullet impact,
21 simulated the bullet hitting brain model from different directions (front, side, rear) and
22 different incident angles (0°, 15°, 30°), then evaluated the craniocerebral injury by
23 analyzing skull stress, intracranial pressure, principal strain, and shear strain.

Results: When impact from the rear, the peak intracranial pressure and skull stress increase by 20%-25% compared to the front impact, and the principal strain and shear strain are 1.5-2.2 times than that of the front impact. In the same impact direction, the severity of brain injury will increase with the increase of incident angle. When the incident angle increases from 0° to 15°, the intracranial pressure and skull stress both increase, the principal strain and shear stress increase sharply with 6-7 times.

Conclusions: Under different shock conditions, the dynamic response of the brain is sensitive, and the impact position and angle of the bullet have important influences on the brain. It is more likely to be caused injury during rear impact, and as the incident angle increases, the severity of the injury will become more serious.

Keywords: Bullet impact experiment; Brain dynamic response; Brain Injury

Background

Traumatic brain injury is caused by external mechanical force or head movement caused by rapid acceleration, deceleration, and rotation [1]. In modern warfare, when the kinetic energy or shock wave of bullets and fragments impacts the bulletproof helmet, the kinetic energy will be transmitted from the skull to the brain tissue, causing the rapid deformation, stretching, shearing, and final destruction of the intracranial soft tissue, resulting in secondary brain damage [2]. Previous scholars have researched wound ballistics and biomechanics through experiments and numerical simulations [3-6]. The researches on the helmet and its cushion foam are as follow, Tham et al. [7] conducted a ballistic test to study the response of the KEVLAR helmet under bullet impact and found that the KEVLAR helmet can withstand the

47 impact of an all-metal armored bullet traveling at a speed of 358m/s without being
48 penetrated. Long et al. [8] studied the protective performance of traditional helmets
49 under the impact and compared the performance differences of different helmet
50 shapes. The researchers also analyzed the helmet shell material and helmet lining or
51 cushioning system [9-11]. In early experimental studies, the main target was live
52 anesthetized animals (such as pigs, dogs, and sheep). Oukara et al. [12] developed
53 corpse and animal impact test models, dummy tests, and finite element brain models
54 for numerical simulations of brain risk assessment, among which numerical models
55 can predict different types of brain injuries. Rafaels et al. [13] conducted statistical
56 analysis on the brain damage caused by bullet impact bulletproof helmets through
57 cadavers brain injury experiment. Due to moral restrictions and legal prohibitions in
58 most countries, human tissue simulants (such as gelatin, soap, etc.) have been
59 introduced into experiments in recent years. Gelatin is used in wound ballistic
60 research because its mechanical properties are considered to be similar to those of
61 human tissues [14-16]. Freitas et al. [17] used the outer skull plus inner soft tissue to
62 replace the brain tissue to study the dynamic response of the brain caused by the
63 bullet impact of the bulletproof helmet. This experimental model can be used to
64 intuitively measure the physical quantity of the brain injury. Simulation methods are
65 also widely used, Yang and Dai et al. [18] studied the impact of bullets at different
66 angles on FE head models wearing helmets for simulation studies and analyzed the
67 comparison of head injuries in different directions. Pintar et al. [19] used experiments
68 and simulation to study the response of the skull and brain tissue under the impact of

bullet-proof helmets. Salimi et al. [20] used simulation analysis to study the impact of helmet liner materials on brain injury. Different liner materials are related to brain acceleration, intracranial pressure, and shear stress.

In recent years, with the continuous upgrading of protective equipment, the penetration ability of bullets into protective equipment has gradually decreased, but the problem of head injuries caused by deformation of the back of the helmet has become increasingly prominent. It is of great significance and value to study the brain trauma caused by the bullet impact of the bullet-proof helmet. This research provides a reference for the optimization design of bulletproof helmets and the improvement of protective structure in the future.

Methods

Rifle impact experiment materials

- (1) 5.56mm rifle bullets
- (2) 5.56mm ballistic gun and lampstand
- (3) Pure PE level-5 bulletproof plate
- (4) EVA cushion foam with the density of 45kg/m³
- (5) Acceleration sensors with a range of 10000g and 5000g
- (6) Pressure sensor with measuring range of 2Mpa and 1MPa
- (7) Multi-channel dynamic signal acquisition and analysis system
- (8) High-speed photography system
- (9) Photoelectric speed measuring device
- (10) Human brain physical model

Rifle impact experiment

According to reports, the U.S. Enhanced Combat Helmet (ECH) has been able to withstand the high-speed impact of rifle bullets. In this experiment, bulletproof plate made of ultra-high molecular weight polyethylene was selected, which use the same material as ECH. Compared with helmet, bulletproof plate is more convenient to observe the dynamic response when impacted, and avoid penetrating damage to head model, ensure that the model can be reused, and reasonably control the cost of experiment. Firstly, drill holes on the skull of model to fix and install the acceleration sensor, and then arrange pressure sensor inside model with the sensitive surface facing impact direction. After the sensor is installed, it is connected to multi-channel dynamic signal acquisition system and debugged to ensure normal use. The rifle bullet launching device is facing the shooting aim point marked on bulletproof plate. Combine the model, bulletproof plate and cushion foam together and fix it on the experimental bench. The assembly process is shown in **Fig.1a**. According to the schematic diagram of rifle bullet impact experiment, the experimental site and equipment are arranged as shown in **Fig.1b**. A photoelectric speed measuring device is arranged between launching device and experimental platform to measure the speed in front of the target, and a high-speed photographing device is arranged on the side of experimental platform. After the installation was completed, 5.56mm rifle bullets were fired to conduct a frontal impact experiment on the head model.

Finite element model

The brain finite element model has been established in the early stage. The brain

pressures, skull responses and the brain skull relative displacements of finite element model have been verified refer to the relevant literature [21-22]. It can be used to study the dynamic response of the brain under the impact of rifle bullets and conduct damage analysis. This model include scalp, bone tissue (cortical bone, spongy bone, in-cortical bone, facebone, mandible), soft tissue (csf, cerebrum, callosum, ventricle, brain stem, cerebellum), membrane tissue (pia mater, dura mater, tentorium cerebelli, falx cerebri), as shown in **Fig.1c**.

The bulletproof plate finite element model is established in HyperMesh (Altair Engineering Inc., Troy, MI, USA). The size of bulletproof plate is 350mm*200mm*20mm. The impact area of the model is encrypted as shown in **Fig.1d**, the grid size of encrypted area is 1mm*1mm*1mm, the remaining grid size is 2mm*1mm*1mm, and the number of grids is 680000. The material of the bulletproof plate refers to the research of Ryan, Garcia et al. [23-24], use MAT22 (MAT_COMPOSITE_DAMAGE) to simulate the material properties of its ultra-high molecular weight polyethylene fiber. The material parameters are as follows **Table 1**.

Table 1 Material parameter of bulletproof plate

ρ (kg/m ³)	E_a /GPa	E_b /GPa	E_c /GPa	ν_{ba}
1006	40.6	40.6	2.6	0.008
ν_{ca}	G_{ab} /GPa	G_{bc} /GPa	G_{ca} /GPa	S_{ZX} /GPa
0.044	1.75	1.6	1.6	0.9
K_{FAIL} /GPa	AOPT	MACF	S_C /GPa	X_T /GPa
2.2	0	3	0.5	3.6
Y_T /GPa	Y_C /GPa	ALPH	S_N /GPa	S_{YZ} /GPa
3.6	3.0	0.5	0.9	0.9

The cushion foam finite model is established in Hypermesh, the size of the foam is 100mm*100mm*30mm, as shown in **Fig.1e**, the grid size is 1mm*1mm*1mm, and the number of grids is 300000. Choose the same EVA foam material as the impact test, simulate its material properties with MAT57 (MAT_LOW_DENSITY_FOAM), its density is 45kg/m³, elastic modulus is 4.16Mpa, and load its stress-strain curve.

The 5.56mm bullet finite model is established and meshed in Hypermesh. As shown in **Fig.1f**, the grid size is 0.5mm*0.5mm*0.5mm, and the number of grids is 2900. In the simulation calculation, the bullet model uses the Johnson-cook relationship to simulate the thermal viscoplastic response of copper. The specific material parameters are shown in **Table 2**. Johnson and Cook express the flow stress as

$$\sigma_y = (A + B\bar{\varepsilon}^n)(1 + c \ln \dot{\varepsilon})$$

where

A, B, C and n are input constants

$\bar{\varepsilon}^n$ effective plastic strain

$$\dot{\varepsilon} = \frac{\dot{\varepsilon}}{EPS0} \text{ normalized effective strain rate}$$

Table 2 Rifle bullet material parameter

A (GPa)	B (GPa)	C	N	m
0.09	0.292	0.025	0.31	1.09
ρ (kg/m ³)	c (J/kg K)	Shear modulus (Gpa)	Bulk modulus (Gpa)	
8950	1.75	47.27	102.4	

Combine bullet, bulletproof plate, cushion foam, and brain model into an impact model, restrict the freedom of bulletproof plate in six directions (the translational and

149 rotational degrees of freedom in the XYZ directions) according to the experimental
 150 conditions. Because the impact time is extremely short, the impact of the head's own
 151 motion is not considered, so the six degrees of freedom of the head are restrained in
 152 impact direction at the same time. In the experiment, the photoelectric velocity
 153 measurement system measured the velocity of the bullet was 970.78m/s, so the rifle
 154 bullet model was given an initial velocity of 970m/s, and the final rifle bullet impact
 155 model is shown in **Fig.1g**.

Fig.1 Rifle impact experiment and Finite element model. **a** Installation process of bullet impact experiment. **b** Schematic diagram of rifle bullet impact experiment. Finite element model of Brain (**c**), Bulletproof plate (**d**), EVA cushion foam (**e**), Rifle bullet (**f**). **g** Rifle bullet impact model.

Result

Finite element model verification based on impact experiment

The initial thickness of bulletproof plate is shown in **Fig.2a**, the average thickness of three different positions is taken as 20.64mm. After the impact experiment, the size of deformation area, the profile of maximum deformation, the rupture of bulletproof plate at the bullet incident point are shown in **Fig.2b**. The corresponding damage of bulletproof plate in the simulation are shown in **Fig.2c**, the comparisons between experiment and simulation are shown in **Fig.2d**.

Refer to the installation position of acceleration sensor in craniocerebral physical model (**Fig.1a**), select the same position in finite element model (**Fig.2e**) to output the skull acceleration value and compare it with the sensor data (**Fig.2f**).

Fig.2 Finite element model verification based on impact experiment. **a** Initial thickness of bulletproof plate. **b** Damage of bulletproof plate after impact experiment. **c** Damage of bulletproof plate in impact simulation. **d** Comparison of experiment and simulation. **e** Points location of finite element. **f** Acceleration of Point 1~3.

The deformation of bulletproof plate in experiment is 13.65mm (34.29mm-20.64mm=13.65mm), and the maximum deformation in simulation is 12.83mm. The size of convex deformation area of bulletproof plate in the experiment is about 75mm*70mm, and the size of the deformation area in the simulation is about 82mm*66mm. The initial time of the experimental curve is the time when the corresponding sensor starts to record data. Compare the acceleration curve of simulation result and experimental result, deviation mainly comes from the difference in the position of points and the difference between physical model and simulation model material. The acceleration peak in simulation is slightly higher and the appearance time is later than the experiment, but the overall peak value and the change trend are consistent, which can verify the effectiveness of finite element model.

Mechanical characteristics and brain injury under different impact directions

Using the established and verified finite element model for simulation analysis, 5.56mm rifle bullets impact the bulletproof plate from the front, side and rear at the speed of 970m/s. The positions of the points measured in the simulation are shown in

Fig.3a, where points A and G, points B and F, points C and E belong to the same organization respectively.

In order to study the propagation law of shock wave in the brain and refer to the evaluation criteria of craniocerebral injury, simulation outputs intracranial pressure, skull stress, principal strain, shear strain at different locations during the impact.

The cloud diagram of maximum intracranial pressure, maximum skull stress, maximum principal strain, maximum shear strain under different impact directions are shown in **Fig.3c**. It can be seen that the intracranial pressure is higher when subjected to rear impact, but none of them reaches the criteria for moderate injury of 173-235KPa proposed by Ward et al. [25]. It can be seen that the peak stress of skull during the frontal impact is the minimum, which is 54.6MPa. The peak stress of the skull during side impact is 54.62MPa, while the rear impact is the maximum of 68.86MPa, but they are all smaller than the 75MPa VonMises stress value of the skull yield strength studied by McElhaney [26]. Therefore, the skull in this simulation will not be fractured, and the grid will not be deleted. Galbraith et al. found that when the principal strain of brain tissue is greater than 0.25, structural damage will occur. When the principal strain is greater than 0.2, the brain will experience functional damage and cause irreversible damage. When the principal strain of the brain is greater than 0.1, the brain will suffer damage but can be restored to normal state [27]. Zhang et al. [28] found that when the shear strain of brain is greater than 0.14, there is a 25% chance of causing some degree of TBI, if the shear strain is greater than 0.19, there is a 50% chance of causing TBI, if the shear strain is greater than 0.24, there is 80%

chance of causing TBI. It can be seen from the simulation that principal strain value and shear strain value of brain during front impact are the smallest, both less than 0.1. During side impact, the principal strain and shear strain of brain are larger than those of front impact, but they are also less than 0.1, so there will be no damage. In the rear impact, the principal strain of the brain reaches 0.017, and the shear strain reaches 0.0138. Therefore, the rear impact is more likely to cause head injury during the impact.

Fig.3c shows the peak history curve of intracranial pressure at each impact direction. It can be seen that the intracranial pressure value rises in oscillation at about 0-0.15ms, and then the curve tends to stabilize in the oscillation. The smallest peak intracranial pressure was 52.8KPa at frontal impact; the maximum intracranial pressure was 64.2KPa at rear impact.

Fig.3d shows the stress change at various points during different impact directions. It can be seen from the figure that from point A to point E, the stress values show a downward trend, and the stress values from point E to point G show an upward trend. The position of point A is closest to the impact side and belongs to the same tissue as point G. Therefore, the stresses at points A and G are relatively large. The positions of points C, D and E are in the brain tissue, the stress values are relatively smaller than other places and decrease along the direction of the impact gradually. Since points F and G are closer to the skull, their stress values are larger, so the stress values of points E, F, and G gradually increase.

Mechanical characteristics and brain injury under different incident angles

The 5.56mm rifle bullet impacts the bulletproof plate vertically at a speed of 970m/s and the angles of the X axis at 15° and 30°. The simulation model and measuring point positions are shown in **Fig.3e**. Among them, point A and point G, point B and point F, point C and point E belong to the same organization at the same time, and the positions of two working conditions are the same.

The cloud diagram of maximum intracranial pressure, skull stress, principal strain, shear strain under different incident angles are shown in **Fig.3f**. It can be seen that the intracranial pressure will increase with the increase of the angle of incidence, but it does not reach the injury standard of 173-235KPa proposed by Ward et al. [25]. It can be seen that the peak skull stress value is 62.83MPa at 15° impact, the peak skull stress value at 30° impact is 66.84MPa, and the peak skull stress value at 0° impact is 54.6MPa. The stress values are all less than the skull yield strength of 75MPa obtained by McElhaney's research. There is no fracture of the skull in the simulation, and no deletion of the grids. It can be seen that the principal strain and the shear strain are the smallest when the impact angle is 0°. When the bullet impacts with an incident angle of 15°, the principal strain and shear strain of the brain are less than 0.1, but they are greater than impact at 0°. When a bullet impacts at an incident angle of 30°, the principal strain and shear strain of the brain are also less than 0.1, but they are greater than the impact at 15°, exceeding 0.05. The simulation results show that as the incident angle of the bullet increases, the principal strain and shear strain of brain tissue will increase, which is more likely to cause brain injury.

Fig.3g shows the peak history curve of intracranial pressure at different incident angles. It can be seen from the curve that the peak intracranial pressure at 0° impact is the smallest with 52.8KPa, the peak intracranial pressure at 15° impact is 60.3Kpa, the peak intracranial pressure at 30° impact is the largest with 63.6KPa.

Fig.3h shows the stress changes at various points when the bullet impacts model at different incident angles. It can be seen that from point A to point C, the stress value shows a downward trend, and the stress value from point E to point G shows an upward trend. Since the points F and G belong to the same tissue as the points B and A respectively, and are closer to the skull, their stress values are larger. At the same time, it can be seen from the data that as the incident angle increases, the stress values of most points in the skull increase.

Maximum principal strain

Maximum shear strain

Peak intracranial pressure

Fig.3 Mechanical characteristics and peak value under different impact directions and angles. **a** Schematic diagram of impact direction and point location. **b** Peak value under different impact directions. **c** History of peak intracranial pressure under different impact directions **d** Stress at each point during different impact directions.

e Schematic diagram of incident angles and point location. f Peak value under different incident angles. g History of peak intracranial pressure under different incident angles. h Stress at each point during different incident angles.

Discussion

This research first conducts rifle bullet impact experiment, use 5.56mm rifle bullets to impact the bulletproof plate-cushion foam-brain physical model, measure and record acceleration data through the sensor and signal acquisition system, then the data are used to verify the simulation of high-speed bullets impact process. The simulation results of brain model under high-speed impaction are basically consistent with the acceleration peaks and changing trends measured by the sensors in the bullet impact experiment. The difference may due to the deviation between test points' position and the simulation points' position and the material characteristics between physical model and finite model. The finite model used in this study includes detailed scalp, hard bone tissue, brain tissue and soft tissue, which are closer to the actual situation of the human brain. The simulation results further prove the accuracy of the model, which can accurately reflect the biomechanical response of the human brain, and it has good sensitivity to the brain dynamics response of different load conditions.

The stress of skull is used to assess whether the skull fracture is caused, and the brain injury is assessed by the intracranial pressure, principal strain and shear strain of the brain. There are significant differences in the damage caused by bullets impacting brain model from different directions (front, side, rear) and different incident angles (0°, 15°, 30°). The changes in intracranial pressure, skull stress, principal strain and

shear strain of brain tissue under different working conditions are analyzed, and the peak comparison of each mechanical parameter are shown in **Fig.4a-b**.

Fig.4a Comparison of peak intracranial pressure and skull stress. **b** Comparison of peak principal strain and shear strain.

According to the research of Zhang et al. and Galbraith et al., when EVA foam is used as the protective liner, it did not cause brain damage. It can be seen from the peak intracranial pressure and peak stress of skull that when impacting the brain in different directions, the intracranial pressure did not reach the threshold of moderate injury and skull fracture. When impact from the rear, the peak intracranial pressure and skull stress increase by 20%-25% compared to the front impact, and the principal strain and shear strain are 1.5-2.2 times than that of the front impact. In the same impact direction, the severity of brain injury will increase with the increase of incident angle. When the incident angle increases from 0° to 15°, the intracranial pressure and skull stress both increase, the principal strain and shear stress increase sharply with 6-7 times. At the same time, it is found that the transmission of shock waves in the model will not only gradually attenuate along the impact direction, but will also be transmitted in the same tissue, which may cause superimposed damage.

Conclusion

The finite element model used in this reasearch can reflect the biomechanical response of human brain and is sensitive to the dynamic response of brain under different impact conditions, the impact position and angle of the bullet have important influence on the response of the brain. It is more likely to be caused injury during rear impact, and as the incident angle increases, the severity of the injury will become more serious.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

XYH and ZHC conducted the experiments. XYH collected and analyzed the data and drafted the manuscript. ZHC, XPH gave technical and contributed to the study design and supervised the project. ZHC obtained funding. All authors read and approved the final manuscript.

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Figures

Figure 1

Rifle impact experiment and Finite element model. a Installation process of bullet impact experiment. b Schematic diagram of rifle bullet impact experiment. Finite element model of Brain (c), Bulletproof plate (d), EVA cushion foam (e), Rifle bullet (f). g Rifle bullet impact model.

Figure 2

Finite element model verification based on impact experiment. a Initial thickness of bulletproof plate. b Damage of bulletproof plate after impact experiment. c Damage of bulletproof plate in impact simulation. d Comparison of experiment and simulation. e Points location of finite element. f Acceleration of Point 1~3.

Figure 3

Mechanical characteristics and peak value under different impact directions and angles. a Schematic diagram of impact direction and point location. b Peak value under different impact directions. c History of peak intracranial pressure under different impact directions d Stress at each point during different impact directions. e Schematic diagram of incident angles and point location. f Peak value under

different incident angles. g History of peak intracranial pressure under different incident angles. h Stress at each point during different incident angles.

Figure 4

a Comparison of peak intracranial pressure and skull stress. b Comparison of peak principal strain and shear strain.