Research on the Dynamic Response of the Cranium and Brain to Shock Waves Based on Biomechanical Model

Jiajia ZOU[1], Bin YANG[1*], Feng GAO[1*], Ronghua ZHOU[2], Xuan MA[1], Xingyu ZHANG[1], Yehui SHI[3, 4]

[1]*School of Transportation Engineering, Nanjing Institute of Technology, Nanjing 211167, Jiangsu, China*

[2]*Zhiwu Yunxiang (Nanjing) Information Technology Co., Ltd., Nanjing 210031, Jiangsu, China*

[3]*Big Data Center of Jiangsu Geological Bureau, Nanjing 210007, Jiangsu, China*

[4]*Nanjing Kuntuo Civil Engineering Technology Co., Ltd., Nanjing 210000, Jiangsu, China*

Email: 18105178207@163.com, yangb123@126.com, g1850696719@163.com, 18611073228@163.com, 15252359272@163.com, 18473256993@163.com, admin@kentop.cc

[*]Correspondence: yangb123@126.com and g1850696719@163.com

Abstract: To investigate the protective effects of helmets against human head injuries under various shock wave conditions. A finite element head-helmet coupling model was developed to analyze how helmets influence biomechanical response parameters, such as intracranial and cranial pressure, when subjected to a single impact wave and its accompanying shock wave. This includes scenarios like single frontal impact, positive continuous impacts, successive sidewall impacts, and simultaneous frontal and lateral impacts. The dynamic changes in brain tissue within an impact environment were examined to evaluate helmet performance in protecting the human head. Under a single frontal impact, helmets effectively reduced intracranial pressures in the frontal, occipital, and parietal lobes by 32%, 38%, and 19%, respectively, while also significantly lowering the stress peak at the back of the skull. During positive continuous impacts, helmets decreased intracranial pressure in the parietal and occipital lobes by 36% and 21%, respectively, although their effect on frontal lobe pressure was limited due to insufficient facial protection. For successive sidewall impacts, helmet protection delayed the impact wave, reducing frontal lobe intracranial pressure by 60 kPa but increasing parietal lobe pressure by 80 kPa, thus alleviating stress on the skull's rear but increasing stress on the opposite side. In the case of simultaneous frontal and lateral impacts, lateral impacts increased parietal intracranial pressure by 20 kPa, with the right hemisphere experiencing more pressure than the left due to the mitigating effect of reflective side impacts on skull stress. Compared to single impact waves, accompanying shock waves pose a greater risk to cranial injuries due to their prolonged impact. As shock waves originate from different directions and heights, helmet protection for the face is minimal. These findings offer valuable insights into the biomechanics of head injuries under shock waves and can inform the design of improved helmets.

Keywords: concomitant shock wave; cranial tissue; dynamic response; protective helmet; biomechanical response

1. Introduction

In today's global community, the frequent occurrence of traffic accidents has made a significant number of casualties alarmingly common. Of particular concern is the high incidence of head injuries from impact shockwaves, especially traumatic brain injuries (TBI), which can account for 15 to 20 percent of all injuries [1-2]. Such injuries severely impact people's neurological functions and quality of life, presenting considerable challenges for medical treatment. Impact can result in different injury patterns depending on the circumstances [3-5]. While helmets are effective head protection devices, comprehensive research on their protective properties in various shockwave scenarios is still lacking.

In recent years, scholars have conducted comprehensive research on shockwave-induced craniocerebral injuries.

Using a multi-body model and a precise head model, Singh et al. [6] recreated the head's kinematics during accidents and found that impact height significantly affected translational and rotational acceleration. Townsend et al. [7] evaluated brain material models in the bTBI computational model through computational and experimental approaches, discovering that brain material parameters greatly influenced strain and intracranial pressure (ICP). Azar et al. [8] studied the factors affecting helmet protection effectiveness and found that goggles and helmets substantially reduced intracranial pressure and mechanical impact in simulations of head-on impacts and high frontal blunt impacts. Accidents reduced impact forces by 49%–52%, while impacts reduced cranial stress and intracranial pressure by 80% and 84%, respectively. Huang et al. [9] developed a shockwave-helmet-head fluid-solid coupling model to simulate helmet responses to shockwaves in impact traumatic brain injuries, finding that an advanced combat helmet (ACH) could reduce brain damage by approximately 5%, whereas full-coverage helmets reduced it by 65%. Li et al. [10] avoided conservative assessments of the Axelsson damage model by understanding the complex behavior of reflected shock waves on the humanoid device's surface. These findings provide valuable references for engineering applications and damage assessment. Ganpule et al. [11] investigated helmet efficiency in reducing IED shockwaves and found that effectiveness depended on the helmet gap. Li et al. [12] examined helmet protection mechanisms against shockwaves from far-field impacts using experimental and numerical simulations, showing reduced peak overpressure at the head's top but potential increases at the rear. Despite the critical role of helmets in preventing shockwave-induced head injuries, their protective effects are limited, necessitating further research to enhance helmet design and materials [13-15].

This paper examines the effects of wearing or not wearing a helmet when the head is exposed to continuous shock waves. While most research has focused on single impact waves, this study explores how the head responds to continuous impacts. By modeling a simplified head-helmet system and the impact environment, we analyze biomechanical response parameters, such as pressure distribution around the head, peak intracranial pressure, and peak cranial stress. This analysis aims to understand the kinetic response of the cranium and brain under continuous shock waves, providing valuable insights for biomechanical studies of head injuries and research into the protective performance of new helmet designs.

2. Models and methods

2.1 Establishment of head-helmet finite element model

The finite element model of the human head-helmet system primarily includes the skull (comprising cortical and trabecular bones), brain, cerebellum, scalp, dura mater, meninges, pons, falx, and cerebrospinal fluid (CSF). The helmet model is made from Kevlar® K129 material [16] and is secured with straps, without using foam padding for impact absorption.

The material properties of the head and helmet are presented in Table 1, with the soft tissue neck parameters sourced from the literature [16].

Table 1. Material characteristics of the head model

Performance data for head modelling materials	Densities(g/cm^3)	Modulus of elasticity (GPa)	Poisson's ratio
Cortical bone	2.00	15	0.22
Cerebrospinal fluid	1.04	0.00015	0.499989
Dura mater	1.14	0.0315	0.45
Face	2.50	5.54	0.22
Cerebral scythe	1.14	0.0315	0.45
Cerebellum	1.04	0.000123	0.49

Neck (soft tissue)	1.06	0.11	0.45
Soft Mening Meninges	1.13	0.0115	0.45
Scalp	1.13	0.0167	0.42
Cerebral Curtain	1.14	0.0315	0.45
Trabecular bone	1.30	1	0.24
Upper brain (cerebrum)	1.04	0.00219	0.4996

2.2.1 Single frontal shock wave simulation

Non-reflective boundary conditions are employed on artificial boundaries to model infinite domains. These conditions are applied in a single planar shock, using five non-reflective surfaces with free-flow boundary conditions to allow material inflow and outflow. Returning the outflow air is essential to prevent an environment with excessive negative pressure. To minimize the reflection of expansion and shear wave energy back into the model, non-reflective and equilibrium outflow boundary conditions are used [17].

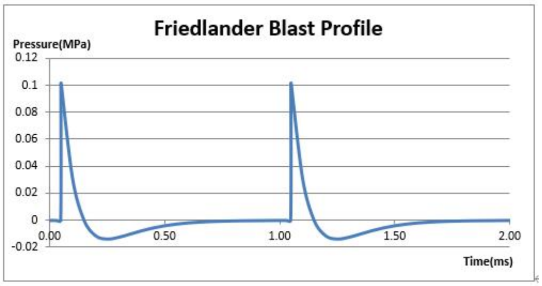

Figure 1. Profile for two continuous impact waves

2.2.2 Simulation of accompanying shock waves

（a） Positive Continuous impacts

In this simulation, the head target is assumed to be far from the shock source and subjected to two successive frontal impacts and two planar shock waves, each with an intensity of one atm. The impact waveform illustrated in Figure 1 is used, and the boundary conditions are set as a non-reflective border between free inflow and equilibrium outflow to accurately recreate this event. To validate the analytical results, the impact test scenarios were examined using simulated head models both with and without helmets.

（b） Successive Sidewall Impacts

In this scenario, two successive impact the frontal plane or face of the head. To simulate the situation where the head is near a wall, the left side of the cube's transverse plane is configured as a reflective boundary wall (330 x 330 x 6 mm). The other four planes are set with non-reflective boundary conditions for "free inflow and equilibrium outflow".

（c） Simultaneous Frontal and Lateral Impacts

This scenario is designed to simulate simultaneous frontal and lateral impact waves impacting the head. In this setup, the lateral and frontal impacts occur concurrently, allowing for a comparative analysis of their combined impact on head injuries versus a single frontal impact.

3. Results

Based on intracranial pressure (ICP) tolerance criteria from brain damage analyses and in vivo animal testing, a peak ICP exceeding 235 kPa may lead to severe brain damage, whereas an ICP below 173 kPa may result in only mild or negligible damage [18]. Shear deformation of the brain occurs when brain tissue is displaced or distorted in different directions due to external forces such as shock waves. This phenomenon can severely affect the brain's structure and function, with an ICP of 15 kPa considered the threshold for the onset of injury [19]. Consequently, the severity of craniocerebral injury can be assessed by measuring intracranial pressure. Additionally, by comparing the cranial fracture threshold from biological experiments with cranial stress from analyses [19-20], von Mises cranial stress can serve as a crucial parameter for evaluating cranial stress. The locations of the measurement nodes for ICP and cranial stress are shown in Figures 2 and 3.

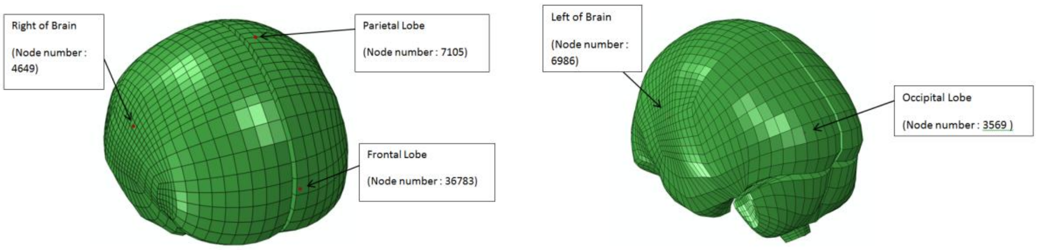

Figure 2. Location of nodes at the brain where intracranial pressure is measured

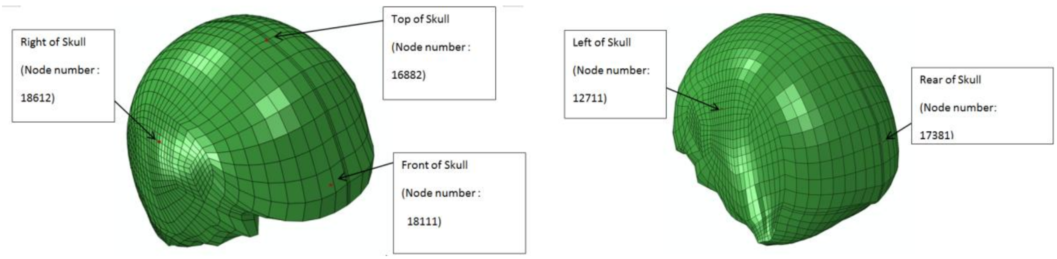

Figure 3. Location of nodes at skull where stresses are measured

3.1 Simulation results of a single frontal impact

By examining the travel of shock waves over the head when a helmet is worn, researchers have found that the wave impacts the face at approximately 0.35 ms, with high pressure gradually accumulating in the space between the jawbone and the neck. However, because the impact wave reflects off the front of the helmet, there is no direct impact on the skull and reduced pressure on it. As depicted in Figure 4, the impact wave enters the helmet from both sides and reaches the back of the head at 0.8 ms.

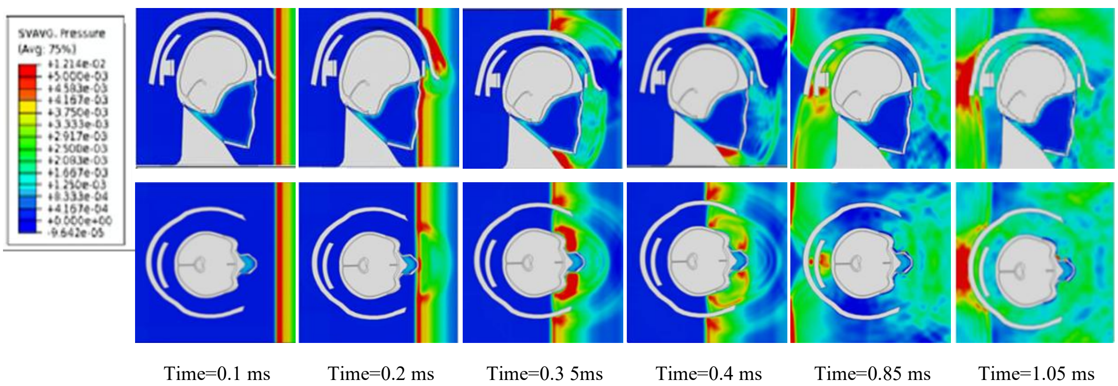

Figure 4. Pressure distribution of a single frontal impact on the head while wearing a helmet

Based on the analysis of intracranial pressure distribution data, the side of the head (temporal lobe) first experiences higher pressure at around 0.55 ms. The intracranial pressure then propagates from anterior to posterior between 0.60 ms and 1.0 ms. The shockwave impacts the anterior side of the head at 0.675 ms, causing cranial stress to spread from the anterior to the parietal area over approximately 1.050 ms. Subsequently, cranial stress moves from the top to the back of the head at 1.325 ms. However, cranial stress returns to the anterior portion of the skull between 1.425 ms and 1.85 ms.

When a impact wave strikes an unhelmeted head and is compared to one wearing a helmet, it is found that the shock wave directly impacts the skull for approximately 0.275 milliseconds. Additionally, the impact wave creates a pressure ring at the back of the skull, resulting in increased pressure that lasts for about 0.8 ms.

According to Grujicic et al. [3], a single impact wave simulation of the Friedlander shock wave distribution was conducted for both helmeted and unhelmeted heads. The results indicated that intracranial pressure in the head without a helmet ranged from 0 to 120 kPa. In contrast, the Advanced Combat Helmet (ACH) effectively provided head protection, maintaining pressures between -80 kPa and 80 kPa [17]. Comparing these simulation results with existing literature revealed a broader range of intracranial pressures, possibly due to the foam padding in the helmet model not performing as expected [17]. Furthermore, in a study by Tan et al. [16], it was noted that the cranial force on a helmeted head should range between 6 and 11 MPa when simulating a 1 atm overpressure TNT shock. A comparison of these results with literature data showed a slightly lower cranial stress level, which might be attributed to differences in the biological head materials used in the two simulations.

3.2 Simulation Results of Positive Continuous impacts

When a helmet is worn, it is shown that the shock wave first strikes the face and then concentrates in the area behind the lower jaw for about 0.375 ms. It is important to note that the shock wave does not directly contact the skull; instead, it reflects off the front of the helmet, thereby reducing the direct impact on the skull. At 0.375 ms, the impact wave enters the helmet through the side openings, as depicted in the head pressure distribution plot (Fig. 5). When the packing is replaced by the helmet band, the shock wave flows into the gap between the head and the helmet, then exits from the back. Consequently, the shock wave wraps around the back of the head and affects the occipital part of the optic nerve. At 0.975 ms, the impact wave returns to the back of the head due to negative pressure, and at 1.2 ms, a second shock impacts the face while enveloping the front and sides of the head. The impact wave focuses on the sides at the gap between the head and helmet, subsequently moving to the back of the helmet where it accumulates at 1.97 ms. At 2.15 ms, the impact wave flows back to the front of the head, with the shock wave accumulating in the gap between the head and helmet. By 2.7 ms, most of the impact wave has gathered at the front of the head.

Based on the analysis of intracranial pressure distribution, it was observed that the shock wave first reached the frontal lobe from the temporal lobe within 0.5 ms. Subsequently, high intracranial pressure spread and propagated from the anterior and posterior regions of the brain. At 1.0 ms, when the shock wave was concentrated, the intracranial pressure converged in the area of the lateral ventricle, the brain's center. At 1.325 ms, a second shock continued to impact the face, transmitting pressure to the brain through the soft tissues and skull. This process again subjected areas of the brain, including the frontal and temporal lobes, to high pressure. Immediately afterward, the pressure wave spread and propagated once more from the front and back of the brain, with the central regions again experiencing high pressure. Comparing the results of a single-plane shock, the lateral ventricles would have experienced a higher degree of intracranial pressure build-up, regardless of helmet use. This implies that the impact from the second shock could have resulted in more severe brain damage.

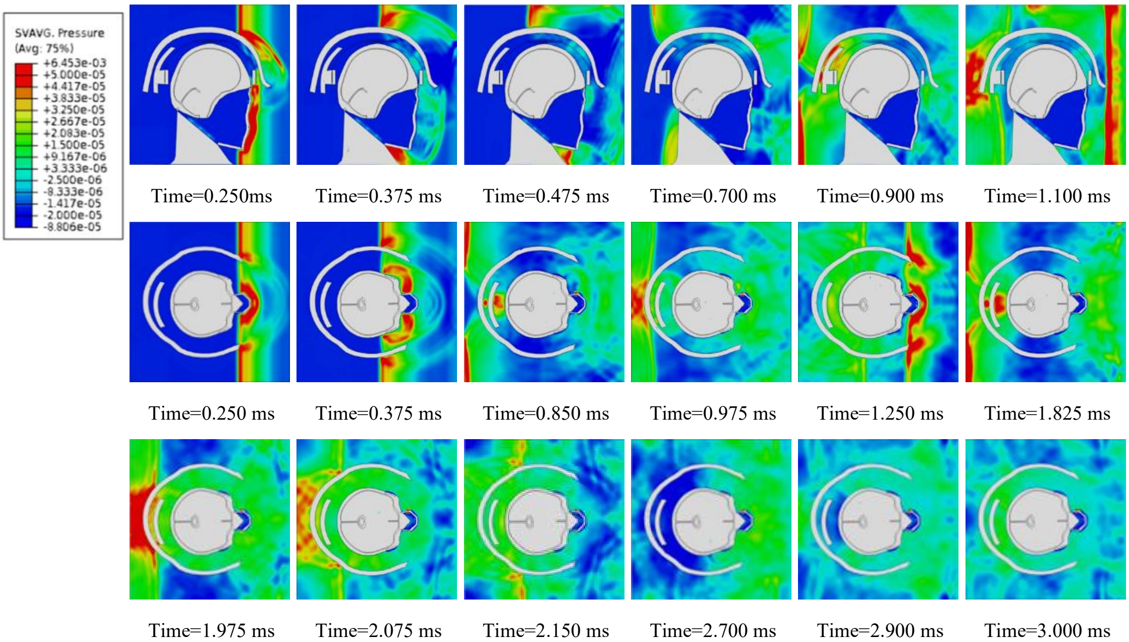

Figure 5. Pressure distribution of continuous frontal impact head while wearing a helmet

An analysis of head shocks in both helmeted and unhelmeted conditions revealed certain variations along with some commonalities. Specifically, at 0.25 ms, the sagittal distribution of impact pressure indicated that the shockwave affected both the face and the skull, suggesting a direct impact on the skull in the unhelmeted condition. This resembles the situation in the helmeted condition, where the shock wave surrounds the back of the head at 0.8 ms and 1.7 ms. When wearing a helmet, the posterior part of the head is protected, which reduces the pressure on the occipital lobe. Therefore, if no helmet is worn, the effect of the impact on the back of the head may be more pronounced.

3.3 Simulation Results of Successive Sidewall Impacts

The pressure distribution diagram, used to analyze the impact on the head of a helmet wearer, shows that the wall on the left side of the head model instantly reflected the initial forward shock wave after it struck the head's surface. During the first phase of the forward impact wave moving towards the back, the rebounded shock wave covered and reached the back of the head. At 0.775 ms, a high-pressure wave appeared behind the neck, possibly creating a "shock" effect at the back of the head. At 0.975 ms, the negative pole of the impact wave shifted, allowing the pressure wave from the first shock to meet the second impact wave at 1.175 ms. By 1.25 ms, both the front and back of the head were surrounded by high-pressure waves, which then gathered again. At 1.775 ms, the high-pressure wave concentrated at the back of the neck. At 1.875 ms, due to a change in the second shock wave, the high-pressure wave moved back to the front of the head. At 2.175 ms, the pressure wave was trapped at the back of the neck, and after reflection, it once again moved forward to the front of the head. By 2.875 ms, the high-pressure wave formed a ring around the front of the head. The head pressure distribution is illustrated in Figure 6.

The intracranial pressure distribution graph shows that high intracranial pressure gradually propagated from the anterior to the posterior part of the brain between 0.225 ms and 0.475 ms. The left side of the occipital and temporal lobes experienced numerous positive pressure spikes when the shock wave rebounded off the wall. Additionally, the right side of the head was under high pressure at 1.325 ms. The high-pressure wave that accumulated on the right side of the head was alleviated when a helmet was worn. This suggests that wearing a helmet reduces intracranial pressure on the right side of the brain.

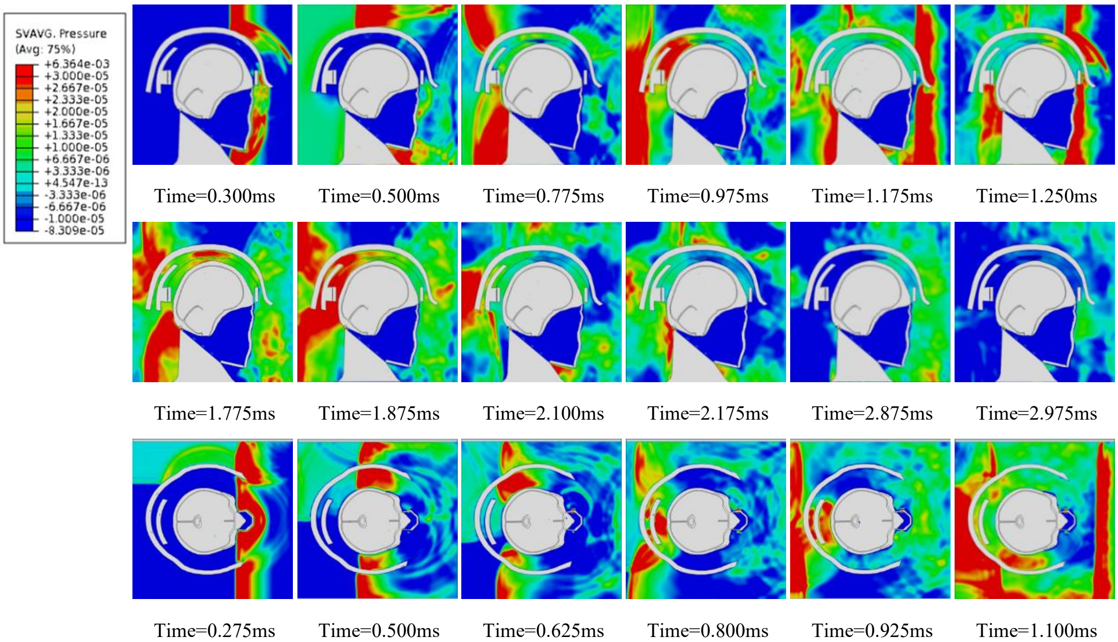

Figure 6. Pressure distribution of continuous lateral impact on the head when wearing a helmet

3.4 Simulation Results of Simultaneous Frontal and Lateral Impacts

Simulation results indicate that the shock initially impacted the left side of the head. At 0.4 ms, high-pressure waves were present on this side. By approximately 0.75 ms, these waves had converged on the right side of the head. At 0.85 ms, high-pressure waves had spread to the back and left side of the head, resulting in a "shock." During this time, the high-pressure wave produced an "impact" on these areas. The wave began to wrap around the head, and by about 1.3 ms, it started to completely envelop it once more. By 2.0 ms, the head was fully surrounded by the impact wave.

Initially, the peak of intracranial pressure (ICP) in the left temporal lobe appeared at 0.275 ms, with the ICP spreading from the front to the back of the head. High ICP was observed in the parietal lobe between 0.675 ms and 0.8 ms. By 1.225 ms, high ICP was concentrated in the lateral ventricles or nuclei of the brain, indicating that intracranial pressure was transmitted from the outside to the inside of the brain. At 1.7 ms, a significant increase in ICP was noted in the right temporal lobe, likely due to the shock wave converging on the right side and creating a powerful impact. Finally, at 2 ms, most of the brain tissue, including the lateral ventricles, experienced a very high ICP shock. The head pressure distribution is illustrated in Figure 7.

The pressure distribution graphs indicate that both helmeted and unhelmeted heads experienced similar shock rates overall. However, the unhelmeted head exhibited significantly higher intracranial pressure on the left side compared to the helmeted head, likely due to the protective effect of the helmet.

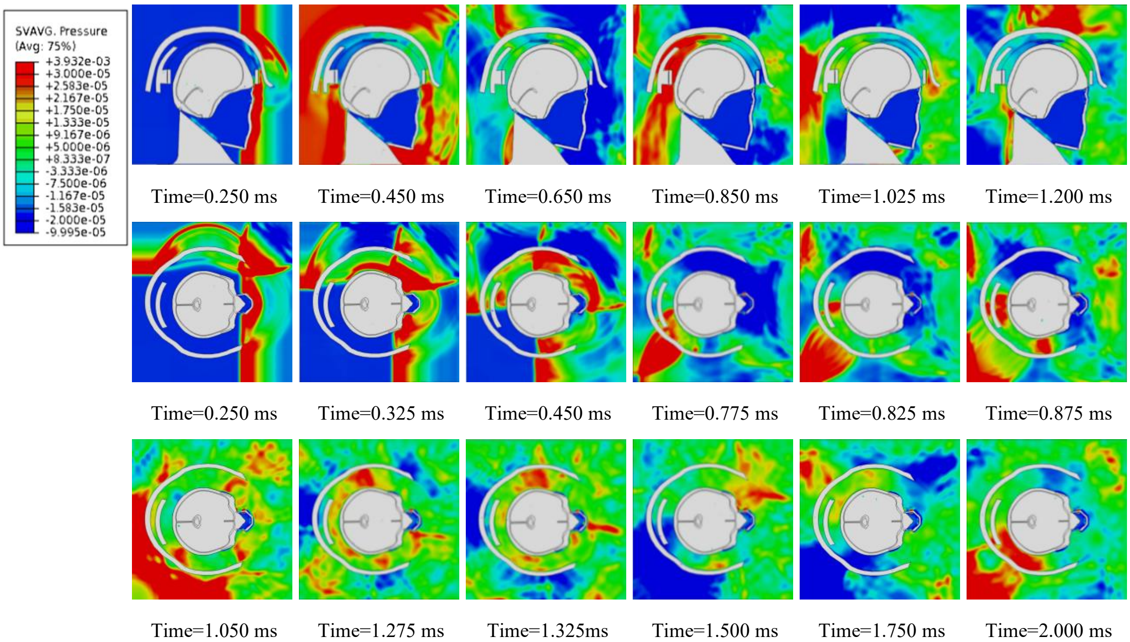

Figure 7. Pressure distribution of synchronous frontal side impact while wearing a helmet

4. Discussion

First, it's essential to thoroughly explain intracranial pressure (ICP). When comparing the peak ICP from a single frontal impact with and without a helmet, it was found that wearing a helmet reduced ICP in the frontal lobe by 32%, and in the occipital and parietal lobes by 38% and 19%, respectively. According to the head injury threshold [19], severe brain injuries are unlikely if ICP remains below 235 kPa. In frontal sequential impacts, the helmet reduced ICP in the parietal lobe by 36% and in the occipital lobe by 21%. However, ICP in the frontal lobe remained stable, suggesting that the helmet provides more substantial protection for the parietal region. Despite this, the benefit is not as pronounced because the parietal region is not the main pathway for stress transfer into the brain [21]. Severe brain injuries are more likely in unhelmeted heads, where ICP in the parietal lobe can reach 330 kPa, exceeding the 235 kPa threshold. Without helmet protection, pressure waves can still reach the brain, though the helmet does delay shock wave arrival. Helmets can substantially reduce the speed of shock wave propagation in successive sidewall impacts. In both frontal and lateral continuous impact scenarios, helmet use decreased frontal lobe pressure from 220 kPa to 160 kPa, and increased it from 210 kPa to 290 kPa. Comparing data from these scenarios reveals an increase in ICP in the occipital lobe during sidewall impacts with a helmet, suggesting that impact wave reflection mainly occurs from the occipital area. Notably, ICP changes in the parietal and occipital lobes were insignificant without a helmet. ICP measurements in the temporal lobes revealed a significant increase on the left side, likely due to frontal wall reflection. Intracranial pressure in the parietal lobe was slightly higher during simultaneous frontal and lateral impacts than in single frontal impacts; however, ICP in the frontal and occipital lobes remained similar between the two scenarios, indicating that additional lateral impacts primarily affect parietal ICP. This suggests that lateral impacts are unlikely to cause severe brain damage, as the parietal lobe is not the main route for pressure entry compared to single shocks. In simultaneous impacts, the effect on the frontal lobe is more significant than on the lateral aspect. Furthermore, higher ICP on the right side of the brain compared to the left might result from reflections from frontal and lateral impacts. According to the impact-induced head injury threshold, there is a potential for severe brain injury with simultaneous impacts, regardless of helmet use [19]. This means the additional lateral impact doesn't significantly raise the risk of severe brain injury.

Secondly, a detailed examination of cranial von Mises stresses is needed. In a single frontal impact, the stresses in the frontal and parietal regions were almost unchanged between unhelmeted and helmeted heads. However, the posterior cranium of the helmeted head experienced relatively higher stress intensities, suggesting that helmets can effectively reduce peak stress at the back of the skull. In positive continuous impacts, cranial stress in the frontal region of helmeted heads was significantly higher than in unhelmeted ones, potentially due to the impact wave between the helmet's front and the forehead, which could increase frontal lobe ICP. When comparing helmeted and unhelmeted states, stresses in the parietal and posterior sections of unhelmeted heads were relatively higher. Thus, helmets provide some relief from shock waves in these areas. In successive sidewall impacts, stress magnitudes did not change significantly in the front and left sides of the head, while stress at the back of the head slightly decreased with helmet use, demonstrating helmet effectiveness. However, stress on the right side increased with a helmet. Graphically, helmeted heads showed one significant peak stress of 10 MPa, with cranial stresses fluctuating between 4 MPa and 6 MPa, whereas unhelmeted heads showed multiple peaks between 6 MPa and 8 MPa. This highlights the helmet's role in reducing stress intensity on the right side of the skull. Helmets effectively reduce cranial stresses in the frontal, parietal, posterior, and left sides in simultaneous frontal and lateral impacts, significantly lessening the impact wave's impact on the brain.

5. Conclusions

Based on the head-helmet model, this study systematically investigated the kinetic response of the cranium and brain, as well as the protective performance of helmets under the influence of a single impact wave and accompanying shock wave. It also focused on analyzing the propagation characteristics of impact waves and the mechanisms of cranial and brain injury under scenarios of positive continuous impacts, successive sidewall impacts, and simultaneous frontal and lateral impacts. The specific conclusions are as follows:

1. Wearing a helmet can significantly reduce intracranial pressure in the parietal and occipital lobes in the event of positive continuous impacts. However, the frontal lobe is not as well protected. The helmet clearly offers protective benefits to the parietal and posterior regions of the head, though it is not entirely effective in preventing stressors from spreading through the main transmission channels of the intracranial cavity. Therefore, individuals without helmets are more susceptible to serious brain injuries, particularly in the parietal area.

2. In the case of successive sidewall impacts, wearing a helmet significantly reduces intracranial pressure on the right side of the brain due to shock impact, thereby delaying impact wave propagation. However, in extreme cases, intracranial pressure in the parietal lobe may still exceed normal limits. Helmets substantially lower intracranial pressure in the frontal lobe compared to scenarios of frontal sequential shocks, though the parietal and occipital lobes remain at risk, with elevated ICP in the occipital lobe possibly due to reflective effects. Despite helmets' ability to reduce stress peaks in the skull, severe brain injuries cannot be entirely prevented in extreme cases.

3. Compared to single shock simulations, the additional lateral impacts during simultaneous frontal and lateral impacts did not significantly affect intracranial pressure in the frontal and occipital lobes, but they did notably affect pressure in the parietal region. In this scenario, helmets reduced the impact of bomb shock waves on the brain and significantly lowered intracranial pressure.

4. Wearing a helmet greatly delayed the arrival time of impact waves in all simulations involving shock waves, thereby enhancing brain protection. However, the protective effect on the face was relatively limited.

Authors contributions

ZJ, BY, FG and RZ: Conceptualization, Methodology, Software, Writing - original draft preparation, Visualization. XM, XZ and YS: Conceptualization, Investigation, Validation, Writing - review & editing, supervision. All authors contributed to the article and approved the submitted version. ZJ, BY, FG and RZ are co-first authors and contributed equally to this study.

Acknowledgement

We appreciate the editors and referees for their valuable remarks and advice, which have significantly enhanced the clarity of the paper. We would also like to express our gratitude for the financial support provided by the National Natural Science Foundation of China (Grant No. 12372079), the Natural Science Foundation of Jiangsu Province, China (Grant No. BK20201470).

Conflict of interest

The authors declare no conflicts of interest.

References

[1] LI, Y., ADANTYK, VAKIEL, P., et al. *Review of mechanisms and research methods for blunt ballistic head injury*. Journal of Biomechanical Engineering, 2023. **145**(1): p. 010801.

[2] LI, Y., FAN, H., GAO, X. L. *Ballistic helmets: Recent advances in materials, protection mechanisms, performance, and head injury mitigation*. Composites Part B: Engineering, 2022. **238**: 109890.

[3] GRUJICIC, A., LABERGE, M., GRUJICIC, M., et al. *Potential Improvements in Shock-Mitigation Efficacy of a Polyurea-Augmented Advanced Combat Helmet*. Journal of Materials Engineering and Performance, 2012. **21**(8): p. 1562-1579.

[4] WHITE, C. S., JONES, R. K., DAMON EG, et al. *The biodynamics of air blast. Albuquerque*, NM, US: Lovelace Foundation for Medical Education and Research, 1971.

[5] KULKARNI, S. G., GAO, X. L., HOMER, S. E., et al. *Ballistic helmets-their design, materials, and performance against traumatic brain injury*. Composite Structures, 2013. **101**: p. 313-331.

[6] SINGH, D., CRONIN, D. *Multi-scale modeling of head kinematics and brain tissue response to blast exposure*. Annals of Biomedical Engineering, 2019. **47**(9): p. 1993-2004.

[7] TOWNSEND, M. T., ALAY E, SKOTAK, M., et al. *Effect of Tissue Material Properties in Blast Loading: Coupled Experimentation and Finite Element Simulation*. Annals of Biomedical Engineering, 2019. **47**(9): p. 2019-2032.

[8] AZAR, A., BHAGAVATHULA, K. B., HOGAN, J., et al. *Protective headgear attenuates forces on the inner table and pressure in the brain parenchyma during blast and impact: an experimental study using a simulant-based surrogate model of the human head*. Journal of Biomechanical Engineering, 2020. **142**(4): 041009.

[9] HUANG, X., CHANG, L., ZHAO, H., et al. *Study on craniocerebral dynamics response and helmet protective performance under the blast waves*. Materials & Design, 2022. **224**: 111408.

[10] LI, G., XU, B. C., HU, B., et al. *Experimental research on lung injury of human under complex blast wave*. Acta Armamentarii, 2024. **45**(5): p. 1681-1691.(in Chinese)

[11] GANPULE, S., GU, L., ALAI, A., et al. *Role of helmet in the mechanics of shock wave propagation under blast loading conditions*. Computer Methods in Biomechanics and Biomedical Engineering, 2012. **15**(11): p. 1233-1244.

[12] LI, J., MA, T., HUANG, C., et al. *Protective mechanism of helmet under far-field shock wave*. International Journal of Impact Engineering, 2020. **143**: 103617.

[13] Duan, Z. X., Zhang, J. Y., Chen, K. J., et al. *Diagnosis and treatment of mild brain injury induced by explosive blast wave*. Chinese Journal of Diagnostics (Electronic Edition), 2016. **4**(1): p. 26-29. (in Chinese)

[14] RODRIGUEZ, O., SCHAEFER, M. L., WESTER, B., et al. *Manganese-enhanced magnetic resonance imaging as a diagnostic and dispositional tool after mild-moderate blast traumatic brain injury*. Journal of Neurotrauma, 2016. **33**(7): p. 662-671.

[15] CAI, Z. H., LI, Z., DONG, J. H., et al. *A study on protective performance of bulletproof helmet under impact loading*. Journal of Vibroengineering, 2016. **18**(4): p. 2495-2507.

[16] Tan, L. B., Lee, H. P., Tan, V. B. C. *Ballistic impact analysis of an advanced combat helmet with interior cushioning system on a Hybrid3 headform*. 2011 Defense Science Research Conference and Expo (DSR). Singapore, Singapore: IEEE, 2011: p. 1-5.

[17] MIHRADI, S., HOMMA, H., KANTO, Y. *Numerical analysis of kidney stone fragmentation by short pulse impingement*. Key Engineering

Materials, 2006. **306-308**: p. 1283-1288.

[18] TAYLOR, P. A., FORD, C. C. *Simulation of blast induced early-time intracranial wave physics leading to traumatic brain injury*. Journal of Biomechanical Engineering, 2009. **131**, 061007-1-061007-5.

[19] RORÍGUEZ-ILLÁN, M., TAN, L. B., TSE, K. M., et al. *Effect of full helmet systems on human head responses under blast loading.* Materials & Design, 2017. **117**: p. 58-71.

[20] NAHUM, A. M., SMITH RW, WARD, C. C. *Intracranial response of a three- dimensional human head finite element model*. Proceedings of Injury Prevention through Biomechanics Symposium, Wayne State University, 1991: 97-103.

[21] COOPER, W. E. *Brain trauma in Iraq*. Technology Review, 2008. **111**(4): p. 10-10.