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CASE REPORT

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A finite element model investigation of gunshot injury

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Abstract Multiple gunshot suicide can be a controversial subject mainly because of wrong opinions concerning immediate incapacitation or alleged backwards hurling. For the last 20 years, experts in medicine and physics have tried to demonstrate what really happens during a gunshot wound. Different methods have been used to achieve this aim such as basic physics or the use of empirical evidence. In this paper, using a finite element model of the human head, we demonstrate that no incapacitation or backwards hurling can occur from a gunshot fired between the eyes which did not enter the cerebrum.

Keywords Forensic science · Human head · Biomechanics of impact · Finite elements · Suicide

Introduction

Human head models are mainly used for car crash evaluations and are not commonly used in forensic sciences. Finite element models can provide interesting tools for the forensic scientists when different head injury mechanisms need to be evaluated [1–3]. Multiple gunshots to the head are always a challenge. In a case of multiple shots to the head, we used a finite element model of the human head to simulate the effect of a contact gunshot, fired between the eyes, on the human head and its content to discuss the possibility of a suicidal death.

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Case history

A 20-year-old man was found dead in his bedroom by his younger brother. Investigators found the body lying on the ground near the bed, with a handgun and a box of bullets beside the body. Examination of the body showed three contact entrance gunshot wounds. One was located in the chest and two were located in the head, one between the eyes and the other above the right ear. The weapon was a single-shot handgun and the box of bullets contained "Super X" .22 caliber bullets. Investigators found blood spatter on the victim's bed leading to the cupboard where the deceased used to store his gun and his ammunition.

Autopsy showed that the bullet fired between the eyes had penetrated the skull through the frontal and ethmoid bones, crossed the sphenoidal sinus and ended in the dorsum sellae, just under the dura mater (Fig. 1). This shot, which was associated with hemorrhage surrounding the two optic nerves and with a bleeding in the nose, certainly caused blindness.

The bullet which was fired above the right ear penetrated the right temporal bone, crossed the brain and ended in the left temporal bone (Fig. 1). This shot passed through the midbrain and led to immediate incapacitation and death.

The bullet fired into the chest penetrated the sternum, hit the right side of the heart, crossed the aorta and the 11th dorsal vertebrae and ended in the spinal chord. This shot caused internal hemorrhage and paraplegia.

In the presence of these three contact wounds, the possibility of a suicide was discussed. In case of suicide, the bullet fired above the right ear leading to immediate incapacitation was certainly the last fired. The victim could still use his arms, rearm his weapon and shoot again after the shot into the chest.

But did the bullet fired between the eyes lead to incapacitation of the victim? Incapacitation can only be caused by two mechanisms: disruption of brain tissue or hypoxemia from bleeding [4–6]. The bullet did not penetrate the cerebrum; therefore, there was no crush or stretch mechanism involved that could lead to incapacitation. Commotio cerebri is caused by sudden acceleration of the

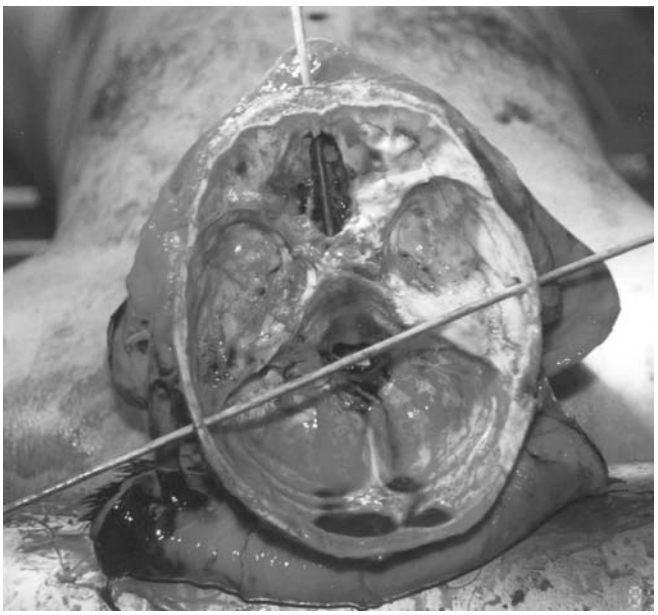

Fig. 1 Photograph of the skull seen from above after brain evisceration, showing the trajectory of the bullet shot between the eyes and of the bullet shot over the right ear

skull. This topic has been clearly discussed by Karger and Kneubuehl [5, 7] but still remains unknown or neglected by some medical experts. To study the generation of commotio cerebri, a biomechanical study using a finite element model of the human head was performed.

Materials and methods

The University Louis Pasteur (ULP) model used is a validated finite element model of the human head developed by Willinger et al. at the University Louis Pasteur of Strasbourg and presented in a previous paper [1, 8]. We shall, therefore, briefly describe this model. The geometry of the inner and outer surfaces of a human adult male skull was digitized. The ULP model includes the main anatomical features: skull, falx, tentorium, subarachnoid space, scalp, cerebrum, cerebellum, and brain stem. The modeling of the skull allows bone fractures to be simulated introducing material discontinuity and an analysis of the effects of impacts to the head.

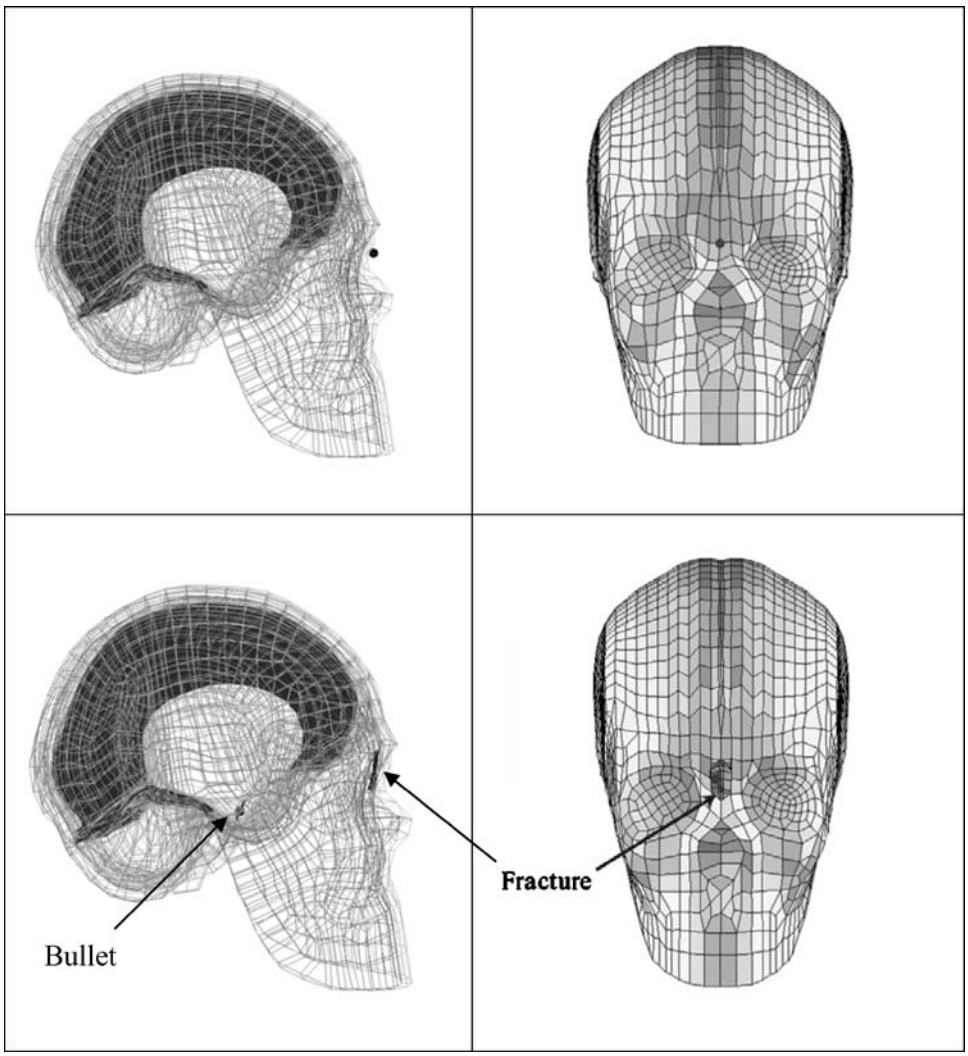

Fig. 2 Diagram showing the position of the bullet fired between the eyes at the beginning (*upper diagram*) and at the end (*lower diagram*) of the simulation

Table 1 Calculated mechanical parameters in comparison to the tissues tolerance limits

	Brain pressure (kPa)	Brain Von Mises stress (kPa)	Global strain energy of the subarachnoid space (J)
Tolerance limit	200	18/38	5.4
Indication	Brain haemorrhages	Brain moderate/severe neurological lesions	Subarachnoid and subdural haematoma
Simulation values	111.5	8	0.09

The finite element mesh is continuous and represents an adult human head. The subarachnoid space was modeled between the brain and the skull to simulate the cerebro-spinal fluid. This space is constituted by a layer of brick elements and entirely surrounds the brain. The tentorium separates the cerebrum and cerebellum, and the falx separates the two hemispheres. A layer of brick elements simulating the cerebro-spinal fluid surrounds these membranes. The scalp was modeled using a layer of brick elements and surrounds the skull and facial bones. Globally, the present human head model consists of 11,939 nodes and 13,208 elements divided in 10,395 bricks and 2,813 shells and has a total mass of 4.5 kg.

To simulate the shot between the eyes, we modeled a 5-mm bullet with an initial velocity of 310 m/s and the initial position was set between the eyes of the ULP model (Fig. 2). Calculation was performed for the 1.5 ms following the impact. The brain pressure and Von Mises stress fields (which represent the shearing stress sustained by the brain) were calculated as well as the global strain energy of the subarachnoid space and the rear movement of the head.

Results

The results of the simulation are detailed in Table 1. Brain pressure has been shown to correlate with brain haemorrhages resulting in brain contusions, oedema and haematoma when reaching values of 200 kPa. Brain Von Mises stress has been shown to correlate with moderate or severe neurological injuries resulting in brief unconsciousness or coma when reaching values of 18 or 38 kPa, respectively. A global strain energy of the subarachnoid space reaching 5.4 J has been shown to correlate with subdural haematoma and subarachnoid bleeding. These head tolerance limits have been developed in a previous paper [1]. The maximum values of the calculated Von Mises stress reached 8 kPa, predicting no neurological lesions. The maximum values of the calculated brain pressure reached 111.5 kPa, largely below the limit for causing brain hemorrhages. This simulation also confirms a very slight but negligeble backward movement of the head (less than 1 mm).

Discussion

Discovering a body with multiple gunshots to the head raises numerous questions especially concerning the possibility of a suicide. Many cases have been studied in the literature but it is always difficult to present these cases to the media or non-specialists. When watching movies, gunshot victims always appear to "jump" backwards when hit by gunshots. This is important for the public to understand that the "hero" or the "villain" has been struck by the bullet. But these movies diffuse a common wrong idea concerning the effects of the impact of ballistic projectiles in real cases, especially for low-caliber bullets. In court or during police investigations, some experts will still tell the audience that a bullet can knock down a man or throw him backwards.

It then becomes difficult for the medical expert concerned with physics to explain to a very doubtful audience that suicide is sometimes possible even if there are multiple gunshot wounds to the head.

In our case report, the bullet which passed through the midbrain undoubtedly caused immediate incapacitation. The bullet fired between the eyes will be the major controversial subject of discussion. This shot did not penetrate the brain, therefore, there was no direct disruption of brain tissue. The two internal carotid arteries and the two cavernous sinuses were intact excluding major bleeding. The .22 bullet has a mass of 2.5 g, measures 5 mm in diameter and has a muzzle velocity of approximately 310 m/s with the weapon used in our case study. This results in an ultrashort time span during which the projectile is acting upon the skull. A high transfer of momentum and energy will result in perforation of the skull without acceleration of the head. Finite element models give a good cinematic image of the case studied that can be shown to a doubting audience. Its use to study head impact due to falls has been illustrated in our previous paper [1]. This paper illustrates that finite element models can also be used when the effects of bullet impacts to the head are discussed. Finite element models can illustrate the effect of any object impacting the brain, bullets as well as other objects such as bottles or stones. The results obtained give information concerning skull displacement, skull fracture, brain hemorrhage, subdural haematomas, or neurological injuries. At the present time, finite element models cannot be used to study the effects of intracranial peak pressures due to gunshots.

The bullet shot between the eyes could have been the first fired, followed by the bullet shot into the chest and a final shot to the right side of the head, the latter passing through the midbrain, rapidly leading to death. An argument for this chronology is the blood spatter seen on the victim's bed. They could be the consequence of a move-

ment of the victim towards the cupboard to reach a box of bullets to rearm the weapon. With the shot between the eyes having caused blindness, the victim had to use the bed as orientation to get to the cupboard. With the shot into the chest causing paraplegia, it would have been difficult for the victim to reach the cupboard if it had been the first shot.

It was found that the victim was depressed because of personal and professional conflicts. Even if, at first sight, a homicide could be suspected because of two gunshot wounds to the head, the possibility of a suicide could not be excluded and is likely to be the manner of death in this case.

Conclusion

Using a finite element model of the human head, we showed that no backward hurling occurred and that no commotio cerebri could be generated by a .22-caliber gunshot between the eyes of the victim. Finite element models can help a non-specialized audience understand what physics and medical experience can tell.

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