

Development of a simplified computational model to study cranial backspatter using SPH

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Abstract

Investigation of crime requires rigorous testing and sound scientific understanding of the evidence to assist with the reconstruction of the criminal event. From the multitude of forensic specializations, bloodstain pattern analysis evidence from cranial gunshot wounding is of particular interest because of the high mortality rate resulting from head wounding compared to other body parts. Traditionally, animal models and physical models of the human anatomy have been used to study the mechanism and extent of ballistic spatter, including backspatter. Backspatter is a retrograde spattering of the target material from the entry wound. The reverse directionality of backspatter has specific evidential value, as it may establish a link between the victim and the shooter via transfer of biological matter. Backspatter evidence has also been used in courts to distinguish between a homicide and a suicide. Despite the importance of backspatter, the understanding of its mechanism has remained inadequate due to ethical issues, difference in anatomical geometry associated with various animal samples, or material property difference among biological and synthetic materials used in physical models. Hence there is a need to develop simulation tools that will use computational models of cranium geometry and configurations relatively similar to those of humans. Such computational models can act as alternatives to animal or physical models for the investigation of backspatter in a variety of situations.

In this study, a mesh-free method called Smoothed Particle Hydrodynamics (SPH) is used to develop a computational model to simulate high speed ballistic impacts. The complex geometry of the human cranium was reduced to a simplified box model equivalent to average female anatomical internal volumes. The inhomogeneous and anisotropic behaviours of the biological materials in a cranium (skin, skull and brain) were simplified to homogeneous and isotropic materials for each component. A physical equivalent model was manufactured and tested under the same ballistic conditions, for computational model validation. The computational model matched well with its physical equivalent experimentation in both material deformation characteristics and the timing of key events. This demonstrated the potential of the simulation models as a better alternative to animal and physical models. The simulation captured the temporary cavity development in the brain simulant well, as well as showing realistic fragmentation, including backspatter. The temporary deformation of the skin entry wound was also a good match to the physical experimentation. The simulation also helped identify the most suitable material models to simulate ballistic impact of the brain simulant. This work provides the basis for a more complex, anatomically accurate geometric cranium model to further develop reliable and robust simulation of cranial ballistic impact.

Keywords: ballistic impact, backspatter, forensic biomechanics, cranial injury, computational modelling, smoothed particle hydrodynamics, hypervelocity impact.

Introduction

One of the most important aspects of crime investigation is to determine the causal event from the evidence found. With the growing number of incidents involving firearms every year, the importance of establishing links between ballistic evidence and its causal parameters has been increasing. This research focuses on retrograde spatter ejected from the entry wound called 'backspatter'. Due to its directionality, backspatter may provide an evidential link between the victim and the assailant (Karger 2008). It can also help distinguish the difference between a homicide from a suicide (Yen, Thali et al. 2003). Backspatter evidence has also been used in court to determine firing distance and positions of the persons involved (Kleiber, Stiller et al. 2001). The most valuable backspatter evidence is a cranial backspatter. This is because 1) the backspatter phenomenon is most pronounced when a near-water density organ such as brain is impacted (Karger 2001); and 2) the human cranium is the most fatal site on the human body for ballistic impact. While the human head represents only 9% of the body, 50% of combat death has been attributed to cranial impact (Michael E. Carey 1989).

There are four possible ways to form a more detailed understanding of backspatter: 1) human research; 2) animal models; 3) physical (man-made) models; or 4) computational models. For ethical reasons, direct backspatter experimentation on human subjects is not an option. Therefore, the use of reliable models is crucial for backspatter research. Such models must be accurate and reliable if valid inferences are to be drawn. Animal models used to date, such as swine or bovine samples (Burnett 1991, Karger, Nusse et al. 1996, Karger, Nusse et al. 1997, Radford 2009), have been limited by the differences in anatomical proportions, with the animal samples featuring a smaller cranial cavity and thicker bone compared to that of a human. As with human testing, animal models also carry significant ethical concerns. To counter the problem, physical models have been developed using synthetic materials and simplified or anatomically realistic geometries (Stephens and Allen 1983, Pex and Vaughan 1987, Radford 2009, Foote 2012, Kwon 2014). The physical models successfully eliminated the ethical issues and more recent models have resolved the anatomical geometry problem (Foote 2012, Carr, Lindstrom et al. 2014, Kwon 2014). However, physical models also have major shortcomings. The cost of the model manufacturing and experimentation is still high and there is limited control over experimental variables and a lack of structural complexity as compared to biological materials. These limitations have promoted research into computational models to simulate cranial ballistic impact and the associated backspatter generation. The ease of model modification, experimentation, and analysis, combined with the low cost, makes the computational model a worthy, if not critical, research topic.

There are two computational methods that have been used to study ballistic impacts: 1) Finite Element Method (FEM) and 2) Smoothed-Particle Hydrodynamics (SPH). FEM is a widely recognised computational method to simulate ballistic impact. The FEM method has been utilised to successfully simulate impacts on ballistic helmets (Aare and Kleiven 2007, Yang and Dai 2010), ballistic gelatine (Datoc 2010), human mandible (Tang, Tu et al. 2012), human brain (Raul, Deck et al. 2007) and human frontal bone (Pinnoji and Mahajan 2007). However, due to its Eulerian approach, FEM cannot handle fragmentation, large deformation and high speed impact very well. This makes FEM unsuitable for backspatter research where the focus is on the fragmented particles produced from a high speed impact. Therefore, this research focussed instead on SPH, using it to obtain approximate numerical solutions of the ballistic impact simulation on human cranial model. The SPH is a Lagrangian computational method, using equations of fluid dynamics, by replacing

the body of fluid with a set of particles. SPH was originally invented to deal with problems in astrophysics; involving fluid masses moving arbitrarily in three dimensions in the absence of boundaries (Monaghan 2012). The mesh-free SPH technique simulates the gunshot wound appropriately and can handle large deformation and fragmentation (Monaghan 2012). SPH has been successfully used to model ballistic impact onto a variety of targets (Das, Collins et al. 2015).

In this research, the complex geometry of the human cranium was reduced to a simplified box model equivalent to average female anatomical internal volumes. The inhomogeneous and anisotropic behaviours of the biological materials in a cranium (skin, skull and brain) were simplified to homogeneous and isotropic materials for each component. As a validation method for the SPH computational model, a physical equivalent model of identical geometry and simulant materials has been manufactured and tested under the same ballistic conditions.

Methods

Computational Model Development

The scalp and the skull layers were represented by a 100 x 100 mm square. The scalp layer thickness was set to 3 mm, while the skull layer thickness was 5 mm. The thickness values were determined based on measurements of 114 MRI scan images acquired from the Centre of Advanced MRI, University of Auckland. The length of the brain layer was fixed to 140 mm so the internal volume of the brain layer was close to 1130 cm³, the average brain volume of a human female (Cosgrove, Mazure et al. 2007). The geometry of the model is shown in Figure 1 (a), while Figure 1 (b) shows the SPH model of the same geometry.

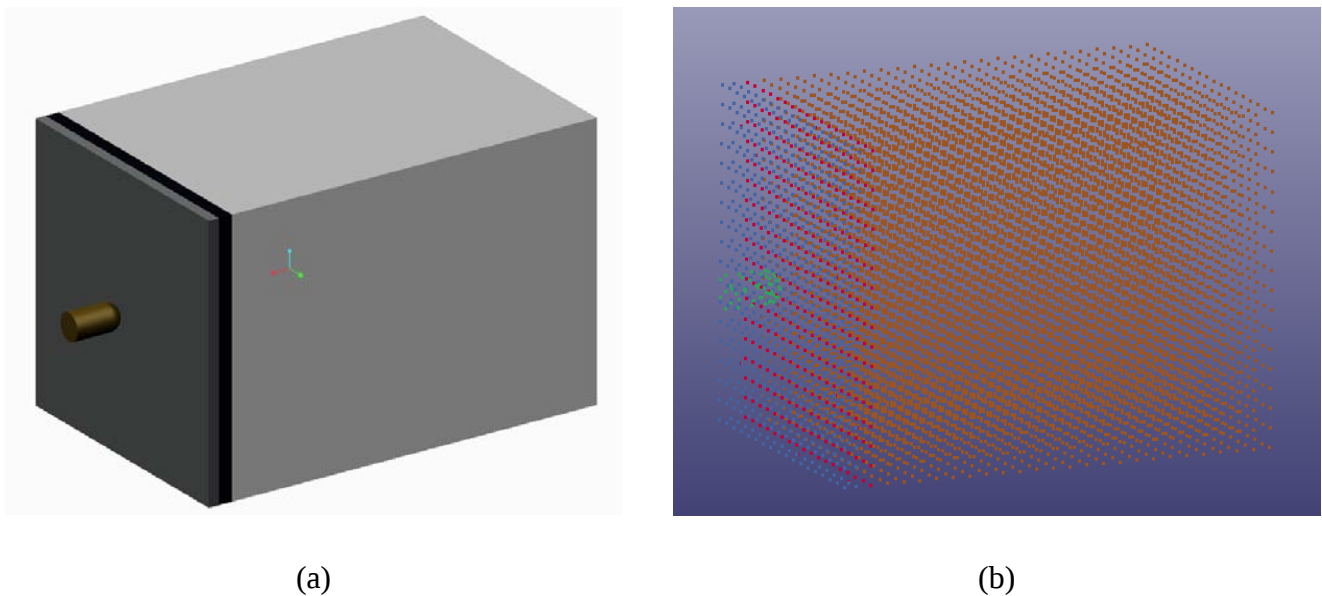


Figure 1. (a) Geometry of the simplified computational model, complete with the bullet (brown), scalp (dark grey), skull (black) and the brain (light grey) layers (b) the SPH model of the same geometry

Gravity and air resistance were assumed to be negligible for the purposes of the simulation. The model had a pinned boundary condition (no translation in x, y and z directions, while rotation is allowed) applied to the outside surfaces except the entry and exit side.

To match the experimental ballistic conditions, computational representation of a 9 mm Luger projectile was used to impact the computational model (Figure 2). The bullet was set to impact the model perpendicular to the scalp surface centre as shown in Figure 1 (a), with an initial speed of ~350m/s, which is the average bullet speed (MidwayUSA).

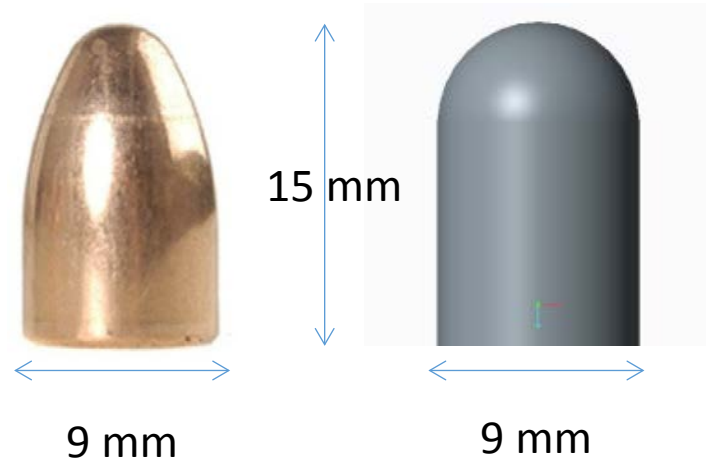


Figure 2. Physical (left) and computational (right) bullet geometry comparison of the projectile part of the 9 mm Luger bullet

The computational model used a hyperelastic failure model for the scalp and an isotropic-elastic model for the skull, based on a previous research (Kwon 2014, Das, Collins et al. 2015). The brain was modelled using either a viscoelastic model or the Plastic-Kinematic model to identify the most suitable material constitutive model to describe the ballistic deformation of a human brain.

The material properties of the scalp and skull simulants were measured in the University of Auckland Centre of Advanced Composite Materials laboratories. The scalp simulant was a Room Temperature Vulcanising (RTV) Silicone, a polyurethane resin was used as the skull simulant, and the brain was modelled using 10% gelatine. The material properties of the 10% gelatine were obtained from the literature (Kelager 2006, Cohen, Cleary et al. 2009).

Physical Equivalent Model

Manufacturing of the physical model was carried out using a casting method. The skin layer was manufactured from curing RTV silicone with a cotton-cellulose sponge insert as the blood reservoir. The bone layer was made from a homogeneous cast of polyurethane. The brain layer was cast using a 10% gelatine solution. The quality of the gelatine was crucial in bullet trajectory visualization. To achieve the desired transparency, a few drops of cinnamon oil were added to the gelatine-water mixture.

The ballistic experimental setup for the physical model was carried out at the Firearms Testing Laboratory in the Mount Albert Science Centre of Environmental Science and Research. A sample was first secured on a holder. The target surface was set perpendicular to the bullet trajectory. A white surface was placed horizontally in front of the sample to capture any backspatter. A high speed camera, Photron Fastcam SA1, was positioned at an angle of approximately 30° to the surface. This oblique angle was used to capture both the scalp and the brain layer surface deformation at the same time. The frame rate was set to 30,000 frames per second to capture the details of the dynamic deformations and backspatter generation. The experimental setup schematic is shown in Figure 3.

The samples were shot using a federal brand American Eagle 9 mm Luger calibre bullet fired from a Glock, Model 17 semi-automatic pistol. The bullet used was a 115 grain Full Metal Jacket (FMJ) projectile, which has a solid lead core with a copper material coating. The bullet was fired with a muzzle to target distance of approximately 1 m to minimize the effect of the muzzle gas on the ballistic response of the sample (Taylor, Laber et al. 2010). After each shot, the samples were photographed and archived with the collected backspatter for subsequent analysis.

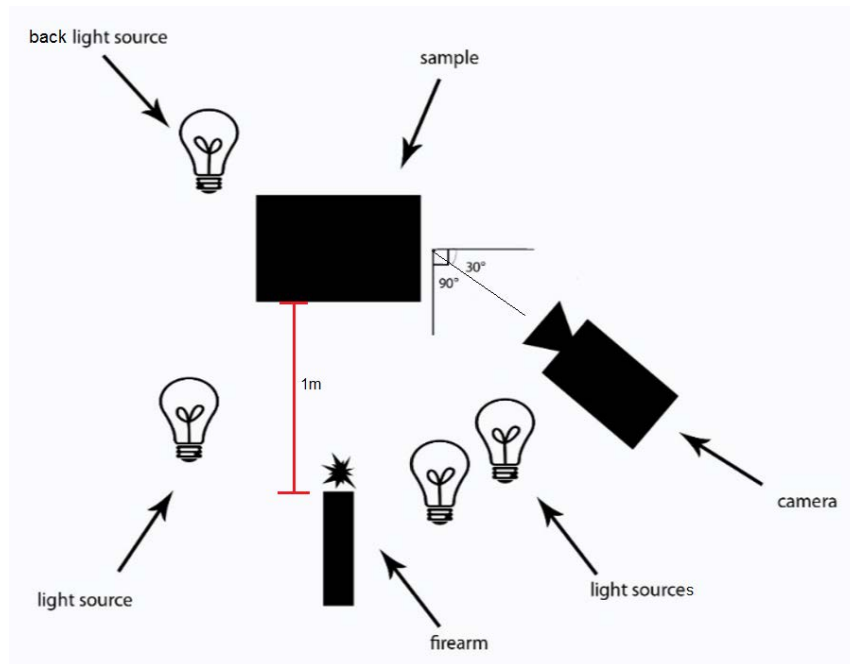


Figure 3. Experimental setup schematic

Results and Discussion

The high speed footage of the experimental results was visually compared to the simulation results. An image of the simulation result was extracted for each key stage of the ballistic deformation. The images were set to be of the same view angle and magnification, and had 50% transparency. The conditioned images were then overlayed onto the high speed footage for comparison. An excerpt of the key deformation stages for both physical and computational model is shown in Figure 4.

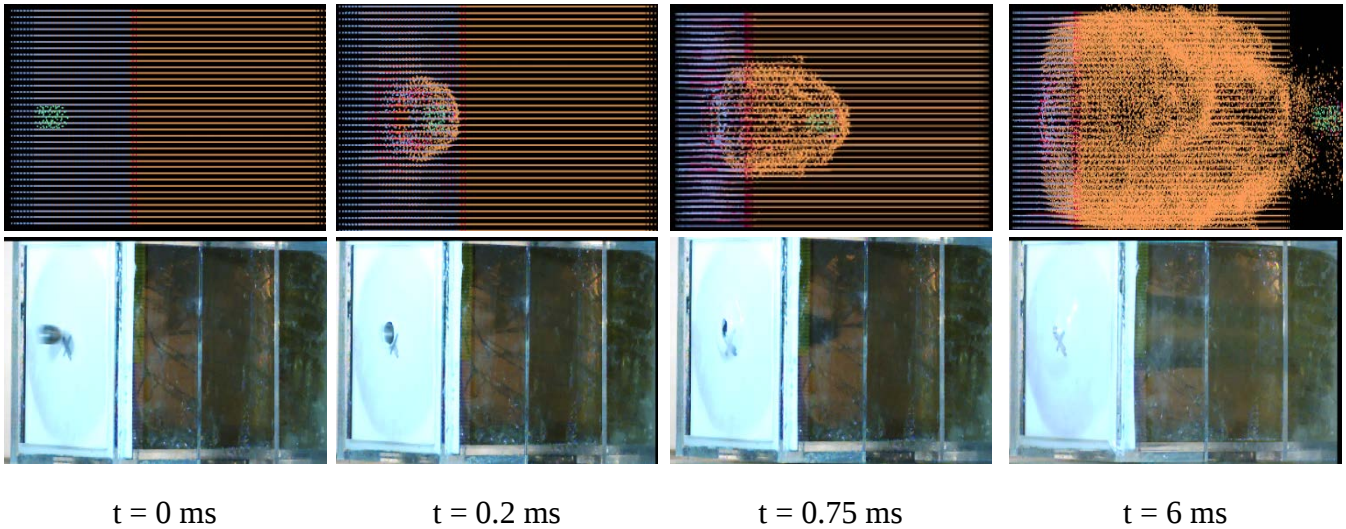


Figure 4. Chronological comparison between the physical and computational model results

The sequence of events observed from the physical model was highly comparable to that of simulation result, in both the spatial dimensions and the timing. For both the physical and the computational models: 1) at 3 ms it was observed that the maximum surface displacement and blow out diameter had been reached; 2) at 3.75 ms, the edges of the blow out are observed to be retracting, but the uniform cylindrical shape still remains; 3) at 6 ms the cavity of the blow out began to collapse while the brain temporary cavity is still expending; 4) after the initial subcutaneous temporary cavitation, the scalp layer recovered its original position without any subsequent oscillatory motion.

Throughout the entire ballistic event, the temporary cavity in the computational model brain layer developed in similar size and speed to the physical equivalent as illustrated in Figure 4. The general tapered shape of the cavity is also replicated throughout the simulation result. Also, backspatter generation from both models was observed.

Of the two material constitutive models, the viscoelastic failure model was unsuccessful at simulating a realistic result. Under this simulation, the bullet stopped in the midst of the brain layer, losing its kinetic energy completely to the brain layer. This was different from the physical model experimental result. On the other hand, the Plastic-Kinematic model produced a simulation result that successfully goes through the computational model, mimicking the experimental result well.

Conclusions

The computational model matched well with its physical equivalent experimentation in both material deformation characteristics and the timing of key events, demonstrating the potential of the simulation models as a better alternative to animal and physical models. The simulation successfully captured the temporary cavity development in the brain simulant, as well as showing realistic fragmentation, including backspatter. The temporary deformation of the skin entry wound was also a good match to the physical experimentation. The simulation also identified the most suitable material constitutive model to simulate ballistic impact of the brain simulant to be the Plastic-Kinematic mode.

As the first skin-skull-brain computational model of human cranium for ballistic backspatter research, this work provides the basis for a more complex anatomically accurate geometric cranium model to further develop reliable and robust simulation of cranial ballistic impact.

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