Military Wound Ballistics Case Study: Development of a Skull/Brain Model

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15.1 Introduction

Penetration of the cranium typically results in secondary projectile formation (bone and primary projectile fragments); the formation of a temporary cavity and resulting increase in internal pressure which is enhanced by the confined space of the cranium and the stiff bones of the skull [1]. This enhanced internal pressure can result in fractures of the base of the cranium, because it is not as strong as other parts of the skull [1]. Radial fractures are typical at the impact point, but concentric fractures can also occur connecting the radial cracks due to flexing of the skull. This through-thickness failure is commonly referred to as cratering [2–4]. Bullet wipe is reported on

the scalp in forensic case studies e.g. [2–4]. The fact that bullet wipe can be identified to specific bullets is of interest forensically when investigating attempted murder or murder incidents in civilian and military scenarios [5].

In combat, head wounds are recognised as accounting for substantial mortality and morbidity; the head accounts for 9 % of the human body, 20 % of penetrating combat injuries and its wounding accounts for 50 % of combat deaths [6]. The major cause of injury during warfare is from fragments and therefore, military helmets are designed to protect from fragments; when they are perforated it is most commonly by high kinetic energy projectiles e.g. high-velocity rifle bullets or fragments due to blast (secondary blast) [7–10].

While a number of models for bullet/fragment-head impact recreations have been proposed, these are not anatomically correct e.g. [3, 4, 11]. The models include a polyurethane sphere filled with 10 % gelatine conditioned at 4 °C [3], a cylinder composed of a plastic/ wood/ polymer outer filled with gelatine [4] and polymeric spheres containing 10 % gelatine [11]. These models reportedly compared well to actual gunshot injuries or secondary blast injuries; however, it would not be possible to mount a helmet on them.

Literature describing ballistic rate impacts on human skulls with or without a simulated brain is sparse [2, 12, 13]. In 1970, Miller reported on the penetration of skulls by steel cubes and spheres,

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Table 15.1 Summary of Watkins' work [13]

Specimen	Test details	Outcome
	1.045 g ball bearing Impact location side of head	
n = 3	~370 m/s	Penetrated skull (n = 1 perforated skull, 72 J deposited)
n = 3	~750 m/s	Perforated skull, 250 J deposited, "significant damage"
n = 3	~1000 m/s	Perforated skull, 440 J deposited, "severe damage"
n = 1	7.62 mm ball (no further details)	Perforated skull, 351 J deposited, damage in between 750 and 1000 m/s ball bearings

Table 15.2 Pertinent examples from the literature of penetrating injury to the head

Reference	Scenario	Outcome
Fenton et al. [2]		
Case 1	303 (no further details) Contact shot mouth	Extensive fractures to the facial and frontal bones Occipital remained whole but removed from the remaining skull Fractures to the base 36 relatively large bone pieces (observation from the images provided)
Case 2	303 (no further details) Contact shot mouth	Similar to case 1 except occipital fractured into multiple pieces
Betz et al. [14] 4 cases	243 Winchester and 7.62 mm (no further details) Contact shots temporal, mouth, sub-mental region	Completely perforated and fractured skull Ejected brain as a result of the vault exploding (Krönlein shot)

this government report is not accessible in the open literature. However, some of Miller's data are mentioned in another report which describes a model for projectiles impacting skulls [12]. The fact that dried skulls and fresh skull caps performed differently, and the need to consider the additional contribution of hair and the scalp in live human impacts with respect to these projectiles were noted [12]. Some early work that is easily accessible was published by Watkins et al. [13]. Watkins used dried Asiatic[1] skulls filled with 20 % gelatine and covered with two layers of chamois covered in gelatine (no details of the chamois were provided and presumably the gelatine used was 20 % by mass). Watkins' work included a series of nine impacts; the majority of this work involved ball bearings at velocities up to ~1000 m/s, but Watkins did note one head was tested with a

7.62 mm ball round (no further details given) at 750 m/s (Table 15.1).

Reports on penetrating ballistic head injuries in the forensic literature are dominated by case studies of suicides; the penetrating ammunition usually being .22 rimfire or shotgun. There are some exceptions that report outcomes of interest to the current work [2, 14] (Table 15.2). Analysis of skull fracture patterns resulting from self-inflicted gunshot injury identified key patterns of injury including the formation of linear fractures and fragmentation with reference to the anatomical structures of the skull [2]. A further interesting study that includes a high-velocity rifle impact considers the reconstruction of the head after injury and does not discuss skull fractures [15].

The aim of this work summarised here was to develop an anatomically correct skull and brain model for use in military wound ballistic studies incorporating helmets.
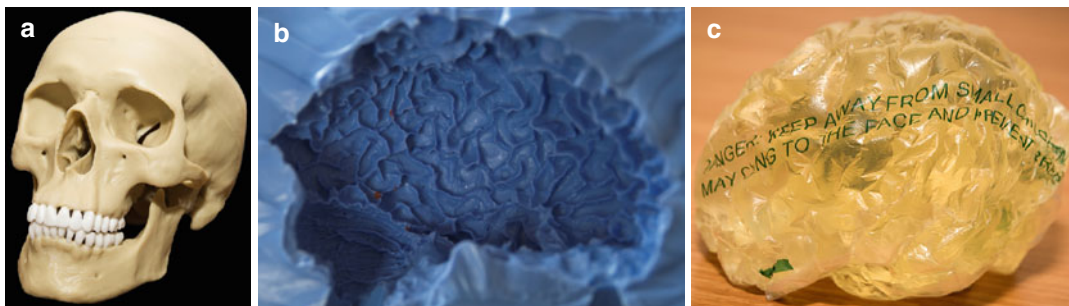
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[1] Watkins' terminology.

Fig. 15.1 Model elements. (**a**) Skull. (**b**) One half of brain mould. (**c**) Cast brain

15.2   Materials and Methods

Anatomically correct polyurethane skulls were manufactured from rapid prototype data obtained by 3D mapping of both the internal and external surfaces of a human skull (Fig. 15.1a). The polyurethane used to manufacture the skulls had a hardness of 85 Shore D, a tensile strength of 70 MPa and an impact strength of 10 kJ/m^2. Tensile strength of bone from human skulls has been reported to be 225 MPa. However, these properties are reported for quasi-static rates; as testing conducted on the polymeric skulls was at ballistic strain rates, the difference in these mechanical properties is not critical, although further work should explore these differences at the appropriate loading rates.

A two-part silicone mould made from a human brain was used to cast 10 % (by mass) gelatine brains (Fig. 15.1b); 10 % gelatine was chosen as the density was similar to reported values for human brain tissue [16]. A thin polymeric bag was inserted into the brain mould and gelatine poured in, the gelatine was allowed to set for 24 h and then conditioned at 4 °C for 24 h [17, 18]. The polymeric bag was softened by the warm gelatine and thus excellent definition of the mould surface was achieved; additionally, the polymeric bag acted as a representation of the meninges (Fig. 15.1c).

Models were shot using 7.62 × 39 mm M43 ball (Chinese, mild steel core, Factory 71 made in 1984) ammunition at a range of 10 m from a No. 3 Enfield proof mount fitted with an AK-47 barrel (Table 15.3). Projectile velocity was tracked using a Weibel Doppler, and impacts filmed using a Phantom V12 high-speed video; projectiles were soft-captured after model perforation using a PermaGel^{TM} block.

Fractured skull pieces were collected and weighed post ballistic testing. Skull pieces showing signs of bullet wipe and bullets soft-captured after skull perforation were subjected to further analysis. The presence and distribution of inorganic residues was confirmed by using scanning electron microscopy coupled with energy-dispersive x-ray spectroscopy (SEM EDS).

15.3   Results and Discussion

Mean projectile impact velocity was 675 m/s (s.d. = 6 m/s). All skulls were perforated as intended. Bullet impact wounds demonstrated cratering damage with radial cracks. Inorganic residues representative of bullet wipe were found at impact sites. Results are presented in Table 15.3 and a typical impact sequence is presented in Fig. 15.2.

Without a 'brain' (skulls 1 and 2), minimal damage to the skull occurred due to the lack of development of a temporary cavity when a projectile passes through the brain and the associated increase in pressure in the cranial vault which leads to multiple fractures of the skull [1]. Damage was confined to the impact and exit sites and associated radial cracking. Models comprising of a skull and brain (skulls 3–6) fragmented into multiple pieces of diverse

Table 15.3 Test details and results

Specimen	Details of test	Results
1	*Skull with no brain, skull not glued, mass = 551 g* Shot 1: impact velocity = 665 m/s, anterior to posterior along the sagital plane, impact location frontal bone Shot 2: impact velocity = 674 m/s, left to right along the coronal plane, impact location parietal bone	Skull remained whole Skull remained whole
2	*Skull with no brain, skull not glued, mass 551 g* Shot 1: impact velocity = 682 m/s, anterior to posterior along the sagital plane, impact location frontal bone Shot 2: impact velocity = 677 m/s, left to right along the coronal plane, impact location parietal bone	Skull remained whole Skull remained whole
3	*Skull completely filled with gelatine, skull glued (bag inserted through the foramen magnum, filled with gelatine), mass = 1277 g* Shot 1: impact velocity = 682 m/s, anterior to posterior along the sagital plane, impact location frontal bone	Fragmented into 22 pieces Facial bones and the majority of the inferior (excluding the occipital) Remaining 21 fragments varied in mass from 0.13 to 84.76 g (mean = 9.46 g, s.d. = 18.54 g)
4	*Skull completely filled with gelatine, skull glued (bag inserted through the foramen magnum, filled with gelatine), mass 1753 g* Shot 1: impact velocity = 666 m/s, left to right along the coronal plane, impact location parietal bone	Fragmented into 20 pieces Facial bones, inferior including the occipital Parietal/occipital (108.99 g) 18 smaller fragments varied in mass from 0.13 to 27.72 g (mean = 7.00 g, s.d. = 6.83 g)
5	*Skull plus moulded brain, skull not glued, mass = 1132 g* Shot 1: impact velocity = 675 m/s, anterior to posterior along the sagital plane, impact location frontal bone	Fragmented into 7 pieces Facial bones and the majority of the inferior including the occipital Frontal/temporal/parietal (90.14 g) Temporal/parietal (60.72 g) 4 small fragments varying in mass from 0.38 to 15.35 g (mean = 7.12 g, s.d. = 6.25 g)
6	*Skull plus moulded brain, skull glued, turned upside down filled with water, mass = 1684 g* Shot 1: impact velocity = 675 m/s, anterior to posterior along the sagital plane, impact location frontal bone	Fragmented into 30 pieces The facial bones, inferior excluding most of the occipital Occipital (56.71 g) Temporal/parietal (45.84 g) 27 smaller fragments varying in mass from 0.14 to 27.06 g (mean = 4.49 g, s.d. = 7.29 g)

+121.88µs +438.75µs +2340µs
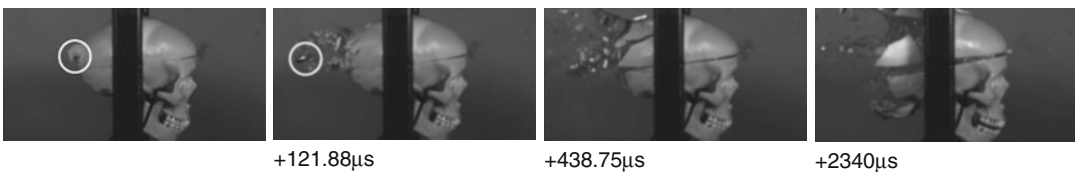
Fig. 15.2 Typical impact sequence (skull 3)

size and shape. These models were reconstructed and compared to data in the forensic anthropology literature. Probably, the most useful comparisons can be found among the case studies reported by Fenton et al. [2] and Betz et al. [14], although the types of ammunition used were reportedly different to that in the current paper. Of particular interest were the complete perforation of the skull, the relatively large pieces of fractured bone, the bilateral fractures

occurring adjacent to buttresses, the fractures to the inferior and posterior of the skull and the ejected brains. All of these features were observed in the skull and brain models developed in the current paper. Thus, the presence of a 'brain' resulted in different fracture patterns (compared to shooting a skull only) that related well to previously proposed models and to data reported in the literature of actual incidents. As the skulls used in the current work were anatomically correct, the various thicknesses of the polymer varied at different points in the skull mimicking a human skull. Post-testing analysis identified that fractures occurred at weaker areas dictated by actual anatomical features. In particular, fractures were influenced by the various buttresses within the skull, as reported in case studies of actual events, e.g. [2]. The amount of gelatine used in the skull to represent the brain affected the severity of the fracture patterns. Use of an anatomically correct brain (skull 5) resulted in the least severe result; although the skull was extensively fractured, the cranial base remained intact. Completely filling the cranial cavity with either gelatine or a gelatine brain and water combination resulted to similar fracture patterns (skulls 3, 4, 6), which were both more severe than with the gelatine brain alone. In particular, it was noticeable that a fully filled cranial cavity resulted in fractures to the inferior and a more catastrophic result.

15.4 Conclusions

An anatomically correct model for studying military wound ballistic and secondary blast events to the human skull and brain has been developed. The advantage of using an anatomically correct skull model in combination with a gelatine brain has been demonstrated by the fracture patterns obtained which compare favourably to the limited reports of actual high velocity rifle wounds to the head. Comparisons with complex secondary blast fragments has not been conducted. Impact and exit wounds were as expected; evidence of cratering and radial

cracking was observed. Bullet-wipe was observed at the impact sites. Completely filling the cranial cavity with either gelatine or a gelatine brain and water combination resulted in similar fracture patterns.

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