Ballistic Injury Biomechanics

29

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Abstract

Penetrating and non-penetrating injuries can result from a ballistic impact. Typical gun shot wounds are the penetrating type. However, when a bullet designed to penetrate hits a piece of personnel protective equipment the result can be a blunt impact injury. Blunt impact injuries can also occur with less-lethal kinetic energy devices. Injuries that result from these high rate impacts are dependent on many factors including: the energy imparted to the body, the surface area that this energy is focused upon as well as the region of the body impacted. Research in the areas of gun shot wounds, direct and indirect impacts to the long bones, behind armor blunt trauma and blunt ballistic impacts will be discussed.

Ballistic injury can be the result of either penetrating or non-penetrating impacts. Typical gun shot wounds are of the penetrating type. However, when the impact occurs over personnel protective equipment or is the result of a round that is design specifically not to penetrate, such as a less-lethal kinetic energy device, non-penetrating, blunt impact injuries can occur.

29.1 Gun Shot Wounds

There are several variables that affect the type of wounds caused by bullets. From the ballistics side, key characteristics of the bullet such as caliber, velocity, mass, orientation on impact and potential fragmentation all contribute to the resulting injury. From the human side, both the soft tissues (skin, muscle) and underlying bone and the proximity of each will dictate the damage observed. There are two major mechanisms of injury: crushing and tearing. Crushing is often caused directly by the bullet, while tearing is the result of the expansion of gases as the bullet transverses through the tissues. The first causes a permanent cavity in the tissues, as opposed to the second, which results in a temporary cavity.

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Gunshot wounds have been described as either penetrating or perforating [1]. Penetrating wounds are when an entrance wound is present, but there is no exit. Perforating wounds have both an entrance and exit wound. In the case where the bullet grazes the body, both soft and boney tissue damage can occur, but the bullet does not actually penetrate into the body. If the wound is shallow and does not demonstrate injury to the deeper layers of the fascia, then it is considered a graze. If deeper layers of tissue are involved, then the wound is labeled as a guttering wound. These wounds are often easier to detect directionality due to the tearing that occurs on the end of the wound where the bullet leaves the skin.

29.1.1 Entrance Versus Exit

One of the first steps of a forensic investigation of gunshot wounds is to determine entrance versus exit wounds. Depending on the region of the body, caliber of round and distance traveled, these wounds may or may not be easily distinguished. Determining entrance and exit wounds will determine directionality of the bullet, which is an important factor in the overall crime scene investigation.

29.1.1.1 Soft Tissue

The amount of soft tissue damage can help distinguish an entrance from an exit wound. Entrance wounds will generally have less tissue damage than exit wounds if the bullet enters perpendicular to the tissue and has not hit an intermediate object. They are circular in nature often with an abraded ring around the circumference. If the bullet enters at a slight angle, the wound will be more oval in shape with a more abraded region found on the entry side of the wound.

If the bullet starts to tumble or becomes unstable in flight, the entrance wound may be irregular in shape or have tearing at the margins. Bullets that ricochet or hit an intermediate target will also have irregular entrance wounds. Depending on the distance, shots that occur over a bony region such as the skull can result in a stellate wound. This is due to the expansion of gases between the skin and bony layers. As the gases expand the soft tissues cannot stretch fast enough to accommodate the increase volume, therefore tearing will occur. It is important not to interpret these types of wounds as exit wounds despite the large amount of tissue damage. This same gas expansion may cause a muzzle imprint in areas where the tissue is free to expand. The skin will expand as the gases enter the underlying tissues and impact upon the muzzle of the firearm. This imprint can often be matched to the weapon if known and available.

Exit wounds can have varying shapes and sizes. Although typically larger than entrance wounds, this may not always be the case. The larger size is due to the bullet tumbling and deforming as it enters into the body. The amount of tumbling will be dependent on the initial velocity when the bullet enters the body and the amount of distance traveled within the body. High-powered rifles may cause stellate wounds upon exit, which resemble those seen the entrance wounds over flat bony regions as described above.

The lack of abraded margins can help distinguish an entrance wound from an exit. However, in the case where the skin is pressed up against a wall or flat surface, shoring will occur which results in abrasion of the skin caused by contact with the flat surface as the bullet exits. Heavy clothing may also create a shored exit wound.

29.1.1.2 Bony Structures

Due to the dipole nature of the skull, entrance and exit wounds in this region can often be distinguished based on the injury patterns to the skull itself. Damage to the inner and outer tables can be different due to the bending that occurs as the bullet strikes the bone and the resulting stresses that arise in the tissues. This discrepancy causes beveling (Fig. 29.1), which is represented by a smaller diameter on the impacted surface versus a larger diameter on the far side of the impact. Entrance wounds will typically have internal

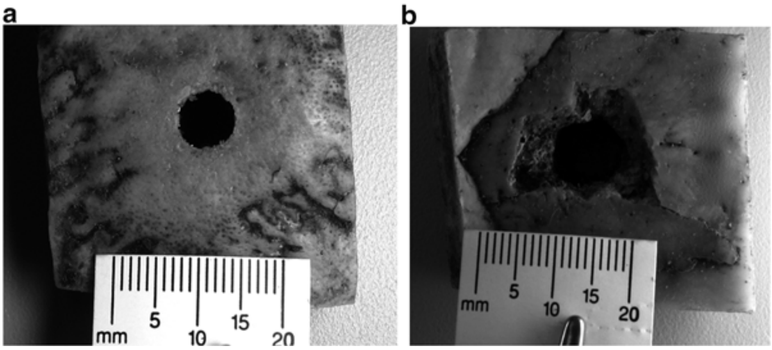

Fig. 29.1 Gunshot wound to the skull. (**a**) Entrance wound on exterior of skull (**b**) exit wound on interior of skull with bevealing

beveling and exit wounds will have external beveling. However, in cases where the bullet has started to yaw, or with high power contact wounds, external beveling can be present on an entrance wounds, but is most likely paired with internal beveling to a greater degree.

Beveling can be found evenly distributed around the wound, indicating a more or less perpendicular entrance. In cases of tangential impacts, the amount of beveling may be asymmetrical with greater amount opposite the entrance of the bullet. Tangential bullets may also produce what are known as “keyhole defects” [2]. As the bullet enters the bone tangentially, chipping will occur on the entrance side and the stresses on the opposite side will cause fracture propagation in the outer table causing a large area of beveling. Internal beveling will also be present which can confirm the wound as entrance. Directionality of the bullet through the skull can also be determined based on the presence of this finding.

A bullet may pass through one portion of the body and reenter into another. The most common occurrence is when an arm is struck and the bullet perforates through and then enters the thorax [1]. This phenomenon can result in both an atypical entrance wound on the thorax as well as an atypical shoring exit wound on the arm if pressed against the body. The reentry wound is often oval or crescent in shape and may not have a ring of abrasion.

29.1.2 Distance

The range of fire, or muzzle to target distance, is often the next determination made in gun shot wound cases. Approximate distances can be established based on the presence or absence of debris from the muzzle. If close enough, this debris can be deposited into the skin and clothing of the victim. Typically four ranges have been delineated: contact, near contact, close and distant.

Contact shots will show the presence of gun shot residue (GSR) and soot on the margins of the wound. The hot gases expelled by the gun will burn the soot into the tissues and it cannot be washed away. This should not be confused with bullet wipe. Bullet wipe is the presence of debris that is transferred to the clothing or skin as the bullet passes through. This can happen in both close and distant range firings.

When the muzzle has been placed close to the skin but not in hard contact, loose or near contact wounds may be seen. Loose contact wounds are represented by a deposition of soot around the entrance wound, which can be wiped away. Near contact wounds have a larger ring of soot and with a larger inner ring of seared tissue, due to the dispersion of powder, that is not easily wiped away.

The presence of stippling or tattooing is an indication that the distance to muzzle was of close range. This distance is from 0.012 m (5 in) to approximately 0.457 m (18 in). Stippling is cause by the gunpowder particles striking the skin and causing punctate abrasions. Unlike the deposition of soot, stippling cannot be washed away. If the muzzle is fired at an angle to the skin, there will be a greater dispersion of stippling in the direction of the firing.

When the muzzle of the gun is greater than 0.457 m (18 in) away, stippling will not be present. However, the lack of stippling alone should not determine distance since clothing and intermediate objects may mask its presence. The size and shape of the entrance wound in distant shots will be more representative of the bullet.

29.1.3 Direct Versus Indirect Fractures

Skeletal injuries to long bones in the extremities can be caused by both direct impact and indirect impact [3]. Indirect fractures are the result of a projectile passing close to a bone but not directly striking it. They are characterized by a simpler fracture pattern and less medullary contamination when compared with direct fractures [4]. Approximately 10 % of all long bone fractures are indirect. Direct fractures occur when a bullet strikes bone with enough force to cause a fracture [5]. In contrast, these fractures are more complex and generally have more comminution.

Between 1968 and 1970, Huelke et al. authored three papers to describe the “bio-ballistics” of direct fractures of the femur. Using stainless steel spheres, the authors conducted direct impacts to both unembalmed and embalmed femoral specimens. One of the basic findings was that both the unembalmed and embalmed specimens responded the same in terms of energy loss versus impact velocity. The authors reported that given the same velocity, the diameter and not the mass of the sphere was the main factor determining damage. Cavitation and shock waves were discussed as the reason for this finding. Although, it was reported that cavitation did not appear until the velocity was 600 and 800 ft/s for spheres measuring .406 and .250 in. respectively [6].

More recent work has studied the pathophysiology of indirect fractures of long bones to isolate variables involved with the production of a fracture. By using both strain gage technology and high-speed video, the temporal relationship between the passage of a bullet and occurrence of long bone fracture has been determined [7]. Dougherty et al. (2011) further analyzed the parameters associated with the production of long bone fracture. Using cadaveric specimens, it was determined that indirect fractures were of a simple (oblique or spiral) pattern (Fig. 29.2). For those specimens with fractures, the average wound track to bone distance was 9.68 mm. In contrast, the non-fractured specimens demonstrated a significantly shorter wound track to bone distance of 15.15 mm (p=0.036). In addition, there were no fractures reported when 9-mm bullets with an average velocity of 263 m/s (862 ft/s) were used or when the M995 bullet velocity was below 975 m/s (3,200 ft/s) [8].

Fig. 29.2 Spiral fracture caused by temporary cavity formation

29.2 Behind Armor Blunt Trauma

29.2.1 Body Armor: Torso

Of approximately 1,200 officers killed in the line of duty since 1980, it is estimated that more than 30 % could have been saved by body armor [9]. According to the James Guelff Body Armor Act, the risk of dying from gunfire is 14 times higher for an officer not wearing a vest [9]. In addition, the US Department of Justice estimates that 25 % of state, local, and tribal law enforcement officers

Table 29.1 NIJ P-BFS performance test summary

Armor type	Test round	Test bullet	Bullet mass	Conditioned armor test velocity	New armor test velocity
IIA	1	9 mm FMJ RN	8.0 g (124 gr)	355 m/s (1,165 ft/s)	373 m/s (1,225 ft/s)
	2	.40 S&W FMJ	11.7 g (180 gr)	325 m/s (1,065 ft/s)	352 m/s (1,155 ft/s)
II	1	9 mm FMJ RN	8.0 g (124 gr)	379 m/s (1,245 ft/s)	398 m/s (1,305 ft/s)
	2	.357 Magnum JSP	10.2 g (158 gr)	408 m/s (1,340 ft/s)	436 m/s (1,430 ft/s)
IIIA	1	.357 SIG FMJ FN	8.1 g (125 gr)	430 m/s (1,410 ft/s)	448 m/s (1,470 ft/s)
	2	.44 Magnum SJHP	15.6 g (240 gr)	408 m/s (1,340 ft/s)	436 m/s (1,430 ft/s)
III	1	7.62 mm NATO FMJ	9.6 g (147 gr)	847 m/s (2,780 ft/s)	–
IV	1	.30 Caliber M2 AP	10.8 g (166 gr)	878 m/s (2,880 ft/s)	–
Special	–	Each test threat to be specified by armor manufacturer or procuring organization			

are not issued body armor. Since establishing the IACP (International Association of Chiefs of Police)/DuPont™ Kevlar® Survivors' Club® in 1987; over 3,000 law enforcement personnel have survived both ballistic and non-ballistic incidents because they were wearing body armor [10].

Body armor is comprised of fibers that have been woven together into sheets. Numerous sheets are used to make up one ballistic panel. The sheets work individually and together to help prevent the penetration of the bullet. Some materials that are used include: Kevlar®, Spectra® Fiber, Aramid Fiber, and Dyneema. The material fibers work to absorb and spread the energy over the entire torso so all of the energy from the impact is not focused on one area of the body, resulting in serious injury.

The current standard for certifying the protective ability of the thoracic armor (NIJ Standard-0101.06) was released in 2008 by the National Institute of Justice. This Ballistic Resistance of Body Armor standard has been revised several times since the original version was released in 1972. Part of the standard since its inception is the measurement of the deformation behind a backing material, also known as Backface Signature (BFS). This testing method provides a discrete value by which the failure of the vest can be determined. A failure is indicated by a deformation of the backing material greater than 44 mm or a penetration of the vest. A penetration of the vest can be due to the projectile itself, a fragment of the projectile or a fragment from the vest.

There are five types of armor that are covered in the current standard (IIA, II, IIIA, III, IV). Each type has a specified threat level that must be used during the certification testing (Table 29.1). Shot patterns on the vest are also specified.

The current 0101.06 standard also includes a ballistic limit determination test. This test involves altering the velocity of the ammunition in order to determine a velocity at which there is a 50 % chance of penetration. The number of minimum shots required depends on the level of armor being tested. Type II through Type IIIA requires a minimum of 12 shots, while there are a minimum of 6 shots required for Types III and IV.

Although often criticized, the BFS test is based on research performed within the military in the 1970s [11–14]. This research involved a biomedical assessment of injuries resulting from specified ammunition striking a selected armor or a blunt impactor striking the body directly designed to mimic the bullet/armor/body interaction. Key areas of the torso were targeted including the lung and heart. The surrogate often used was an Angora goat, however some studies cite the use of a porcine or canine surrogate. Lung and heart injury as well as non-lethality were key parameters studied.

An extension of this research involved parametric modeling of blunt trauma lethality [11, 14]. Input parameters from the projectile such as mass, velocity, diameter and those of the armor; mass per unit area, were combined with the characteristics (mass and body wall thickness) of the subject being impacted. These input parameters were used then used to predict a level of lethality for the impact.

Newer models to predict the risk of injury as a result of BABT have been developed including biomechanical [15] and finite element models [16, 17]. These models have been developed to address the current limitations of the clay standard, however none have been incorporated into the current standard.

29.2.2 Case Studies: Torso

In an effort to determine the types of BABT injuries being sustained by law enforcement agents, a subset of data was collected from the IACP/DuPont™ Kevlar® Survivors' Club® database. This database is maintained by IACP and represents those officers who have survived due to the fact they were wearing body armor. It includes not only the ballistic cases but also stab/slash and blunt force trauma. Survivors are asked to complete a questionnaire about their incident and the resulting injuries.

As part of a recent ongoing study, cases involving ballistic impacts to the torso were studied. Additional information was collected specific to their injuries including the medical record. Of the 77 cases collected, 71 had adequate data available. Data for each case were obtained through phone interviews, medical records, and police reports. Injured officers were between the ages of 22 and 54, with the average being 34 ± 8 years of age. From the 71 cases that were collected for this study, there were a total of 90 shots stopped by personal body armor. The majority of the shots impacted the anterior chest (74 %, n = 65), followed by abdomen (16 %, n = 12), posterior upper torso (9 %, n = 8), and posterior lower torso (6 %, n = 5).

The level of protection offered by a ballistic vest is an important element of officer safety. The NIJ body armor performance standard has been revised several times since its inception to reflect the growing threats faced by officers. As previously discussed, vests are certified using a combination of weapons and rounds that are commonly used by law enforcement and criminals. The most current standard classifies armor into five types: IIA, II, IIIA, III, and IV. The first three levels are soft armor that protect against various handgun and shotgun ammunitions, while the last two levels are hard plates used in conjunction with soft armor to protect against rifle and armor piercing rounds. The majority of officers in this study wore either a threat level IIA or II vest (Fig. 29.3). From all of the cases, 25 % of the officers had additional protection from a trauma plate or pack.

The injuries that occurred from the 90 shots stopped by the armor have been classified as blunt trauma and backface signature injuries (Table 29.2). The majority of the injuries resulting from impacts to the vest were categorized as blunt trauma injuries (60 %, n = 54). These include less

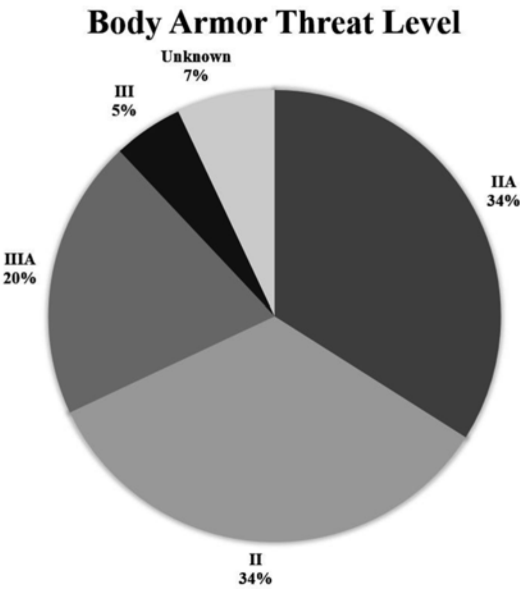

Fig. 29.3 Percentage of body armor threat level based on case studies

Table 29.2 Summary of case study data

	Body armor threat level				
Injuries	IIA	II	IIIA	III	Unknown
Chest blunt trauma	11	18	6	1	3
Chest BFS	7	2	2	1	2
Abdominal blunt trauma	5	1	3	–	–
Abdominal BFS	–	1	2	–	–
Posterior torso blunt trauma	1	3	–	1	1
Posterior torso BFS	1	–	1	–	–
Edge shot – GSW	2	1	–	1	–
No injuries	5	3	3	–	–
Unknown	1	–	1	–	–
Total	33	29	18	4	6

severe injuries involving contusions, abrasions, and rib fractures. Backface signature (BFS) injuries were the next most common injury among the sample population (21 %, n = 19). BFS injuries occur when there is a penetrating injury to the chest even though the bullet is captured within the armor [18]. These injuries have become more prevalent in recent years due to the desired increased in flexibility of the armor systems.

Eleven of the impacts to the vest resulted in no notable injury (12 %). Four impacts struck the edge of the vest and resulted in a gunshot wound (4 %) and the remaining two impacts generated injuries that were unknown (2 %).

Typically, the blunt trauma noted was a mild to severe contusions and abrasions. In addition, rib fractures, liver lacerations, and lung contusions were noted. Four officers sustained rib fractures, one officer experienced a lacerated liver, and one officer was found to have micro-fractures of the ribs and a lung contusion from impacts stopped by their protective vest.

29.2.3 Ballistic Helmets

Not unlike the body armor standard, the NIJ standard 0101.06 for Ballistic Helmets provides guidelines for the certification of ballistic helmets by law enforcement officers. A specialized headform with witness plate and accelerometer at the center of gravity is used. Specific threat levels are referenced for levels of protection: I, IIA, and II (see Table 29.3). Four fair hits without penetration and acceleration levels not to exceed 400 g's are required for certification. This standard is currently being revised by the NIJ.

In an effort to determine the prediction of skull fracture during ballistic loading of the helmet, Bass et al. [19] conducted a series of PMHS tests. Nine (9) helmeted PMHS were impacted with 9 mm ammunition and an additional four (4) were impacted with compliant direct impacts. The authors produced fractures in 5 out of the 9 ballistic impacts. These fractures were reported to be both simple linear and complex linear/depressed in nature. A 50 % risk of skull fracture was reported to occur at peak pressures of 51,200 kPa. It was also determined, that the acceleration based Head Injury Criterion (HIC) was not a good predictor.

Table 29.3 Standard threat levels for NIJ level of protection for ballistic helmets

Helmet	Test round	Test bullet	Bullet mass	Velocity
I	1	22 LRHV Lead	2.6 g (50 gr)	320 ± 12 m/s (1,050 ± 40 ft/s)
	2	38 special RN lead	10.2 g (158 gr)	259 ± 15 m/s (850 ± 50 ft/s)
IIA	1	.357 Magnum JSP	10.2 g (158 gr)	381 ± 15 m/s (1,250 ± 50 ft/s)
	2	9 mm FMJ	8.0 g (124 gr)	332 ± 15 m/s (1,090 ± 50 ft/s)
II	1	.357 Magnum JSP	10.2 g (158 gr)	425 ± m/s (1,395 ± 50 ft/s)
	2	9 mm FMJ	8.0 g (124 gr)	358 ± 15 m/s (1,175 ± 50 ft/s)

Using a finite element model, Pintar et al. [20] explored pressures and strains within the brain of a helmeted head from standardized ballistic threats. An instrumented headform with seven uni-axial load cells was used to determine the force-time histories used as input to the model. It was determined that the volume that exceeded the pressure tolerance level of 40 MPa was dependent on the impact direction: left (5 %), right (24 %), rear (47 %) and front (93 %). None of the elements exceeded the strain limits of .2 % with the standard helmet.

Hisley et al. [21] explored the use of digital image correlation to determine the energy available on the backface of standard helmets. It was determined that the loads were mechanically similar to those seen with blunt ballistic impacts with less-lethal projectiles.

29.3 Blunt Ballistic Impacts

The utilization of less-lethal force in both law enforcement and military operations has increased over the past several years. These less-lethal techniques allow for the use of force that is designed to incapacitate or subdue individuals with a low risk of lethality. Less-lethal arsenals include contact weapons, chemical

Table 29.4 Specifications for less-lethal munitions being manufactured

Caliber of munition	Mass of submunition	Muzzle Velocity	Materials
12 gauge	20–50 g	76–243 m/s	Rubber fin Bean bag Rubber ball
37/40 mm	20–140 g	50–137 m/s	Foam Wood Bean bag Rubber ball

agents, directed energy devices, capture devices and projectiles. Each type of technology is designed to inflict enough force to deter the situation without causing a fatal outcome.

Projectiles or kinetic energy (KE) rounds give a wide range of applicability with a relative ease of deployment. Often times, they are designed to deploy from weapon systems that are already in the controlling force's possession. Manufacturers have developed a variety of munitions to meet various situational needs. Single fire munitions allow for encounters with a single individual. Multiple projectile rounds are designed to control large crowds and potential riot situations. The proximity of the disturbance has been addressed in the development of both close-range and standard-range rounds.

These munitions differ from the normal ballistic weapons in that they have an increased mass but are deployed at a decreased velocity. A variety of munitions are being manufactured that include both 12 gauge and 37/40 mm rounds. These munitions vary in terms of the number and type of submunition deployed and the specified muzzle velocity (Table 29.4). The deployment of these KE rounds can result in blunt ballistic impacts, which has been defined as those impacts with a mass of 20–200 g and an impact velocity of 20–250 m/s.

Although KE munitions address the largest spectrum of situations while affording the greatest protection for the officer, the frequency of use and the types of injuries being inflicted are not regularly monitored. With no standardized reporting system, case reports are currently the only source of documentation [22–25].

Injury data from primarily Northern Ireland is available to describe the types and severity of injuries associated with the deployment of one type of non-lethal kinetic energy rounds. "Plastic bullets" were first used in Northern Ireland in 1973 as a means for riot control. They were intended to replace a less accurate rubber bullet previously used by security forces [23]. These "safer" bullets are cylindrical in shape measuring 100 mm in length with a 37-mm flat diameter. They are reported to weigh 135 g and are made from a polyvinyl chloride [22]. The muzzle velocity at which these munitions are fired range from 71.5 m/s (160 mph) to 89.4 m/s (200 mph) [24].

In 1987, Metress and Metress reported on 13 deaths resulting from impacts with plastic batons in Northern Ireland. It was reported that these fatalities were the result of impacts to either the head (nine impacts) or chest (four impacts). Deployment of the fatal impacts were reported to be less than 20 yards which contradicts the recommended 'rules of engagement' [24]. An additional death was reported in 1989 [22] for a total of 14 deaths since 1973.

Ritchie (1992) collected data from 1975 to 1989 by means of a retrospective chart review at a district general hospital in Belfast. A total of 123 patients were treated in emergency rooms with 38 being admitted for further care. Of the 126 injuries sustained by these patients, 19 (15 %) were to the head, 22 (17.5 %) were to the chest, 10 (7.9 %) were to the maxillofacial region, 17 (13.5 %) were to the abdomen, 24 (19 %) were to the upper limb, 33 (26.2 %) were to the lower limb and 1 (.8 %) was to the groin. The only death reported was due to ventricular fibrillation of heart function as a result of a blunt chest injury. Ritchie (1992) classified the injuries as either serious or non-serious but did not state a criterion for determining what qualified as a serious injury.

In 2004, Hubbs and Klinger released the first large dataset based on injuries related to less-lethal KE munitions in the United States. The authors investigated 969 firings of less-lethal KE munitions with 867 (92 %) striking the human body. It was reported that the abdomen was the area of the body most commonly impacted at 33 % (n = 263). The chest (n = 152), back (n = 85), leg (n = 119) and arm (n = 115) were the other most commonly impacted regions. Bruising and abrasions account for 81.5 % of the injuries, however 10 deaths were reported. Two (2) of these fatalities were due to the "miss-loads" with the law enforcement agents mistaking breaching rounds as a less-lethal ammunition. Four (4) of the cases involved KE munitions that penetrated into the body causing a fatal wound.

29.3.1 Thoracic Impacts

As part of the ongoing effort to evaluate, predict and prevent injuries caused by KE munitions, several studies have explored the biomechanics of blunt ballistic impacts to various body regions. One of the first regions studied was the thorax. Three impact conditions were established using a rigid impactor: (a) 140 g mass at 20 m/s (b) 140 g mass at 40 m/s and (c) 30 g mass at 60 m/s. Force-time, deflection-time and force-deflection curves characterizing the response of the body to blunt ballistic impacts were established using cadaveric specimens [26]. The determination of a valid injury criterion for assessing blunt ballistic impacts involved the review and re-analysis of existing data. Injury analysis was also conducted on the cadaveric specimens used to establish the biomechanical corridors. From these analyses, the injury criterion of Viscous Criterion (VC) was determined to adequately predict the risk of injury from blunt ballistic impacts. The reanalysis of data first collected by Cooper and Maynard (1986) demonstrated a VC of 2.8 predicted a 25 % risk of severe lung injury. A less severe skeletal injury of Abbreviated Injury Scale (AIS) = 2 is predicted by a VC of .8, based on data from cadaveric specimens [27].

29.3.2 Abdominal Impacts

Similar work was conducted for blunt ballistic impacts to the abdomen [28]. The impact condition was a 45 g rigid projectile with a targeted impact velocity of 60 m/s. Both cadaveric and sus scorfa specimens were used to determine biomechanical response corridors and injury criteria respectively. Six cadaveric specimens were impacted in the epigastric region to create a biomechanical corridor with an average peak force of 4,741 ± 553 N and an average peak deflection of 22 mm. The Blunt Criterion (BC) is based on natural log of the impact energy divided by the product of the specimen mass to the one-third power, wall thickness of the specimen and the area of impact. This criterion was found to be predictive of a 50 % risk of AIS two to three injuries to the liver (BC of .51) and bowel (BC of 1.32).

29.3.3 Head Impacts

While the head is never intended to be the region of impact with these munitions, impacts to the face and skull have been reported. Therefore, a determination of the biomechanical characteristics of the skull/facial structures and resulting fracture tolerance level was made [29]. Thirty-two (32) blunt ballistic impacts were performed to 11 unembalmed, post-mortem human subject heads. Impact locations included the temporal parietal, frontal and zygoma bones. An impactor with a mass of 103.3 g and diameter of 38.1 mm was launched using an air cannon system at velocities between 5.1 and 37.7 m/s. Impacts were paired to achieve a fracture/no fracture impact on each specimen.

For the temporal parietal impacts (n = 14), peak forces for impact condition A (18.8 g ± 2.1 m/s) were 3,211 ± 429 N with deformations at peak force of 7.9 ± 1.6. Peak forces for impact condition B (33.5 g ± 1.5 m/s) were 5,189 ± 992 N with deformations at peak force of 10.5 ± 2.3 mm. Three key injury criteria were found to be predictive: BC, force and strain [30]. Based on logistic curves, a 50 % risk of skull fracture is represented by a BC of 1.61, force of 5,970 N and strain of 5062 $\mu\varepsilon$ or 0.51 %.

Of the five specimens tested for frontal and zygomatic impacts, there were a total of 20 impacts. There were 4 fractures out of the 10 impacts for both the frontal and zygomatic bones. Frontal bone fractures ranged from linear fractures to comminuted depressed fractures.

In one case, there was a severe linear fracture than ran continuously from the impact site down across the sphenoid, temporal, parietal and occipital bones and ending approximately 30 mm from the external occipital protuberance. For the zygomatic region, there were two tripod fractures in this test series [29]. In addition to the tripod fractures, there were many linear and comminuted fractures to the zygoma, maxilla and bones within the orbit of the eye. The range for frontal bone fractures was from 4,413 N to 9,438 N while non-fracture values were from 2,630 N to 6,623 N. The range for zygomatic fractures was 575 N to 2,746 N. Non-fracture values were from 468 N to 3,711 N.

29.4 Summary

The study of terminal ballistics and target effects is an important process in the treatment and prevention of injury. Understanding the mechanisms of injury will guide medical providers on how to treat these injuries in a trauma setting. The development and revision of standards to evaluate personnel protective equipment rely heavily on injury biomechanics. Ongoing research to determine both the biomechanical responses of the body to such impacts and ways to predict the resulting injuries using surrogates (both biomechanical and computer based), are key steps in the injury prevention process.

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