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Review Paper
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Wound ballistics of firearm-related injuries—Part 2: Mechanisms of skeletal injury and characteristics of maxillofacial ballistic trauma[☆]

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Abstract. Maxillofacial firearm-related injuries vary in extent and severity because of the characteristics and behaviour of the projectile(s), and the complexity of the anatomical structures involved, whereas the degree of tissue disruption is also affected by the distance of the shot. In low-energy injuries there is limited damage to the underlying skeleton, which usually dominates the clinical picture, dictating a more straightforward therapeutic approach. High-energy injuries are associated with extensive hard and soft tissue disruption, and are characterized by a surrounding zone of damaged tissue that is prone to progressive necrosis as a result of compromised blood supply and wound sepsis. Current treatment protocols for these injuries emphasize the importance of serial debridement for effective wound control while favouring early definitive reconstruction.

Keywords: Wound ballistics; Gunshot wounds; Missile injuries; Maxillofacial injuries; Maxillofacial trauma.

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Although firearm-related injuries inflicted to the maxillofacial region frequently affect adjacent structures of the neurocranium or neck, by current criteria the head, face, and neck are considered separately in the context of ballistic trauma.[1–3] This is justified by the complex anatomy and articulation of the maxillofacial structures resulting in different injury patterns, which are also more difficult to reproduce in ballistic models.[2,4–6] As a result of these difficulties, there is a limited number of experimental studies investigating the mechanisms of maxillofacial missile injuries,[5–8] by contrast to the extensive literature dealing with their treatment.

In this second part of a review article on wound ballistics, specific mechanisms of ballistic bone penetration are described as a basis for understanding the pathophysiology of maxillofacial ballistic trauma. Maxillofacial gunshot (bullet) and shotgun (pellet) injuries are then presented,

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[☆] The complete paper is respectfully dedicated to Professor Daniel M. Laskin.

with respect to injury patterns commonly encountered and their surgical implications.

Mechanisms of ballistic bone injury

Bone tissue offers increased resistance to penetration compared to soft tissue due to its hardness,[9,10] in addition to its greater density and strength.[11] With bone impacts, both the retardant effect on the penetrating missile and the potential for energy transfer are marked.[11–13] Under these circumstances, the critical factors for injury are the limited capacity of osseous tissue to absorb the energy of impact without fracturing[10] and the toughness of cortical bone, which determines the extent of crack propagation.[14,15] Furthermore, recent evidence suggests that there are similarities between ballistic fractures in bone and glass, indicating that under the energy transfer associated with ballistic injuries, bone behaves as a brittle material.[16]

In a classic series of experiments, Huelke et al.,[17–20] using human cadaveric femurs as targets, showed that the degree of bone injury produced by spherical projectiles increased with progressively higher velocities, ranging in severity from incomplete penetration or simple ‘drill-hole’ defects, to comminuted fractures with complete separation of the bone ends. These authors demonstrated mathematically that the energy expended by the projectile penetrating normal and mildly osteoporotic femurs may actually be a linear rather than a quadratic function of the impact velocity, due to the resistance of bone.[20] This relationship was depicted by a drop in the percentage of energy loss during penetration as the impact velocity was increased,[17,19] because velocity affects the kinetic energy of the projectile raised to the second power, much more than it does with the amount of the energy transferred to the bone. In these series,[19] impacts to the dense cortical bone of the femoral shaft caused significantly greater energy expenditure than those directed to the metaphyseal region where cancellous bone predominates. Also, comminuted fractures were more common in the shaft, which was related to the narrow tubular configuration of the cortex in this area, the latter feature effectively distributing the loading generated by the impact around the entire periphery of the bone.[19,20]

Bone marrow has fluid properties allowing cavity formation within it by high-velocity projectiles,[11,21] also suggested by Huelke et al.[17,19] following penetration of the distal metaphyseal regions of femurs. In those experiments, defects of explosive character at the exit site were observed as a manifestation of cavitational effect by projectiles penetrating at velocities above 300–500 m/s, in extreme cases resulting in complete separation of the femoral condyles from the shaft.[19] Contrary to soft tissue, cavitation in bone is not followed by collapse of the cavity walls due to lack of elasticity, but rather the hydraulic pressure built-up results in immediate pulverization of the surrounding bone structure.[11,19] According to Kneubuehl,[22] this mechanism is primarily responsible for ballistic bone fractures, whereas in the absence of bone marrow, as in flat bones, bullets tend to create drill-hole defects. Cavitation was not prominent with shaft impacts in the series of Huelke et al.,[20] due to the limited bone marrow contained in these parts.

In a final series,[23] Harger and Huelke also showed that, at higher impact velocities, the diameter of the projectile has greater influence than its mass on the energy expenditure and the resultant bone damage, which is consistent with the magnitude of cavitational effects as related to the presenting area of the penetrating body. They concluded that the bone damage produced as a result of cavitation depends primarily on projectile velocity and size,[19] whereas at lower velocities, cavitation is not a prominent feature and the mass of the projectile becomes relatively more important.[23]

It follows that the energy transfer in ballistic bone injuries is a more complex phenomenon than in soft tissue; admittedly it also remains less well understood.[16,24] The drag force opposing the motion of the projectile within bone has different characteristics than in soft tissue, being independent of the projectile velocity according to Harvey et al.[25] Actually, because the amount of energy transferred during ballistic penetration is influenced by the time spent by the bullet in contact with the bone, which is inversely proportional to its velocity, it is possible for a relatively slow non-deforming handgun bullet to cause more damage than a stable rifle bullet.[10,21,22] Microfractures created by the penetrating projectile within the cortical bone substance[8,16] can partly explain this intricate response. These microfractures tend to radiate around the wound channel and beneath the impact site,[16] creating an area of lesser resistance ahead of the advancing projectile so that it makes its way through the bone more easily. A high-velocity bullet upon impact is expected to produce such defects more extensively, thereafter requiring relatively lower amounts of energy for the penetration process.[26]

Military and hunting rifles, as well as Magnum handguns, produce high-energy injuries with extensive bone comminution, documented both in experimental studies[27,28] and retrospective reviews.[29] It has also been observed that maxillofacial injuries by military rifle bullets at close range show greater comminution than those inflicted from a long distance with much of the bullet’s energy used up.[30] However, Clasper and Hodgetts[31] have reported an unusual case of accidental point-blank wounding by an M16 rifle bullet of current (NATO) design, resulting in a drill-hole defect in the humeral head, despite an apparently oblique course of the projectile through bone; the low-energy transfer in this case was explained by the bullet penetrating mostly cancellous bone, and the short wound track through soft tissue due to the low muscle bulk of the area.[31] Undoubtedly, an important contributing factor for such a low-energy bone injury despite high impact velocity is the streamlined shape of military rifle bullets eliciting lower drag forces. This could be validated in correlation with a recently published finite element analysis of mandibular ballistic injuries, which revealed significantly less energy loss by 7.62-mm military rifle bullets compared with 6.3-mm steel spheres, when the former penetrated at high velocities perpendicular to the bone surface.[6]

High-velocity missiles penetrating into soft tissue are capable of causing indirect fractures of adjacent long bones by the expansion of the temporary cavity in their wake.[12,25,32,33] These fractures represent a definite feature of high-energy transfer,[13,34,35] notwithstanding they are simple rather than comminuted.[12,32,33,35] Indirect fractures of the skull base occur with high-energy penetrating head trauma, but because of the unyielding conditions within the cranial cavity, even handgun bullets penetrating intracranially can create enough hydraulic pressure to cause linear fractures of the thin orbital plates, manifesting as peri-orbital haematoma.[21,22,36,37] The autopsy on President Lincoln showed shattered orbits, supposedly from this mechanism.[38]

Ballistic fractures are almost always accompanied by damage to the surrounding soft tissues, which may be augmented by bone fragmentation, especially in the skull or pelvis.[11] Bone fragments created by high-velocity penetration are dispersed in all directions.[8,10] Harvey et al.[25] suggested that fragments driven out into the adjacent temporary cavity are forced back with the collapse of the cavity, retaining a connection with the parent bone possibly