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Reconstructing the War Injured Patient

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Ballistics of Gunshot Wounds

Fadel M. Chahine

Introduction

The incidence of gunshot wounds and blast injuries parallels the global rise in wars, conflicts, and terrorism. As such, the devastating power of weapons poses a new worldwide surgical challenge to surgeons dealing with penetrating trauma.

"Wound ballistics" is the study of the wounding mechanism of missiles [1], a term which usually designates diverse projectiles (bullets, shrapnel, fragments, etc.) with sufficient kinetic energy to penetrate a living target [1].

As such, the severity of gunshot wounds and tissue damage is related to the amount of energy transmitted [2]. Specifically, following impact, a complex projectile-tissue interaction occurs during penetration. This is related physically to the projectile's dynamics, and biologically to the local tissue reaction, although the severity of injury is ultimately related to the proximity of the wound track to vital organs and large vessels [1].

Ballistics of Bullets and Projectiles

Once the trigger is pulled, a quick expansion of gas ensues from combustion of the propellant, with concomitant rise in temperature up to 2800 °C, resulting in pressures as high as 25 tons per square foot. This is translated into launching the bullet with enough kinetic energy and devastating potentials [2, 3].

Characteristics of Firearms

The general design of a gun is that of a long tube referred to as the barrel, along with a chamber, which receives the bullet and contains the propellant, and the primer [3].

The Barrel

With a longer barrel, more time is available for bullet acceleration by the expanding gases, which signifies that for identical bullets, guns with a longer barrel produce a higher velocity bullet [2].

Rifling

The barrel may contain internal groovings, a characteristic referred to as rifling, and allows for the bullet's spin, which is necessary for appropriate orientation during flight with its nose forward [3].

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Low- Versus High-Velocity/Energy Firearms

Projectiles were traditionally labeled as "low" or "high" velocity, in relation to the speed of sound in air (350 m/s). This classification was pertinent to match small arms (<350 m/s), handguns (350–600 m/s), and explosive effects seen with rifles at speeds above 600–700 m/s [3].

Characteristics of Bullets

Caliber

This is a measure of the width of a bullet. In the metric system, it refers to the diameter of the bullet in millimeters (e.g., 9 mm), whereas a 30-caliber ammunition by American manufacturers is a label of English origin that refers to a diameter of 30 hundredth of an inch [4].

Nose Profile/Contour

The shape of the projectile's nose is important for maintenance of velocity and energy inflight [3]. Designs vary from the round tip of pistols to the slender/pointed profile of military assault rifles, with various effects on ballistics performance.

Composition

Most bullets are composed of a lead alloy, although lead-free (nontoxic) metallic bullets are available [5].

Shell/Jacket

Bullets may include a lead or steel core covered by a "jacket" of a harder metal such as cupronickel or steel alloy [5].

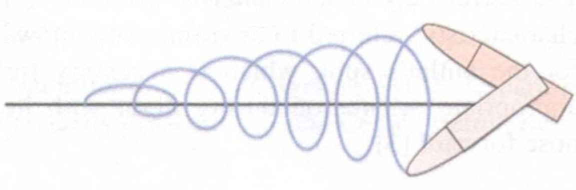

Fig. 1.1 Precession or rotation of the bullet around the center of mass due to spin

Construction

Partially jacketed bullets may either refer to an exposed or a hollowed-out tip, which flattens upon impact. Full metal-jacketed (FMJ) bullets on the other hand are immune to tip deformation thanks to the jacket enclosing the tip [5].

From Barrel to Target: How the Bullet Travels

Yaw

This is defined as the deviation of the long axis of the bullet from its line of flight [6].

Spin

Rotatory movement of the bullet secondary to rifling, which is necessary for appropriate orientation during flight with its nose forward [3].

Precession

Rotation of the bullet around the center of mass due to spin (Fig. 1.1).

Nutation

Small circular motions at the bullet tip (Fig. 1.2).

Energy Transfer in Gunshot Wounds

The Fallacy of Equating Wound Severity with Velocity

A better understanding of gunshot wounds eventually uncovered the direct relationship between the severity of the gunshot injury and the amount of energy transferred by the projectile, which is ultimately related to the velocity and distance travelled. As such, a more pertinent classification regards "high-" versus "low"-energy injuries [2]. For instance, published ballistics data reveals that the muzzle energy drops markedly beyond 45 m for the majority of handgun bullets, and beyond 100 m for rifle bullets [3]. However, most civilian gunshot wounds occur at ranges of 10 m [3].

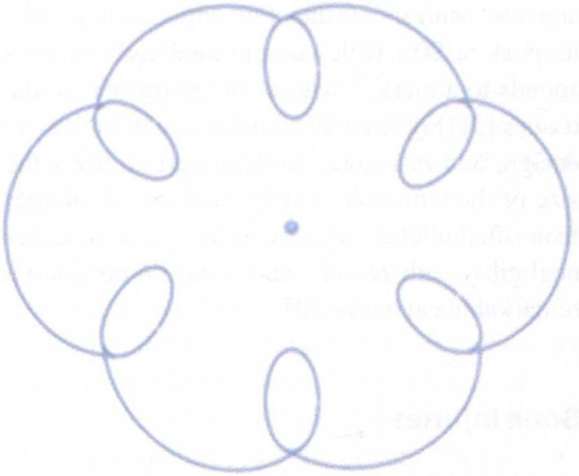

Fig. 1.2 Nutation, small circular motions at the bullet tip

- *High/low energy inaccuracy—importance of energy deposited in tissue*

Nevertheless, describing gunshot wounds as high "versus" low energy was a misleading estimate because impact energy (kinetic energy) is not the only factor. In reality, tissue disruption is due to the amount of energy dissipated and transferred from the bullet to the tissues, and quantified as $E = 1/2M(V_{entering}^2 - V_{exiting}^2)$ [2, 3].

- *Energy transfer and tissue resistance—relation to presented surface area*

The amount of energy transferred from the bullet to the tissues, which generates the damage, depends on four main variables [6].

The first factor is the amount of kinetic energy possessed by the bullet at the time of impact, which is a function of its velocity and mass.

The angle of yaw of a bullet at the time of impact, which is defined as the deviation of the long axis of the bullet from its line of flight, also influences the amount of energy transferred to the tissues. The greater the angle of yaw of a bullet when it strikes the body, the greater is the contact surface area, and hence the greater is the loss of kinetic energy.

In fact, as the bullet moves further from the muzzle and with its destabilizing gas effects, the maximum amplitude of yaw gradually decreases. This correlates with the observations that close-up wounds are often more destructive than distant wounds because of increased bullet stability with increasing range. In addition, this explanation supports the observation that a rifle bullet penetrates deeper at 100 m than at 3 m [6].

With tumbling of the bullet, a much larger cross-sectional area of the bullet to be presented to the target is needed. Hence, a shorter projectile will tumble sooner than a larger projectile [6].

The third factor that governs the amount of kinetic energy lost and transferred to the tissues in the body is the bullet's characteristics: its configuration, caliber, and construction. Bullets with a blunt nose, which are less streamlined than pointed spitzer bullets, are more retarded by the tissues, and subsequently lose greater amounts of its kinetic energy. By contradistinction to the fully-jacketed bullets, an expanding ammunition disintegrates in the tissues. Consequently, by shattering and mushrooming they are more retarded than fully-jacketed bullets [6].

Of note, the caliber of a bullet and its shape are important determinants of the initial value of the area of interphase between the bullet and the tissues, and subsequently influence the drag of the bullet. Once the bullet is deformed, the shape and caliber decrease in importance [6].

The fourth and final characteristic that quantifies the amount of kinetic energy lost by a bullet is the density, strength, and elasticity of tissue struck, as well as the length of the wound track. Retardation and loss of kinetic energy are directly proportional to the density of the penetrated tissue [6].

Mechanism of Gunshot Wounds

Once a bullet has lost all its kinetic energy, it can no longer move forward. Hence, a bullet found in the tissues has already transferred all its energy. The resulting track is a blind-end wound with only an entry hole. Otherwise, a piercing wound may result, with the bullet exiting the body through another hole, which tends to be larger and more irregular than the entrance wound, secondary to the projectile's tumbling [3].

Direct Tissue Damage

A permanent wound channel is formed due to crush injury from overpressure in front of the projectile, followed by breakup of the tissue encountered by the bullet [3]. This track is surrounded by an area of irreversible tissue damage that ultimately undergoes necrosis, and an outer extravasation or hemorrhagic zone with no evidence of gross tissue damage [3].

Other mechanisms of injury also apply in close-range gunshot wounds, whereby the damage is worsened by the blast effect of the gases escaping through the muzzle [3], and tissue burning may be a consequence of bullets retained in the wound [3].

Cavitation

The soft tissues have a limited capacity to react to the pressure wave changes created by the penetrating bullet, which explains how tissue displacement lags behind the bullet, and the ensuing deformity is termed the temporary cavity [3]. Should the displaced tissues be elastic and accumulate enough energy, the cavity walls may collapse, resulting in pulsations of expansion and contraction which wane until the "permanent wound channel" settles following the "temporary cavitation" [3].

The rate of energy transfer as well as the dimensions of the bullet along the track modulate the size of the temporary cavity. In fact, the spindle-shaped temporary cavity becomes more apparent with increasing yaw angle, and reaches its peak at 90°, which as outlined earlier corresponds to a marked rise in energy transfer to the tissues [3] (Fig. 1.3). In addition, the bullet's size, design, and resistance to deformation affect the size of the temporary cavity as some are smaller than rifle bullets, and their surface area increases negligibly with yawing, and hence do not elicit a remarkable cavitation [3].

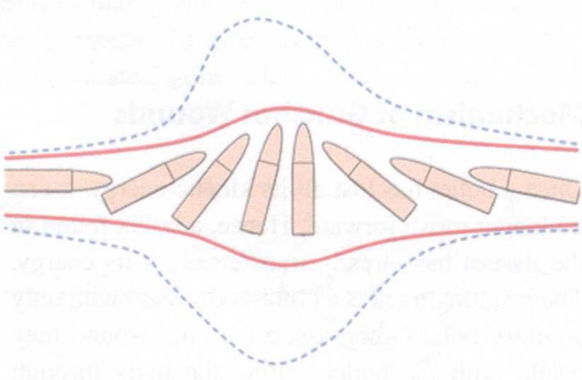

Fig. 1.3 Cavitation of the bullet during tissue penetration

Bone Injuries

When it comes to ballistic bone injuries, the higher density and particularly its hardness compared to soft tissues impede and retard the penetrating bullet markedly. The physical and mechanical properties of bone underlie the complex ballistic interaction, which often leads to the bullet's deformation and breakup [3].

In general, important considerations include the projectile's energy at impact, angle of interaction between the projectile and bony surface, as well as bone thickness [3]. In particular, cancellous bone is associated with a greater energy-absorptive capacity, and limits the extension of a fracture line. Cancellous bone is usually more abundant in the metaphyseal regions of long bones, where "drill-hole" defects—a characteristic of low-energy ballistic penetration—are more common [3].

As for bone marrow, its fluid properties allow for more cavitation [3], especially in cases of explosive high-energy ballistic impacts, which translate into comminuted fractures [3].

Nevertheless, bone comminution may occur with low-energy ballistic penetration.

While the radiologic picture is indiscernible from high-energy impacts, clinical evaluation of the associated soft-tissue injury is helpful [3].

Head Injuries

The bone–projectile interaction is an important factor to examine in cranial vault penetrations.

"Gutter wound" refers to tangential bullet wounds of the skull, and may include the outer table or the entire bone thickness [3].

In general, if a bullet penetrates the skull, it may undergo deformation, and carries enough remaining energy to reach the opposite side without necessarily exiting [3]. The travelling bullet may also lead to secondary missiles in the form of bone fragments.

Interestingly, the dimension of the wound channel in the brain is not directly related to the muzzle energy of the bullet, nor its caliber [3].

The peculiarity of gunshot wounds to the head lies in the limited and constricted volume, which prevents expansion of the temporary cavity. The pressure buildup boosts the effects of cavitation even in low-energy penetrations, and may only be dissipated by bursting the skull [3]. The magnitude of temporary cavitation can be visualized as parenchymal changes that extend beyond the permanent wound channel [3].

Contamination

The vacuum created by the travelling bullet acts to suck foreign material and debris into the wound, in addition to the contamination already present on the surface of the bullet traversing the dirty battlefield, soiled clothes, and colonized skin [3]. Of note, the bullet surface is not sterilized by the heating incurred, as previously believed [3].

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Biodynamics of Blast Injuries

2

Ghassan Soleiman Abu-Sittah
and Odette M. Abou Ghanem

Introduction

Explosive devices have become a major weapon in current armed conflicts, antipersonnel landmines, and terrorist bombing. This has changed the trends of prevalence of the wounding mechanisms over the past several decades. Shrapnel injuries are now more common than bullet injuries in wars between armies and can cause up to 80% of casualties due to the preponderance of blasts and explosive devices in conflicts [1]. In addition, these explosive weapon systems have a greater distance range of injury compared to the close-range firearm systems [1]. The detonated explosives generate high winds and propel debris causing conventional blunt and penetrating trauma. However, explosive devices do not only cause injury through fragmentation which has similar wound ballistics as gunshot injuries discussed in the previous chapter. Explosive systems can cause a special set of lesions that have particular pathology, their own diagnostic challenges, and specific management requirements known as primary blast injuries. This chapter discusses the biodynamics of blasts and their mechanisms of injury with an overview of the current understanding of primary blast injuries and their effects primarily on the respiratory, gastrointestinal, and auditory system.

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Blast Physics

An explosive is a substance, solid or liquid, that once detonates will chemically convert instantaneously into gas through an intense exothermic reaction releasing large amounts of energy [2]. The gas expands radially outward from the location of explosion at supersonic speeds (usually greater than 5000 m/s) in a process termed detonation [3]. This expanding gas causes an instantaneous acute rise in pressure creating a supersonic wave called the blast wave or shock wave. The blast wave displaces the surrounding medium, be it air or water, generating winds of enormous velocity called blast winds that propel people and objects [4]. The displaced medium in front of the blast wave is compressed which heats and accelerates its molecules creating a pressure that exceeds atmospheric pressure called blast overpressure (BOP) [5]. The air molecules are compressed to such a density that the blast wave itself acts like a solid hitting the victim [6]. The

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blast pressure dissipates over time and space. These changes in pressure due to the blast wave vary depending on whether the detonation took place in open air or closed space. The classic Friedlander wave describes the characteristic pressure changes over time of a blast wave outdoors, the so-called free-field wave (Fig. 2.1a). It is an idealized blast overpressure waveform, with an acute instantaneous rise in pressure to a peak overpressure and then dissipation exponentially over time until back to atmospheric pressure in what is called the positive blast phase. This peak overpressure is the maximum pressure reached and is commonly referred to as BOP. It decreases

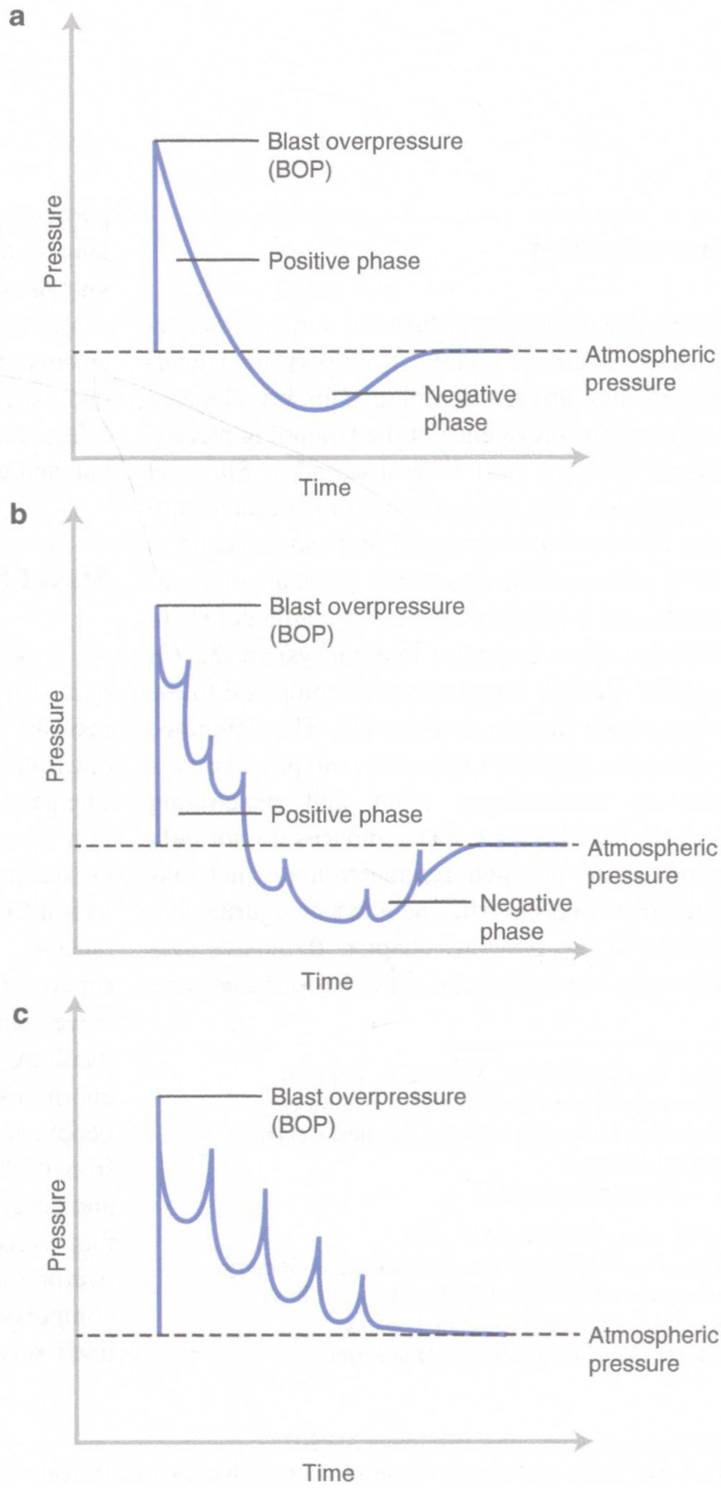

Fig. 2.1 (**a**) Free-field wave—open-space wave. Classic Friedlander wave: An idealized blast overpressure waveform. (**b**) Simple free-field wave. A more realistic waveform. (**c**) Enclosed-space waveform. Blast overpressure is amplified, and positive pressure wave is prolonged

so rapidly (inversely proportional to the cube of the distance) as the distance from the detonation center increases, persons must be within tens of meters close to the epicenter to sustain a primary blast injury [2]. However, pressure keeps decreasing to subatmospheric pressures in what is called the negative-pressure suction wave before returning to ambient pressure. A more realistic waveform of a simple free-field wave has both positive and negative phases roughly very similar to the Friedlander but with multiple peaks and troughs, very close in amplitudes, that represent vibration or reflection of the surrounding surfaces, at least the ground (Fig. 2.1b). In enclosed space explosion, however, the blast overpressure is significantly amplified and the positive pressure phase is prolonged. This is due to the confinement of the pressure waves that reflect back from the multiple surrounding solid surfaces which increases their force and causes multiple pressure peaks and troughs (Fig. 2.1c) [7]. This understanding of blast overpressure magnitude, positive pressure phase, and propagation speed of a blast wave is fundamental for the understanding of the biologic effects and management of blast injuries.

Many factors affect the likelihood and severity of blast injuries. One important factor is the medium in which the explosion takes place. For example, water molecules do not get as compressed by the blast wave as the air molecules do. Therefore, the blast wave propagates more rapidly and dissipates more slowly in a water medium causing more injury than an explosion does in an air medium [8]. Another important factor to consider is the distance at which a person or an object is from the detonation epicenter. This distance determines how exposed the victim is to the blast overpressure [9]. The blast energy dissipates and the pressure drops inversely proportional to the distance cubed. For example, if individual A is at a distance d from the detonation and individual B is at a distance 2d double that of A's, then the BOP that individual B is exposed to is 1/8 that individual A is exposed to. A 1-kg explosive will generate blast overpressure of 500 Kpa at the site of detonation which is fatal and drops exponentially to 20 Kpa at 3 m from the center which causes minimal injury [4]. Another substantial factor that determines blast overpressure exposure is the surrounding solid surfaces. These surfaces reflect the pressure waves and amplify their forces, hence exposing people next to them to a higher blast overpressure compared to those away from them and at the same radius from the detonation center. It is the reason behind which closed-space explosions have the potential to cause more severe injuries and higher mortality that open-field explosion [10, 11].

Mechanisms of Blast Injuries

Traditionally, blast injuries have been classified into four categories according to the mechanism by which the blast wave causes these injuries. A fifth type of blast injuries has been recently suggested.

Primary blast injuries (PBI) are the direct effects of the interaction of different organs in the body with the pressure changes of the blast wave. These injuries are unique to higher order explosives which make most civilian physicians unfamiliar with them. The organ damage in PBI is produced by the interaction of the blast wave at the interface between tissues of different densities or the interface between tissues and trapped air. Consequently, gas-containing structures, like the lung, GI tract, and ear, are most commonly affected by PBI [12]. These types of injuries are the main focus of this chapter and are discussed in great details in the following section.

Secondary blast injuries occur when objects energized by the explosion strike an individual, causing either blunt or penetrating trauma (e.g., bomb fragments, shrapnel). Fragments displaced by the blast winds travel a much longer distance than that traveled by the blast overpressure. This is why secondary blast injuries can occur up to thousands of meters away from the explosion site while PBI occurs within tens of meters only [13]. Penetrating secondary blast injuries from fragmentation of the detonated weapon or the secondary fragments resulting from the explosion are a leading cause of morality in terrorist attacks not including building collapse [14].

Tertiary blast injuries occur when the victim's body or body parts are displaced by the blast winds