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THE BIOPHYSICS AND PATHOPHYSIOLOGY OF MISSILE INJURY

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Introduction

Back ground

Weapons have been invented, refined and adapted over the course of human history. Most of today's antipersonnel weapons cause ballistic wounds, and their origins can be traced back over thousands of years. Between the years 1945-1987, there were 214 local wars with 100 millions casualties and 25 millions deaths. Since then there were increase in both local wars and the efficacy of weaponry, so the number of victims has increased and this should claim more attention from medical professions. All over the world, one person injured by gunshot every one minute and one killed every 10 minute.

Definitions

Ballistics is the study of thrown objected missiles or it is the science of the motion of a projectile through the barrel of a firearm (internal ballistics), during its subsequent flight through air or space (external ballistics) and during its final, complicated motion after striking the target (terminal ballistics).

Blast producing injury refers to those detrimental changes occurring in an organism exposed to the effects of changes in the pressure produced by the explosion.

Brief historical review

Sticks or clubs were the earliest and the only weapons man used**.** The bow was first used in the Akkadians / Sumerians war at 1500 BC. At 1000 BC sling used to aid throwing by which they improve the range and the velocity of the projectile. At 400 BC, Romans are stored energy by using of powerful bow to throw a projectile, but at 300BC they use springs rather than a bow as a mechanical stone thrower.

Chinese were the first who had invented black powder 1000 years ago but it is only after the first world war were they describe the blast injury as specific entity. The earliest record of firearm was in 1326 by firing cannon. Since the thirteen century gun powder widely used and represent one major

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contribution to missile injury. Machine gun first invented in 1870; it makes mark progression from rapid manual reloading to automatic reloading, firing and cartridge ejection. It is only in 1915 when the old shrapnel shell replaced by the high velocity explosive artillery rounds.

Wound ballistics is a term originally used by Callender and French (1935) whom study the interaction of the projectiles with living tissues.

Firearm types

There are three basic types of firearm: rifles, handguns, and shotguns. Rifles are the most powerful and are known for their longer barrels and higher velocities when compared to handguns. These high energy weapons are designed to be held with both arms and all rifles are considered as high velocity weapons.

Handguns are the least powerful type. Because of their short barrel, they have decrease velocity, kinetic energy, and accuracy when compared to rifles. Handguns available in two designs – revolvers and pistols. Shotguns characteristic feature is the smooth barrel (it is not helically grooved to impart spin and stability to a bullet) as in rifle and handguns. Shotgun fires a missile consisting of cylinder with primer and gun powder at its base .the projectile portion of the shell, consist of a few to hundreds of lead or steel spheres called pellets which separated from the gun powder by plastic or cardboard wadding which is frequently found in the wound. The pellets are fired in a medium velocity (1000 – 1500 ft/s). The degree of damage depends on the distance from the target and the size of the pellets fired. Because of the shape of the spherical pellets compared with the pointed bullets, shotguns pellets decelerated rapidly, degrading kinetic energy to heat as their trajectories diverge after leaving the muzzle of the shotgun. Beyond 50 yards (45 m), the wounding capacity of these pellets generally is negligible, compared with effective ranges of hundreds to thousands of yards in the case of rifle.

Fragmentation weapons

Fragmenting anti-personal weapons such as mortars and high explosive shells and mines (anti persons and anti tanks), have caused the most wounds in armed conflicts of the 20th century. These fragmenting weapons produce a variety of fragment sizes. The weapons designer apparently created arms that usually produce fragments weighting less than 1 g, but more than100 mg. such fragments regarded as the optimal size for anti-personnel projectile. Over the last years there were many changes done in their design to improve the probability of a hit and increase the effective area of the munitions. The principal changes are the use of scattered submunitions (bomblets), and controlled fragmentation of submunitions to create large numbers of small fragments with a mass between 200 mg and 500 mg, by this way the incidence of casualties with multiple wounds has increased, with soft tissue wounds to the lower limbs predominating. These submunitions are initiated at a high velocity (greater than 1000 ms/s), but their low mass and irregular shape lead to a rapid reduction in velocity. Most casualties surviving to reach surgical facilities will be struck by fragments with a velocity below 600 ms/s. The most important finding in tissue wounding is that skin damage is much localized and that muscle damage is limited with little necrotic tissue in the track. The extent of the muscle damage improves with time, healing within few days, provided the wound remains without infection.

Biophysics and pathophysiology

Missiles injuries can cause wide spread distribution destruction of a variety of structures and organs, so it is important to know the mechanism of missile injury and effect of missile since the beginning of its trip so that we can imagine the effect of destruction in the structures and tissues.

As mentioned above; ballistics is the study of firing, flight and effect of projectile. Bullet velocity and yaw angle at impact are basic parameters in wound ballistics studies.

Internal ballistics

Describes projectile flight within the weapon (barrel of firearm). In this stage the chemical energy of propellant which is gun powder in case of firearm will convert to the kinetic energy of the bullet. This stage also consider the time course and interrelations of pressure, volume and velocity in the bore of the firearm and the induction of spin of bullet to achieve stability in the flight by the rifling which is the helical groove in the internal surface of barrel.

The firearm is loaded with the cartridge that contains explosive primer, gun powder and the bullet. After the trigger is released, it drives a firing pin into the cartridge which contains the primer at its base; spark will be created which ignites the gun powder which propels the bullet down wards the barrel. During its path in the barrel, the bullet begins to spin as it traverses the rifling.

The exit velocity of the bullet which also called "The Muzzle" which is determined by:

1. Bullet's mass; the greater the mass, the harder to propel with the same amount of gun powder.
2. The amount of gun powder in the cartridge; when the gun powder amount is larger, the explosion will be greater.
3. The length of barrel; the longer the barrel, the higher the velocity because the long barrel will give good time for more spin which give more chance for accumulation of gaseous pressure and stability.

As soon as the bullet exits the barrel, the gaseous pressure that propelled it forwards quickly dissipates but the bullet leaves the muzzle still accelerating under the rapidly falling pressure of gas which begin to escape from the muzzle. Because of the rifling the bullet is accelerated not only linearly but also angularly. The resulting spin imparts stability to the trajectory of the bullet and tends to suppress erratic flight, typically in a form of "yaw" which is the angle between the long axis of the bullet and its line of flight. The bullet is also tumbles forwards and end over end rotation around the bullet's center of mass.

External ballistics

It describes the flight of the projectile through the atmosphere as it travels towards its target.

As the accelerating bullet is forced through the muzzle, the turbulence of the emerging gas will induce slight yaw in a form of only few degrees which becomes more significant once the target is struck. In the atmosphere, there will be corresponding increase in the resistance to the bullet; this resistance also called "drag". The drag will increase progressively leading to substantial drop in the bullet velocity. The amount of atmospheric drag depends on:

1. Bullet speed; faster bullet retarded more proportionally than slower one.
2. Bullet size and shape; the bigger the bullet the more drag and more speed retardation.
3. Centre of mass; as the centre of the mass in the base of the bullet, increases the resistance to flight.

Terminal ballistics and tissue wounding

It describes the final path of the bullet and its effect on the living tissue.

The extent of tissue wounding or the effect of the bullet on the tissue determine by:

1. The release of the kinetic energy (KE) to the target. KE can be define as:

$$KE \approx MV^2$$

Where M = mass and V = velocity.

The total energy released to the target can therefore be represented by

$$KE = KE\ entry - KE\ exit$$

From this formula, it is evident that a higher entry KE due to increase bullet mass and velocity.

There are two velocities which are;

1) Muzzle or initial velocity.
2) Velocity at impact.

According to bullet velocity (muzzle – impact velocity) we can classify weapons into three categories:

i) Low velocity missile: in which bullet velocity not exceeding 1000 ft/s or 305 m/s like pistol bullet. These bullets will exhibit an entrance and exit wounds smaller than the diameter of the bullet and a track of tissue damage not much greater in diameter. The mechanism of injury is through laceration and crushing and it is limited to the missile pathway.

ii) High velocity missile: in which bullet velocity exceeds 3000 ft/s or 914 m/s like bullet of military rifle or sporting rifle which may exhibit a similar entrance, but the exit may range from same to several times the diameter of the bullet. Also there may be no exit or a numerous exit depending on the shape and con-struction of the bullet and the tensile strength and density of the wounded tissue. The track of this type of missile may be surrounded by tissue destruction extending as much as several centimeters radially from the track secondary to the momentary intense compression and subsequent stretching of surrounding tissue to many times its normal dimensions. So the injuries effects through laceration, crushing, missile waves and cavita-tion effects.

iii) Medium velocity missile: in which bullet velocity between 1000 – 3000 ft/s or 305 – 914 m/s like the shotguns by which the bullet behavior like high velocity missile.

If the exit KE is still high then minor tissue damage may result. Bullet that passes cleanly through the target and exits with significant velocity will not cause as much damage as a bullet with similar entry KE that completely decelerates and comes to rest within the target. In addition projectile with a higher impact velocity have a greater drag within the tissue, and hence have a greater KE, and this will lead greater tissue damage.

2. interaction between the projectile and tissue: when target is strucked, three tissue phenomena are noted:

i. Sonic pressure waves: which travels at approximately

4800 ft/s, preceding the projectile following impact? In some studies, showed that these pressure waves, al-though producing pressures up to 117 atmospheres, it lasted only for a few microseconds. These waves can be isolated from both permanent and temporary cavities and the old studies show that it did not have any significant disruption capacity on tissue. Recently, investigators have re-examined the issue of sonic waves and its effect on the wounds and they demo-nstrate that it can disrupt the neural function, even at sites in the body distant to bullet impact.

ii. Cavitations: This is first recognized by Woodruff in 1898. Low velocity missile tend to push the tissue aside, producing tissue destruction only slightly greater than the diameter of the missile. In a high velocity missile, the kinetic energy of the bullet is dissipated in part by an acceleration of tissue forward and laterally away from the bullet and track, generating in milliseconds a cavity filled with vapor water at sub atmospheric pressure. Then the cavity continues to enlarge even after the bullet has passed. The resultant stretching, compressing and shearing of tissue may produce damage extending several centimeters lateral to the bullet and its track. Vessels, nerves and other structures that not in direct contact with the missile may be damaged. Within milliseconds, the cavity collapses because of tissue recoil and atmospheric pressure, leaving the track of the bullet; these two cavities are called the temporary and permanent cavities.

Temporary cavity

The temporary cavity is caused by the release of energy into structure adjacent to the bullet path causing a radial stretch of these tissues. The cavity created behind the bullet path, creating pressures between 4 atmospheres and sub atmospheric pressure. The size of this cavity may reach up to 30 times the volume of the bullet. The effect of the temporary cavitations depends on the tensile strength of the affected tissue. Highly elastic tissue such as the lungs and muscles will easily accommodate the stretching created by this cavity. Other, less elastic tissue, such as liver, spinal cord and bone may seriously damage by this wave. How seriously the tissue damage depends on the kinetic energy at impact and the specific gravity of the tissue.

Permanent cavity

It is the cavity produced by the bullet entry consists of that tissue which crushed by the bullet. Different permanent cavities are produced by different types of missiles depending on the interaction of the bullet with the tissues. The volume of the permanent cavity depends on the yaw of the bullet at its entrance, the velocity of the missile, the size and the design of the bullet and bullet deformation and fragmentation.

As the projectile strikes its target, the stabilization effect of its spin is quickly overcome by the density of the tissue. The bullet can yaw to 90 degrees and often may come to rest at a 180 degrees angle to its initial path. The yaw growth in its target is directly related to the yaw entry. The process of tumbling within the target significantly increases the destructive capacity of the projectile. The bullet's yaw when reach 90 degree within the tissue will increase the effective diameter (increase the diameter of the cavity); this explains the small entrance of the bullet with massive internal tissue damage. In high velocity, if the path of the missile is short, missile the exit wound may be larger ragged compared with the modest wound of entrance. In longer path, the maximal rate of degradation of kinetic energy may occur deeper within, creating extensive damage through cavitations but leaving entrance and exit wounds appearing as those caused by low velocity missiles.

Secondary missile

The bullet and its fragments may impart sufficient kinetic energy to dense tissue such as bone and, occasionally, metals from buttons and buckles of wearing apparel, or that the temporary cavity produced close to the bone the latter may shatter and propel to many small pieces creating what is called secondary missile. These missile produce tissue damage in a way similar to the permanent cavity. They are more destructive than the primary missiles, this is because these fragments are very sharp, are already lying inside the body and are takes erratic, unpredictable, and unexpected courses. At high velocities, bullets tend to yaw in tissue, increasing their profiles tending to increase the rate of dissipation of kinetic energy, thus increasing the probability of fragmentation of the primary missile and formation of secondary missiles.

Critical application of the following principles - the relation between the mass and the velocity of the projectile and its potential for imparting destructive forces to tissues, the production of secondary missiles and the mechanism of cavitation – will guide the surgeon to the extent of damage, the need of debridment, and the potential for infection as well as the possibilities for reconstruction.

Pathophysiology of blast injury

Blast and blast related injuries are the commonest injuries encountered in the war and terrorist incidents. To understand the nature of blast injuries, it is imperative to analyze the blast and understand the biomechanics of the blast. The type and extent of injury from explosion depend on the type of munitions employed and the environment in which they detonate. Modern military munitions are specifically designed to produce metallic fragments within a specific mass range to ensure consistent and effective performance over large range. Two weapons may produce blast injury, these are; the bombs and mines weather antipersons or antitank.

Blast explosion can cause injury in five ways; these are:

1) The primary injury

This is caused directly by the blast waves and encompasses injury to air-containing organs such as the lung and the bowel, and to solid viscera. It is important to appreciate that most of the salvageable cases amongst the blast victims are those cases suffered injuries other than primary and tertiary injuries. All persons within the lethal zone die from the effect of the blast wave itself. This lethal zone depends on the size of the charge; for example a 32 kg charge, the lethal zone is about 4 meters. In nuclear explosion this may be in kilometers. The high pressure, high energy blast wave on entering the human body is transmitted in three forms:

1. *Stress waves:* these are longitudinal pressure waves traveling like and at the speed of sound. They cause small rapid distortion of the tissue (stress), which in itself may not be detrimental but the effect is most pronounced at the interfaces of acoustic impedance. Therefore, the maximum damage is expected in air filled viscera like ear, lungs and gastrointestinal tract. The wave reflection within the body also causes reinforcement. The reflection from mediastimum and rib cage is responsible for greater damage near these structures.
2. *Shock wave:* These are similar to stress waves in being longitudinal but have a higher velocity and therefore, cause greater damage.
3. *Shear waves:* These are slow transverse waves which cause greater distortion of the tissue as opposed to the previously describe waves. Because of this greater distortion to tissues, they cause greater tissue damage. They can cause gross movement of tissues in relation to each other. They are responsible for disruption of various vascular pedicles.

Explosion in the air will results in:

- **i.** A pressure pulse which emanates radially from an explosive source at the speed of sound in air.
- **ii.** A negative pressure component immediately following the pressure rise.
- **iii.** High transient winds which accompany the pressure variations and whose

direction may be either positive or negative with respect to the explosive source.

iv. Other effects such as fire and ground shock which are major contributors to the explosive damage.

Explosion in the water: water as a medium less yielding than air due to:

i. Differences in density (water is approximately 800 times more dense than air).
ii. Differences in the compressibility (water is approximately 10 000 times less compressible than air).

Other factors being equal, corresponding values for pressure are therefore much higher in a water shock wave than those produced in air. The biological effects of underwater blast cannot be conveniently classified to primary, secondary and tertiary effects, as with air blast, but instead must be related to the physical phenomenon of the underwater explosions which are;

1. Shock pulse.
2. Shock pulse after flow.
3. Bubble pulse.
4. Bubble pulse after flow.

When the under water explosion takes place the gaseous products are subjected to a high pressure, and although the surrounding water is of low compressibility, pressure is transmitted to the water layer in contact with the gases and a shock wave is propagated radially at approximately the speed of sound in water (1450 m/s). the shock wave rises to its maximum in the order of 1 ms and decays towards zero in the order of a very few milliseconds. Of the total energy of the explosion, approximately one-quarter is radiated in the shock wave.

Specific effects of the blast wave

The ear: the tympanic membrane being diaphragmatic in nature, and because its place with two acoustic interfaces which are the air / tissue and the tissue / air interfaces, this place makes it more vulnerable to injury by the blast waves. Healthy tympanic membrane would rupture at a pressure of 100 kpa/cm² applied for duration of 10 msec or more while a previously scarred tympanic membrane ruptures at a pressure as low as 15 kpa. The tympanic membrane is the mirror for lung injury i.e. if the tympanic membrane are intact, extremely unlikely that lungs are suffered the effect of the blast. Other ear injury are; the disruption of the ossicular chain, damage to the organ of Corti, and vestibular damage.

The lungs these are air filled organs, and are susceptible to the effects of blast waves. The extent of the lung damage range from minor damage to the alveoli at pressure of 175 kpa for 4 msec to severe fatal lung damage at a pressure of 500 kpa. Blast wave may cause damage to the capillary alveolar interface resulting in blood and extracellular fluid leak into the alveoli leading to the phenomenon of Adult Respiratory Distress Syndrome.

The heart changes in the heart vary from minor ECG finding to the severe types of arrhythmias. Direct heart contusion may result from direct effect of blast. Indirectly lung damage may result in right ventricular stress and coronary air embolism.

The gastrointestinal tract shock waves may cause damage at air tissue interface in this tract, usually in form of ecchymosis which may lead to paralytic ileus. The shear waves may lead to mesenteric disruption. Gastrointestinal tract injury in the absence of lung injury is rarely happened.

Nervous system blast waves may cause transient concussion, conduction disorder, disruption of blood brain barrier, axonal degeneration, and air sinus fractures.

2) The secondary injury

This means the effect of the flying missiles. The blast may produce a large number of flying missiles. The missiles may emanate from the bomb itself like pieces of its casting, the various substances kept in the bomb to act as shrapnel, or any object in the immediate vicinity of the blast may be energized to act as shrapnel. These are usually high energy high velocity missiles. In this case the kinetic energy of the missiles (KE) = 1/2 mv². The factors governing the energy transfer to the victim from these missiles are the same of those in case of bullet injuries. These missiles being irregular in shape and having varying flight characteristics. The secondary missiles produce a variety of injuries including lacerations, contusions, penetrating wounds and fractures, depending on the mass, profile, velocity and angle of impact of the missiles and area of the body involved. The resultant damage of the secondary missiles is more marked, and their wound is heavily contaminated. The secondary missiles can cause both penetrating and blunt injuries. The power of the penetration depends on the mass of the fragments and its impact velocity. The blunt injury may affect the heart, the liver and the spleen, the most critical area for lethality is the head and a good deal of information relating to skull fracturing loads and impact velocities. Tattooing of the exposed skin by tiny pieces of dirt is a common problem, and tattoos are often deep.

3) The tertiary injury

This means the effect of blast wind. Blast wind generally has a longer duration and less pressure and its effect is purely mechanical. The blast wind may lead to displacement and translation of the body and May resulted in gross injury, either directly due to the accelerations imparted by the blast wind or indirectly due to the deceleration resulted from the impaction with other fixed or moving objects. The degree of injury depends on the magnitude of the accelerative and decelerative forces, the time and distances over which they act, the shape, area and resistance of impact, and so on. If the wind strong enough it can cause amputation of the exposed parts or even total disintegration of the body. Injuries caused by the blast wind are of two types;

i. Unsalvageable or lethal group: in which the injury involve the head, neck, trunk, and upper limbs.
ii. Salvageable group: in which the injury involve the lower limbs.

4) Flash burns

Very high air temperatures are generated for short periods during the explosion, resulting in local fires and flash burns to victim close to the explosion.

5) psychological effect

when the missile fall down near person, it may not harm him organically but it may produce psychological trauma in form of psychosis especially when he saw his friends or his family died in front of him. The psychosis sometimes becomes so severe leading to suicide attempt.

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