Factors affecting temporary cavity generation during gunshot wound formation in animals – new aspects in the light of flow mechanics: a review

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ABSTRACT: There is controversy regarding the causes of temporary cavity generation during gunshot wound formation. Analysis of gunshot wounds in hunted animals suggests that a bullet's frontal surface shape is the primary factor in forming a temporary pulsating cavity, and that cavity size is not directly affected by bullet velocity.

Keywords: temporary cavity; gunshot wound; bullet

Contents

1. Introduction

One currently held view posits that bullet velocity is the main factor affecting the size of a temporary cavity (Lindsey 1980; Owen-Smith 1981; Swan 1987; Ryan et al. 1988). This proposition differs from our own observations, particularly with regard to parenchymal organs. It has been noted that the liver always disintegrates after being hit with a single "Brenneke" type bullet, which is regarded as slow. In contrast, bullets from rifled firearms, which are regarded as fast, sometimes destroy only lobes or small parts of the liver, as has been observed on a large scale during armed conflicts (Mays 1971; Carroll et al. 1973; Pachter and Spencer 1979; Cannon et al. 2011). Lungs and the heart, through which bullets have passed, have proven to be the best for observations and drawing conclusions. Lungs, which have high rupture strength due to their high flexibility, allow the determination of the extent of temporary cavity formation even through gross anatomical observation by allowing the establishment of an area of collateral hyperaemia (Figure 1). The resistance of these organs to the action of bullets has been observed on the battlefield (West 1946; Yao et al. 1968).

Gunshot wounds in 20 roe deers (*Capreolus capreolus*), 11 wild boars (*Sus scrofa*), and 10 foxes (*Vulpes vulpes*) killed during hunts were subjected to detailed macroscopic analysis. By examining the mechanical damage, the authors were able to link the extent of the damage with bullet type (shape, design, etc.), as well as with bullet deformation and fragmentation during tissue penetration. A similar procedure has been employed by other authors (Feuchtwanger 1982; Fackler 1986, 1987, 1996; Fackler et al. 1988; Nichols and Welch 2004).

Pioneering research on this topic has been published by Lindsey and Fackler (from the 80's of last century) and also other authors (Feuchtwanger 1982; Barach et al. 1986; Fackler 1987, 1996; Fackler et al. 1988; Korac et al. 2000, 2006; Nichols and

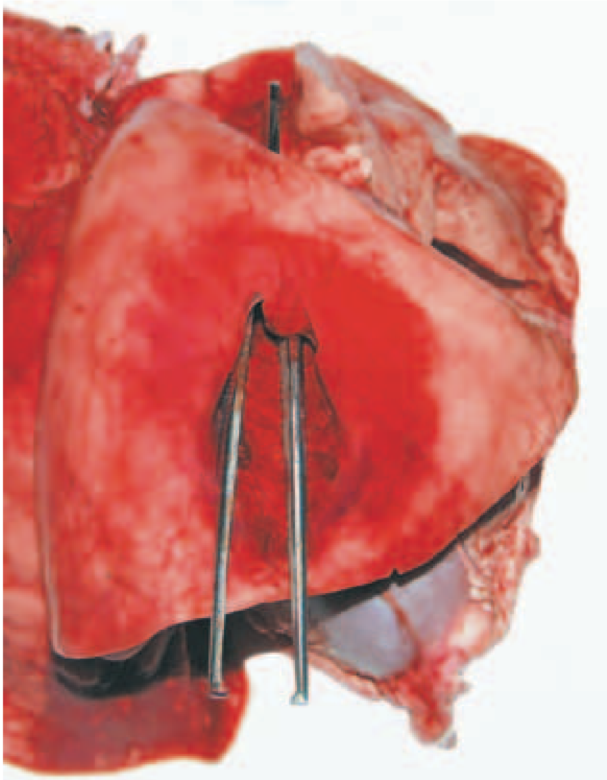

Figure 1. An irregular hyperaemic zone around a wound in the lungs of a roe deer was caused by a temporary cavity after being shot with a half-jacket (deformable) bullet

Welch 2004). These researchers, making observations under laboratory conditions, demonstrated temporary cavity formation as the result of different bullet types. Although this research indicates that the bullet's shape is the primary factor influencing the generation of a temporary cavity, it does not explain the mechanisms underlying this phenomenon.

Only in isolated papers have authors specified the laws of physics responsible for specific phenomena related to bullet movement and which influence this movement (Wlodarczyk 2002; Kneubuehl et al. 2011). To our knowledge, there are no available literature reports that explain the diverse effects of bullet penetration on the bodies of gunshot wound victims, particularly factors influencing the shape and size of temporary cavities.

2. Mechanism of interaction between the bullet and the body of a gunshot wound victim

A moving bullet causes piling of the tissues located in front of it. The destructive action of the bullet's frontal surface causes destroyed tissues and body fluids to form a two-phase medium composed of fluids and solids. A three-phase medium may be created if there are gases (e.g., air) in the tissues being destroyed. Thus, the bullet moves in a self-generated multi-phase medium. Simultaneously, an area of disturbance triggered by the bullet's movement and interactions between the elements that comprise this multi-phase medium emerges behind the bullet's frontal surface (West 1946; Feuchtwanger 1982; Kundu and Cohen 2008). The generation of chaotic and intensified movement of the conglomerate of body fluids, damaged tissues, gases, and sometimes small bullet fragments leads to rapid propagation of the energy carried by these elements. The energy transfer causes tissue dislocation outwards from the bullet's axis of motion. Recollapse of the dislocated layers takes place in elastic tissues, followed by renewed outward movement. This pulsatory tissue movement around the bullet's path is observed as a temporary cavity. Because of the tissues' relatively high inertia, the piling of tissues, growing in cascades, continues even after the bullet has moved a considerable distance (Fackler et al. 1988). The described movement causes a sudden increase of pressure in tissues that may lead to their damage, particularly when the gunshot wound involves organs devoid of elastic elements (e.g., liver, kidneys). In contrast, elastic tissues (e.g., muscles, lungs) are largely resistant to this type of damage (West 1946; Fackler 1987; Korac et al. 2006). The effect of a temporary cavity, in the form of circulatory disturbances, can be observed macroscopically (Figure 1). However, disturbances occurring in the external zone are visible only in microscopic preparations (Korac et al. 2000).

The law of conservation of energy asserts that only the adoption of the bullet's energy by tissues and organs enables their displacement or destruction. Hence, the formation of a temporary cavity depends on the adoption of the bullet's energy by tissues. The bullet-tissue interaction (i.e., the forces operating at the moment of energy exchange) appears to be particularly crucial. Only some regularities can be observed, and solely under laboratory conditions with extreme simplifications (e.g., shooting at homogeneous media or homogeneous tissues and organs). The obtained results are not always reproducible, and cannot form the basis for conclusions about the effects of gunshot wounds in real conditions (battlefield, hunting).

3. Fluid mechanics

3.1. Flow specificity

Flow around bodies, even by single-phase media, is always a very complex phenomenon. Even modern hydraulic engineering uses physical models of facilities and structures subject to flow mechanics because the complexity of the factors that influence specific flows is unpredictable, even in computer simulations (Orzechowski et al. 2001; Kundu and Cohen 2008). Two forces act on everybody moving in fluid and on each body that is being flowed around by a fluid: one force (called the lift force) is directed perpendicular to the flow velocity vector, and a second force (called the profile drag force) is directed opposite to the flow velocity vector (Orzechowski et al. 2001; Kundu and Cohen 2008). In practice, only the profile drag force affects the bullet as it penetrates tissues and organs. Separating the components of this force into frictional drag and pressure drag is of no importance to the present discussion.

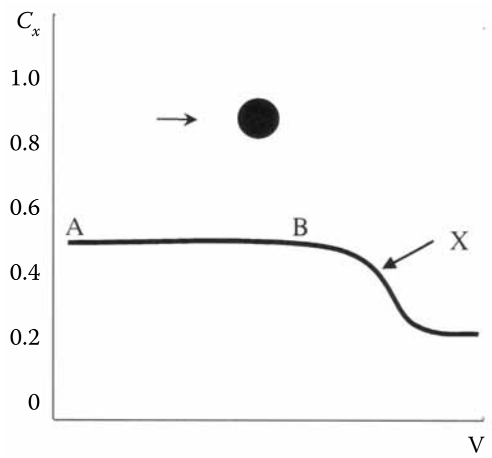

Figure 2. The drag coefficient (c_x) as a function of flow-around velocity for a sphere (similarly for a cylinder – V). The initial value of c_x increases slightly with increases in V (A – B). At a certain substantial velocity (beyond point B), the value of the drag coefficient falls abruptly. This phenomenon is called the drag crisis. X = denotes the place where the drag crisis appears

3.2. Selected rules of physics that determine the flows

All types of flow around bodies can be divided into laminar (stationary) and turbulent flow. For every specific flow around a body, there are certain values (Reynolds number [Re] and high Reynolds number [Re_{cr}]) that indicate the type of flow around the body (Orzechowski et al. 2001; Kundu and Cohen 2008). Elements of a fluid (or fluid system) in turbulent movement usually shift in the direction of mass transport, making it difficult to predict pulsatory movements in all possible directions (Kundu and Cohen 2008; Kneubuehl et al. 2011). The moment that determines the change of the flow from stationary to turbulent is the breakaway of the boundary layers, fluid layers directly adhering to the solid body that is being flowed around. During the action of flow around solid bodies, the so-called boundary layer forms between fluid molecules and the surface of the body that is being flowed around. This layer is characterised by reduced flow velocity compared to free flow velocity (v_∞), and its thickness is a function of the distance from the body that is being flowed around (Orzechowski et al. 2001). An undisturbed laminar boundary layer guarantees holding minimal profile drag, which translates into a low level of energy exchange. In turn, this low level of energy exchange prevents or limits the possibility of generating a temporary cavity. In practice, such flows around bodies are the goal in the construction of airplanes, land vehicles, and floating vessels (Orzechowski et al. 2001). Under specific conditions, the boundary layer may break away from the body that is being flowed around, which leads to increased energy exchange and, as a further consequence, causes specific disturbances in the medium. The very moment of this breakaway depends on flow-around velocity and the shape of the element that is being flowed around. The boundary layer is only able to break away from streamlined profiles in the presence of a high angle of attack, defined as the angle between the longitudinal axis of the profile and the flow direction vector. For bodies with non-streamlined profiles (e.g., a cylinder), the boundary layer always breaks away. A similar and more distinct phenomenon takes place with regard to sharp-edged plates that are positioned perpendicular to the flow-around direction (Figure 2; Orzechowski et al. 2001; Kundu and Cohen 2008).

According to Orzechowski et al. (2001) and Kundu and Cohen (2008) the profile drag R_x is calculated using dimensional analysis for every flow-around case:

$$R_x = c_x A \frac{\rho v_\infty^2}{2}$$

where:
R_x = profile drag
c_x = profile drag coefficient
A = conventional reference surface
ρ = fluid density
v = undisturbed flow velocity

The profile drag coefficient (c_x) depends on the shape of the body that is being flowed around, its position in relation to the flow vector, and the Reynolds and Mach numbers, where the Mach number can be ignored in the range Ma < 0.4 (Orzechowski et al. 2001).

The Reynolds number, although an imperfect characteristic, is currently used to assess the stability of flows, around bodies and around each other. This characteristic must be always determined empirically for specific systems. The Reynolds number is a variable characteristic and depends on the specific conditions that exist at a given moment and place. It is important that a temporary cavity can form only after the breakaway of the boundary layers, which always occurs during turbulent flows around bodies. The breakaway of the boundary layer allows a much lower energy transfer in the case of laminar flows than in the case of turbulent flows (Orzechowski et al. 2001; Kundu and Cohen 2008).

To present the complex character of flows, we should look at the factors affecting the Reynolds number:

$$Re = \frac{\rho v D}{\mu}$$

where:
Re = Reynolds number
ρ = fluid density
v = fluid velocity
D = dimensional characteristics of the body that is being flowed around
μ = fluid viscosity

The fluid density ρ is easy to calculate for single-phase media and multiphase media, with known and homogeneous proportions of the elements making up the medium (Orzechowski et al. 2001; Kundu and Cohen 2008).

3.3. Elements determining the arousal of pulsating cavities

In the case of a bullet penetrating the body of a human or animal, the determination of this parameter is difficult, and verges on impossible. Tearing tissues and individual anatomical elements, the bullet creates a three-phase medium in front of itself and around itself, in which the continuous phase is water (contained in blood, lymph, intercellular fluid, cells) and the dispersed phase is solid elements of tissues and individual anatomical structures and gases released from the tissues being damaged. The composition of such a medium is variable in time and impossible to determine beforehand. Sucked-in solid elements (e.g., small parts of clothing and hairs) can reach the dispersed phase behind the bullet together with atmospheric air.

Irrespective of the bullet's design and speed, it is not possible to determine the density of the fluid (medium) in which the bullet is moving at a particular moment. In addition, the parameters of such a medium are variable in time and space and the changes happen very quickly. When a bullet penetrates the body of a living being, the characteristic fluid velocity (v) is equal to the velocity of the bullet. This velocity decreases during tissue penetration and the degree of its change may have a stepwise character, depending on interaction with individual parts of tissues and organs. In addition, the bullet's path can also change. At the same time, this interaction depends on the state of individual organs at a given moment. For example, bullet penetration through the lungs depends to a certain extent on the inhalation or exhalation phase, just as penetration through the cardiac muscle depends on the systolic or diastolic phase; this applies to other muscles, as well.

Another factor influencing the value of the Reynolds number is the dimensional characteristics of the body that is being flowed around (D) (Orzechowski et al. 2001).

For a bullet, it is the shape of its frontal surface perpendicular to the axis of the bullet's path. The value of D may undergo changes in time during the process of target penetration.

The final factor is absolute fluid viscosity (μ). In previously describing the density of fluid (ρ) in which the bullet moves, it was mentioned that this value is impossible to determine. In the case of absolute fluid viscosity, for the same reasons, the determination of a specific value for μ is also impossible. The described findings demonstrate that it is not possible to determine the Reynolds number for every individual gunshot wound case, and therefore it is not possible to determine the profile drag coefficient (c_x). At the same time, the direct influence of the bullet's shape on the value of the Reynolds number must be borne in mind. This influence translates directly into the flow-around type; in the case of a gunshot wound, it translates directly into the size of the temporary cavity (Orzechowski et al. 2001).

The formula used to determine the profile drag (R_x) also contains a component called the conventional reference surface A. This parameter, which reflects the current shape of the bullet and its longitudinal dimension, undergoes continuous changes during tissue penetration, as does the value of the profile drag itself. The R_x vector can also change, which renders impossible any predictions regarding the parameters of the temporary cavity.

When bodies comparable to the shape of bullets (e.g., a sphere) are fired from small arms, the movement of the boundary layer is always turbulent. During the initial phase, the value of the profile drag coefficient (c_x) decreases as flow velocity increases. This value grows slightly at slightly higher velocities, and a further increase in the velocity causes a sharp drop in the value of c_x. This phenomenon is called the drag crisis, and it results from a drop in the pressure exerted on a considerable surface area of the body that is being flowed around, in comparison to the pressure of the fluid flowing around that body.

The drag crisis appears at substantial flow-around velocities (Figure 2). In this state, the ensuing turbulent flow of the medium around the body becomes very chaotic, and the transfer of energy is dispersed in all directions. Therefore, only a small portion of the energy is transferred perpendicularly to the surrounding tissues, enabling the generation of a smaller temporary cavity than the potential capabilities (including speed) of a moving bullet might otherwise indicate (Orzechowski et al. 2001).

Shotgun pellets are designed to undergo deformations during target penetration, thus assuming non-streamlined shapes. Military bullets also undergo deformations during target penetration, although their original shape is streamlined and they have a copper alloy jacket on the entire frontal and lateral surfaces (a requirement of international war conventions). The full jacket requirement does not prohibit the introduction of other structural components (e.g., placing a hard core or empty chambers inside) that would enable their deformation or disintegration after a hit or loss of stability (Fackler et al. 1988). The constructional requirements for small arms (i.e., pistols and revolvers) make bullets for these arms unstable and deformable, particularly during the infliction of gunshot wounds from a longer distance (Mays 1971).

For example, the flow-around resistance coefficient (c_x) of hemispherical cups depends on their position in relation to the movement of the fluid flowing around the body, and ranges from 0.36 to 1.44 with a Reynolds number of 4×10^5. The Reynolds number will always be much higher for a sharp-edged plate positioned perpendicular to the flow-around velocity vector than for bodies with other profiles. In the zone in front of the plate, in its central part along the BA segment, a growth in the pressure of the fluid flowing around the plate compared to the pressure of this fluid takes place; in the zone from point B to C this pressure decreases abruptly, as does the pressure behind the plate. A number of whirls occur behind the plate, resulting from departing the boundary layer already on the outer edge of the plate – point D (Figure 3) (Orzechowski et al. 2001).

The phenomenon of cavitation must also be included during the discussion of phenomena occurring during gunshot wounds (Orzechowski et al. 2001). This sudden and short-lived formation of steam bubbles in the boundary layer and their abrupt subsidence further complicates the phenomena described above (Kundu and Cohen 2008). In addition, if massive and resistant elements of hydraulic engineering facilities can suffer damage as a result of cavitation, this phenomenon can also damage the jackets of military bullets, making them more susceptible to disintegration and fragmentation.

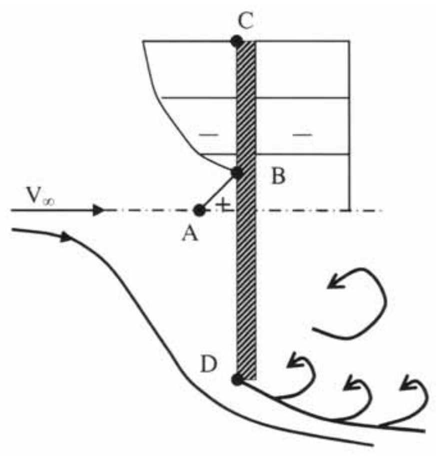

Figure 3. Diagram of the generation of a temporary pulsating cavity using the example of the flow around a sharp-edged plate (C–D) positioned perpendicular to the direction of the free flow velocity (V) vector

After considering the described regularities and our own observations, it can be concluded that bullet design (and principally, a bullet's shape and deformability) is the main factor responsible for the generation of a temporary cavity. In addition, the bullet's frontal surface, which undergoes random deformations during tissue and organ penetration, can create asymmetrical temporary cavities. Therefore, each bullet can generate temporary cavities of different sizes, and bullet velocity is not a factor influencing the size of the temporary cavity.

4. CONCLUSIONS

In summary, we have reached the following conclusions. The shape of the bullet's frontal surface during the process of tissue penetration is the primary factor in the formation of a temporary cavity. The size of a temporary cavity does not depend directly on bullet velocity. Every gunshot wound should be analysed individually, regardless of the type of weapon that inflicted the wound.

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