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TECHNICAL NOTE

ANTHROPOLOGY

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Physical Components of Soft-Tissue Ballistic Wounding and Their Involvement in the Generation of Blood Backspatter*

ABSTRACT: Gunshot backspatter comprises biological material expelled backward through bullet entry holes. Crime scene investigators analyze backspatter patterns to infer wounding circumstances. An understanding of the mechanism of backspatter generation, and the relationship between spatter patterns and bullet and tissue characteristics, would enhance the predictive value of such analysis. We examined soft-tissue ballistic wounding responses to determine the underlying components and how these might be relevant to the generation of backspatter. We identified five mechanistic components to ballistic wounding (elastic, viscous, crushing, cutting, and thermal), each related to mechanical disciplines (respectively, solid mechanics, fluid mechanics, fracture mechanics, rheology, and thermodynamics). We identified potential roles for these five components in backspatter formation and provide a scenario whereby a sequence of events incorporating these components could lead to backspatter generation and expulsion. This research provides a framework for the mathematical representation, and subsequent computational predictive modeling, of backspatter generation and pattern formation.

KEYWORDS: forensic science, bloodstain pattern analysis, blood backspatter, projectile wound mechanics, impact biomechanics, phenomenological model

Backspatter comprises blood and other biological materials that have traveled in the opposite direction to the external force applied and is usually associated with an entrance wound created by a projectile (1). Backspatter patterns at crime scenes are analyzed by criminal investigators to infer the circumstances surrounding a shooting event. Backspatter on the hands or clothing of a suspect can be used as evidence of proximity which may in turn be evidence of guilt. Individual backspatter stains have been observed to range from <0.5 mm to more than 3 mm in diameter (2,3), with the smallest considered to arise from material ejected from the wound as a fine spray or aerosol (3). Several processes for the generation of backspatter have been proposed (4–6), but current descriptions do not lend themselves to direct mathematical representation, and therefore quantification and analysis, of underlying mechanisms. An understanding of the mechanism of backspatter generation, and the relationship between spatter patterns and bullet and tissue characteristics, would enhance the predictive value of estimations of the circumstances surrounding a shooting event.

A bullet traveling through tissue at high speed results in a complex process of destruction. Experimental bullet incapacitation and simulant wound profile studies have observed what happens when bullets penetrate tissues and identified processes contributing to wounding (4,7–13). Two main ballistic wounding processes have been described, namely crushing of the tissues that come into contact with the bullet, which leaves a permanent wound track through the tissue, and outward acceleration and stretching of the tissues adjoining the permanent track, which creates a temporary cavity behind the bullet. The involvement of such wounding processes in the generation of backspatter has not been investigated directly, however. The purpose of this paper is to investigate the components underlying ballistic wounding and, using basic physical principles of mechanics (forces, motion, and energy flow), identify how these could be relevant to the generation of backspatter. This phenomenological framework will set the groundwork for the mathematical representation, and subsequent computational predictive modeling, of backspatter generation and pattern formation. The discussion will be largely confined to soft-tissue ballistic wounding, as such tissues are prime candidates for involvement in the generation of blood backspatter.

Components of Soft-Tissue Ballistic Wounding

In the present study, we first reduce reported processes of soft-tissue ballistic wounding to five mechanistic components. Each of these components is generally concerned with a different mechanical discipline: classical solid mechanics, fluid mechanics, fracture mechanics, rheology, and thermodynamics. Although described separately, the components are acknowledged to be overlapping and interdependent, as are the different disciplines underlying them. We

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also provide real-world and ballistic examples to illustrate the mechanical principles put forward. The potential contribution of each of these five components of the wounding response to the generation and expulsion of blood backspatter is discussed.

In the reference frame used, radial and axial were, respectively, the directions perpendicular to and in-line with bullet travel. For simplicity, the response is described as if symmetric around the bullet axis, although many biological systems will have some asymmetry owing to irregular tissue shapes or composition, bone edge effects, and bullet tumbling. Additional ballistic effects, such as from firearm combustion gases (14), that may accompany close-range shots are not considered at this time, and neither are bullet deformation and the effects of bone fracture and fragmentation. Fragments which enter the tissue, however, can be considered as separate penetrating objects, and therefore, their effects can be described by ballistic wounding processes.

Elastic Component (Axial Direction)

The kinetic energy of a bullet is the product of its mass and the square of its velocity. Several authors maintain that the amount of this energy absorbed by the tissue is crucial to the wounding effects of bullet penetration (15–17) and the generation of backspatter (5). Some of the energy is absorbed in an elastic manner in the axial direction. In other words, energy is stored as strain energy in the direction of bullet travel within the tissue elastic structures such as elastin and collagen (18). We describe this as the elastic component of ballistic wounding.

The elastic component is the simplest of the five components presented and can be completely described using solid mechanics, the field of continuum mechanics dealing with materials that have a defined rest shape. Continuum mechanics studies the physics of materials that can be described as a continuous mass and is divided into solid mechanics and fluid mechanics. Throughout the elastic recoil process, tissue would maintain a defined shape. The elastic component would be most apparent with low-velocity projectiles (19), but still may be observed in wounding with high-velocity bullets. It is evident in, for example, situations where the bullet tracks backward in tissue or simulant before stopping (11) or skin elasticity prevents the bullet from exiting (20). In these situations, some of the elastic energy stored in the tissue is returned back to the bullet as a form of kinetic energy as the compressed tissue relaxes, that is, effectively pulling the bullet backward. A bullet bouncing off a hard rubber material is an example of where the axial-elastic component dominates the response behavior.

As the elastic response involves acceleration of tissue retrograde to the bullet path, it potentially could provide a mechanism for the expulsion of backspatter. The elastic storage and return of energy could propel blood and tissue fragments back to the entrance hole, although this would be more apparent in highly elastic tissues such as muscle and skin than in brain (4).

Viscous Component

Even at resting state, biological soft tissue, although considered solid, is a composite of mostly liquid water and interconnected and free-floating complex molecules. When struck at high velocity, soft tissue responds in a complex manner resulting in a partial separation of its liquid and solid aspects accompanying structural strain and failure. We refer to this process of the bullet eliciting a liquid effect from a "solid" tissue as the viscous component of ballistic wounding.

The viscous component is described by fluid mechanics, the other field of continuum mechanics. A fluid is a material that flows and, given enough time, will take on the shape of its container. Thus, unlike a solid, fluid has no defined rest shape. During penetration of the bullet, the large shear strain generated in the tissue will cause flow (one layer moving with respect to another), and this will continue even after the imposing force is removed, that is, after the passing of the bullet. The massive amount of kinetic energy imparted instantaneously to the material will tend to dissipate as frictional heat as the material continues to flow. In the case of the high forces typical of ballistic impact, a separation of the liquid may occur directly behind the bullet creating a void (a perfect vacuum), which subsequently collapses (21). The simple case of shooting into water is an example of where the viscous component would dominate the material response (22).

The viscous component may play a role in the generation of backspatter by propelling crushed tissue fragments around the bullet. These fragments would then provide material behind the path of the bullet which could be ejected as backspatter. The viscous component may also include a cavitation effect, in which the rebound of the collapsing void may propel material toward the entrance hole.

Crushing Component

Crushing is the most noted component of wound ballistics (4,7–11). Crushing refers to the compression of tissue ahead of the bullet, that is, in the axial direction, to a force exceeding the tissue's yield strength (in contrast to the elastic component, when the local axial force is less than the elastic yield strength). The resulting rupture of molecular bonds in the axial direction allows a compressed section of damaged tissue to build up in front of the bullet and, in the case of bullet perforation, creates the typical forwardspatter.

The crushing process can be described with fracture mechanics, a field that uses methods of solid mechanics but also may involve treating the material as a noncontinuous medium. In wound ballistics, fracture, destruction, and axial displacement of tissue contributes to the formation of the permanent cavity (4). Permanent cavities can be smaller than the diameter of the bullet (11), indicating that not all the tissue in the bullet's path was crushed but some was instead pushed aside (by the viscous or cutting components) and thus able to return after the bullet had passed through. Alternatively, a permanent cavity larger than the bullet and increasing in size with penetration depth may indicate a crushing action extending beyond the bullet diameter in the axial direction. During the crushing process, part of the kinetic energy of the bullet is transformed into internal and kinetic energy of the crushed tissue. The internal energy arises from the work carried out to break the chemical bonds of the tissue, and the kinetic energy arises from the work carried out to accelerate the tissue mass forward. Within a short time, most of this energy is usually transformed into thermal energy by heating the surroundings (23). Crushing would dominate in impacted materials with low-strength elastic bonds, such as wax, resulting in a clean permanent hole with little damage outside the bullet diameter.

The crushing component could be involved in the generation of backspatter by the creation of loose biological material that can subsequently be propelled backward through other mechanisms. The crush component also creates the permanent hole giving biological material access to the entrance hole.

Cutting Component (Includes Radial-Elastic)

Cutting is the second-most familiar component and responsible for the commonly noted phenomenon of the temporary cavity (4,8,9,11,16,24). Cutting refers to the compression of tissue to the side, that is, in the radial direction (7,25), and has also been referred to as the stretch mechanism (4). For a local region of tissue to be cut or separated, the force applied must first exceed the tissue's bond strength. The cut region is then accelerated in the radial direction. Depending on the degree of the force and the type of soft tissue, this radial expansion can reach a maximum diameter before recoiling elastically. The elastic expansion and recoil in the radial direction creates a temporary cavity (13,15).

While the actual cutting can be covered by fracture mechanics, the response of the material in the radial direction has both solid and fluid characteristics and thus can be described using rheology. Spanning solid mechanics and fluid mechanics, rheology describes materials with rate-dependent and nonreversible behavior, that is, with properties of plastic solids and non-Newtonian fluids. The cutting component would dominate the response in an impact with a layered composite material containing weak inter-layer bonds such as wood. Cutting between the grains with a sharp instrument such as an axe simply cuts and elastically recoils the wood layers leaving little trace of a track.

The cutting component probably plays a major role in backspatter formation by setting up an oscillating pressure wave in a radial direction (13), which can then propel biological material in cycles out through the entrance and exit holes after the passing of the bullet. The pressure wave set up through the tissue may also squeeze liquid into the temporary cavity and thus provide material for backspatter.

Thermal Component

The thermal component of ballistic wounding refers to a chemical reaction or phase change response and is the least recognized. Combustion involves chemical reactions set off by thermal heating and phase change refers to the vaporization of tissue. The discipline of thermodynamics describes and mathematically represents such processes (23). This component would result in the creation and subsequent expansion of gaseous material within the wound cavity. Heat from a bullet is generally considered to have little effect in ballistic wounding (24,26), with "bullet burns" instead thought to be owing to gas of combustion from the firearm, but further research is needed to clarify whether the thermal component has a role in wounding.

The thermal component, if significant, could be a mechanism for the generation of backspatter by providing an explosion gas that propels the biological material through the wound cavity.

Possible Backspatter Mechanisms

It is proposed that the generation of backspatter involves a sequence of events incorporating the components presented earlier. A possible scenario is described. As the bullet penetrates biological tissue, there may be some initial splashing (a surface disturbance in the form of a circular and expanding wave). As the bullet then passes through the tissue, it crushes material ahead of its path, some of which flows around the bullet owing to the viscous effect. This is accompanied by an expansion of the cavity behind the bullet owing to the cutting effect of the bullet. The ensuing radial pressure wave also squeezes material within the expanding tissue into this temporary cavity where it combines with the crushed material. The elastic recoil of the cavity and collapse of the cavitation hole imposes a large pressure on the loose material within this area. The permanent track created by the crushing effect provides a pathway for the loose material to project out the bullet entrance hole and, if present, exit hole. The axial-elastic recoil assists in the retrograde propulsion of material. Oscillations of the temporary cavity owing to radial-elastic recoil of the cutting component continue to pressurize and pump material out of the entrance hole.

Which components dominate the generation of backspatter will depend on factors such as the type of bullet and tissue, and the bullet velocity. The elastic and cutting components may be emphasized in highly elastic tissue such as muscle while less elastic tissue may display a relatively greater crushing and viscous behavior. Further research should be conducted to link the mechanical characteristics of the tissue type to the observed backspatter patterns. Modeling of backspatter generation and pattern formation can also be simplified by identifying mechanisms that dominate the process and thus account for the majority of the behavior.

Effects such as bullet deformation and bone interaction, although not considered here, could be integrated into the analysis of backspatter within this phenomenological framework. For example, a nonexpanding jacketed bullet will likely create a larger cutting effect while an expanding bullet would create a greater crushing effect. The effect of shock waves, ultra-high-velocity mechanical waves (approximately 1450 m s^{-1}) set up by the projectile which do not involve long-range motion of the tissue, has also not been considered. There is still controversy on the role shock plays in incapacitation (8,11,15,27,28), but there is evidence that suggests it has no effect on wound track formation (8) or backspatter (14). It is possible shock waves can delaminate tissue (29,30) and thus assist in freeing up material for expulsion, but further research is required to resolve this.

Summary

To date, most literature reviews on ballistic wounding have been concerned with the incapacitation effect or penetration characteristics of projectiles. This paper relates the observed responses to a penetrating projectile to the creation of blood backspatter. Using a mechanical discipline approach, the complex ballistic wounding process has been reduced to five proposed components. Each of these components could potentially contribute to a mechanism for the creation of backspatter. This paper sets the groundwork for mathematical and physical modeling of blood backspatter and for building a predictive model of backspatter generation and pattern formation.

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