Review Article

Gunshot Wounds: 1. Bullets, Ballistics, and Mechanisms of Injury

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The nature and severity of a bullet wound depend on the characteristics of the bullet and of the tissues through which it travels. In addition to the mass and velocity of the bullet, its orientation and whether it fragments or deforms affect the nature of the wound. Two major mechanisms of wounding are described: crushing and stretching of tissue. Understanding the mechanisms by which bullets disrupt tissue can help physicians to evaluate and treat wounds.

The characteristics and severity of a gunshot wound are determined by the design of the weapon and projectile, the intermediate targets the projectile encounters between the gun muzzle and the body, and the sequence of tissues encountered along the projectile path. Although the skill of the person firing the weapon affects the trajectory, chance also plays a role. If the missile path includes a large bone, or if the projectile strikes a button, belt buckle, or other hard object, the severity of the wound often increases [1, 2]. To some extent, whether the bullet hits a particular wound-modifying structure (surface or anatomic) is a chance event. For any projectile, if the path includes a critical anatomic structure, the result may be fatal, just as if the structure had been stabbed by a knife. In general, projectile wounds are most severe when the missile yaws early in its path through tissue, fragments, is large, and is traveling at high speed.

Civilian bullets are often more damaging to tissue than are military bullets fired from rounds otherwise configured identically [1, 3]. (A round is one complete unit of ammunition. This includes the bullet, the cartridge case, the powder, and the primer.) Unlike military bullets, civilian bullets are not required to have a full metal jacket (a metal jacket completely covering the bullet tip [3]), and are therefore much more likely to deform or fragment in tissue. Because of this, wounds produced by civilian hunting rifles, shotguns, and large-caliber handguns are often more severe than military combat wounds [3]. An enemy soldier wounded in war, who is sufficiently disabled to no longer fight but is not killed, uses more enemy resources than one who is killed. In addition to the loss of the soldier on the battlefield, personnel and material are required to care for and feed the wounded soldier.

Mechanisms of Wounding

Both missile and tissue characteristics determine the nature of the wound. Missile characteristics are partly inherent (mass, shape, construction) and are partly conferred by the weapon (longitudinal and rotational velocity). Tissue characteristics (elasticity, density, anatomic relationships) also strongly affect the nature of the wound. The severity of a bullet wound is influenced by the bullet's orientation during its flight through tissue and by whether the bullet fragments [1] or deforms (into, for example, the typical mushroom shape of the expanding hollow-point or soft-point bullet).

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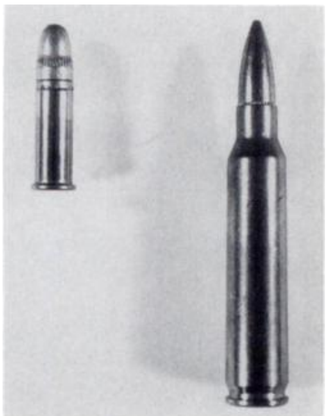

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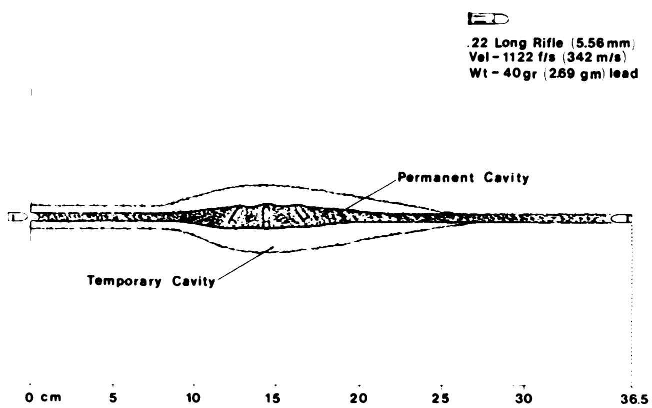

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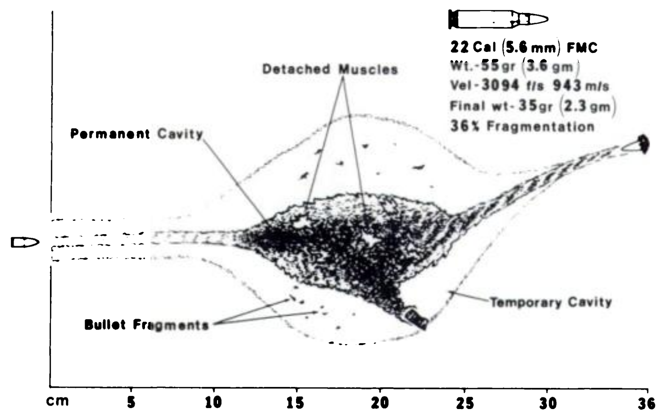

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Fig. 1.—*A*, Photograph shows .22 long-rifle round (*left*) and M16 round (*right*).

***B* and *C*, Wound profiles of same .22 long-rifle (*B*) and .224 caliber M-193 round of M16A1 rifle (*C*). (Full metal case [FMC] is a synonym for full metal jacket [FMJ], type of bullet used in military.)**

This figure shows that caliber (bullet diameter in hundredths of an inch) is only one indicator of wounding potential, and not a very good one. Because of much higher velocity (3094 ft/sec [943 m/sec], as opposed to 1122 ft/sec [342 m/sec] for the .22 long-rifle bullet), because it fragments in tissue, and because of the greater bullet mass, the M16 bullet potentially can cause a much more severe wound if part struck is sufficiently thick. Note that both permanent cavity and temporary cavity are much larger. As is usual, temporary and permanent cavities of .22 long-rifle bullet are largest when bullet is at 90° of yaw.

Two major mechanisms of wounding occur: the crushing of the tissue struck by the projectile (forming the permanent cavity), and the radial stretching of the projectile path walls (forming a temporary cavity) (Fig. 1).

In addition, a sonic pressure wave precedes the projectile through tissue. The sonic pressure wave plays no part in wounding. In air, the speed of sound is approximately 300 m/sec; in soft tissue, it is approximately 1500 m/sec. When a bullet enters soft tissue, the sonic pressure wave forms a hemispherical arc ahead of the advancing bullet. The short-lived sonic pressure pulse created may reach pressures of up to 100 atm (1.01×10^7 Pa). The duration of this pulse is approximately 2 μsec [4]. Research reported in 1947 [5] determined that this sonic shock wave has no damaging effect on tissue, a finding since confirmed by clinical experience with sonic pressure wave lithotripsy, in which tissue receives sonic pressure waves two to three times greater than that produced by a supersonic rifle bullet [6]. The sonic pressure wave must not be confused with the temporary cavity, which is discussed later.

Crushing of Tissue

A missile crushes the tissue it strikes, thereby creating a permanent wound channel (permanent cavity). Yaw is the angle between the long axis of the bullet and its path of flight. If the bullet is traveling with its pointed end forward and its long axis parallel to the longitudinal axis of flight (0° of yaw), it crushes a tube of tissue no greater than its approximate diameter. When the bullet yaws to 90°, the entire long axis of the bullet strikes tissue, and the amount crushed may be three times greater than at 0° of yaw.

When striking soft tissue with sufficient velocity, soft-point and hollow-point bullets deform into a mushroom shape. This increases surface area and wound severity. For most big-game hunting, such bullets are mandated by law. This is to increase the probability of killing quickly, rather than creating a disabling but nonlethal wound, allowing escape and prolonged suffering. If the mushroomed diameter is 2.5 times greater than the initial diameter of the bullet, the area of tissue crushed by the bullet is 6.25 times greater than the amount that would have been crushed by the undeformed bullet.

Bullet fragmentation also increases the volume of tissue crushed [1, 7]. After bullet fragmentation, surface area is increased, and much more tissue is crushed. For large handgun (e.g., .44 magnum) and rifle bullets, the striking of bone is one of the causes of early bullet fragmentation.

Comminuted fracture may be created by rifle and large handgun bullets striking bone (Fig. 2). Bone fragments can become secondary missiles, crushing tissue. Many handgun

Fig. 2.—Radiograph shows a severely disruptive bullet wound of leg. Gross comminution of fractures, missile fragmentation, and severe soft-tissue disruption suggest either a large-caliber handgun, a rifle, or a shotgun with large-diameter shot such as .00 buckshot. This wound was due to a large handgun (probably a .44 magnum). A center-fire rifle or large handgun is much more likely to produce severely comminuted fracture than is a smaller handgun. Soft-tissue and vascular damage associated with these fractures delays healing and increases complications.

bullets are unable to fragment bone significantly. When a large bone is struck, it is likely that a bullet will expend its wounding potential in the patient and will not exit.

Bullet fragments and secondary missiles (bone fragments, teeth, dental fillings, coins, etc.) are likely to increase the severity of the wound. Multiple perforations weaken tissue and create focal points for stress (stress risers), which are particularly vulnerable to the effect of temporary cavitation stretch [1, 4].

Unjacketed lead bullets cannot be driven faster than about 2000 ft/sec (610 m/sec) without some of the lead stripping off in the barrel of the gun. This is avoided if a jacket made of a harder metal (such as copper or a copper alloy), is used to surround the lead. The jacket of a military bullet completely covers the bullet tip (a full metal jacket). Civilian hollow-point and soft-point bullets usually have a jacket that surrounds part of the bullet (a semi-jacketed bullet), leaving the front portion exposed so that it can expand.

The soft-point and hollow-point bullets of center-fire rifle rounds usually deform into a mushroom shape in tissue, increasing the volume of tissue crushed. In contrast, even the magnum versions of some handgun bullets designed for expansion fail to mushroom [8]. This is most likely with short-barrel handguns. The shorter the barrel length, the shorter the time available for bullet acceleration by the expanding gases created by burning gunpowder. Therefore, when identical rounds are fired, the gun with the shorter barrel produces a lower-velocity bullet. Its velocity may be too low to induce mushrooming after impact.

Mushroom-type expansion is intended with civilian hollow-point and soft-point bullets. They also can fragment. Military full-metal-jacket bullets either stay intact or fragment; they do not mushroom. Although the M-193 military bullet of the M16 rifle fragments in soft-tissue with a characteristic pattern depending on range [9, 10], other full-metal-jacket military bullets, such as those fired from the AK-47, the AK-74, and the NATO 7.62-mm rifle (American version), typically do not fragment unless they strike bone.

Temporary Cavitation (Tissue Stretch)

During flight, a bullet is stabilized against yaw by the spin imparted to it by the spinal grooves (rifling) in the gun barrel [11]. The longer (and heavier) the bullet in relation to its diameter, the more rapidly it must be rotated to avoid significant yaw in flight. Therefore, a gun barrel intended to fire a heavier bullet has rifling that makes a full turn in fewer inches of barrel length than the rifling in a barrel intended for a shorter, lighter bullet of the same caliber.

Fired from an appropriate and well-designed weapon, a bullet flies in air with its nose pointed forward; it yaws only 1 to 3° [6]. Yaw occurs around the bullet's center of mass [6]. In pointed rifle bullets, the center of mass is behind the midpoint of the bullet's long axis. Although the bullet's most naturally stable in-flight orientation would be with its heaviest part forward, for aerodynamically efficient flight, it must fly point forward.

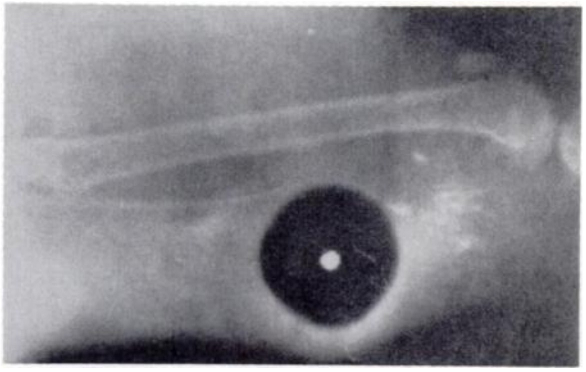
Although the bullet's spin is adequate to stabilize it against yaw in its flight through air, it is not adequate to stabilize it in its path through tissue, because of the higher density of the medium [12]. If it does not deform, a pointed bullet eventually yaws to a base-forward position (180° of yaw). Expanding bullets lose the physical stimulus to yaw, because after "mushrooming" their heaviest part is forward.

As a bullet passes through 90° of yaw, it is crushing its maximal amount of tissue (unless it fragments, which will crush more). It is slowed down rapidly, as its wounding potential is used up moving tissue radially away from its path. This force creates the temporary cavity. This aspect of the wounding process is analogous to the splash of a diver entering the water.

If a diver enters the water very straight and point forward (similar to the point-forward configuration of a bullet at zero degrees of yaw), the splash may be minimal. If the diver does a belly-flop (similar to a bullet at 90° of yaw), a large splash is induced. In tissue, this splash, the temporary cavity, produces localized blunt trauma (Fig. 3) [1, 4].

The maximal size of the temporary cavity occurs several milliseconds after the bullet has passed through the tissue [11]. Because forces follow paths of least resistance, temporary cavitation is likely to be asymmetric and spread out through tissue planes [4].

The temporary cavity caused by common handgun bullets is too small to be a significant wounding factor in all but the most sensitive tissues (brain and liver) [4]. Center-fire rifle bullets and large handgun bullets (e.g., .44 magnum) often induce a large temporary cavity (10–25 cm [4–10 in.] diameter) in tissue. This can be a significant wounding factor, depending on the characteristics of the tissue in which it forms [4, 13].



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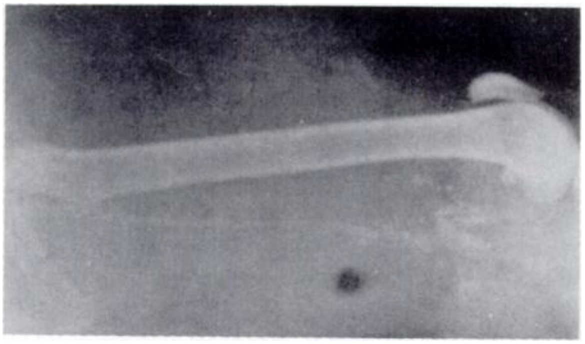

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Fig. 3.—*A* and *B*, High-speed radiographs of thigh of a cat during (*A*) and after (*B*) passage of a 4/32-in. (3.2 mm) steel sphere with impact velocity of 3200 ft/sec (975 m/sec). Sciatic nerve of cat's thigh made radiopaque with iodobenzene. Images obtained with beam parallel to path of missile.

Microsecond radiograph during passage (*A*) shows anterior displacement of sciatic nerve by temporary cavity. Tissues surrounding path of projectile are undergoing blunt trauma and tissue stretch because of temporary cavity formation.

Radiograph made immediately after shot (*B*) shows permanent cavity (wound channel) is considerably smaller than temporary cavity. Sciatic nerve is in its usual anatomic position. Nerve and vessel injury from stretch may have occurred. (Courtesy of Leonard D. Heaton, James B. Coates, Jr., and James C. Beyer; reprinted with permission from Wound Ballistics, Office of the Surgeon General, Department of the Army, 1962, p. 209.)

Near-water-density, less elastic tissue (e.g., brain, liver, or spleen), fluid-filled organs (including the heart, bladder, or gastrointestinal tract), and dense tissue (e.g., bone) may be damaged severely when a large temporary cavity contacts them [11]. More elastic tissue (e.g., skeletal muscle) and lower-density elastic tissue (e.g., lung) are less affected by the formation of a temporary cavity [14, 15]. Because of these tissue differences, the transmitted forces of temporary cavitation caused by a bullet traveling 800–950 m/sec can cause a more severe pulmonary contusion when the bullet traverses the chest wall musculature than the pulmonary contusion that would have occurred had the same bullet passed directly through the lung [3, 15, 16].

Although formation of a large temporary cavity often has devastating effects in the brain or liver, its effect in wounds of the extremities has frequently been exaggerated in articles about wound ballistics [4, 6, 17]. Fracture of large bones not hit by the bullet and tearing of major vessels or nerves by the temporary cavity are often mentioned in the literature (e.g., DeMuth [3]), but are rare in clinical experience. This includes a systematic review of 1400 rifle wounds sustained in the Vietnamese War and analyzed in the Wound Data and Munitions Effectiveness Team (WDMET) study (Bellamy RF, personal communication). Most of the permanent damage in wounds of the extremities is the result of structures being hit by the intact bullet, bullet fragments, or secondary missiles. As in all blunt trauma, shear forces develop and tear structures at points where one side is fixed and the other side is free to move. The temporary cavity is no exception. In the unlikely event that the blunt trauma of the temporary cavity tears a vessel wall, this is particularly likely to occur at the vessel origin.

Ballistic Properties and the Wound Produced

Recent controlled animal experiments with military rifle bullets [18] have clearly disproved the assertion that all tissue exposed to temporary cavitation is destroyed. These studies also show that not only does the 14-cm-diameter temporary cavity produced by the AK-74 assault rifle not destroy a great amount of muscle, but the sizable stellate exit wound it causes in the uncomplicated thigh wound ensures excellent wound drainage, which assists healing [14, 18, 19]. This is consistent with the pathophysiology of wound healing and the history of the treatment of wounds received in war [18, 19]. A history that the wound was caused by a "high-velocity bullet" does *not* mandate radical excision of the wound path [4, 6, 13, 14, 19–21].

The characteristics of the wounded tissue, the thickness of the body part, the point in the path of the bullet at which yaw or fragmentation occurs, and other factors strongly influence the wound produced. Bullets of equal wounding potential may produce wounds of quite different severity, depending on which tissues they traverse. The heavier, slower bullet crushes more tissue but induces less temporary cavitation. Most of the wounding potential of the lighter, faster bullet is likely to be used up forming a larger temporary cavity, but this bullet leaves a smaller permanent cavity. The heavier, slower bullet causes a more severe wound in elastic tissue than the lighter, faster bullet, which uses up much of its potential producing tissue stretch (temporary cavitation). This tissue stretch may be absorbed with little or no ill effect by elastic tissue such as lung or muscle. In nonelastic tissue, such as liver or brain, the temporary cavity produced by the lighter, faster bullet can produce a more severe wound.

Experiments with ballistic gelatin (which duplicates the projectile deformation and penetration depth of living animal muscle [13]) have shown that most full-metal-jacketed rifle bullets yaw significantly only at tissue depths greater than the diameter of human extremities [10]. In the first 12 cm (the average thickness of an adult human thigh) of a soft-tissue wound path, there is often little or no difference between the wounding effects of low- and high-velocity bullets when the high-velocity bullet is of the military full-metal-jacket type [4, 10]. This is particularly true of the relatively heavier military rifle bullets, such as those fired by the AK-47 and NATO 7.62-mm (American version) rifles [4]. A wound of an extremity caused by an AK-47 bullet that does not hit bone is often

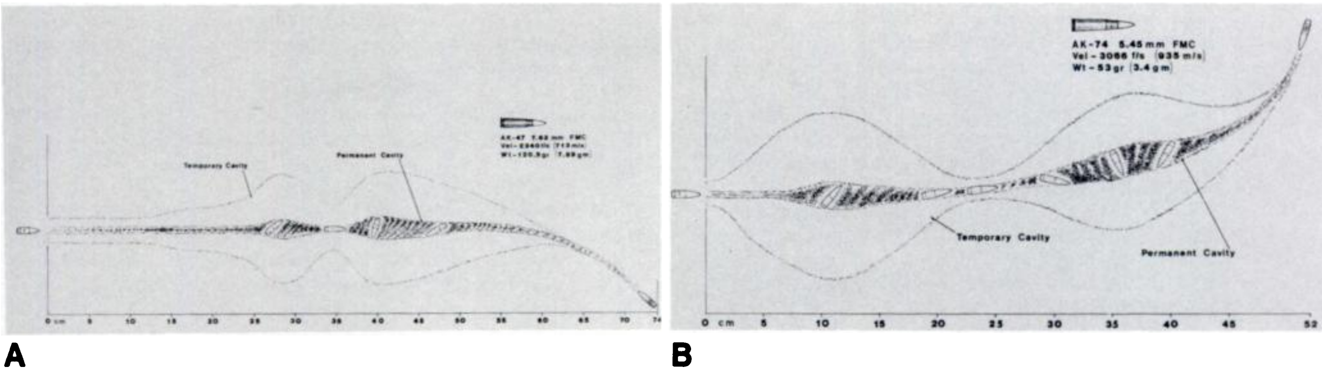

Fig. 4.—*A* and *B*, These wound profiles illustrate use of ballistic principles for "wound design." Wound profiles of AK-47 (*A*) and AK-74 (*B*) bullets in ballistic gelatin are presented. AK-47 has been standard military rifle of Soviet bloc but is being replaced with AK-74. AK-47 fires a 7.89-g full-metal-jacket (FMC) bullet 7.62 mm in diameter at a muzzle velocity of 713 m/sec (2340 ft/sec). AK-74 fires a 5.45-mm, 3.4-g FMC bullet at 935 m/sec (3066 ft/sec). AK-74 bullet is designed to yaw earlier in its wound path than AK-47 bullet does (see text). Extremity wounds from AK-74 can be expected to be much more severe than those from AK-47. This is especially true for wound paths in extremities that are entirely through soft tissue and do not include a large bone.

similar to a handgun bullet wound. A soft- or hollow-point bullet fired from a civilian rifle deforms soon after entering tissue and produces a much more severe extremity wound. Compare the first 12 cm of the wound profile of the .22 long-rifle round in Figure 1 with the wound profile of the AK-47 round in Figure 4. If a high-velocity, heavy bullet does not deform, fragment, or hit a bone, it may exit an extremity with much of its wounding potential unspent. These same bullets are often lethal in chest or abdominal wounds because the trunk is thicker than an extremity and allows the bullet a sufficiently long path through tissue to yaw. Note that maximal temporary cavitation induced by the AK-47 bullet (Fig. 4A) during the first cycle of bullet yaw is at a tissue depth of 28 cm, much greater than the diameter of a human extremity. The second cycle of bullet yaw occurs at a depth too great to be of significance in most wound paths in humans.

The AK-74 bullet (Fig. 4B) is lighter than the AK-47 bullet and is internally constructed to cause early yaw. It causes its maximal temporary cavity at a tissue depth of 11 cm. Extremity wounds from the AK-74 can be expected to be much more severe than those from the AK-47 [9, 22]. The lighter, smaller round allows a soldier to carry many more rounds of ammunition. This was the primary motivation for development of the M16 and the AK-74 [4].

Figure 1 shows that caliber (bullet diameter in hundredths of an inch) is only one indicator of wounding potential, and it is not a very good one. Although the .22 long-rifle bullet and the M-16 bullet are similar in diameter (caliber), the M16 bullet is heavier (3.6 vs 2.7 g for the .22 long-rifle bullet), mainly because the M16 bullet is longer. Each bullet is seen protruding from the end of its cartridge case. The bullet is the portion of the round that leaves the end of the gun barrel after firing. Because of its much higher velocity (3094 ft/sec [943 m/sec], as opposed to 1122 ft/sec [342 m/sec] for the .22 long-rifle bullet), because it fragments in tissue, and because of its greater bullet mass, the M16 bullet causes a much more severe wound. Note that both the permanent cavity and the temporary cavity are much larger. As is usual, the temporary and permanent cavities of the .22 long-rifle bullet are largest when the bullet is at 90° of yaw. Note also that the large temporary and permanent cavities formed by the M16 bullet occur mainly from 11 to 30 cm deep in tissue. The bullet has its highest velocity when it enters the tissue, but forms a small wound channel at that point. Only when it fragments or yaws to 90° is its severe wounding effect realized. At that point it is traveling slower. Bullet velocity, then, is only one factor in wounding [7, 20, 23].

Bullets are not sterilized by the heat of firing. They can carry bacteria from the body surface or body organs, including a penetrated colon, deep into the wound [12, 24].

Conclusions

Understanding the mechanisms by which penetrating projectiles disrupt tissue can assist the physician in evaluating and treating the wound in a rational manner. Both missile and tissue characteristics determine the nature of the wound.

Two major mechanisms of wounding exist: crushing and stretching of tissue. The elasticity and density of a tissue and the thickness of the body part wounded strongly affect the wound produced. Missile mass, construction, tendency to fragment or yaw, and velocity are key factors in determining the wounding potential of a missile. Velocity often dominates discussions of wound ballistics; however, a bullet can inflict more lethal damage to tissue by fragmentation and yaw than by high velocity.

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