# Chapter 4

# THE PHYSICS AND BIOPHYSICS OF WOUND BALLISTICS

RONALD F. BELLAMY, M.D., FACS* AND RUSS ZAJTCHUK, M.D., FACS**

---

*Colonel, United States Army; Acting Chief, Department of Surgery, Walter Reed Army Medical Center, Washington, D.C. 20307-5001
**Colonel, United States Army; Deputy Commander, Walter Reed Army Medical Center, Washington, D.C. 20307-5001

## INTRODUCTION

*Ballistics* is the science that studies the motion and impact of *projectiles* (that is, objects that are designed to be hurled or shot forward). Thus, ballistics pertains only to inert, not to self-propelled, objects.

When the behavior of bullets is studied, ballistics is usually considered in three parts: *(a) internal,* which seeks to understand what happens to the projectile while it is still within the gun barrel, where enormous pressures act for an instant upon it; *(b) external,* which seeks to describe the factors (air resistance and gravity being the most important) that determine the projectile's trajectory between the muzzle and the target; and *(c) terminal,* which seeks to describe the interaction of the projectile and the target. *Wound ballistics* is the study of the terminal ballistics of both fragments and bullets in living human tissue, and *ballistic wounds* are penetrating injuries caused by projectiles.

While the nature of ballistic wounds would seem to depend upon *(a)* the physical characteristics of the projectile, *(b)* the biophysical properties of the target tissue, and *(c)* the interaction between the projectile and the tissue, this seemingly rational classification is difficult to apply. Important physical properties of the projectile, such as its construction, become apparent only during the interaction of the projectile with the target tissue. Thus, projectile construction as a determinant of wounding is best considered as a manifestation of the projectile-tissue interaction. Also, because little is known about the material strength and viscoelastic properties of human tissue, integrating their biophysical properties into a meaningful theory of wound ballistics is difficult.

Because of these limitations, this chapter discusses *(a)* the physical characteristics of projectiles, which culminate in their ability to penetrate the target, *(b)* the biophysics of the projectile-target interaction, and *(c)* ballistic tissue damage. For the medical officer, however, the problems of ballistic wounds are inseparable from the problems of wound management, especially the treatment of wounds of soft tissue. More than 90% of battlefield casualties sustain soft-tissue wounds. Because of this incidence, the clinically relevant aspects of wound ballistics, especially the management of soft-tissue wounds, constitute a separate chapter.

## THE PHYSICAL CHARACTERISTICS OF PROJECTILES

### Mass

While physicists consider mass and weight to be quite different, for the purposes of practical ballistics the mass of a projectile is numerically identical to its weight, and is usually conceptualized as being *(a)* located at a point within the projectile and *(b)* usually located near its geometric center—its *center of mass.* The forward motion of the center of mass defines the projectile's *trajectory* (that is, its line of flight).

Most bullets that modern military small arms fire weigh 3.5–12.0 g; typical nineteenth-century bullets commonly weighed 20–30 g (Table 4-1). Cannonballs and the largest fragments from older, random-fragmentation shells weighed many kilograms, but the projectiles from the explosive, improved-fragmentation munitions used today weigh 50 mg to several grams (Table 4-2).

*Density* is the ratio of the mass of an object to its volume. Bullets usually contain lead, which has a density of 11.4 g/cm$^3$, and are disproportionately smaller than fragments, which are usually made of steel, which has a density of 7.9 g/cm$^3$. Lightweight metals such as aluminum, which has a density of 2.7 g/cm$^3$, have been used as part of a bullet's core, and are the constituents of the fragments that are formed from the outer walls of certain modern explosive munitions. Tungsten, at the other end of the density spectrum with a density of 19.4 g/cm$^3$, is used as the core penetrator in small-caliber bullets of advanced design.

### Shape

A projectile's shape, in addition to its mass, determines how the projectile will behave not only on its trajectory through air but also as it strikes and penetrates its target. Shapes of projectiles vary from arrow-like fléchettes to the irregular chunks of random fragments. The shape of a chunky fragment is difficult to quantify, but the pointed, curved shape of a bullet's nose, its *ogive,* and the cross-sectional area of projectiles can be described.

***Ogive.*** The ogive measures the number of projectile calibers that would constitute the radius of a hypo-

## TABLE 4-1

## CHARACTERISTICS OF IMPORTANT MILITARY SMALL-ARM PROJECTILES

| Weapon | Era | Construction of Projectile | Diameter (mm) | Weight (g) | Muzzle Velocity (m/s) | Kinetic Energy (muzzle) (J) | Important Features |
|---|---|---|---|---|---|---|---|
| Smooth-bore musket* | 1700 | Soft lead round hall | 18 | 33 | 180 | 530 | Deformation |
| Muzzle-loading rille" | 1850 | Soft **lead** conoiddl bullet | 17 | 37 | 300 | 1,655 | Deformation |
| Breech-loading rifle* | 1870 | Hard lead cylindro-conoidal bullet | 11 | 25 | 430 | 2,300 | Deformation |
| Breech-loading magazine rifle" | 1890 | Blunt nose lead core, steel jacket | 7.9 | 14 | 600 | 2.650 | Good stability |
| Single-shot bolt action rifle* | 1910 | Pointed nose lead core, | 7.9 | 9 | 830 | 3,100 | Poor stability |
| Vickers Mk 7 machine gun (GB)** | WWI | Aluminum cap lead core, copper jacket | 1.1 | 11 | 750 | 3,060 | Poor stability |
| Karahincr Model 1898 single shot. (GER)** | | steel jacket | 7.9 | 11 | 740 | 3,000 | Poor stability |
| ACP M1911 automatic pistol (USA)** | | Lead core copper jacket | 11.7 | 15 | 265 | 527 | Good stability |
| PPSh machine pistol (USSR)** | WWII | Lead core | 7.62 | 4.8 | 490 | 560 | Multiple hits possible |
| Garand **MI** semiautomatic rifle (USA)** | | Lead core copper jacket | 7.62 | 10.5 | 830 | 3,600 | Poor stability |
| MG 42 machine gun (GER)** | | Lead cure steel jacket | 7.92 | 11 | 800 | 3.600 | Poor stability |
| **AK47 assault rifle (USSR)**** | post–WWII | Steel and lead core steel jacket, M43 **hall** | 7.62 | 7.6 | 730 | 2,000 | Poor stability multiple hits |
| M16 assault rifle (USA)** | | Lead core copper jacket, M193 | 5.56 | 3.5 | 980 | 1,650 | Fragmentation multiple hits |

Note: Representative values are shown: numerical quantities are rounded; ihe bullets from WWI and post–WWI periods are spitzers except those tired hy the ACP M1911 and the PPSh, which have the characteristic round-nos design of pistol ammunition.

*La Garde, L. A. 1916. *Gunshot Injuries* 2d revised edition. **New** York: William Wood and Company.

** Hogg, I. V. and **Weeks.** J. 1985. *Military Small* Arms *of rhe 20th Century*. 5th ed. Northfield, IL: DBI Bods. Inc.

TABLE 4-2

CHARACTERISTICS OF PROJECTILES FROM EXPLOSIVE MUNITIONS

| Weapons and Projectiles | Projectile Characteristics<br>Mass*** (g) | Velocity† (m/s) | Kinetic Energy (J) | Important Features |
|---|---|---|---|---|
| Muzzle-loading cannon;<br>French 12-pounder cannonball; solid lead* | 5,450 | –300 | 260,000 | Massive crush |
| Spherical case shot; lead ball shrapnel** | 60 | –200 at 100 m | 400 | Deformation |
| High-explosive shell projectile;<br>irregular iron or steel fragments<br>with different mass | 30 | –1,100 at 200 ft | 18,000 | Catastrophic injury |
| | 4 | –500 at 200 ft | 550 | |
| | 0.3 | –690 at 30 ft | 70 | Most common size |
| Fléchettes | 1.5 | –400 at 200 m | 140 | Multiple hits |
| Modern Claymore mines; steel ball shrapnel** | 0.6 | –700 at 50 m | 150 | Multiple hits |

*Not an explosive munition, but included for purposes of comparison.

**Strictly defined, shrapnel means preformed fragments **(the** already made within the explosive munition). Thus, fragments from a random-fragmentation shell are not shrapnel. **Also** note that by strict definition, fléchettes are shrapnel.

***Representative values.

†Velocity of the fragments at the time of detonation from the explosive munition at **a** defined distance from the weapon. The values represent velocity at stated distance, if given, or maximum velocity of the projectile.

Sources:

Douglas. H. 1860. *A treatise* 5th rev. ed. London: John Murray, Albemarle Street.
(cannonball)

Beyer, J. C., ed. 1962. *Wound ballistics.* **Washington, D.C.: Office of the** Department of the Army.
(spherical case shot and high-explosive)

Explosive Ordnance Disposal **Group.** Quantico Marine *Corps* Base, **VA**
(Claymore mines; fléchettes)

thetical circle that includes the ogive as an arc. Thus, when a bullet has an ogive of 7, the curved portion of its nose forms an arc of a circle with **a** radius seven times the projectile's caliber (Figure **4-1).** The round-nosed jacketed bullets that were introduced at the end of **the nineteenth century had ogives of** 1.5–2.0. **The** spitzer bullets that followed had ogives of 6–7.

***Cross-Sectional Area.*** Another index of shape is the projectile's maximum cross-sectional area perpendicular to its line of flight (A). Complicating the role of shape as a physical parameter, a projectile not symmetrical in the three dimensions of space will present **differing cross-sectional areas as it wobbles around** its asymmetric axes. A sphere, since it has perfect sym-

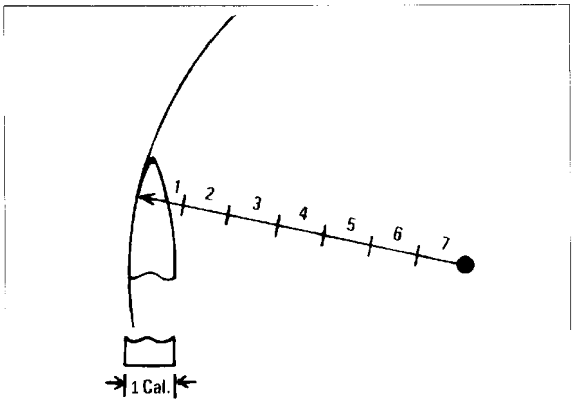

Fig. 4-1. Calculation of ogive. The nose of the bullet forms an arc of a circle. The radius of this circle is expressed as the number of calibers (in this example, 7) that equal the absolute length of the radius.

metry, and chunky fragments that are nearly symmetrical cannot present different cross-sectional areas as they move along their trajectories. But an elongated cylinder such as a bullet, which is symmetrical only around its long axis, can *tumble* (that is, flip end-over-end) around its center of mass. Its cross-sectional area will not be constant because, at least part of the time, a tumbling bullet's side (rather than its nose or base) will be perpendicular to the line of flight.

***Sectional Density.*** Dividing a projectile's mass by its cross-sectional area (that is, M/A) yields a parameter known as the sectional (or frontal) density. A long, narrow fléchette, because it has a tiny cross-sectional area, has a high sectional density compared to a sphere or an irregular chunky fragment.

### Velocity

Velocity is usually considered to be the single most important property of a projectile. This may be true in theory. In practice, however, the velocity of a projectile as it hits its target is usually not known because its velocity decreases as a projectile travels along its trajectory. Because a bullet's impact velocity usually is estimated from the small arm's published muzzle velocity, the estimate requires knowledge of the distance from the weapon to the target. The impact velocity of a projectile from an explosive munition is even more difficult to quantify. While accurate measurements of a bullet's velocity—as a function of downrange distance—can be made in the laboratory using electronic timers (chronometers), measuring a fragment's velocity requires sophisticated photo-optic techniques, which are available in only a few weapons-research institutes.

Most impact velocities range between 80 m/s (about 250 fps), the minimum velocity required for a round or pointed projectile to penetrate human skin, and 1,500 m/s (about 4,900 fps), the highest velocity at which a projectile from an explosive munition is likely to wound a casualty who will not have been killed by proximity to the blast.

Projectiles are customarily described as "low-" or "high-velocity," but the actual corresponding speeds have not been well defined. This textbook arbitrarily defines *low velocity* as slower than the speed of sound in air (that is, 334 m/s or 1,100 fps) and *ultrahigh velocity* as the speed of sound in soft tissue (that is, 1,500 m/s or 4,900 fps). (Projectiles with ultrahigh velocities are uncommon on a battlefield.) Since the first observations of "explosive" wounds occurred when "high-velocity" bullets were fielded in the mid-nineteenth century, it seems reasonable to connect the two. Therefore, this textbook defines *high velocity* as that at which explosive effects begin to be commonly seen (that is, 600–700 m/s, or 2,000–2,300 fps). Velocities between 1,100 fps and 2,000 fps are known as *intermediate* or *medium*. The velocity of a typical musket ball that Hunter described in the eighteenth century as "great" (that is, 180 m/s) was actually low velocity by our definition (Table 4-1). Rifles firing high-velocity bullets have been the norm since the end of the nineteenth century, and velocity has barely increased since the early twentieth century. The velocity of the M193 ball fired by the M16 rifle of 1965 is only about 10% greater than that of the 1910 spitzer bullets.

Table 4-1 lists the muzzle velocities of some common bullets. Because bullets are streamlined, they maintain their velocities far better than projectiles from explosive munitions do, with the exception of flechettes (Figure 4-2).

### Kinetic Energy

Energy is the ability to do work, and any physical body that moves has an ability to exert force and to do work—simply by virtue of its motion—called *kinetic energy* (KE). This derived parameter, measured now in *joules* (J) but formerly in foot-pounds, can be calculated when the projectile's properties of mass and velocity are known:

$$KE = \frac{MV^2}{2}$$

Since velocity V enters the equation raised to the second power, changes in a projectile's velocity cause greater changes in its kinetic energy than do changes in the projectile's mass M. The dominant features of military small arms bullet-design during the past two

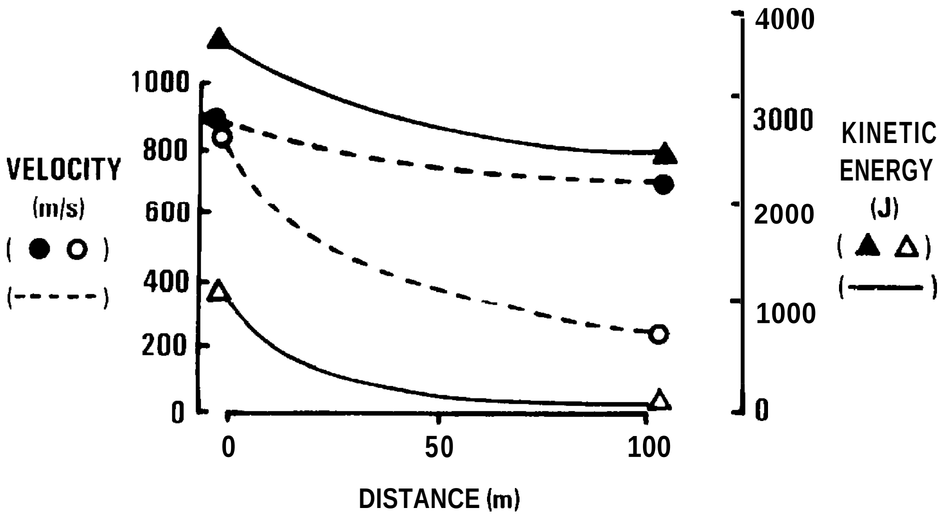

Fig. 4-2. The decrements in velocity (broken lines) and kinetic energy (solid lines) for a typical "chunky" fragment (open circle and triangle) and a 7.62-mm bullet (closed circle and triangle) in air. The fragment is assumed to weigh 3 g and the mass of the bullet is 9.75g. For purposes of illustration, the initial velocities of both projectiles is taken as *862* m/s. The decrements in velocity and kinetic energy are much greater in the unstreamlined fragment than in the streamlined bullet.
Source: Reference 7.

centuries were *(a)* reducing the bullet's mass and *(b)* increasing its velocity, which consequently increased its kinetic energy. For example, a typical musket ball used in 1850 had a kinetic energy of about 1,665J, while one of the most important rifles used in World War 11, the American M1, fired a bullet that had a muzzle-kinetic energy of 3,600 J. Only since World War II has reducing projectile mass outstripped increasing velocity, resulting in a consequent fall in kinetic energy: The M193 ball fired by the M16A1 rifle had a muzzle-kinetic energy of only 1,650 J.

As with high velocity, we can speak of high kinetic energy. As was true of velocity, a projectile's kinetic energy at impact depends upon the target's distance from the muzzle or the site of detonation. The kinetic energy of an irregularly shaped fragment degrades faster than does the kinetic energy of a streamlined bullet (Figure 4-2).

## Drag

A medium, whether air, water, or human tissue, hinders or resists a projectile as it passes through. This resistance is called *drag,* which degrades both velocity and kinetic energy (Figure 4-2), and is an important determinant of the magnitude of ballistic injury.

Drag depends upon the properties of both the projectile and the medium it passes through. As a projectile penetrates, the medium in its path is split apart and displaced to the side. The medium's splitting and displacement both create drag, and their net effect slows and may ultimately stop the projectile.

Displacement of the medium is the most important source of drag as a projectile moves through air. As the gas molecules in air are displaced, drag arises from three sources (the sources of drag are much more complicated when a projectile passes through tissue):

- Air is compressed at the tip of the projectile, forming a region of high pressure. This is by far the most important source of drag for a projectile moving through air at velocities greater than the speed of sound.
- Turbulence occurs at the base of the projectile as the displaced air returns to its original position.
- Friction occurs as air slides around the body of the projectile. This is the least important source of drag.

The mathematical expression for the **drag** that occurs when a projectile passes through a fluid is:

$$\text{Drag} = 1/2[(CD)(d)(A)(V^2)]$$

where *CD* is the proportionality constant known as the coefficient of drag, *d* is the density of the target medium, A is the projectile's cross-sectional area, and V its velocity.

The drag equation indicates that, if all other factors remain the same, changing the density of the medium from that of air to that of water (1.00 g/cm$^3$) will result in a thousandfold increase in drag. Similarly, increasing the cross-sectional area of the projectile (for example, as when a deforming bullet such as a dumdum hits a solid target, or when a bullet tumbles) will increase drag. Because velocity is raised to the second power in the equation, doubling the projectile's velocity increases drag fourfold.

All other factors, such as the coefficient of drag and the shape, being the same, drag is much greater with high- than with low-velocity projectiles. For example, high-velocity rifle bullets **slow** more rapidly than do similarly shaped pistol bullets.

The drag equation omits a factor for the splitting of the medium, a phenomenon that depends upon the medium's material strength. Because of this omission, the increase in drag that occurs when a projectile passes from air into human soft tissue will be much greater than a prediction based simply on the change in density (from 0.001 g/cm$^3$ in air to 1.05 g/cm$^3$ in muscle). This factor is unknown and is one of the areas that requires the attention of sophisticated ballistics researchers.

When drag is treated mathematically as the force of retardation, it is usually normalized for projectile mass (that is, drag/mass) and can be expressed:

$$[(CD)(d)(V^2)(A/M)]$$

or, by transposition:

$$\frac{(CD)(d)(V^2)}{M/A}$$

However, a projectile's sectional density (M/A) is an important determinant of drag: the higher the sectional density, the lower the drag. The velocity of a heavy, narrow projectile (such as a long penetrator rod made of tungsten) will degrade less rapidly than the velocity of a lightweight, large projectile (such as an artillery rocket) will.

Projectiles undergo an enormous force of retardation when they cause ballistic injuries. When traveling point-forward through air, a bullet with a velocity of about 2,000 fps will be retarded by a force of about one *newton* (N, the force that imparts to a mass of 1 kg an acceleration of 1 m/s$^2$), which is equivalent to about **3** psi. Forces measuring tens of thousands of newtons develop during maximum retardation in a tissue simulant such as gelatin or in soft tissue.’,’

## Coefficient of Drag

The coefficient of drag (CD) depends upon a combination of *(a)* **the** ratio of the **projectile's velocity to the** speed of sound in the medium through which the projectile is traveling, *(b)* the shape of the projectile, and *(c)* the viscoelastic properties of that medium.

While a projectile's shape is the most important determinant of the coefficient of drag, for the data to be interpreted correctly, the velocity at the time the measurement was made must also be known. A projectile's CD is not constant for a given shape, because it depends upon the ratio of the velocity of the projectile (Vp) to the velocity of sound in the medium (Vs), that is, Vp/Vs. This ratio is known as the Mach number. By definition, a Mach number less than 1 is *subsonic*, and greater than 1 is *supersonic*. When the Mach number is 0.6–0.7 or less, CD is relatively constant, but as the Mach number increases from 0.8–1.2 (the *transonic* region), a three- to fourfold increase in CD, and therefore in drag, occurs. **As** the Mach number approaches 2.0, CD falls again, but is always higher than it was in the subsonic region. At very low velocity (that is, less than 100 m/s), the coefficient of drag increases greatly, but because the velocity is so low, the increase in the absolute magnitude of drag is probably of little consequence.[3] Although projectiles may travel at supersonic speeds through air, they rarely exceed the speed of sound characteristic of the target tissue (except lung) while they are penetrating it.

Irregular fragments have very high CDs (that is, a value greater than 2.0). A round-nose bullet of the type that was introduced in the 1890s has a CD (in air, in the subsonic region) of about 0.9. The spitzer bullet that was introduced 10 years later had a CD (in air, in the subsonic region) of 0.4. The difference between the two CD values appears to be small, but the superior aerodynamic property of a pointed bullet compared to a round-nose bullet is that a spitzer's CD increases less rapidly in the supersonic and transonic regions.

The viscoelastic properties of the medium are the third (and least important) determinant of CD. When balls are fired into various media at subsonic speeds (that is, the velocity of sound in the medium is greater than the velocity of the projectile through the medium), although the CDs of the media do vary,“ the variance is not great: in water, the CD is 0.30; in gelatin (20%) at 20° C, 0.35; in swine skeletal muscle, 0.45; and in swine skin, the CD is 0.53. While precise CDs for human tissue have not been determined, they probably do not differ significantly from these.

The CD is difficult to measure. Until recently, a bullet's *aerodynamic performance* (that is, its deceleration as a function of its velocity) was estimated by dividing the experimentally determined drag of a bullet of standardized shape by a constant known as the *ballistic coefficient,* which is directly related to both that bullet's sectional density and its ogive. Thus, a heavy, narrow, spitzer bullet has a high ballistic coefficient and therefore low drag compared to the standardized bullet. Currently, the ballistic coefficient is most frequently used to evaluate handgun bullets. The ballistic coefficient and the coefficient of drag give information that appears to be similar, but the parameters are quite different and should not be confused.[5]

### Stability

**A** projectile that maintains a constant cross-sectional area perpendicular to its line of flight is said to be stable. It has minimal drag compared to a projectile that is unstable and therefore *tumbling* (that is, it flips over in the plane parallel to its line of flight). Unstable projectiles lack both range and accuracy and have little military value. An elongated cylindrical projectile like a bullet is inherently unstable, but it can be stabilized by being spun around its long axis, which imparts *gyroscopic stability.* The factors that render an unspun bullet unstable demonstrate this phenomenon.

***The Center of Pressure.*** The hypothetical unspun bullet in Figure 4-3 is shown with its line of flight and long axis exactly coinciding. As air resists the forward motion of the bullet, an area of high pressure develops near the bullet's nose. The airflow from the nose back around the bullet is symmetrical because *(a)* the bullet is symmetrical and *(b)* the bullet's line of flight and its long axis coincide. The force retarding the bullet's forward motion (that is, drag) therefore acts symmetrically on the bullet, and can be imagined to be located at a site known as the *center of pressure* (CP). In the hypothetical example shown in Figure 4-3, the center of pressure lies on both the line of flight and the long axis. In this instance, the sole effect of the center of pressure is to retard the forward motion of the bullet.

***Tumbling.*** An unspun bullet is unstable because the slightest separation of its line of flight and its long axis—as a gust of wind might cause—will cause the area of high pressure at the bullet's nose to move to one side. The airflow will no longer be symmetrical around the long axis, creating unequal air pressures above and below the bullet, generating lift. The force acting at the center of pressure will separate into two vectors (Figure **4-4**): *(a)* drag, which continues to retard the forward motion of the bullet and *(b)* the new lift force, which attempts to flip the bullet over around its center of mass. **A** perpetuating cycle develops: the greater the separation of the long axis and the line of flight, the greater the lift force; the greater the lift force, the more the long axis and the line of flight will be separated, until the bullet turns over or tumbles. Theoretically, once tumbling begins it will continue because the center of pressure, which remains near the projectile's leading edge, will always be located ahead of the center of mass. More commonly, though, as a bullet slows in tissue, it only tumbles once, then progresses base-forward.

***Gyroscopic Stabilization.*** Even a minor disturbance can cause any unspun projectile to tumble if its center of pressure is located ahead of its center of mass. But a minor disturbance affects a spinning projectile differently. The separation of the projectile's long axis and line of flight generates lift, but rather than causing the projectile to tumble, the lift force interacts with the spin to produce an angular force or *torque,* which displaces the long axis of the projectile perpendicular to the line of flight. Because the long axis and line of flight are separated, lift continues to be generated as the projectile moves forward through air. Lift and spin continue to act together to produce a torque that effects a continuous displacement of the projectile's long axis in the plane perpendicular to its line of flight. Thus, the projectile's long axis rotates around the line of flight, describing a cone. Viewed head-on (Figure 4-5), the projectile's nose rotates around its center of mass, in the same direction as the spin.

***Precession and Yaw.*** This rotation around its center of mass is known as *precession;* the angle that the long axis deviates from the line of flight is known as the *angle of yaw* (Figure 4-6). In a spinning bullet, precession is the response to a disturbance that in an unspun bullet would cause tumbling. But gyroscopic stabilization does more than simply prevent tumbling. If precession occurs over a long enough time, the angle of yaw will nearly disappear (that is, the bullet's long axis and its line of flight will again converge). This aspect of gyroscopic stabilization depends upon the fact that air resistance acting near the bullet's base creates a torque that pushes the portion of the bullet behind the center of mass back toward the line of flight. **As** precession is damped by air resistance, the angle of yaw becomes smaller. Since a bullet's drag is approximately proportional to the square of its angle of yaw,

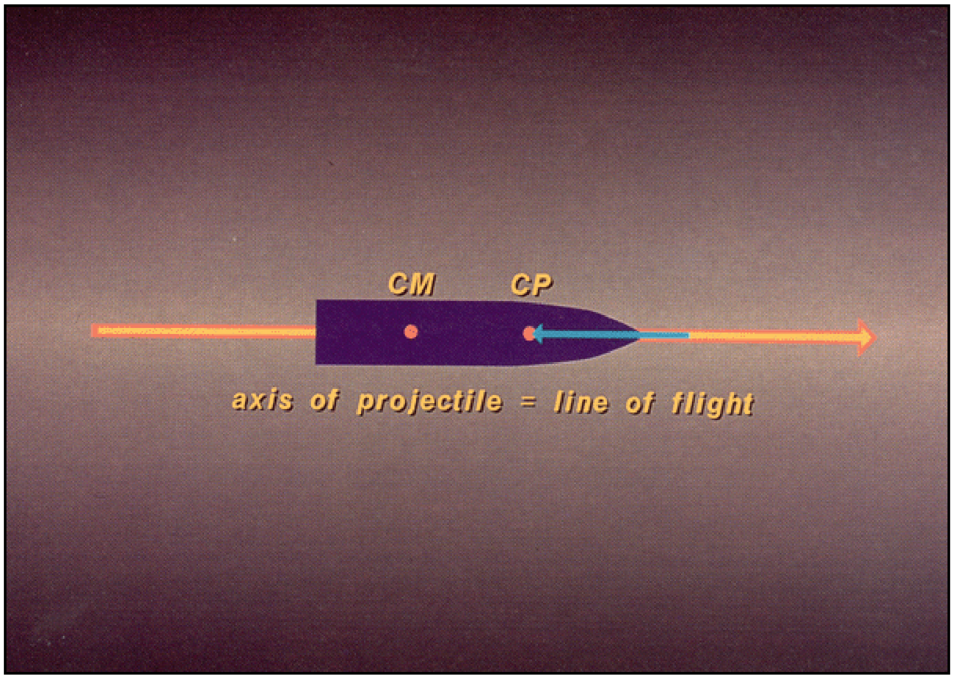

Fig. 4-3. The forces that act on a projectile moving with both its long axis and line of flight coinciding (yellow lines). Air resistance creates a force (light blue line) that acts through the center of pressure (CP) to retard the forward motion of the center of mass (CM). Since this force acts along both the line of flight and the long axis, its sole effect is to create drag.

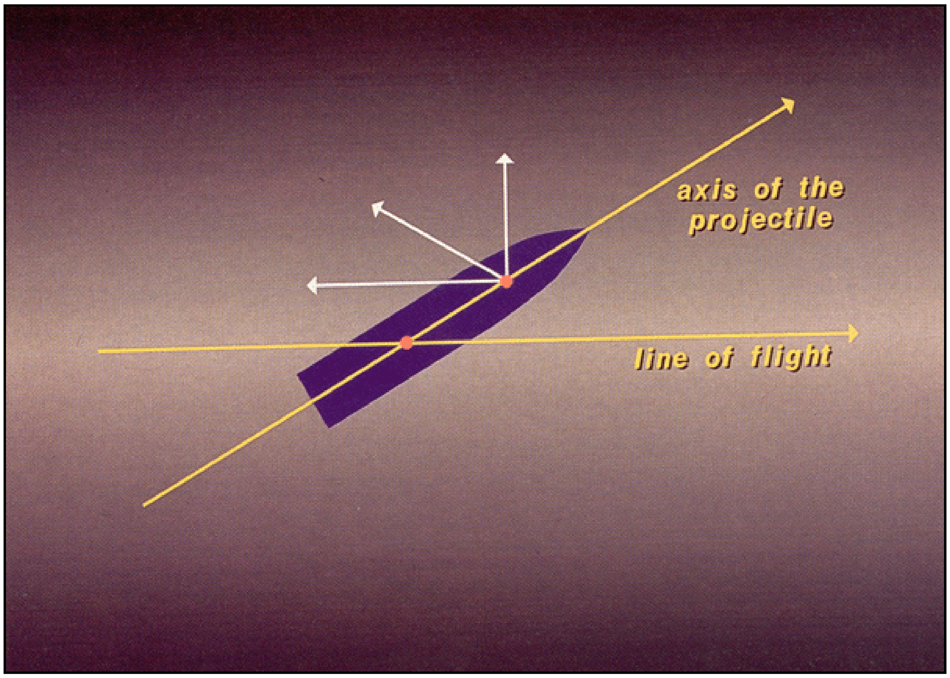

Fig. 4-4. The forces acting on an unspun, moving projectile that has been disturbed. The long axis no longer coincides with the line of flight (yellow lines). The force arising from air resistance acting at the center of pressure (CP) decomposes into two force vectors. One force acts parallel to the line of flight; this force–drag—retards the forward motion of the center of mass (CM). The [illegible] the [illegible] to flip the projectile over around its CM.

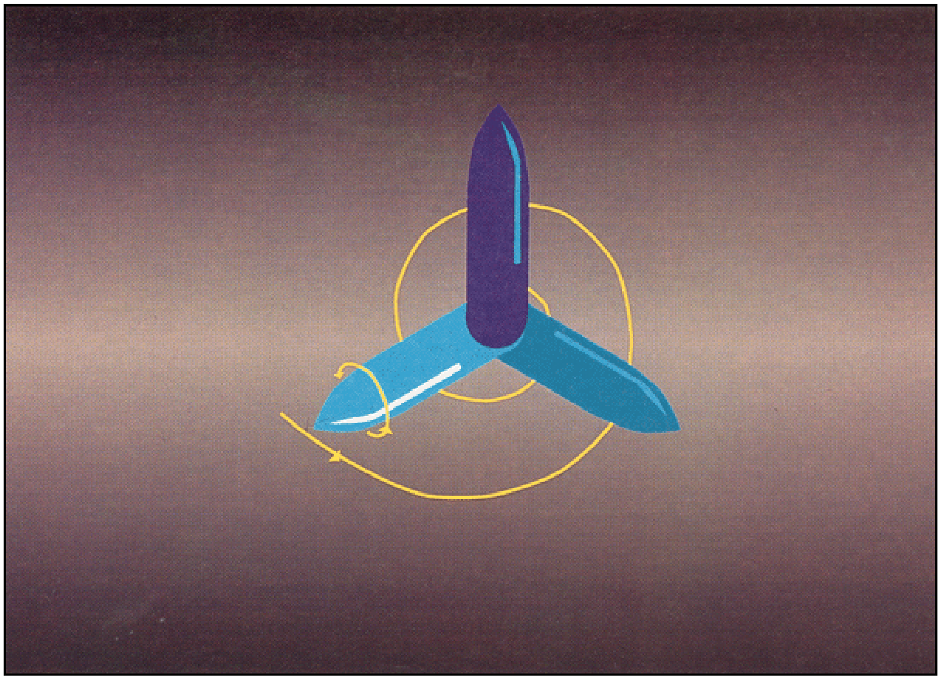

Fig. 4-5. In a spinning projectile, the forces associated with spin and lift interact to create a new force, or torque, which makes the nose of the projectile revolve around the center of mass in a plane perpendicular to the line of flight. This motion is known as precession.

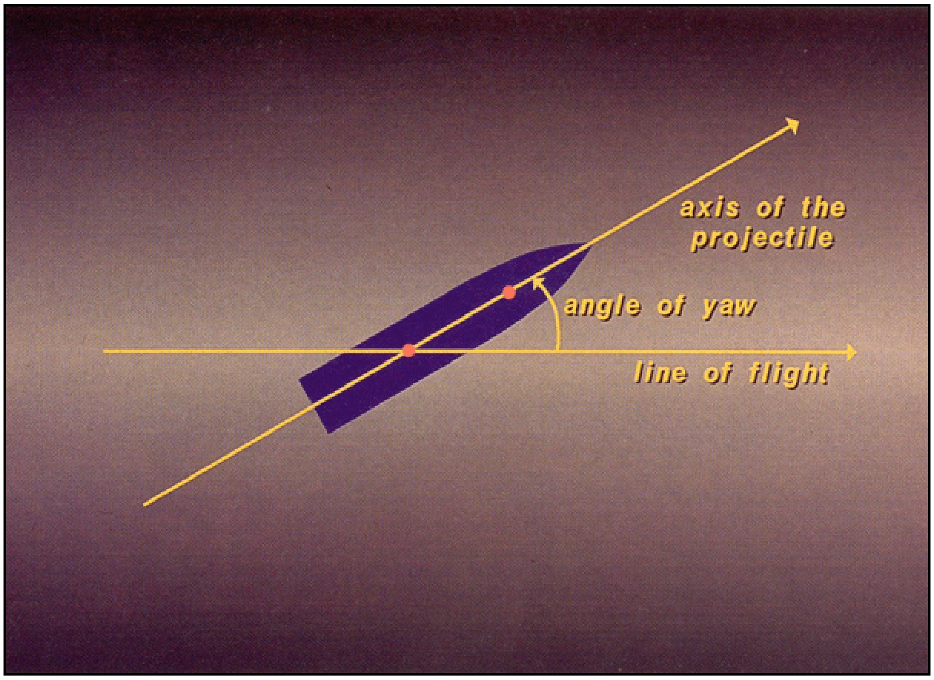

**Fig. 4-6.** The angle between the long axis of the projectile and the line of flight is known as the angle of yaw.

a gyroscopically stabilized bullet, since it has a smaller angle of yaw, will maintain its velocity and improve its long-distance performance. (The actual motion of a spun projectile is complex and involves more than just precession. Interested readers can find a more, comprehensive treatment of the subject in manuals such as Farrar and Leeming's *Military Ballistics.)*

***The Stability Equation.*** The factors that determine gyroscopic stabilization can be described mathematically. Stability is proportional to:

$$\frac{(\text{rate of spin})^2}{(d)\ (\text{the distance between CM and CP})\ (V^2)}$$

where *d* is the density of the medium and V is the projectile's velocity. For a given rate of spin, the equation indicates that the larger the factors in the denominator, the more likely a given disturbance will destabilize a projectile. The density of the medium and the distance separating the centers of mass (CM) and pressure (CP) are especially important.

Bullets have poor stability in tissue. In passing from air to soft tissue, the density of the medium increases from 0.001 $g/cm^3$ to 1.05 $g/cm^3$. Even if all other factors remained unchanged, in order to obtain the same degree of stability in soft tissue as in air, a bullet would need to be spun about thirty-two times faster—a practical impossibility.

A short distance separating the centers of mass and pressure is crucial to a bullet's stability. The pointed bullets that were introduced early in the twentieth century became more unstable than the earlier round-nose bullets, because a pointed bullet's center of mass (located toward the base near the bullet's geometric center) was much farther from its center of pressure (located in the tip) than was a round-nose bullet's. Bullets fired from handguns tend to be more stable than rifle bullets; because handgun bullets are shorter, the separation between their centers of pressure and mass is smaller.

All other factors being equal, the faster a projectile spins, the slower will be the rate of precession, the more acute will be the angle of yaw, and the quicker will its long axis and line of flight realign. Stability is relative; a sufficiently powerful disturbance will make any bullet tumble.

***Rifling.*** The spiral grooves on the inside of a rifled barrel force a bullet to spin around its long axis as it travels the length of the barrel. The rate of spin that a rifle barrel imparts is determined by the weapon's design, and for a typical rifle bullet is several hundred thousand revolutions per minute Although an impressive figure, the bullet's angular velocity (that is, the velocity characteristic of a rotating object) is much less than its linear velocity; a value of about 250 fps is common. The number of spirals and their *twist* (that is, the number of caliber lengths required for the bullet to make a complete revolution) are unique for each rifle and the bullet it is designed to fire. For example, the M16A1 was designed with a twist of 55 (12 inches). The newer version, the M16A2, has a twist of ***32*** (7 inches). The bullet that the M16A2 M855) is longer than the bullet that its predecessor fires, and therefore it requires a faster twist to obtain the same degree of stability. Because the bullet is longer, its centers of mass and pressure are farther apart, and it is more likely to become unstable. The stability equation shows that, other factors remaining the same, the longer the bullet (and thus the greater the separation between the centers of mass and pressure), the faster the spin required for a given degree of stability. Although the M16A1 rifle can fire M855 rounds, the bullets will not be optimally spin-stabilized and therefore will be unusually prone to yaw and tumble.

***Internal and External a Bullet's Stability.*** While even wind gusts and transient encounters with leaves may disturb a bullet's trajectory so much that it precesses, bullets commonly display marked yaw as they are propelled out of the muzzle of a small arm. Factors that are likely to destabilize a bullet include:

- Imperfections in the bullet and damage it sustains as it passes down the barrel can cause the center of mass to lie outside the bullet's long axis
- The bullet can actually tilt within a badly worn barrel and already be yawing significantly when it leaves the muzzle
- The barrel can vibrate and hit the bullet as it exits, causing it to yaw
- Rapidly moving gases exiting from the muzzle can strike the base of the bullet downrange and deflect it from its line of flight[6]

Downrange 30–40 m, the interaction of the bullet's spin and air resistance will have dampened precession and markedly decreased the angle of yaw. But when a projectile passes from one medium to another of different density, (that is, from air to soft tissue), it becomes less stable. A soldier who is shot from closer than 30 m will probably be hit by a bullet that yaws significantly, and any preexisting yaw will greatly increase when the bullet penetrates tissue. Experimental evidence shows that the angle of yaw of a bullet may increase from 1”–2”in air to 180”in tissue.’

***Fin Stabilization.*** Not all projectiles of military importance have to be spun to be stable. Bombs, rockets, and more recently, flechettes, are inherently stable because they have fins. Like arrows, the tail fins of flechettes have a huge surface area. Their center of pressure is displaced to the rear behind the center of mass, which is located near the tip. When flechettes are propelled point-forward they cannot tumble in air, and they make tiny wounds of entrance and exit. But when they are packed fin-forward into their canisters, as some American munitions manufacturers pack them, the flechettes must tumble—to reposition themselves so that the center of mass is near the leading edge and the center of pressure is at —before they can become aerodynamically stable.

But fin-stabilized projectiles are the exceptions. Military projectiles characteristically behave like the rifle bullet shown in Figure 4-7, displaying marked precession and yaw after emerging from the muzzle. Gyroscopic stabilization gradually realigns the bullet's long axis with its line of flight; as the bullet nears its target, its angle of yaw will have decreased to only 1°–2". When the bullet penetrates the much denser target, it destabilizes; its angle of yaw increases rapidly to 90° and the bullet tumbles.

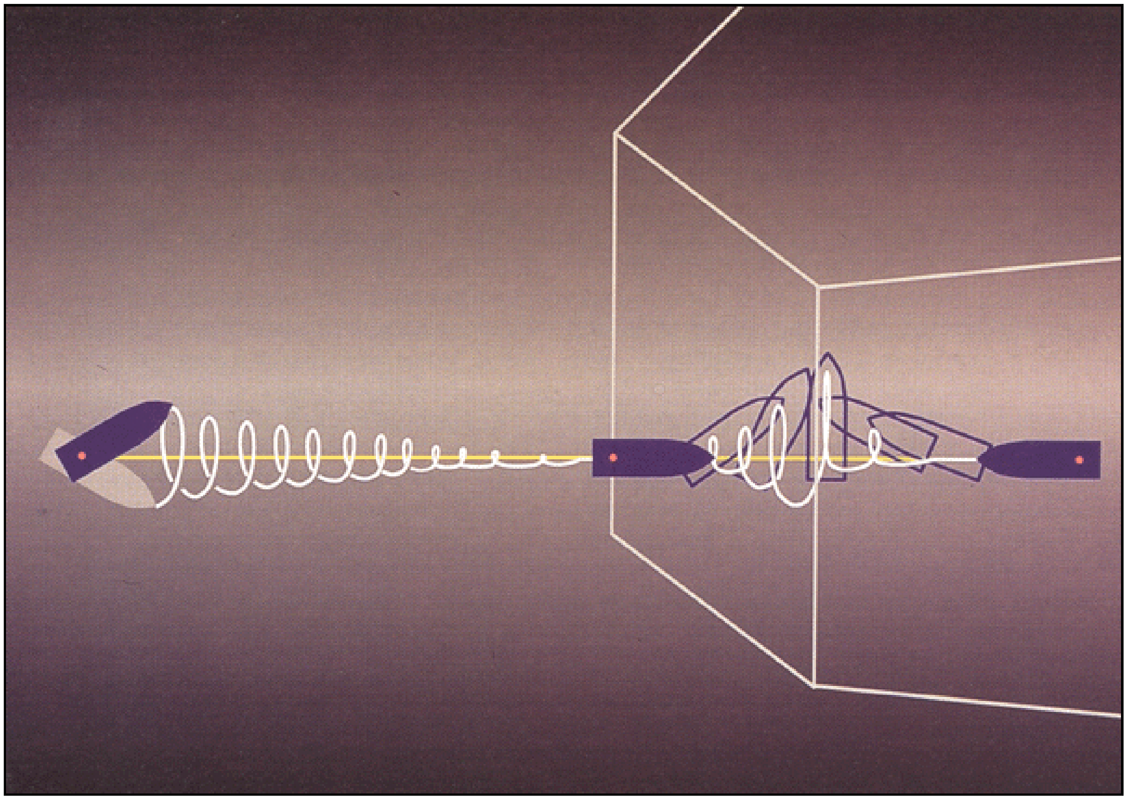

Fig. 4-7. The idealized behavior of many rifle bullets. The bullet emerges from the rifle muzzle with a significant angle of yaw. Gyroscopic stabilization gradually aligns the long axis of the bullet and the line of flight. After travelling about 100 m downrange, the angle of yaw has become very small. When the bullet enters the much more dense target tissue, it rapidly destabilizes. The angle of yaw increases until the bullet tumbles.