GUNSHOT WOUNDS: A SOURCE OF LEAD IN THE ENVIRONMENT

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ABSTRACT.—Ingested lead shotgun pellets and rifle bullet fragments have been shown to be an important source of lead poisoning in water birds, raptors, avian scavengers, and even seed-eating birds. Ingestion of spent lead shotgun pellets by waterfowl and secondary ingestion by Bald Eagles (*Haliaeetus leucocephalus*) scavenging on waterfowl led to the change of hunting regulations that prohibit the use of toxic lead pellets for waterfowl hunting in the United States. However, bullets containing toxic lead are still widely used to hunt large game animals and "varmints" and are a source of lead in the environment available to wildlife.

Basic bullet materials available to the bullet manufacturer include lead alloys, lead with external copper wash, lead core with copper jacket, pure copper, and bismuth. Lead and bismuth are highly frangible, whereas pure copper bullets tend to remain intact after impact. Bullet fragmentation increases the degree of lead contamination in tissue ingested by scavengers feeding on hunter-killed animal remains. Modern bullet design, velocity, composition, and bone impact are significant factors in the character and distribution of lead particles in carcasses, gut piles, and wound tissue left in the field by hunters. Prior to the 1900s, bullets were made entirely of lead. Their velocities were relatively slow (<2000 feet per second), and their tendency to fragment was accordingly lower than that of modern ammunition. Development of smokeless powder in the 1890s increased bullet speeds above 2000 feet (610 m) per second, causing lead bullets to melt in the barrels and produce fouling which reduced accuracy. Copper jacketed lead-core bullets were therefore developed, which permitted velocities that may exceed 3000 or even 4000 ft/sec in modern firearms. Standard hunting bullets now typically travel at 2600 to 3100 ft/sec, speeds highly conducive to fragmentation. Plastic-tipped "hollow-point bullets" used for varmint hunting are actually designed to completely fragment, leaving the entire mass of the bullet to contaminate the carcass.

Hunters value bullets that are accurate and have adequate impact and destructive power to humanely kill the target animal. To decrease the incidence of lead exposure in wildlife and in humans that consume game animals, alternatives to traditional lead-based bullets have been and are being developed. These bullets must be proven to be both as accurate and as lethal as traditional lead bullets in producing humane kills before they are accepted for general use by the hunting community. Additionally, they must be reasonably priced. *Received 8 September 2008, accepted 19 November 2008.*

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THE TOXICOLOGY AND THE PATHOLOGICAL EFFECTS of ingested lead projectiles are well documented in waterfowl, birds of prey (Locke and Thomas 1996), and avian scavengers such as the endangered California Condor (*Gymnogyps californianus*) (Parish et al. 2007). The institution of non-toxic shot regulations for waterfowl hunting throughout the United States and Canada has made much progress in reducing the occurrence of lead poisoned waterfowl and scavengers that feed on waterfowl carrying lead shot. In recent years, another form of ammunition lead has been recognized as a source of exposure in scavenging birds and even potentially in humans, namely, lead fragments emanating from lead-core rifle bullets used in big game hunting (Hunt et al. 2006) and "varmint hunting" (Knopper el al. 2006, Pauli and Buskirk 2007). The leading cause of death in the California Condor reintroduction effort in Arizona is lead poisoning from scavenged carcasses of big game animals killed with lead core bullets (Cade 2007).

Currently, most high velocity bullets manufactured for centerfire rifles have a copper jacket overlaying a lead core. They are engineered to mushroom in the wound track of the target animal, and in doing so, they tend to disperse lead particles into the wound tissue (Hunt et al. 2006). Such fragmentation is generally thought undesirable for big game hunting because of reduced penetration and meat wastage, but varmint shooters prefer bullets that fragment. In either case, scavenging birds feed on the tissues of bullet-killed animals and ingest the lead fragments dispersing from the bullet path. Acute lead poisoning may result and it is often lethal; moreover, there are questions about possible long-lasting sublethal manifestations, especially from repeated exposure (see Douglas-Stroebel 1992, Gangoso et al. in press).

Some of the lead available to scavenging birds such as eagles and condors may come from the use of lead shot for upland game and other types of shotgun hunting not currently covered in the nontoxic shot waterfowl hunting regulations. However, by far the greater potential sources are rifle-killed mammal carcasses, including "varmints" killed and left in the field (Knopper et al. 2006) and the gut piles and unrecovered carcasses of big game animals killed during the fall hunting seasons. Hunt et al. (2007) and Green et al. (2009, this volume), show the relationship of condor blood lead levels with deer hunting seasons and condor movements into deer hunting areas, demonstrating a direct effect of the use of standard centerfire bullets containing lead cores (Parish et al. 2007).

As in the substitution of nontoxic metals for lead in shotgun shells used for waterfowl hunting, alternative technologies are being developed for environmentally safer rifle bullets for use in other types of hunting. Acceptance of these alternatives by the hunting public is desirable, but may require substantial research and educational outreach to validate and explain the impact of this source of lead in the environment, the functionality and the efficiency of the new forms of bullets, and the potential health implications for humans who eat game animals contaminated with lead fragments.

Our objective is to familiarize the reader with the mechanisms that contribute to the dispersion of lead and copper bullet fragments in a carcass of a big game animal. Understanding the factors that promote bullet fragmentation is basic to the further development of alternative bullets with decreased potential for poisoning wildlife and humans who eat hunter harvested game animals.

DEVELOPMENT OF MODERN HUNTING BULLETS

The history of the development of lead core bullets and their increasing tendency to fragment into smaller particles with a greater potential for ingestion began near the close of the 19th Century with the development of modern high velocity centerfire rifles that employed smokeless gunpowder. Prior to that, black powder rifles used solid lead bullets that traveled at less than 1600 ft/sec (488 m/sec). These relatively slow-moving bullets simply deformed or sometimes broke apart into relatively large pieces when they struck the target animal. Today, shotgun slugs, travelling at these slower velocities, are used in many near-urban areas for deer hunting, and black powder rifles have resurged in popularity for big game hunting throughout the country. Because of the lower velocity and construction of bullets used, bullets of neither weapon fragment to the degree exhibited by higher velocity centerfire rifle bullets.

The development of bullets with a copper jacket over a lead core used in modern high velocity hunting rifles followed the development of smokeless powders that produced greater volumes of gases and whose burning rates could be adjusted to specific needs by the manufacturer. The original intent of the copper jacket over the lead projectile was to prevent the lead fouling of the rifling of the gun barrel, which decreased the accuracy of the rifle. This occurred after a few shots due to the "melting" of the lead from the bullet by the higher pressures and barrel friction produced by the larger volumes of gas. The combination of smokeless powder and copper jacketing produced bullets that travelled at much higher velocities and with flatter trajectories than those of earlier rifles. The original bullets for use with smokeless powder were developed for the military and were fully-jacketed, meaning that the lead core was completely encased in copper.

Soft-nosed or semijacketed bullets with lead cores were soon developed for hunting large game mammals such as deer and elk. These bullets were designed to mushroom so as to maximize the wounding potential and provide for quicker, more humane kills. The incomplete jacket exposed a portion of the lead core on the nose of the bullet to the forces of tissue impact. Fragmentation was an emergent property of greater velocities and mushrooming designs. Later, however, hollow point bullets were designed specifically for the "varmint shooter" to fragment completely when striking small thin-skinned animals such as rodents, rabbits and coyotes. Plastic or metallic inserts in the nose of the bullet are often incorporated into the design to streamline the bullet and to act as a wedge to facilitate expansion or fragmentation on impact. The striking of bone early in the wound path may cause additional malformation and fragmentation of the bullet. The result from soft points and hollow points is a "snowstorm" of small to minute, irregular metal fragments throughout the wound channel (Fig. 1). The remaining, partially fragmented, deformed base of the soft-point bullet may or may not exit into the environment.

Hunting cartridges are now available in a wide variety of sizes and calibers and contain bullets of various weights and designs. Each was developed for a different perceived need of the hunting community. For example, a 55-grain (3.6 g) bullet for a .22-caliber rifle barrel is available in the ubiquitous .22-caliber "long rifle" rimfire cartridge and with a normal velocity of <1300 ft/sec, but also for the very high velocity .223 centerfire magnum cartridge whose bullet travels up to 4000 ft/sec. The lower velocity bullet leaves relatively few fragments in the wound compared to the numerous very small fragments of the high velocity bullet that literally "explodes" when the target animal is hit. These high velocity small caliber bullets are used primarily for shooting "varmints," the carcasses of which are usually left in the field and available to scavengers (Knopper et al. 2006, Pauli and Buskirk 2007).

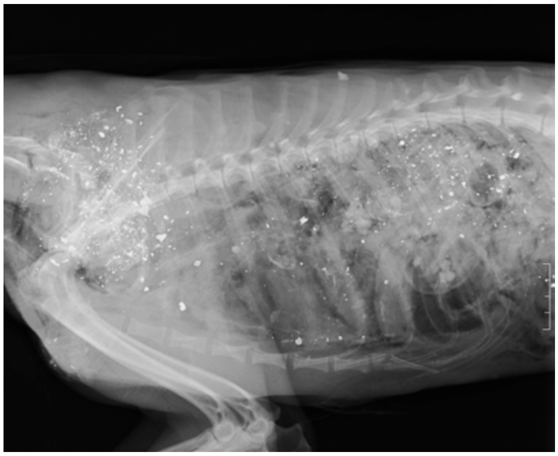

Figure 1. Radiograph of "lead snowstorm" in rifle-killed coyote.

Cartridges used for big game hunting are generally loaded with larger bullets weighing 100–225 grains and with muzzle velocities of 2500–3100 ft/sec, depending on the intended use. Most are designed to mushroom yet retain most of their original weight as they penetrate the tissues of the game animal. Virtually all modern lead-based bullets fragment to some extent, most of them shedding 30% or more of their original mass. As a consequence, the abandoned gut piles of rifle-killed big game animals, as well as carcasses lost to wounding, typically contain numerous bullet fragments accessible to scavengers (Hunt et al. 2006).

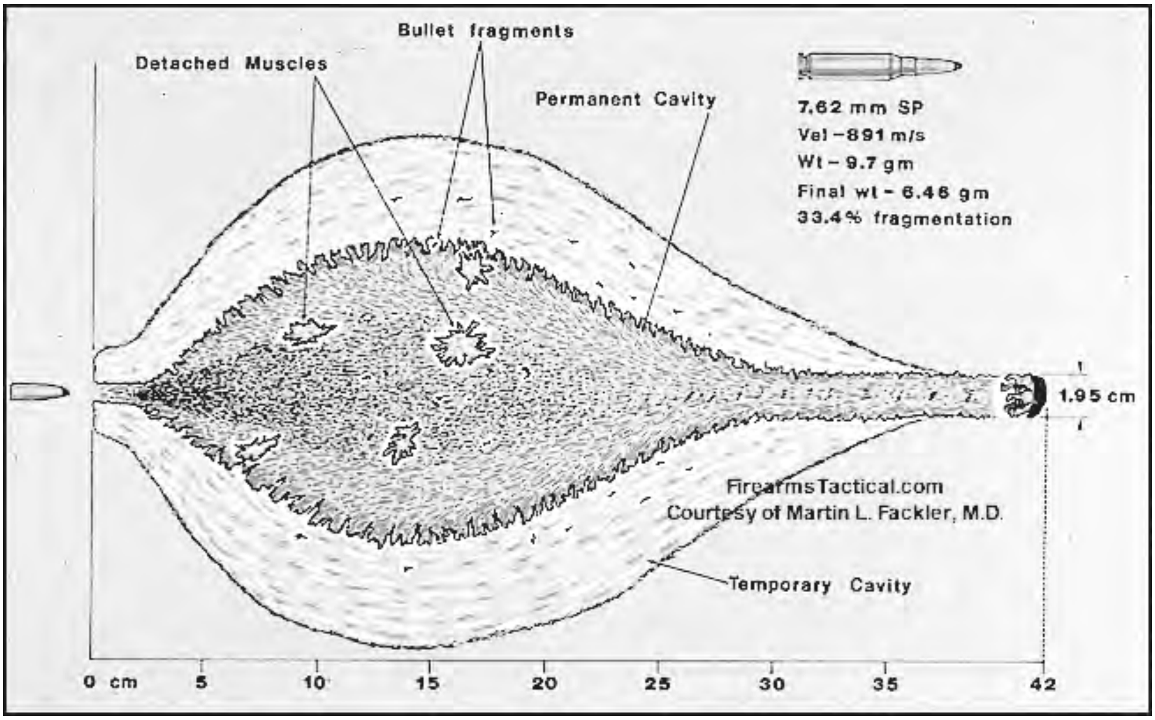

Figure 2. Wound Profile of 7.62 cal, 150 grain soft-nosed bullet (from Fackler 1986).

WOUND BALLISTICS: THE MECHANISM OF BULLET WOUND PRODUCTION

The study of ballistics includes the factors that influence the flight of the bullet from the end of the gun barrel to the target. Hunters strive to kill humanely. To this end, the two essential aspects of bullet performance are accuracy and lethality. The former proceeds from the ignition of gunpowder in the cartridge case to the pressurization of gases propelling the bullet through the rifling of the barrel. These events send the bullet spinning through the air as unerringly as possible to the precise point of aim, namely a center of vital processes, the destruction of which will produce a quick and painless death. Wound ballistics, in contrast, is the study of the impact of the bullet and its penetration of tissue. The velocity and mass of the bullet determine the amount of kinetic energy potentially imparted to the target animal (Fackler 1986). The relevant velocity therefore is that of the bullet as it strikes the target, not the velocity at which the bullet leaves the muzzle of the gun. Distance to the target decreases the velocity to some extent, and this decrease may be proportionately greater for larger projectiles or those not aerodynamically designed.

$$\text{Kinetic Energy} = \text{Mass x Velocity}^2$$

Velocity is exponential, whereas the mass of the bullet is linear in the equation that describes the amount of kinetic energy available within the bullet to transfer to the target animal. Therefore, the velocity of the bullet has proportionally much more influence than the weight of the bullet in the wounding process. The mass retained by the bullet after initial penetration of the skin and partial fragmentation is an important factor in the depth of penetration of the bullet along the wound track; a bullet that loses mass through fragmentation shows less penetration, whereas the tendency of the bullet to mushroom, tumble, and fragment while traveling through the tissue are factors influencing the amount of tissue destruction. All these factors are influenced by bullet construction, namely, the internal components and the thickness and extent of coverage of the copper jacket.

The biological significance of the smaller fragments from higher velocity bullets versus larger bullet fragments in wound tissue or animal carcasses is that smaller irregular lead particles have a higher surface area relative to the mass of the fragment; they are therefore more likely to be quickly eroded by the gastric acids of the animal ingesting them and thus more efficiently absorbed within the intestines. Additionally, large fragments may have a greater likelihood than smaller ones of being regurgitated or avoided altogether by raptors.

Wounds in the carcass of an animal hit by a high velocity bullet are produced by three separate mechanisms. As the semijacketed or soft-nosed bullet passes through tissue, it disperses its energy, a product of the mass and velocity, into the surrounding tissue. This mechanism produces a radiating tissue expansion perpendicular to the path of the bullet called the "temporary wound cavity" (Figure 2). Tissue is torn by this wave of energy that is often referred to as hydrostatic pressure. Tissue such as liver, which has poor elasticity, tears and fragments whereas lung tissue is highly elastic and may expand and contract without tearing. This may be visualized in a slow-motion film of a bullet entering a tissue-simulating gel block and showing characteristics like ripples in a pool around a pebble striking the water. As the bullet passes through tissue and starts to mushroom and break apart, secondary projectiles consisting of bullet fragments and disrupted bone fragments cause additional damage alongside the bullet path by lacerating tissue. The third mechanism is the crushing of tissue along the wound path by the mushroomed and tumbling bullet itself. This is referred to as the "permanent wound cavity."

Translating this into a wound path through a carcass is more complicated. Differences in elasticity in various tissues account for variable wound path damage profiles. A bullet that fragments (soft-nosed) compared to a non-fragmenting bullet (solid or fully jacketed) of equal mass and velocity has a larger permanent wound cavity that, in theory, would cause a more extensive wound if it penetrated to the same degree (Fackler 1986). Factors making the study of animal wounds additionally complex are the sizes of target animals and the specific tissues encountered along the wound path. Impacted bone, for example, may increase the degree of fragmentation and produce secondary projectiles (bone fragments). In summary, evaluation of any given bullet's effectiveness in killing the targeted animal is often a very subjective process.

Generally speaking, the slower the projectile, the narrower the wound path. A slower-moving shotgun slug will not cause the same large diameter temporary wound cavity and exit-wound as a high velocity centerfire bullet as it passes through a carcass of similar size, even though the shotgun slug may be significantly larger in mass and could cause a larger permanent wound channel than a smaller high velocity bullet. For this and for reasons of accuracy and trajectory, hunters have increasingly preferred higher velocity bullets. Some hunters argue that the tendency of such bullets to fragment makes them kill more humanely than those that only mushroom. However, in addition to their greatly reduced penetration, the reduced bullet core may divert into nonvital areas. Finally, there is a greater potential for meat wastage though the production of bloodshot, lead-infused tissue. Accordingly, there have been numerous design innovations to prevent fragmentation and maintain bullet mass. Among these, are (1) "bonding" techniques whereby the copper jacket is soldered or otherwise made to adhere to the lead core, (2) copper partitions placed between the rear of the bullet and its mushrooming nose, (3) reductions of the lead core and its encapsulation in a thin steel sheath, and (4) construction of bullets made entirely of copper.

FUTURE DIRECTIONS

Copper bullets are now available that do not tend to fragment on impact and do not contain the lead core common to most hunting bullets. These bullets are designed to mushroom and expend most of their kinetic energy within the carcass so as to humanely and effectively kill large game animals. Interestingly, the development of copper expanding bullets had little to do with environmental or health considerations, but rather with the desire among big game hunters for deep-penetrating non-fragmenting bullets. Reports on the accuracy and killing performance of copper expanding bullets in hunting have been highly favorable (McMurchy 2003, Towsley 2005, Sullivan et al. 2007). The Barnes Bullet Company has been the pioneer of this technology, but other companies are following suit. The use of these bullets in areas of high use by endangered California Condors with seasonal big game hunting and varmint shooting has promise in reducing the exposure to lead fragments in their diet and those of other scavengers (Sieg et al. 2009, this volume). Copper bullets also show promise in reducing the contamination of game meat for human consumption (Cornatzer et al. 2009, this volume). Other technologies may eventually have application for hunting, including variations of the so-called "green bullet" developed by the military. This bullet substitutes a compressed metallic (nonlead) matrix for the lead bullet core. These bullets have been extensively used at practice shooting ranges and for some urban military combat situations.

Education of the hunting public concerning the impacts on wildlife of lead in the environment is an essential component of wildlife conservation (Friend 2009, this volume). The research showing that steel shot was a reasonable substitute for lead shot for waterfowl was extensive, and once proven scientifically, there followed an educational program to inform the hunting public on how to use steel shot effectively for waterfowl hunting. Voluntary use of copper bullets in behalf of condors in Arizona is promising, and follow-up questionnaires are showing that hunters are finding the new copper expanding bullets comparable in lethality and accuracy for Mule Deer and elk (Sullivan et al. 2007). Any significant changes in hunting regulations designed to reduce toxic lead availability to wildlife should be preceded by research into wound ballistics to validate that non-lead bullets are effective and humane in killing the targeted animal and accurate in existing rifles. Educational programs should also explain the negative impacts of toxic lead in the environment as well as the potential for human health impacts, especially to fetuses and children.

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