Review Article Compte rendu

Achieving humane outcomes in killing livestock by free bullet I: Penetrating brain injury

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Abstract — Humane killing of farm animals by free bullet is a commonly used second-best option in emergency situations and disease control operations. Theoretical justification has been weak in experimental reports of firearm system use in the field. Veterinarians require an in-depth understanding of killing with free bullet to take corrective action when systems fail under field application. This review describes the technical considerations in choosing safe, effective firearm systems to effectively kill minimally restrained livestock at close range. Frequently referenced firearm/bullet recommendations are excessively powerful and unnecessarily hazardous. Based on ballistic energetic performance and mechanical design, the rifle chambered for low energy pistol ammunition, using non-toxic controlled expanding bullets, has the technical capability to deliver immediate insensibility and death at a distance of 5 m or less. At 1 m distance, the .410 shotgun with steel or porcelain shot meets the environmental safety, ballistic, and mechanical challenges and has workplace safety advantages over rifle-based systems.

Résumé — Atteinte de résultats non cruels lors de l'abattage du bétail par balle libre. I : lésion cérébrale par pénétration. L'abattage sans cruauté des animaux de ferme par balle libre est une option de deuxième choix communément utilisée dans des situations d'urgence et des opérations de maitrise des maladies. La justification théorique a été faible dans les rapports expérimentaux sur l'utilisation de systèmes d'armes à feu sur le terrain. Les vétérinaires ont besoin d'une compréhension approfondie de l'abattage par balle libre afin de prendre des mesures correctrices lors de l'échec des systèmes dans l'application sur le terrain. Ce compte rendu décrit les considérations techniques pour le choix de systèmes d'armes à feu efficaces afin de tuer efficacement à courte distance du bétail retenu de façon minimale. Les recommandations fréquemment mentionnées pour les armes et les balles sont excessivement puissantes et inutilement dangereuses. Selon la performance énergétique balistique et la conception mécanique, l'arme à feu chambrée pour des munitions de pistolet à faible énergie, en utilisant des balles à expansion contrôlée non toxiques, possède la capacité technique d'infliger une insensibilité immédiate et la mort à une distance de 5 m ou moins. À une distance de 1 m, le fusil .410 avec de la grenaille d'acier ou de porcelaine satisfait aux exigences en matière d'environnement, de balistique et de mécanique et présente des avantages pour la sécurité au travail par rapport aux systèmes à carabines.

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Introduction

Veterinarians are in the business of killing animals; killing for food (abattoir regulation), killing surplus companion animals in shelters (humane killing), setting endpoints in animal experimentation, and euthanasia of the debilitated and suffering family pet. As veterinarians, we also kill surplus zoo animals; in the pursuit of biosecurity we advise on the killing or exclusion of pest animals, disease control, and wildlife management. Licensed veterinarians will always be involved in technical advice in minimizing pain and distress in the killing of animals. In the 2001 foot-and-mouth disease eradication in the UK, veterinarians were accountable to ensure the humane killing of animals on farm including killing with free bullet. Euthanasia, as used in veterinary discourse, includes the ethical construct that the animal benefits from assisted death. Lethal pest control, the killing of surplus animals, and humane slaughter are forms of humane killing.

In any major slaughterhouse there is a veterinarian responsible to assure food safety and the humane handling of the animals at the time of killing. Abattoir design allows for a wide variety of technology to assure humane killing including physical, electrical, and chemical (inhaled gas) methods to be used. In the slaughterhouse and in emergency depopulation, large livestock are rendered unconscious by a penetrating brain injury (PBI) either from a captive bolt pistol or a free bullet and are usually

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killed by pithing or exsanguination. For most slaughter livestock, free bullet is the second-best choice, acceptable where animal restraint is insufficient to safely apply a captive bolt. The more powerful of the commercial captive bolt pistols deliver less than 400 J of energy to the surface of the skull (1,2). This standard energy bolus delivered by a captive bolt is fatal in 98% of cows and 82% of heavy bulls with well-maintained captive bolt devices, where the animals are well-restrained and the operator is an experienced person (3). There may be deficits in all 3 of these factors in field conditions in the event of natural disasters involving animals (flood, drought, trade interruption) and foreign animal disease eradication (4).

There are 3 outcome dimensions to consider in planning and delivery of the humane killing of animals with free bullet: i) the animal experiences immediate unconsciousness; ii) minimize risks that constitute a threat to others (missing the target, over-penetration, and ricochet); and iii) the bullet-caused injury should have maximal lethality. The intent of this paper is to review and identify safe, reliable, potential ballistic (weapon) systems with near zero survival rate when applied to livestock. A weapon system includes the operator, the firearm, and the ammunition.

Physiology of bullet injury and death

Terminal ballistics, the study of projectile interaction with living tissue, has been extensively studied with application for the treatment of war casualties, urban violence, and in the development of more effective systems to assure immediate incapacitation of humans in police use of force. Individual humans, fatally wounded by police, can continue destructive behavior for a short period of time. This failure to immediately incapacitate has resulted in significant technical innovation in police handgun systems, specifically, controlled expanding bullets on soft tissue targets. Gunshot wounds with penetrating brain injury (PBI) in humans lead to acute respiratory arrest (apnea) and death in a short period of time, even in low energy cranial penetration with limited tissue damage (5).

The International System of Units (SI) Joule (J) is infrequently used in medicine. It is equal to the energy transferred to (or work done on) an object when a force of 1 newton acts on that object in the direction of its motion through a distance of 1 m (newton meter or N·m). The SI base units of joule are $kg \cdot m^2 \cdot s^{-2}$. There are other mathematical approaches to discussion of missile dynamics, but in the interest of effective communication this paper will primarily use J as the unit of energy in ballistic injury. About 72 J are required to penetrate the human skull and 250 J is absorbed by the human head in perforation by a 6 mm steel ball (6). In application to gunshot injury the .22 rimfire (5.6 × 15R — metric designation) with 145 J will dependably penetrate the human skull and not exit, whereas the 9 mm Parabellum 459 J will invariably perforate the human skull under similar conditions (7). Missile energy is not the only factor contributing to PBI; however, it is a relatively easy concept to grasp and to compare different mechanisms and manifestations of injury in terminal ballistic research (8).

The wounding effect of missiles is exceedingly complex as it depends on the kinetic energy of the missile, the behavior of the missile in the tissue, and the nature of the tissue. Soft tissue injury has been the focus of study in human applied terminal ballistics for several reasons. In medical treatment research non-head wounds are more common than penetrating head injury and persons with non-head wounds are more likely to arrive at the emergency room alive (9). In penetrating soft tissue (muscle, abdomen), a highly elastic medium, the projectile sheds energy by 3 methods; crushing/laceration, stretching-rebounding of tissue, and transient high-pressure waves. Work is done (J of energy consumed) to crush the tissue in the direct path of the moving projectile creating a permanent cavity and in creating a pressure wave that precedes the projectile. In the immediate wake of the moving projectile, energy is shed to stretch the tissue at right angles to the projectile path forming a temporary cavity. Bullets in transit not only have directional momentum but also rotational momentum if accelerated through a rifled barrel. Standard rifle bullets may be spinning at 200 000 revolutions per min (8). Modern controlled expanding handgun bullets are engineered to remain intact (retain their weight), expand causing transfer of energy to tissue and come to rest without exiting the target.

Ballistic gelatin is the medium of choice to examine the behavior of missiles in tissue (10). The medical understanding of injury by projectiles was pioneered by the US military medical and ballistic team at the Letterman Army Institute of Research, Presidio of San Francisco (Figure 1) (11,12). Ordnance gelatin, 10% gelatin solution shot at 4°C reproduces the projectile penetration depth as well as projectile deformation and fragmentation pattern as living muscle (pig thigh) (13) and is the basis for ballistics testing and research (14).

The elasticity of brain tissue in an intact skull is limited. In missile penetration of the calvarium, high pressure from the temporary cavity pushes the surface of the brain with great force against the inner table of the skull and the brain stem is displaced into the foramen magnum (7) resulting in severe shear and stretch tissue injury distant from the missile tract. In ballistic PBI, axonal injury can occur in areas of the brain distant from the track of the projectile, especially the brainstem (15) and rapid or immediate respiratory arrest is the typical clinical response to captive bolt use in the abattoir (1) and in human suicide using the captive bolt (16). High intracranial pressure from ballistic skull penetration causes distal axonal injury especially in the midbrain (17). In a human skull model developed by Zhang et al (18) using .25 caliber and 9 × 19 mm non-expanding pistol challenge, between 200 and 550 kPa peak pressure developed within 0.5 ms of penetrating the brain.

The cat model of PBI was designed for the test animal to survive causing limited right cerebral hemisphere trauma and avoiding fatal injury of the brainstem. The same shot taken through an intact skull using a small sphere of 31.7 mg (2-mm, 4.9 gr steel) at speed to deliver 2.5 J was fatal in 2/3 of cats due to immediate respiratory arrest. A trans-skull missile carrying 1.4 J, targeting the cerebral hemisphere, resulted in a 40% immediate death from apnea even though the missile did not directly damage brain stem respiratory centers. Cats experiencing apnea for 6 min were considered "dead" (19).

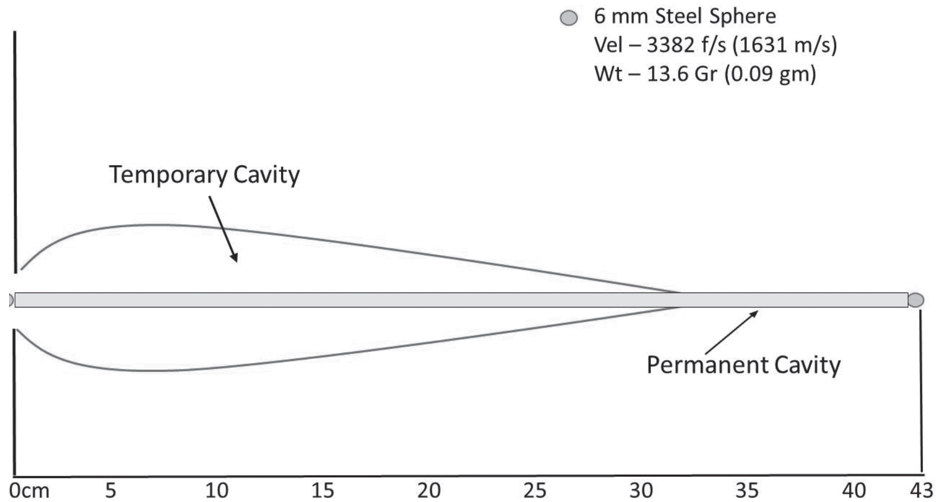

Figure 1. Example cavity formation by penetration of ballistic gelatin by a 6 mm steel sphere, initial energy 468 J. Maximum temporary cavity is formed in the initial 10 cm. Solid spheres maintain their shape and temporary cavity reflects initial tissue inertia and projectile decreasing speed. Redrawn from Figure 14 in Fackler and Malinowski (11).

In the rat model, immediately following ballistic skull penetration, there is a transient (< 0.1 s), dramatic elevation of ICP reaching 280.0 ± 86.0 mm accompanied by a profound decrease in cerebral perfusion pressure of -180.2 ± 90.1 mmHg (20). Relatively low energy firearm related penetrating brain injury can result in hydraulic pressure effects with development of complex fracturing of the skull (15,21).

Gerber and Moody (22) shot 11 rhesus monkeys through a 7-mm burr hole with a .17 inch (4.32 mm) steel ball (0.3297 g, 5.1 grain), with a muzzle velocity of 170.1 m/s (560 ft/s), muzzle 3 cm from the skull delivering about 4.82 J of kinetic energy. The location of the burr hole was 1.5 cm lateral to the sagittal suture with the posterior edge on the coronal suture (off the centerline through the top of the skull). All 11 monkeys experienced apnea or other respiratory disruption immediately on injury. Five of 11 died within 46 min of trauma and 6 survived to elective euthanasia 5 to 7 d after trauma. The trajectory was too far forward to strike the cerebellum or brain stem, intracranial pressure was not measured. Two animals died of initial apnea, while 2 experienced a period of apnea lasting more than 12 s. Only one of the 6 survivors displayed apnea for more than 12 s.

In a similar study, 20 rhesus monkeys immobilized with phencyclidine hydrochloride, and receiving phencyclidine hydrochloride intra muscularly hourly [1 mg/kg body weight (BW)] were shot through a 7-mm burr hole from the back of the skull directed towards the dorsal orbi, a trajectory distant and at right angles to the brainstem (23). The energy of the projectile ranged from 0.49 to 5.02 J. Injury of 1.26 J caused respiration to slow in rate but increase in tidal volume. Pupils did not react to light for up to 2 min after wounding. About 45% of standard injury monkey group died within 6 h. Of 7 animals which received the 5.02 J injury, 4 experienced life-threatening apnea and required immediate ventilator support. Two of the remaining 3 required ventilator support within 30 min of injury. All animals experienced central origin hypotension following injury, systemic hypotension was not due to blood loss.

A histological study was conducted of penetrating brain injury causing death of ten 5- to 6-month-old veal calves, comparing a standard lead core full metal jacket (FMJ) 9 mm $\times$ 19 Luger Parabellum and the same cartridge with a copper hollow-point bullet (HP), both projectiles having a nominal muzzle energy just over 500 J (24). Both projectiles caused immediate death when the trajectory was trans-temporal, right to left. The projectiles penetrated skin and 3 to 4 cm of temporal muscle and 5 to 7 mm of dense bone before entering the cranial vault. The 5 FMJ rounds perforated the skull depositing about 236 J of energy based on loss of speed of the intact bullet. The copper HP bullet broke apart or was deformed by transit through the medium and lodged in the inner surface of the contralateral temporal bone or under the skin of the skull after penetrating the skull but not the head of the calves (24). Histology was consistent with compression and shearing of the brain tissue of the central brain and brainstem as the proximate cause of death. Clinically the animals collapsed in respiratory arrest with extremely short survival times.

Using fresh pig heads and low energy 222 J standardized 9 mm Parabellum rounds (identical weight and muzzle velocity), FMJ bullets over-penetrated the target, whereas a series of controlled expanding, non-fragmenting projectiles were all contained within the skull (25).

In a recent study of stunning horses at slaughter using .22LR copper-plated lead, hollow-point calculated muzzle energy of 248 J (CCI Velociter 40 gr, 1435 ft/s; Cascade Cartridge, Lewiston, Idaho, USA), 78% passed through the cranium, over penetration resulting in lead contamination in the neck muscles (26). In a study using a .22 rimfire in an Equine Infectious Anemia control program, firing from 1.5 m, 3 of 8 equidae were killed with a single shot; all horses were killed when the projectile entered the cranial cavity (27). Insufficient information was provided to calculate projectile muzzle energy in this paper, although targeting variation was sufficient to explain the system failure (27).

In a histological review of 42 human fatal handgun PBI the proximate cause of death was consistent with acute intracranial pressure on the brain stem from the passage of the missile through the brain (28). The Brenneke head shot is a rare human forensic finding, in which a high energy shotgun slug entering the human skull horizontally at the level of the cranial floor results in explosive rise in intracranial pressure sufficient to completely fracture the skull and remove the brain, and separate the skull cap from the rest of the skull (29).

Projectile delivery systems

There are 3 primary types of small arms; handguns (pistol and revolver), rifles, and shotguns and 2 projectile types, single and multiple (shot). Handguns and rifles were primarily developed for military purposes and later adapted for police, civilian, or game hunting purposes. The shotgun is primarily a tool for small game and bird hunting and was later adapted for military and police use. The chamber is the metal space tightly holding the bullet when the chemical reaction in the gunpowder is initiated. In human targets, the mortality rate from a 500 J (handgun) abdominal perforation injury is about 12%, whereas an abdominal wound with civilian expanding hunting rifle bullet delivering 3000 J is well over 90% (30).

The auto-loading pistols are a light defensive weapon carrying between 7 and 18 "bullets," generating low chamber gas pressure and designed to be aimed and fired by a single hand. Revolvers are handguns that are constructed with multiple chambers to allow significantly higher chamber pressure than pistols but generally can be fired less than 7 times before reloading. Due to their light weight and the effects of recoil, handguns use a low energy single projectile (bullet), through a short-rifled barrel, generally slower than or around the speed of sound (331.2 m/s at 20°C), and with kinetic energy < 500 J. Their use is primarily in inter-human conflict within a 3-meter shooter-target distance, as handgun accuracy is highly degraded at longer distances. In review of police handgun shooting accuracy in the United States, targets of police shooting have a less than 50-50 chance of being struck with a bullet (31). Handgun performance is an active research area and a public health concern. To be effective in police use of force, handgun ammunition must penetrate intermediate obstructions (windshield, car door, clothing) on their way to vital organs, expand and lacerate tissue to incapacitate the target by blood loss.

The most adaptable handgun caliber in North America is the revolver round .38 special/357 magnum. Most handguns and carbines chambered for .357 magnum will also fire .38 special as the brass casings differ only in length. In the personal protection market both low energy (minimized recoil) and high energy ammunition are manufactured. As an example, Hornady Critical Defence Lite© .38 SPCL FTX (90 gr, 1200 ft/s) has a muzzle energy of 390 J, whereas the same company manufactures the .357 Mag 158 gr XTP (1250 ft/s) with calculated muzzle energy of 743 J.

The shotgun, with a smooth bore and long barrel, is used in hunting and designed to accelerate many small round pieces of metal (small round lead or steel balls) to nearly the speed of sound. It is designed for shooting birds in flight or small mammals in motion. Shotguns are operated using both hands like a rifle and use high gas chamber pressure as the kinetic energy of individual pellet (shot) rapidly depletes as distance from the muzzle increases. Shotguns come in every imaginable form from single shot to semi-automatic and range in caliber from .41″ (four-ten) to .775″ (10 Ga) and there are 12 or more different sizes of shot. The shotgun is an adaptable family of firearms due to unlimited combinations of size of bore, projectile choice, and accelerant.

When the shotgun is fired, high gas pressures develop and accelerate the wadding and/or plastic cup which traps metal spheres down the length of the barrel. Modern gunpowder requires about 18 in (46 cm) of barrel to complete the conversion from powder to gas. The choke is a partial constriction of the bore of a shotgun barrel at its muzzle so as to place compressive stress on the pack of individual metal spheres. When expelled from the muzzle that compressive energy is released by the even dispersion of pellets. The radial velocity within the shot mass is determined by the gas pressure at the moment of emergence of the shot mass from the muzzle. For forensic purposes there is no detectible pellet dispersion in the first 0.92 m (3 ft) of trajectory (32); subsequently the pellet radial dispersion is about 2.5 cm for each meter travelled.

Rifles were developed from earlier smooth bore firearms to increase accuracy (33). Rifling is the helical groove pattern that is cut into the internal (bore) surface of a gun's barrel. These groves exert torque as the tight-fitting projectile is accelerated along the gun barrel imparting spin around its longitudinal axis and increasing later stability in flight. Rifles and carbines (short rifles) require both hands to operate and are designed to accelerate a single projectile as opposed to multiple pellets. Rifles come in a wide range of calibers (diameter of the projectile in inches) from .17″ to .50″ (4.38 to 12.7 mm). The standard full-sized rifle is most commonly in .30 caliber (7.62 mm diameter) and designed to expel a sleek missile-shaped projectile at 3 to 4× the speed of sound, delivering up to 4000 J of energy to the target. Full-sized rifles with a projectile speed of 2500 m/s or greater have the advantage of reasonable accuracy out to 100 m. Accuracy is a function of human performance and firearm system mechanical limitations. High quality varmint hunting rifles in .22 and .17 caliber (small fast projectile) have an inherent rifle precision of a 1 inch (2.5 cm) shot variability at 100 yd (91 m) (34) well within the error of captive bolt placement in the abattoir (3).

The .22 rimfire Long Rifle (LR) (.22LR, 5.56 × 15 mm) is a common and international firearm caliber. The .22LR is the firearm system used in the winter Olympic sport of biathlon, with a shooting distance of 50 m. In biathlon shooting in the prone position, the target diameter is 45 mm; when shooting in the standing position, the target diameter is 115 mm to adjust for the human error introduced by less stable body position. Biathlon competitors hit rate is between 80% and 85% on both target sizes. In night shooting of European rabbits *(Oryxtolagus cuniculis)* in Australia, the "ethical range," the maximal distance with a high probability of humanely killing the target using .22 rimfire is 80 m, although in practice around 30 m is operational with 76% of rabbits killed with 1 shot (35).

Table 1. Common ammunition sold in Canada. Canadian ammunition is labeled in American Engineering Units not SI Units.

Common name	Mass (Grains)	Velocity (ft/s)	Energy (J)
.22 short HV HPL	27	1105	99
.22 LR	37	1260	177
.22 LR	33	1465	213
.38 Special	110	975	315
.38 Special	158	900	385
9 mm Luger	135	1060	457
.38 Special + P	150	1050	498
9 mm Luger	115	1210	507
.40 Smith & Wesson	135	1185	571
9 mm Luger	124	1300	631
.40 Smith & Wesson	155	1195	666
.357 Magnum	101	1650	828
.410 rifled slug (1/5 ounce)	87.5	1785	839
.410 shot (1/2 ounce)	219	1200	949
.357 Magnum	125	1600	963
.357 Magnum	180	1400	1062
.357 Magnum	158	1600	1218
.30 Carbine	110	1965	1279
.300 AAC Blackout[a]	194	1000	584

[a] Lehigh Defence, Quakertown, Pennsylvania is a speciality ammunition manufacturer, notable primarily for its line of solid copper bullets and speciality sub-sonic rounds for standard hunting rifles with energy similar to a .410 smoothbore shotgun slug.

The .22LR cartridges have the profile of pistol cartridges, although most firearms chambered for this caliber are recreational and target rifles. The low chamber expanding gas pressure inherent to the rimfire allows for rimfire firearms to be very light and inexpensive. Maximum projectile energy is limited to about 250 J [calculated from manufacturer data (.22LR. CCL Stinger, 32 gr, 500 m/s)]. Cartridges designed for indoor target use may have as little as 40 to 50 J of energy. Larger caliber pistol projectile speeds are similar to the .22 and are often sub-sonic (Table 1); the speed of sound in dry air is 343 m/s at 20°C. In soft tissue injury with a low velocity bullet, up to 300 m/s, damage is mainly due to crushing effect of its passage through tissue dependent on the deformation of the projectile in tissue (36).

Options for humane killing of livestock are limited to using firearm-ammunition systems that have been developed for other purposes and are readily available in the local market. Availability is also a condition of local firearm legal restrictions.

Projectile performance

The ideal free projectile system for the safe and humane killing of large livestock in abattoirs and in disease eradication would be non-toxic, resistant to expansion or deformation in transit through the skin and sub-cutaneous tissue, and would penetrate the skull. When travelling intra-cranially, the projectile expands to increase laceration and crushing of tissue, sheds all kinetic energy in brain tissue transit, creates high intracranial pressure, and fails to exit the far side of the skull. Understanding the physics and bio-physics of projectiles within the tissue of the target (terminal ballistics) is required in the challenge of planning to create high quality, repeatable penetrating brain injury (PBI) that results in immediate death of livestock.

Until the early 1970's police forces in western democracies used military law of war compliant full metal jacket (FMJ) non-expanding projectiles in police issue revolvers. The police found that in firefights, individuals shot by police could be struck several times by FMJ projectiles before being deterred from ongoing aggression. Police lobbied for firearms with increased "stopping power" which lead to the development of more lethal projectiles for handguns (37,38) and the adoption of more powerful handguns (37,39). The US National Institute of Justice communicated the acceptability of expanding handgun ammunition for law enforcement in the USA. The International Committee of the Red Cross, under the rules for conventional warfare, would consider it a war crime to use currently accepted police handgun ammunition (expanding bullet) against an enemy combatant.

To achieve blood loss target required for near immediate incapacitation and to prevent over-penetration, it is desirable that low velocity (energy) police bullets penetrate and expand at least 1.5 times the original cross-sectional area. The mushrooming of hollow-point bullets is caused by the high fluid pressures that occur at the tip of the missile passing at sufficient speed through tissue. Large hollow-point projectiles will accomplish this engineering requirement; however, the large hollow can be plugged by clothing or skin and are also rendered non-expanding by intermediate targets such as windshields and car doors. Cartridges used in auto loading pistols must maintain the profile of the original FMJ ammunition to avoid jamming, a limitation in auto loading pistol design. These mechanical restrictions limit the size of the hollow-point in HP auto loading ammunition. There has been significant innovation in controlled expansion, non-fragmenting bullets for handguns to achieve performance goals. Modern handgun ammunition delivers expansion shortly after penetration and high volume of energy transfer over short distances in tissue (40).

Ammotech Action 5 bullet (Figure 2) is one example of technical innovation (40). With this product, a plastic insert is fixed in the copper based hollow-point bullet to maintain appropriate mechanical profile, facilitate automatic loading and ballistic performance in air and act as a wedge interacting with tissue. This missile will pierce many non-fluid barriers and retain the mushroom expansion properties in tissue.

Free bullet killing is widely used in wildlife population management especially in cervid and porcine species. This activity often occurs in urban and suburban areas where noise and stray bullets are public health hazards. Subsonic expanding .30 caliber rifle ammunition has been developed for removing deer and feral swine from urban ecosystems (41). The projectiles in this class of ammunition are heavy (200 gr, 13 g) and are designed to expand at slow speeds of tissue penetration at 268 m/s and muzzle energy of only 600 J. To meet reasonable animal welfare outcomes, there is no margin of error in targeting the heart or brain in deer or feral pig culling using this novel weapon system (41).

The properly operated slaughterhouse captive bolt gun delivers a humane and almost always fatal brain injury and is the standard against which free bullet killing is often compared. Cartridge based captive bolt pistols generate less than 500 J energy much of which is absorbed by the bolt retraction system (42). It requires about 70 J to penetrate the human cranium and

	1	2	3	4	5	6	7	8	9
V_i m/s		248	313	349	395	436	454	498	560
Energy J		187	298	371	474	597	628	755	955

Figure 2. Example of a modern controlled expansion projectile, 9 mm Parabellum, lead free, Action-5 bullet (RUAG Ammotech, Laxenburg, Austria). Vi is velocity at impact. Modern controlled expansion bullets have a velocity operational range wherein they perform as designed. Image 1 is the pre-fired bullet (6.1 g, 94 gr). Projectiles 2 to 9 were accelerated in stepwise increasing velocity (energy) and retrieved from ballistic gelatin. Bullet 3 is subsonic and 4 at 349 m/s is supersonic (at 20°C the speed of sound in air is 343 m/s). Bullets 6 to 8 display good expansion, 1.5 to 1.61 times the 9 mm original diameter. Bullet 9 was accelerated to a speed that exceeded the engineering integrity of the projectile design and the expanding metal was torn away decreasing the wounding potential and increasing risk of over penetration (40).

about 20 additional J to cause death (6). To penetrate the skull of 9 sheep required on average 15.9 J which was similar for red deer; for mature Angus cattle penetration of the skull requited 127 J of kinetic energy (43).

There are several reports of field testing of individual weapon systems without measurement or discussion of terminal ballistics. It is not a technical surprise that a 12 ga shotgun with a 1 oz (28 g, 437.5 gr) slug or 9 Buckshot, combined weight of 28 g with a muzzle energy of 3200 J would be more than sufficient power to kill mature pigs (44).

Baker and Scrimgeour (45) specifically tested and recommended the use of a .223 Remington (5.56 × 45 mm NATO) and a frangible projectile Core-Shot (Buffalo Bullet, Whittier, California, USA) for the killing of cattle from a 25 m distance. This specific projectile is no longer available and manufacturers label information was not reported. Similar currently available target rounds 55 gr, 3000 ft/s have the kinetic energy around 1500 J. Frangible bullets (.22 rimfire) were originally developed for use in arcade shooting galleries, a technical innovation for human safety as the bullet disintegrates on contact with the target. There is no industry standard for frangible bullets. In one study of frangible police training ammunition (Greenshield; Simunition, Repentigny, Quebec), .38 Special and 9-mm handgun projectiles failed to break up and exited pig heads intact creating a wound similar to similar FMJ ammunition (46). High-velocity .223-caliber rifle frangible ammunition, when tested in the same manner, penetrated and fragmented extensively within the cranium, leaving large, permanent wound cavities associated with explosive skull fractures (46).

Frangible projectiles are produced by placing a mixture of metal dust and binding material in a press-mold with or without low heat and squeezing the metal particles into a bullet shape. The compressed dust is then often reinforced with a partial metal jacket. Frangible bullets are intended to have nearly no penetrating power; they return to dust upon hitting a significant resistance and are usually lead-free, as tin and copper dust is commonly used in the projectile. There is limited research available to evaluate the many variants of frangible bullets as an option for animal welfare killing. Testing of this innovation for humane killing may be disappointing as the product line has been developed to be non-lethal.

Technical summary

Penetrating brain injuries (PBI) carry the highest case fatality rate in human trauma medicine exceeding 90% (47). Gunshot is the most common cause of human PBI with only 10% of patients arriving alive at emergency and 50% of those dying in hospital (48). Penetrating brain injury from free bullet incapacitates by causing a temporary cavity resulting in high intracranial pressure and brain tissue shear damage in the respiratory centers in the midbrain and frequent explosive skull fracture. Brain injury from the captive bolt is primarily from tissue crushing along the path of the bolt and targeting the brainstem is essential. In human suicide and homicide with captive bolt there is some evidence that, although temporary cavity formation is not prominent, the "hydraulic burst effect" is sufficient to cause basilar skull fracture (49).

For planning purposes, the energy costs of penetrating the skull of a bovine are between 180 and 250 J, and with an efficient deforming projectile, limiting velocity to deliver 400 to 600 J would minimize the risk of perforating the skull (over penetration). Assuming that distance to the target is 3 to 10 m, the firearm-projectile system required, is an accurate, deforming preferably non-lead bullet with a muzzle velocity delivering around 400 to 600 J at skull impact. Modern hunting rifle calibers at close range deliver several times the energy required for a lethal intra-cranial projectile and present significant nontarget human and animal injury risk of over-penetration.

In perfect placement of the shot, the projectile would penetrate the skull, immediately expand, travel through the brain case, obliterate the midbrain-brainstem and come to rest in the foramen ovale or the foramen of C1 or C2 vertebrae. This would require a carbine or rifle format for accuracy, chambered for a pistol cartridge for controlled energy (Table 1). Rifles chambered for revolver ammunition are available in addition to the readily available .22LR rimfire system.

Ammunition manufacturing is a regulated industry with performance standards and compulsory labelling. Ammunition labels indicate the caliber, muzzle velocity, and weight and style

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of projectile on the original packaging and essential information on the base of each cartridge or shell. In North America the Sporting Arms and Ammunition Manufactures' Institute (SAAMI) is the quality standards organization for manufacturers of ammunition. The standards include a limit on the pressure generated by specific cartridges, the limits of between piece variability, and assurance that the muzzle velocity meets the manufacturer's label. The official velocity variance allowed by SAAMI is ± 90 ft/s (27.4 m/s) on any production run of centerfire small arms ammunition (50) and ± 90 ft/s on any production run of rimfire ammunition.

Discussion

Homo sapiens is the only species of animal to have developed and perfected the super-power of killing at a distance. The scientific understanding and technological advancement of killing with projectiles can be effectively applied to the problem of massive humane killing of infected and surplus animals in disease control actions and humane killing of large fractious species in slaughter situations. Immediately killing animals by careful deposition of fatal intracranial overpressure by free ballistic missile is an extremely complex bio-physical challenge. There is no situation independent best recommendation for choice of a weapon system. We hope that the information provided herein will assist the veterinarians and individuals charged with assuring animal welfare in emergency and disaster situations.

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Answers to Quiz Corner
Les réponses du test éclair

1. **E)** Valvular endocardiosis is an age-related, degenerative change in which there is accumulation of a myxomatous connective tissue matrix within the valve leaflets, causing nodular thickening. The suffix "-osis" implies a degenerative condition; bacterial infection of the heart valves would lead to valvular endocarditis, or inflammation of the valves. Since endocardiosis most commonly affects the atrioventricular valves (and the mitral valve more commonly than the tricuspid), the condition may be associated with a systolic heart murmur.

E) L'endocardiose valvulaire est une dégénérescence associée à l'âge, dans laquelle il y a une accumulation des tissus conjonctifs myxomateux dans les festons des valves, causant un épaississement nodulaire. Le suffixe «ose» implique une affection dégénérative; une infection bactérienne des valves cardiaques causerait une endocardite valvulaire ou une inflammation des valves. Puisque l'endocardiose affecte le plus communément les valves atrioventriculaires (et la valve mitrale plus souvent que la valve tricuspide), l'affection peut être associée à un souffle systolique.

2. **E)** Amlodipine is a calcium channel blocker used to treat systemic hypertension.

E) L'amlodipine est un inhibiteur calcique utilisé pour traiter l'hypertension systémique.

3. **A)** Atrial fibrillation is the only arrhythmia characterized by an irregularly irregular rhythm and no P waves.

A) La fibrillation auriculaire est la seule arythmie caractérisée par un rythme irrégulièrement irrégulier et aucune onde P.

4. **D)** Aversion therapy is usually effective at treating cribbing.

D) Le traitement par aversion est habituellement efficace contre le tic à l'appui.

5. **C)** *Streptococcus agalactiae* is the only contagious pathogen. *Escherichia coli, Klebsiella pneumoniae,* and *Streptococcus uberis* are environmental organisms and concurrent large increases in clinical case incidence rates would be expected. *Staphylococcus chromogenes* is normal flora of cows' teat skin; it is associated with subclinical mastitis but does not behave in a contagious manner.

C) *Streptococcus agalatiae* est le seul agent pathogène contagieux. *Escherichia coli, Klebsiella pneumoniae* et *Streptococcus uberis* sont des organismes de l'environnement et on peut soupçonner une grande augmentation du taux d'incidence des cas cliniques. *Staphylococcus chromogenes* représente la flore normale de la peau des trayons des vaches; cette bactérie est associée à la mammite subclinique, mais elle ne se comporte pas comme un agent pathogène.