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Review

Animal welfare testing for shooting and darting free-ranging wildlife: a review and recommendations

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Abstract. Several important techniques for managing wildlife rely on ballistics (the behaviour of projectiles), including killing techniques (shooting) as well as capture and marking methods (darting). Because all ballistic techniques have the capacity to harm animals, animal welfare is an important consideration. Standardised testing approaches that have allowed refinement for other physical killing and capture methods (e.g. traps for mammals) have not been applied broadly to ballistic methods. At the same time, new technology is becoming available for shooting (e.g. subsonic and lead-free ammunition) and darting (e.g. dye-marker darts). We present several case studies demonstrating (a) how basic ballistic testing can be performed for novel firearms and/or projectiles, (b) the benefits of identifying methods producing undesirable results before operational use, and (c) the welfare risks associated with bypassing testing of a technique before broad-scale application. Following the approach that has been used internationally to test kill-traps, we suggest the following four-step testing process: (1) range and field testing to confirm accuracy and precision, the delivery of appropriate kinetic energy levels and projectile behaviour, (2) post-mortem assessment of ballistic injury in cadavers, (3) small-scale live animal pilot studies with predetermined threshold pass/fail levels, and (4) broad-scale use with reporting of the frequency of adverse animal welfare outcomes. We present this as a practical approach for maintaining and improving animal welfare standards when considering the use of ballistic technology for wildlife management.

Keywords: ethics, fertility control, human dimensions, pest control, population control.

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Introduction

Over the past two decades, the attention devoted to animal welfare in wildlife management has increased markedly (Dubois *et al.* 2017). Methods used to kill and capture wildlife have generally received the most attention but some contexts have received more attention than others (Hampton and Hyndman 2019). For example, animal welfare research into trap designs for fur-bearing wildlife has been undertaken since 1956 (Warburton and Hall 1995). However, there have been far fewer animal welfare studies of wildlife shooting (firing bullets or shot at animals with an intention to kill), with a general exception for studies of wounding/crippling in game birds (Pierce *et al.* 2015). Darting (firing hollow syringes at animals with an intention to inject liquid) is used to capture and mark wildlife and has also been subjected to few animal welfare studies until recently (Jung *et al.* 2019; Latham *et al.* 2020; Hampton *et al.* 2020*a*). Shooting and darting are examples of wildlife management techniques that rely on ballistics, the behaviour of projectiles (Caudell 2013).

Few animal-based studies have been devoted to quantifying animal welfare outcomes for ballistic techniques applied to wildlife. Many management agencies prefer to use procedural documents that specify ballistic inputs that are assumed, but untested, to generate desirable outcomes (Hampton *et al.* 2016*b*). At the same time, new technology is rapidly becoming available for shooting (e.g. subsonic (low velocity) bullets; Caudell *et al.* 2013; and lead-free bullets; Kanstrup *et al.* 2016) and darting (e.g. transmitter darts; Siegal-Willott *et al.* 2009; Hampton *et al.* 2019*a*). There is inconsistency in which newly available ballistic technology is being approved for use in different management agencies and a lack of transparency in what (if any) testing is being applied before approval. However, there are some regulated wildlife shooting contexts in which minimum bullet weights and calibres are stipulated. This approach is rarely applied to darting or the majority of shooting methods, suggesting that a more structured animal welfare testing approach is required.

Not all contexts in which ballistic techniques are applied to wildlife are amenable to politically palatable regulation. For those professional uses that are, regulators may set minimum 'welfare standards' for animal-based welfare outcomes (Reynolds 2004). Such standards offer the advantages of setting an achievable threshold for desirable animal-based outcomes without prescribing approved and non-approved approaches, thus encouraging innovation and improvement (Morriss and Warburton 2014). Animal welfare would be improved greatly if a structured approach (Hampton *et al.* 2016*b*) could be used to assess and approve shooting and darting methods, before they are considered for operational use.

Ballistics broadly comprises four areas of study (Caudell 2013), including internal ballistics (accelerating projectiles inside a gun barrel), intermediate ballistics (projectiles leaving a barrel), exterior ballistics (interactions between projectiles and air) and terminal ballistics (projectiles penetrating or striking a medium denser than air). In the present study, we consider two ballistic methods, darting and shooting. Other wildlife management tools, such as archery (including bow hunting and crossbows; Kilpatrick *et al.* 2004), net guns (Webb *et al.* 2008) and paintball guns (Skalski *et al.* 2005) that also use ballistic technology, will not be discussed here, although some similar principles apply. We restrict our discussion to professional applications of ballistics, including wildlife research and management, and commercial harvesting. Ballistics are also important for recreational, subsistence and traditional hunting; however, in these contexts, animal welfare scrutiny is rarely applied and regulation is more difficult to enforce (Hampton and Hyndman 2019). At the outset, it is important to recognise the role of human factors in the performance of all ballistic methods; this makes any application of animal welfare standards more complex than for other technologies applied in wildlife research. Here, we do not address human factors in shooting and darting, rather we focus on ballistic aspects.

Shooting

Shooting is one of the most universally used wildlife management tools for commercial harvesting, culling of pest and overabundant species, subsistence hunting, recreational hunting, protection from dangerous animals and euthanasia of injured animals (Caudell *et al.* 2009; Bengsen *et al.* 2020). A wide array of firearm types is used for shooting wildlife from centrefire to rimfire rifles, shotguns and pistols. Shooting can be used at point-blank range (e.g. euthanasia of whales; Øen and Knudsen 2007) and extending to ranges of 200 m and greater for hunting (Stokke *et al.* 2019). A variety of anatomical target zones are used for shooting, including the head (Lewis *et al.* 1997), neck (DeNicola *et al.* 2019) and thorax (Aebischer *et al.* 2014). Multiple shot sizes, slugs, chokes and loads are used for shotguns (Pierce *et al.* 2015; Broadway *et al.* 2020). In addition, power sources other than gunpowder are increasingly being used for shooting. Among designs recently applied to wildlife shooting are rifles powered by compressed air and hobby-grade electric spring-powered pistols (Table 1). A broad variety of projectiles also are available from solid to soft-point and hollow-point bullets, lead-based and lead-free ammunition, sintered bullets (made from compressed powdered metal) and specialised ammunition such as rubber bullets and biobullets (Table 1). Here, for simplicity, we focus on rifle bullets used to kill large mammals. Methods used for shotgun pattern testing that consider chokes, loads, shot size and type and the resulting effects on wounding are relatively well described in game bird literature (see Pierce *et al.* 2015).

Table 1. Examples of recently developed technology for wildlife shooting

Application	Species	Country	Source
Subsonic centrefire bullets	White-tailed deer (*Odocoileus virginianus*)	USA	Caudell *et al.* 2013
Subsonic rimfire bullets	Red fox (*Vulpes vulpes*)	Australia	Marks 2010
Lead-free centrefire bullets	Moose (*Alces alces*)	Norway	Stokke *et al.* 2017
Lead-free rimfire bullets	Columbian ground squirrels (*Urocitellus columbianus*)	USA	McTee *et al.* 2017
Sintered bullets	European rabbits (*Oryctolagus cuniculus*)	Australia	Hampton *et al.* 2020*b*
Rubber bullets	Black bear (*Ursus americanus*)	USA	Spencer *et al.* 2007
Biobullets	White-tailed deer (*O. virginianus*)	USA	DeNicola *et al.* 1996
Compressed air rifles	White-tailed deer (*O. virginianus*)	USA	Texas Parks and Wildlife Department 2018
Spring-powered rifles	Brushtail possum (*Trichosurus vulpecula*)	New Zealand	Rouco *et al.* 2015
Electric spring-powered pistols	Brown treesnake (*Boiga irregularis*)	USA	Knox *et al.* 2018

Compared with other commonly used wildlife management tools, there is a recognised lack of professionalism in the way shooting methods are chosen and standardised (Caudell *et al.* 2009). Evidence-based approaches, as used for traps, are rarely applied to the selection and application of shooting methods. Instead, the eminence of people considered to be experts has often guided decisions, and the generic transfer of methods from recreational hunting to professional wildlife-damage management has often occurred (Caudell *et al.* 2009). General principles are well understood for shooting, but most data have been derived from military studies of shooting humans (Caudell 2013). Briefly, bullets produce their effects by crushing, stretching and lacerating surrounding tissue. The extent of these effects depends on bullet sectional density, construction and inertia. Bullets kill in the following two main ways: by causing trauma to the central nervous system causing irreversible unconsciousness (in the case of shots that affect the cranium or cervical spine; Øen and Knudsen 2007) and by causing fatal haemorrhage (usually in the case of shots that affect the thorax; Stokke *et al.* 2018). One knowledge gap is how firearm and bullet configurations influence the outcomes of shooting programs, given the spectrum of species managed and equipment options (Caudell 2013; Hampton *et al.* 2016*a*).

Darting

Darting systems rely on propelling a projectile that is designed to be non-lethal (a dart) with a projector (a dart rifle, pistol, blowpipe or crossbow). Most darting applications are for remote injection of chemical agents over distance (5–50 m) to animals that are too difficult to approach to hand-inject. Most commonly, remote injection is used for chemical immobilisation of large animals (Kreeger and Arnemo 2018). However, darts have also been used to allow remote injection of fertility-control treatments (e.g. immunocontraceptive vaccines; Delsink *et al.* 2007; Rutberg *et al.* 2017; Carey *et al.* 2020), vaccines against infectious diseases (e.g. brucellosis), anthelmintics (worming preparations), antibiotics and biomarkers (e.g. tetracycline; Table 2).

Darts are also used for wildlife management applications other than remote injection of liquids (Table 2). Remote injection darts have been adapted to deliver passive integrated transponder (PIT) tags and fertility-control implants (Table 2). Darts are commercially available that do not facilitate remote injection of liquids, but rather collect tissue or create noise. Biopsy darts have been used for tissue collection to collect skin samples for DNA (Quérouil *et al.* 2010; Beausoleil *et al.* 2016), isotope (Pagano *et al.* 2014) and lipid (Hooker *et al.* 2001) analysis. Products known as 'bear scare darts' (or 'remote animal deterrents') are not really darts because they are not equipped with a needle, but result in a loud explosion on impact, designed to scare animals (e.g. polar bears, *Ursus maritimus*; Calvert *et al.* 1998) away from human infrastructure (Pneu-Dart 2020).

Darting poses animal welfare risks that are often under-recognised by agencies conducting or permitting wildlife operations (Hampton *et al.* 2016*c*). Regardless of the dart type, ballistic injury risk is inherent to all darting. Darts may injure animals in two ways, including the collision between the dart and the animal (Valkenburg *et al.* 1999) and the mechanism of the expulsion of the darts' contents (Cattet *et al.* 2006). For both processes, steps can be taken to improve animal welfare outcomes. For the first mechanism, the aim is to deliver darts with the minimum kinetic energy required to meet the purpose of darting (expulsion of contents, collect tissue, or create noise) and is discussed further below. For the second mechanism, dart designs that minimise the velocity at which liquid contents are ejected, and which have injection ports facing different directions, have been shown to reduce injection-site trauma in darted animals (Cattet *et al.* 2006). Achieving predictable dart weight through filling with precise volumes of solution has been shown to be critical to precise dart placement (Dematteis *et al.* 2009).

Animal welfare testing

Standardised animal welfare testing approaches that have refined other physical killing and capture methods, notably trapping (Proulx *et al.* 2020), have rarely been applied to ballistic methods. Adoption of a standardised testing approach would likely improve the animal welfare outcomes and transparency of shooting and darting and would assist research ethics and use committees in determining which techniques and equipment to allow or oppose.

Human factors

Trapping is a useful template for considering animal welfare testing of ballistic techniques, but has some important limitations. A crucial difference between trapping and shooting is that

Table 2. Examples of applications of darts for managing wildlife species

Application	Species	Country	Source
Chemical immobilisation	Moose (*Alces alces*)	Norway	Arnemo *et al.* 2006
Chemical immobilisation and telemetry	Red deer (*Cervus elaphus*)	Australia	Amos *et al.* 2014
Fertility control vaccination	Eastern grey kangaroo (*Macropus giganteus*)	Australia	Wimpenny and Hinds 2018
Fertility control implants	White-tailed deer (*Odocoileus virginianus*)	USA	DeNicola *et al.* 1997
Infectious disease vaccination	American bison (*Bison bison*)	USA	Olsen and Johnson 2012
Antibiotic injection	Humpback whale (*Megaptera novaeangliae*)	USA	Gulland *et al.* 2008
Anthelmintic injection	Bighorn sheep (*Ovis canadensis*)	USA	Pederson 1984
Biomarker injection	Polar bear (*Ursus arctos*)	USA	Taylor and Lee 1994
PIT tag administration	Elk (*C. elaphus*)	USA	Walter *et al.* 2012
Dye marking	Elk (*C. elaphus*)	USA	Aune *et al.* 2002
Biopsy collection	Cougar (*Puma concolor*)	USA	Beausoleil *et al.* 2016
Remote animal deterrents ('scare' darts)	Polar bear (*U. arctos*)	Canada	Calvert *et al.* 1998

traps and animals interact, with a relatively minor (but not negligible; see Hadidian *et al.* 2016) influence of human factors, whereas for ballistic methods, human factors are profound because shooter proficiency is involved (Aebischer *et al.* 2014). In few exceptions, humans are not involved in firing ballistic devices, such as using a remote-controlled automated blowpipe system for the capture of Eurasian lynx (*Lynx lynx*; Ryser *et al.* 2005). In all other cases, technology can be tested; however, ultimately the skills and decisions of the shooter will have a profound influence on animal welfare outcomes (Hampton *et al.* 2014). This limitation does not preclude the application of animal welfare testing to ballistics, and the skills of human operators can also be tested through quantification of parameters such as accuracy.

Accuracy and precision

Technically, the following two parallel and independent terms are normally used to describe the process of reliably striking a target: accuracy, measuring how closely a projectile strikes relative to the centre of a preferred target, and precision, measuring the closeness of shots to each other (even if this is not in the preferred target). Accuracy and precision are of fundamental importance to all ballistic methods, because the ability to accurately place a shot may influence animal welfare outcomes more than does any other variable (McCann *et al.* 2016; Kreeger and Arnemo 2018). Precision of shooting and darting methods can be evaluated by the size of shot groupings on a shooting range relative to the size of targeted anatomical zones in the target animals (DeNicola *et al.* 2019). Generally speaking, when comparing bullets to darts, precision is directly related to projectile velocity and inversely related to projectile size. As such, much higher levels of precision can be achieved with shooting than darting. This is also influenced by differences in exterior ballistics, whereby bullets are gyroscopically stabilised in air (Caudell *et al.* 2012), whereas darts are stabilised by posterior drag and anterior centre of gravity. Accuracy and precision are also profoundly affected by the stability of the shooting platform and position. As such, much higher levels of shooting accuracy and precision are achievable from stationary ground vehicles (Lewis *et al.* 1997; Hampton and Forsyth 2016) than from helicopters (Hampton *et al.* 2014) or moving boats (Daoust and Caraguel 2012).

Testing at a shooting range can be used to measure accuracy and precision with a given firearm–projectile combination at a given shooting distance, and with a given shooting position. It can also be used to assess the proficiency of individual shooters in meeting desirable standards. For example, McCann *et al.* (2016) described competence testing required for volunteer shooters before field work in an elk (*Cervus elaphus*)-culling program. Shooters were required to score three of five shots within a 200 mm diameter circle (considered to represent the size of the thoracic target area of an elk) at 183 m (220 yards; chosen to represent a realistic shooting distance for stalkers) to qualify for involvement in the program. Similar competence tests are required for head shooting of kangaroos (*Macropus* and *Osphranter* spp.) for commercial harvesters in Australia (Commonwealth of Australia 2008). Standards of accuracy and precision are usually determined on the basis of shot placement objectives (i.e. head, neck or chest shooting), anticipated engagement distances and shooting position (prone is most stable, followed by kneeling or sitting, and freehand; Aebischer *et al.* 2014). If a shooter is incapable of consistently achieving shot groupings smaller than the anatomical target size with a firearm–projectile combination at a realistic shooting distance, targeting live animals in that manner is inadvisable (Kreeger and Arnemo 2018). These considerations pertain to shooting much more than darting.

Kinetic energy

Kinetic energy (E_K) is an important determinant of the capacity of a projectile to kill or injure an animal (Blackmore 1985; Hampton *et al.* 2016*a*). The E_K delivered is of critical importance for the capacity of physical euthanasia and killing methods to induce immediate insensibility (when the cranium or central nervous system is shot). This has been demonstrated for kill-traps (Warburton and Hall 1995), captive bolt euthanasia devices (Blackmore 1985), euthanasia of livestock by shooting (Thomson *et al.* 2013) and marine mammal shooting (Daoust and Cattet 2004; Øen and Knudsen 2007; Mörner *et al.* 2013). Projectile energy is also an important determinant of the outcomes of wildlife darting (Valkenburg *et al.* 1999; Cattet *et al.* 2006), because the E_K transferred from the dart to the animal is an important wounding mechanism, leading to injuries such as penetration of body cavities and broken bones (Tribe *et al.* 2014; Colgan *et al.* 2019).

The equation for calculating E_K is:

$$E_K = \frac{1}{2}mv^2$$

where E_K is measured in joules (J), m is mass (kg) and v is velocity (m s^{-1}; Thomson *et al.* 2013; Hampton *et al.* 2016*a*; Kreeger and Arnemo 2018). Hence, the velocity and mass of the projectile (bullet or dart) are the two variables that determine E_K delivery. An important point is that the E_K when the projectile leaves the firearm ('muzzle energy' when distance is zero) will differ from the E_K when the projectile strikes the animal (terminal or impact energy), such that the longer the shooting distance, the lower the E_K at impact. Another important point is the *relative* transfer of E_K to target tissue. A projectile that passes through an animal with much of its E_K remaining is far different from one that is frangible or malleable and transfers all (or most) of its E_K (McTee *et al.* 2017).

The aim of shooting is to maximise E_K transferred to sensitive anatomical structures of target animals (e.g. brain, thorax) to minimise the likelihood of animals remaining alive, sensible and mobile, and thereby escaping and enduring unnecessary suffering. Many regulated shooting practices specify minimum E_K levels (e.g. >980 J @ 100 m for Eurasian beaver (*Castor fibre*) hunting; Parker *et al.* 2006). There is evidence that firearm-bullet configurations that deliver inadequate E_K result in elevated frequencies of non-fatal wounding and non-immediate insensibility (Caudell *et al.* 2013; Hampton *et al.* 2016*a*). Any chosen cartridge type for shooting will have a fixed E_K at the muzzle, regardless of the distance to the target, whereas muzzle E_K levels for darts are adjusted on the basis of the estimated distance to the target and dart size (Kreeger and Arnemo 2018).

For darting, the aim is to minimise E_K while still having sufficient E_K to penetrate tissue and deliver the payload (Valkenburg *et al.* 1999), because excessively high E_K levels can lead to broken bones (Tribe *et al.* 2014; Colgan *et al.* 2019), penetration of the thorax or abdomen (Tsuruga *et al.* 1999), excessive tissue trauma (Cattet *et al.* 2006) or deep wounds that predispose animals to subcutaneous infections. There also are case reports of fatal (Barnes and Rogers 1980) and non-fatal but debilitating (Tobias *et al.* 1996) infections in animals secondary to darting. Some darting practices specify maximum E_K levels, e.g. ≤12 J for eastern grey kangaroos (*Macropus giganteus*; Wimpenny and Hinds 2018). However, a low E_K level may result in desirable wound ballistics but not allow sufficient accuracy. Hence, a delicate balancing act is required for darting, such that the E_K level allows desired accuracy and results in dart discharge, but does not cause extensive ballistic injury.

Projectile behaviour

The behaviour of projectiles (bullets or darts) once they impact on animal tissue is described as terminal or wound ballistics (Caudell 2013). Aside from intended shot placement, the accuracy of a shot, and the E_K it strikes an animal with, the design of projectiles will determine the extent of injuries caused. Bullets are designed to maximise the ballistic injury they create, whereas darts are designed to minimise it. Several projectile variables in shooting influence animal welfare outcomes, including bullet material, design and yaw (Caudell 2013). Traditional lead-based bullets used for wildlife shooting typically fragment to maximise the size of the temporal cavity they create, whereas most lead-free bullets achieve similar results through deforming (mushrooming) rather than fragmenting (Stokke *et al.* 2017), noting that some newer lead-free bullets are designed to fragment (Thomas *et al.* 2016; Hampton *et al*. 2021). Bullet behaviour (including fragmentation) can be more important than E_K for determining animal welfare outcomes in many contexts. For example, bullets with a low E_K that fragment rapidly deliver superior outcomes for thorax shooting of red foxes (*Vulpes vulpes*) compared with solid bullets with a higher E_K that pass-through animals without fragmenting and with much of their E_K intact (M. Kraabøl, unpubl. data).

Darts can cause undesirable impact injuries via the mechanism through which their contents are expelled as well as the E_K they deliver (Cattet *et al.* 2006). The extent of this trauma is affected by the velocity with which liquid is ejected, and the direction in which it is ejected (Cattet *et al.* 2006). For both bullets and darts, cadaver tests (Daoust and Cattet 2004; Knox *et al.* 2018) and tissue simulants such as ballistic gel (ordnance gelatin; Cattet *et al.* 2006; Knox *et al.* 2018) or ballistic soap (Gremse *et al.* 2014) can be used to assess projectile behaviour.

Case studies

We present three case studies to argue that a structured testing approach is required for assessing ballistic technologies to establish the most appropriate conditions before full-scale management application, show how methods posing a high risk of adverse animal welfare impacts can be identified, and demonstrate undesirable outcomes of not following this evaluation methodology.

Inanimate target testing of shooting methods

The New South Wales National Parks and Wildlife Service (NSW NPWS) in Australia has developed a standardised process for non-animal ballistic testing for any previously unused shooting methods (Hampton *et al*. 2021). The process consists of conducting extensive trials on a shooting range before commencing testing on animals. Once a firearm–projectile combination has achieved desired benchmarks (i.e. accuracy, E_K and projectile fragmentation/deformation) in shooting-range tests, animal-based trials are commenced, beginning with cadaver trials and progressing to live animal testing. The animal-based portion of the assessment process will not be described in detail here. The research (conducted by GE, RH, and others) did not use live animals so did not require animal ethics approval.

The NSW NPWS testing process has been used to assess firearm–projectile combinations for several shooting applications. These have included helicopter shooting of feral goats (*Capra hircus*) and wild pigs/boar (*Sus scrofa*), and use of subsonic ammunition for night-time shooting of peri-urban fallow deer (*Dama dama*), rusa deer (*Rusa timorensis*) and feral goats. In addition, noise testing has been performed for shooting methods using suppressors that are designed for urban environments (Williams *et al.* 2018). For any shooting application that has not previously been assessed, a range of potentially suitable projectile types are first chosen on the basis of manufacturer data relating to velocity, mass and projectile behaviour (fragmentation, deformation). Range tests are then performed to estimate the accuracy and E_K at realistic shooting distances (25 m for helicopter shooting simulation and 100 m for ground shooting). This process involves using a chronograph set close to the shooter (Fig. 1*a*) to measure bullet velocity and, hence, calculate muzzle E_K, and using shot grouping patterns used to assess achievable accuracy (Fig. 1*b*).

Ballistic gel tests are used to assess projectile behaviour in target animals and estimate the magnitude of variables such as temporal cavity size, distance before temporal cavity expansion, and penetration depth of the bullet (Fig. 1*c*; Caudell 2013). Associated with these parameters are the degree of fragmentation (and hence weight loss) and deformation (Fig. 1*d*) of bullets, and relative E_K transfer to the tissue. Ballistic gel tests are used to compare any proposed projectiles with projectiles currently in use as a benchmark testing process. Proposed projectiles are shot into gel blocks on the same day as currently used projectiles, and the outcomes are assessed to eliminate the influence of variables such as gel consistency and air temperature that may confound these comparisons. Outcomes of range testing are regarded as 'go/no-go' points, such that only bullets that achieve desired benchmarks of accuracy, E_K, and terminal ballistics are approved for animal-based trials.

Subsonic ammunition for 0.308 Winchester® rifles has been assessed for the shooting of kangaroos, feral goats and fallow deer in peri-urban situations where shooting noise and disturbance to local residents are of concern (see Hampton and Forsyth 2016). Accuracy and ballistic gel testing of subsonic bullets in 0.308 Winchester® calibre (described in Caudell *et al.* 2012) led to the adoption of 50 m as a maximum shooting distance for that configuration and the mandatory use of a digital laser range finder to ensure that shooters could accurately allow for the effect of shooting distance when using low-velocity projectiles.

Fig. 1. Shooting range methods used for testing new ballistic technology before beginning animal-based trials, eastern Australia, 2018. (*a*) Use of a chronograph to measure projectile velocity, (*b*) assessment of precision through shot grouping, (*c*) use of tissue simulant gel to assess terminal ballistics patterns, and (*d*) examination of bullet weight retention and deformation.

Fertility-control darting of eastern grey kangaroos

In 2015, a trial commenced to develop and test remote delivery of a fertility-control agent for peri-urban eastern grey kangaroos in south-eastern Australia (Wimpenny and Hinds 2018). The trial aimed to administer the GnRH (gonadotropin-releasing hormone) vaccine, GonaCon Immunocontraceptive Vaccine, to female kangaroos via darting. Three potential obstacles were identified. First, GonaCon is a viscous emulsion, making efficacious delivery by remote injection uncertain (Evans *et al.* 2015; McCann *et al.* 2017). Second, treated kangaroos needed to be visually identified to minimise the risk of animals being re-treated or left untreated. Third, there was concern about the potential for injuries arising from either the explosive injection of the viscous vaccine (Cattet *et al.* 2006) or ballistic injury as a result of excessive E_K if darts heavier than the standard 1cc (1.0 mL) remote-injection darts were used for eastern grey kangaroos (Wimpenny and Hinds 2018). The research was conducted by CW, RB, DF, LH, TP and others under University of Canberra AEC licences CEAE 14-14 and CEAE 16-16.

A three-stage testing process was used for the trial. First, benchtop tests were performed for dart E_K at realistic shooting distances (15–35 m) by using a chronograph set close to the target to measure dart velocity and, hence, calculate E_K delivered to the target animal. Chronographs have been previously used in similar ways to assess dart velocity, but past studies have measured muzzle velocity, not velocity at the target (see Valkenburg *et al.* 1999). Second, a small-scale pilot study assessed wound patterns caused by dart vaccination compared with chemical immobilisation darting in kangaroos euthanased at three time periods after darting. Third, a small-scale field trial assessed the longer-term animal welfare outcomes for wild kangaroos fitted with identification collars. Each of these steps was treated as a 'go/no-go' point, such that a decision to continue the trial or not was made at the end of each step. The testing process was terminated if the modified darting protocol created adverse outcomes (low precision and high E_K) that failed to meet pre-determined thresholds and, hence, were deemed likely to cause undesirable animal welfare impacts.

Various dart types were tested on a shooting range in stage one, including injection-marker darts and standard 1cc remote-injection darts. The threshold level of E_K chosen for a darting configuration to proceed to the second stage of the trial was ~12 J, on the basis of the recommendations of Friedrich (1998) and prior experience with kangaroos dissected following darting (Wimpenny and Hinds 2018). It should be noted that this E_K threshold may be regarded as conservative. Higher E_K thresholds have been used for ungulate species with thicker skin and more robust anatomy. For example, a threshold of 20 J has been used for white-tailed deer (A. DeNicola, unpubl. data). PneuDart® (PneuDart Inc., Williamsport, PA, USA) injection-marker darts that spray the animal's fur with visually identifiable paint, as well as injecting their contents into the animal (Delsink *et al.* 2007), were tested. However, injection-marker darts are larger and heavier (15.6 g when filled with 1.0 mL of GonaCon-like emulsion and 1.0 mL of marking paint) than standard 1cc remote-injection darts (7.5 g when filled with 1.0 mL of

GonaCon-like emulsion), which were also tested. Chronograph results showed that sufficient shot precision could not be achieved at realistic darting distances unless darts struck the target with an E_K of >12 J (dart velocity >40 m s^{-1}). This result was regarded as a 'no-go' point and injection-marker darts did not progress any further in the trial. The standard 1cc PneuDart® darts were shown to be capable of injecting viscous GonaCon into the muscle of kangaroo carcasses while staying below the E_K threshold, so were selected for further testing and proceeded to the second stage.

For the second stage of the trial, kangaroos treated with both 1cc GonaCon darts and 1cc darts filled with the chemical immobilisation combination Zoletil™ (tiletamine–zolazepam) were euthanased after darting (Fig. 2*a*) to evaluate ballistic injury and the spread of GonaCon in live tissue. The priority for stage two was assessing the extent of pathology at the GonaCon injection site (Powers *et al.* 2014) and it was decided that a marker system could be devised later if it was found that GonaCon could be injected effectively and safely into live tissue via darting. Hence, a marking method was not evaluated at this stage of the trial. Post-mortem examination of dart wounds at 5, 30 and 120 days post-darting demonstrated that the ballistic injury caused by dart vaccination with a standard 1cc dart (Fig. 2*b*) was comparable to darting with Zoletil™, so the trial progressed to the third stage, which assessed long-term immunocontraceptive effects rather than impacts related to ballistics (Wimpenny and Hinds 2018). We acknowledge that euthanasia of animals to examine ballistic injury from darting would be unlikely to receive public support for species not considered invasive or over-abundant, especially threatened or locally depleted species, which are the subject of many darting projects.

Shooting of adult harp seals

The harvesting of harp seals (*Pagophilus groenlandicus*) in Atlantic Canada is one of the oldest and most contentious commercial wildlife harvesting industries in the world. Harvesting operations have traditionally focussed on newborn and, subsequently, juvenile seals. However, in recent years, the industry has declined considerably, and faced with limited market access, remaining commercial harvesters have begun to explore new markets and alternative harvesting approaches. In 2016, some harvesting operations targeted adult rather than juvenile seals, and used shooting (Fig. 3*a*) rather than blunt trauma from a club or a hakapik. An independent observer (JOH) collected animal-welfare data from a 2016 harvesting voyage in Atlantic Canada. The research was conducted by JOH under Canada Department of Fisheries and Oceans experimental licence NL-3226-16.

The observer collected data from 96 seals that were shot at from a single sealing vessel using 0.223 Remington® calibre rifles, fitted with variable 3–9 × 40 telescopic sights, firing 50 grain hollow-point or 62 grain soft-point ammunition (delivering muzzle E_K levels of ~1700 J). Seals were shot from a moving boat at distances ranging from 15 to 200 m (mean 110 m; Fig. 3*a*). The frequency of various animal welfare outcomes is presented in Table 3 as per past assessments of shooting methods (Hampton and Forsyth 2016). Of note is the frequency of seals being 'struck-and-lost' (Sjare and Stenson 2002) of 21% (Fig. 3*b*). This parameter is an example of an adverse animal-welfare event (Hampton *et al.* 2019*b*). Struck-and-lost is a term used for marine mammals and is not analogous to non-fatal wounding as the fate of animals that are struck and disappear below the water is unknown (Sjare and Stenson 2002).

Post-mortem data showed that 73% of killed seals (35 of 48 seals) were shot in the cranium, the intended target. These results suggest that accuracy levels achievable under field conditions, with the projectiles used, were not sufficient to induce immediate insensibility in a majority of animals, when struck-and-lost seals were included. These outcomes were likely to be influenced by a low level of accuracy as well as a low E_K relative to achievable accuracy. Shooter decision-making was also influential; for example, if shooting had been restricted to shorter distances, outcomes would almost certainly have been improved.

Before operational use of adult seal shooting, to our knowledge, no research trials (benchtop, post-mortem or pilot studies) were undertaken to determine the effectiveness of different firearm-bullet configurations at different distances for rendering adult seals immediately insensible. Such trials have been performed for juvenile seals (Daoust and Cattet 2004; Daoust *et al.* 2013) and have been associated with desirable animal welfare outcomes (absence of struck-and-lost seals and a high frequency of immediate insensibility; Daoust and Caraguel 2012). The lack of ballistic trials before the operational use of adult seal shooting is likely to have contributed to the poor animal welfare outcomes

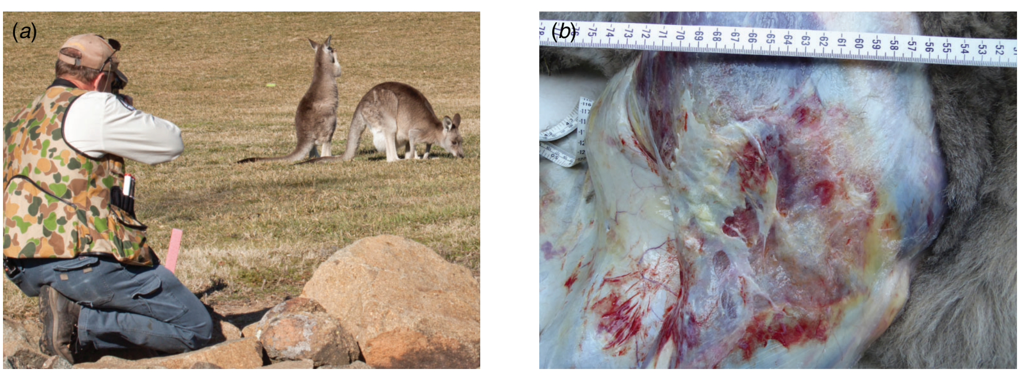

Fig. 2. Darting of adult eastern grey kangaroos (*Macropus giganteus*) for fertility control, south-eastern Australia, 2015. (*a*) A dart fired at the rump of a habituated kangaroo and (*b*) post-mortem assessment of ballistic pathology from dart impact and remote injection 5 days post-darting.

Fig. 3. Boat-based shooting practices used to harvest adult harp seals (*Pagophilus groenlandicus*) in pack ice in Atlantic Canada, 2016. (*a*, *b*) Arrows indicate the position of targeted seals and extended shooting distances, (*c*) a conscious seal having been shot in the neck (arrow) and remaining conscious and mobile and (*d*) an arrow indicates the typical blood trail evidence of a struck-and-lost seal.

Table 3. Summary of animal welfare data collected during boat-based shooting at 96 adult harp seals (*Pagophilus groenlandicus*) in Atlantic Canada, March 2016

95% CIs were estimated using the Clopper–Pearson exact method as per Hampton *et al.* (2019*b*)

Category	Frequency (95% CI)
Shot at	–
Escaping unwounded	0.22 (0.14–0.31)
Hit	0.78 (0.69–0.86)
Hit and killed	0.50 (0.40–0.60)
Hit and rendered immediately insensible	0.30 (0.21–0.99)
Hit and killed after wounding	0.20 (0.12–0.29)
Struck-and-lost	0.21 (0.13–0.30)

observed. It is questionable whether the required level of precision to consistently shoot the head of a seal could be achieved by shooting from a moving boat over ~110 m. It is notable that other sealing nations have developed ballistic requirements for adult harp seal shooting, namely Norway, requiring minimum impact E_K levels of 2200 J (Norwegian Scientific Committee for Food Safety 2007). Although the E_K levels of the shooting method, and all other procedures observed, met the requirements of the *Marine Mammal Regulations of the Fisheries Act of Canada* (Anonymous 2018), compliance with procedural documents clearly did not guarantee favourable animal welfare outcomes (Hampton *et al.* 2016*b*).

Lessons from case studies

The first case study (shooting-range testing) demonstrated a thorough pre-animal testing protocol for shooting methods. We presented the second case study (kangaroo darting) as an example of integrating benchtop and animal testing before operational use of a new technology. It is likely that the kangaroo program avoided poor operational animal welfare outcomes by abandoning operational plans after negative benchtop and cadaver testing. We believe this represents an ideal 'how to' case study for wildlife management agencies. The approach is similar to methodical testing procedures used recently for administering PIT tags via remote injection (Walter *et al.* 2012) and electric spring-powered pistols for killing of snakes (Knox *et al.* 2018; Table 1). However, the third case study (harp seals) demonstrated undesirable animal welfare outcomes from an operational activity in the absence of methodical consideration of ballistics and we suggest that it represents a 'how not to' example for unfamiliar ballistic applications. In this particular instance, the failure of the harp seal harvesting program to perform prior benchtop or cadaver testing is likely to have resulted in poor animal welfare outcomes and poor efficiency during operations.

A template for refinement: international kill-trap testing

It is evident that refinement is required for the way in which newly developed ballistic technology is tested and the way in which new applications for existing ballistic technology are applied in wildlife management. In general, evidence-based approaches have been neglected in favour of tradition and eminence-based recommendations. This approach has precluded the quantitative assessment of shooting methods and refinement of practices (Hampton *et al.* 2016*b*). Refinement can easily be achieved through the use of animal-based measures to validate existing management methods and assess newly developed, and potentially superior, methods (Morriss and Warburton 2014).

We suggest that the example of international kill-trap testing shows how transparent communication of testing results can lead to effective regulation of newly developed technology. Trap research provides a useful template for such testing and has followed a science-based ethic (Warburton and Norton 2009), ensuring that critical animal welfare parameters are quantified and that assessment is performed independently (i.e. not by trap manufacturers; Warburton and Orchard 1996). International welfare standards were developed for testing traps (International Organisation for Standardisation 1999) and these were adapted to set achievable thresholds for welfare performance (e.g. animals caught in lethal traps should be rendered permanently insensible in <3 min; Warburton *et al.* 2000; Morriss and Warburton 2014). Adoption of these standards led to international agreements among trapping countries (Harrop 1998).

Trapping assessment protocols exemplify the most refined use of a standardised testing approach for wildlife management applications, whereby new designs are approved or rejected for widespread use on the basis of quantified animal-based measures. For lethal (kill) traps, a useful metric is the proportion of animals rendered insensible within a specified duration (Warburton and Orchard 1996; Iossa *et al.* 2007). For non-lethal traps, a useful metric is the proportion of animals displaying injuries (Fleming *et al.* 1998; Byrne *et al.* 2015). Before animal-based testing is used, standardised trap testing generally relies on initial benchtop testing to ensure that newly developed technology can achieve desirable physical benchmarks associated with required animal-welfare outcomes. For example, strike location accuracy and clamping force are used as physical metrics to assess the suitability of newly developed kill traps (Warburton and Hall 1995; Warburton and Orchard 1996). Shot accuracy is an important determinant of animal welfare outcomes for ballistic methods in a similar way to strike location (Aebischer *et al.* 2014), and transfer of E_K may be a suitable physical measure in a similar way to clamping force (Warburton and Hall 1995). We suggest that shooting methods that deliver accuracy or E_K levels markedly below those of existing effective methods should not generally progress to live animal trials because of the high likelihood of undesirable animal welfare outcomes.

Operator effects are complicating factors when attempting to apply the testing approach used for traps to methods using shooting or darting. The concept of setting standards for traps assumes that the defining properties of the method are invested in the trap hardware. In reality, operator skills may be at least as important as the hardware itself (Reynolds 2004); these effects are greater for darting and shooting, and require considerable operator skill, experience, dexterity and reading of animal behaviour (Aebischer *et al.* 2014; Hampton *et al.* 2014). We contend that the ability to predict animal behaviour is particularly important for darting, and it varies widely even among similar species, or the same species in different contexts. Because darts travel with a low velocity, animals may move a considerable distance between when a dart is fired and when it strikes the animal (R. Barnsley, unpubl. data). Nonetheless, from the current position of no standardised animal welfare testing for ballistic technology, the trap-testing system can be cautiously applied to ballistic technology, provided operator effects are acknowledged and allowed for. Ballistic methods involve the obvious complication that test results will reflect a combination of technology selection and operator skill to determine whether a method is acceptable.

A four-step testing process

Following the approach that has been used internationally to test kill-traps, we suggest the following four-step testing process for newly developed or newly applied ballistic technology: (1) bench-top and range testing focusing on accuracy, the delivery of E_K levels, and projectile behaviour with testing of equipment and personnel under field conditions (Aebischer *et al.* 2014), rather than only on the range; (2) post-mortem assessment of ballistic injury in cadavers, including consideration of exit wounds for shooting methods; (3) small-scale pilot studies with predetermined threshold pass/fail levels; and (4) broad-scale use with the reporting of key adverse outcomes (e.g. 2% non-fatal wounding; McCann *et al.* 2016). An example of applying such a testing process was demonstrated by the recent study of Hampton *et al.* (2020*b*). We contend that precision assessments should be conducted using applied shooting techniques to simulate realistic field conditions, in addition to shooting range testing (Aebischer *et al.* 2014).

We suggest that there is an important relationship between accuracy and required E_K for shooting methods. Accurate shooting methods may achieve high animal welfare outcomes with low E_K levels (e.g. kangaroo culling), whereas inaccurate methods require high E_K levels to achieve comparable outcomes. For animal welfare outcomes to be improved for adult harp seal shooting, E_K levels should be increased and steps taken to increase shooting accuracy (e.g. setting a maximum shooting distance <100 m). The E_K levels used for boat-based adult harp seal shooting were less than half of those used for helicopter shooting of wild pigs/boar (~3300 J; Hampton *et al*. 2021), an animal of similar size also shot from moving platforms. This may be influenced by a difference in intended shot placement, with thoracic shots used for wild pigs compared with cranial shots for seals. Wild pigs are also shot-to-waste from helicopters (Parkes *et al.* 2010), whereas adult harp seals are harvested for meat and blubber, influencing how much ballistic trauma is desirable, but there must be a trade-off between animal welfare and harvesting of meat and other animal products for consumptive shooting practices (Hampton *et al.* 2016*a*).

Setting welfare standards

Setting threshold levels for animal-based welfare measures that are considered to be desirable or acceptable is an approach known as the adoption of welfare standards (Warburton and Hall 1995). This process is required for step three of our proposed testing protocol. Appropriate animal welfare measures that may be used to set standards include the frequency of non-fatal wounding (Aebischer *et al.* 2014), the frequency of immediate insensibility (head shooting; Hampton and Forsyth 2016), the frequency of exit wounds or the average flight distance (thorax shooting; Stokke *et al.* 2018). However, the designation of binary acceptable/unacceptable levels in these continuously distributed outcomes is inherently subjective because it requires value judgements on what ought to be achieved, leading to disagreement among people with different values (Warburton *et al.* 2008). For example, one person may consider it acceptable that a shooting method is capable of rendering 75% of test animals immediately insensible, whereas another may consider 95% to be their desired level. This can be resolved only through consulting with a range of stakeholders and compromising to reach agreement on outcomes that are likely to be an improvement on the current situation but achievable under field conditions (Iossa *et al.* 2007).

Future studies

The approach presented here could be applied to many other contexts by future researchers. Our focus has been on newly developed techniques used in professional wildlife management, but a similar approach could be used for other uses, including non-professional activities such as recreational hunting, and traditional ballistic methods. We make this recommendation bearing in mind that animal welfare expectations are under constant change and societal benchmarks for what is acceptable are not fixed.

We encourage proactive and transparent animal welfare testing of all newly developed ballistic techniques before they are approved for operational use in wildlife populations. The information produced would be beneficial for management activities as well as research. Animal ethics or use committees are tasked with assessing research proposals related to capture and killing of wildlife but are presently often operating in a knowledge vacuum. Moreover, it is essential that wildlife management operations demonstrate high animal welfare standards with the use of new and existing technology to ensure that social licence (Hampton and Teh-White 2019) for culling, harvesting and capture programs is not eroded.

Conflicts of interest

The authors declare no conflicts of interest.

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