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Assessment of Lead-Free .22 LR Bullets for Shooting European Rabbits

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ABSTRACT In response to health threats posed by toxic lead to humans and scavenging wildlife, there is currently a focus on transitioning from lead-based to lead-free bullets for shooting (harvesting, culling, or recreational hunting) of wild animals. However, the efficacy of lead-free bullets for shooting small mammals has seldom been evaluated. We compared the animal welfare outcomes and costs of using lead-based and lead-free bullets in the world's most popular cartridge, the rimfire .22 LR, for shooting wild European rabbits (*Oryctolagus cuniculus*) in Australia, during August 2019. Ballistic testing revealed that lead-free bullets were less precise than one type of commonly used lead-based bullet when shot from one rifle. We shot at 53 and 115 rabbits with lead-based and lead-free bullets, respectively. A substantially lower percentage of rabbits that were hit were wounded (2%) with lead-based bullets compared with lead-free bullets (20%). Hence, fewer shots were needed to kill rabbits with lead-based (1.27) than lead-free (3.98) bullets. Radiographic examination of 28 rabbits shot with lead-based bullets and 27 rabbits shot with lead-free bullets revealed metallic fragments present in 82% and 41% of carcasses, respectively. In 52% of rabbits shot with lead-free bullets, there was no radiographic evidence of bullets or fragments, indicating pass-through shots. The greater cost per bullet and larger number of bullets required to kill a rabbit meant that using lead-free bullets cost 6 times more per rabbit killed than using lead-based bullets. The only commercially available lead-free .22 LR bullets in Australia at the time of our study produced substantially poorer animal welfare outcomes, and were more expensive per killed rabbit, than lead-based bullets. Lead-free bullets designed to reduce lead exposure to scavenging wildlife and humans and should be assessed in terms of animal welfare outcomes and costs prior to being considered for widespread use.

KEY WORDS animal welfare, Australia, culling, European rabbit, harvesting, hunting regulation, scavenging, shooting, toxicology.

In response to the health threats posed by toxic lead to humans and scavenging wildlife, there is currently a focus on transitioning from lead-based to lead-free bullets for shooting (i.e., harvesting, culling, recreational hunting) of wild animals (Martin et al. 2017, Arnemo et al. 2019, Newth et al. 2019, Schulz et al. 2019, Thomas et al. 2019). Recently, attention devoted to animal welfare in wildlife management has increased markedly, including for shooting methods (Hampton et al. 2016, Stokke et al. 2018, DeNicola et al. 2019). Animal welfare concerns have impeded the adoption of lead-free bullets (Caudell et al. 2012). Consequently, there is a requirement for evidence-based assessment of animal welfare effects (i.e., frequency of adverse events such as nonfatal wounding) for new lead-free bullet technology (Caudell et al. 2012, Trinogga et al. 2013, Stokke et al. 2019).

Several studies have evaluated the efficacy and animal welfare implications of using lead-free bullets for recreational hunting of large ungulates such as roe deer (*Capreolus capreolus*) in the United Kingdom (Knott et al. 2009) and Scandinavia (Kanstrup et al. 2016), elk (*Cervus elaphus*/*canadensis*) in the United States (McCann et al. 2016), and moose (*Alces alces*) in Scandinavia (Stokke et al. 2017). These studies have reported no significant differences in animal welfare outcomes from lead-based and lead-free bullets, although the methods used to quantify those outcomes have varied. The majority of the aforementioned studies have assessed centerfire cartridges in calibers >0.270 (6.5 mm). Less attention has focused on the use of small calibers for the shooting of small mammals (Pauli and Buskirk 2007).

Rimfire cartridges have traditionally been used to shoot small mammals (<10 kg body mass) such as European rabbit (*Oryctolagus cuniculus;* Hampton et al.

2015), red fox (*Vulpes vulpes;* Marks 2010), and several squirrel species, including Belding's ground squirrels (*Urocitellus beldingi;* Herring et al. 2016) and Columbian ground squirrels (*Urocitellus columbianus;* McTee et al. 2017). The 3 most common contemporary rimfire cartridges are .22 LR (.22 long rifle), .22 WMR (.22 Winchester® Magnum Rimfire; Winchester, New Haven, CT, USA), and .17 HMR (.17 Hornady® Magnum Rimfire; Hornady, Grand Island, NE, USA). Rimfire cartridges have a maximum caliber of 0.22 of 1 inch (5.6 mm) and are typically less expensive and less powerful than centerfire cartridges (Hampton et al. 2016). Surprisingly, no published study has assessed the efficacy of lead-free bullets for shooting small mammals in the world's most popular rimfire cartridge, the .22 LR (Manzalini et al. 2019). Although McTee et al. (2017) assessed lead-free rimfire bullets for shooting Columbian ground squirrels, they could not examine the performance of .22 LR because of the unavailability of lead-free bullets. We report a comparison of lead-based and lead-free .22 LR ammunition for shooting of European rabbits in Australia. Our goal was to assess the frequencies of adverse animal welfare events and cost-effectiveness of the 2 bullet types under conditions typical of field shooting in Australia.

STUDY AREA

Our ballistics trials were conducted on forested private properties near Hartford, Connecticut, USA. The properties had a cold temperate climate; vegetation was a mix of deciduous woodlands, fields, and wetlands typical of New England (Swihart et al. 1995). The properties had traditionally high squirrel densities and were used for recreational hunting of squirrels and white-tailed deer (*Odocoileus virginianus*). Our live animal trials were conducted on extensive livestock grazing properties near Broken Hill, New South Wales, Australia. The properties had a semiarid climate;

vegetation was a mixed shrubland–grassland community typical of extensive livestock grazing properties in southern Australia (Dunkerley and Brown 1999). The properties had traditionally high rabbit densities and were used for commercial kangaroo (*Macropus* spp.) and rabbit harvesting. For further details, see Hampton et al. (2016).

METHODS

The research was approved by Murdoch University Animal Ethics Committee (O3103/19). We used 2 types of factory-loaded ammunition: 1) lead-based expanding Winchester® Power-Point 40-grain (gr) hollow-point ammunition (Winchester Australia Ltd., Moolap, VIC, Australia), as per Hampton et al. (2016), and 2) lead-free CCI® Copper 21-gr hollow-point ammunition (CCI Ammunition, Lewiston, ID, USA; Fig. 1a). The lead-free bullets were of "sintered" copper construction, meaning they were made from compressed powdered metal (Caudell et al. 2012). The lead-free bullets were advertised by the manufacturer as being for "small game" (CCI Ammunition). The manufacturer did not recommend a maximum shooting distance on product packaging or their website. The 2 cartridges differed in kinetic energy, with the lead-based bullets having a muzzle kinetic energy of 198 joules (J) and the lead-free bullets having a muzzle kinetic energy of 127 J (Hampton et al. 2016). To estimate cost-effectiveness, we calculated the number of bullets fired for each rabbit confirmed to be killed for each ammunition type and multiplied this by the purchase price.

We performed ballistic testing using paper bullseye targets typically used in range practice to assess the precision of the lead-free bullets at realistic shooting distances (~50 m) and carcasses to assess bullet penetration of an animal of a similar size, gray squirrels (*Sciurus carolinensis*). We fired 4 3-shot groups with each cartridge type at the paper target from 50 m. Group size was calculated as per McCann et al. (2016). We killed 6 squirrels via head-shooting and placed the 6 fresh (killed within 4 hours) squirrel carcasses in sternal recumbency (side profile), backed by cardboard. We shot at them from 5 m to assess whether adequate thoracic penetration occurred and the extent of bullet pass-through (DeNicola et al. 2019). This step was designed to assess the ability of bullets to penetrate the body of a small mammal but was an imperfect simulation of shooting a live animal at a realistic shooting distance (~50 m).

Based on the sample size simulator in Hampton et al. (2019), designed to calculate the minimum sample size for studies quantifying the frequency of adverse animal welfare outcomes with reasonable statistical confidence, we aimed to assess outcomes of shooting n = 200 wild European rabbits with each of the 2 bullet types. We conducted our rabbit shooting trial on 3 consecutive nights during 14–16 August 2019. All shooting occurred during the hours of darkness (1800–0600 hr) and within 2 days of a full moon. Our shooting and observation procedures were identical to those described in Hampton et al. (2016): we used a customized 4-wheel drive vehicle as the platform for the shooter and observer (Fig. 1b); the shooter was a professional rabbit harvester; and the observer (JOH) was a veterinarian experienced in collecting animal welfare data from wildlife shooting programs. These data include animals being missed by shots, nonfatally wounded animals, and patterns of ballistic pathology (Hampton et al. 2015, 2016). We used a Brno® .22 LR bolt-action rifle (Zbrojovka Brno, Abrdovice, Czech Republic) with a variable 3–9× magnification Redfield® telescopic sight (Redfield, Beaverton, OR, USA) set at 9× magnification and zeroed at 50 m. We used a roof-mounted spotlight, controlled by the shooter, to locate rabbits. All shots were from a stationary vehicle at a stationary rabbit. We used the rabbit's thorax as the aim point for all shots. The shooter changed between the 2 types of ammunition after 20–40 shots had been fired with one ammunition type. The same zero (point of impact) was observed with both ammunition types at 50 m, so we did not deem it necessary to use 2 different rifles or to resight the rifle between ammunition types. We acknowledge that using ≥2 different rifles would have been preferable. All other aspects of shooting procedures were identical to those described in Hampton et al. (2016).

We used a Pulsar® Digisight LRF n960 night vision monocular (Yukon Advanced Optics Worldwide, Vilnius, Lithuania) to observe shooting events, and a stopwatch to record time from first shooting to incapacitation (seconds), as per Hampton et al. (2016). There were 3 possible outcomes for each shot: 1) the rabbit was missed; 2) the rabbit was hit and wounded; and 3) the rabbit was hit and killed. If a rabbit was killed by a shot, we recorded whether the bullet strike 'instantly incapacitated' the rabbit, which was defined as movement ceasing upon bullet impact (Caudell 2013, McTee et al. 2017). For each rabbit that was deemed 'killed,' we approached within 30 seconds to confirm death. When the rabbit was confirmed dead, we conducted a postmortem categorization of the location of bullet wound tracts following the methods of Hampton et al. (2016).

We used radiography to assess the terminal ballistic performance of bullets in animal tissues (Herring et al. 2016, DeNicola et al. 2019, Broadway et al. 2020). We collected a random sample of 27–28 rabbits shot with each bullet type, tagged each rabbit with a unique identification number, and refrigerated them until they could be radiographed. We radiographed the rabbits using a portable Cuattro® digital radiography system (Cuattro, Golden, CO, USA) set at 68 Kilovoltage peak and 1.0 milliampere-seconds. We detected metallic fragments or whole projectiles in radiographs using the methods described by Trinogga et al. (2019). We recorded the presence or absence of metallic fragments, dust, or whole projectiles following Herring et al. (2016).

RESULTS

The mean group sizes for the lead-based and lead-free bullets were 24 mm (SD = 10 mm; *n* = 12) and 59 mm (SD = 13 mm; *n* = 12), respectively. There was complete pass-through (i.e., the projectile travelled through the animal via an exit wound rather than terminating in the tissues; DeNicola et al. 2019) on all 6 gray squirrel carcasses shot with lead-free bullets.

We shot at 53 rabbits with lead-based bullets and 115 rabbits with lead-free bullets, resulting in the killing of 48 (91%) and 52 (45%) rabbits, respectively (Table 1). These sample sizes were smaller than the desired 200 for each bullet type because we discontinued the trial after 3 nights once approximately 50 rabbits had been killed with each bullet type because of the relatively high frequency of adverse events observed for lead-free bullets. Mean shooting distances for lead-based and lead-free bullets were identical (45 m; Fig. 2). The mean number of shots fired at each rabbit was 1.15 (SD = 0.36; range = 1–2) for lead-based bullets and 1.80 (SD = 1.37; range = 1–8) for lead-free bullets. The mean number of bullets fired per rabbit killed was 1.27 for lead-based bullets and 3.98 for lead-free bullets (Table 1). As per previous studies, the frequency of adverse events can also be expressed as a proportion of a subset of animals at which shots were taken: the frequency of ‘instant incapacitation’ (% of animals killed that immediately collapse) was 65% for lead-based bullets and 35% for lead-free bullets. The frequency of nonfatal wounding, expressed as 'wounding rate' (% of animals hit that escape wounded), was 10 times lower for lead-based (2%) than for lead-free (20%) bullets.

From radiography, metallic fragments were visible in 82% of 28 rabbits shot with lead-based bullets and 41% of 27 rabbits shot with lead-free bullets (Fig. 1c). Whole projectiles were never detected in rabbits shot with lead-based bullets, but were detected in 2 (7%) rabbits shot with lead-free bullets (Fig. 1d). Hence, we inferred that bullet pass-through occurred for 18% of rabbits shot with lead-based bullets and 52% of rabbits shot with lead-free bullets. The 2 projectiles that were retained in the body showed no radiographic evidence of fragmentation, deformation, or mushrooming. In the other 18% of rabbits shot with lead-based bullets and 52% of rabbits shot with lead-free bullets, there was no radiographic evidence of bullets or fragments, indicating pass-through shots.

The costs of purchasing lead-based and lead-free ammunition was AUD$0.20 and AUD$0.40, respectively. Hence, the cost per harvested rabbit was >6 times greater for lead-free (AUD$1.59) than for lead-based (AUD$0.25) bullets.

DISCUSSION

Our results demonstrated that the only lead-free bullets commercially available in Australia at the time of our study produced a substantially greater frequency of adverse animal welfare events compared with commonly used lead-based bullets when used to shoot rabbits. Our results were surprising given that many studies have shown comparable outcomes for lead-based and lead-free centerfire ammunition (Knott et al. 2009, Kanstrup et al. 2016, McCann et al. 2016, Martin et al. 2017, Trinogga et al. 2019). However, the majority of the aforementioned studies have assessed centerfire cartridges in calibers >0.270 (6.5 mm), but bullet stabilization problems exist for calibers up to and including 0.270 because of a mismatch between lead-free bullet length and barrel twist (Caudell et al. 2012).

Inferior animal welfare outcomes were produced by the lead-free bullets in our study, namely a greater frequency of missed shots and nonfatal wounded animals and a lower frequency of instantly incapacitated animals. These outcomes were the product of lower precision (as indicated by larger group sizes and a greater proportion of rabbits being missed) and poorer terminal ballistics (as revealed by a greater proportion of rabbits being nonfatally wounded). One potential adjustment for the poorer ballistic performance of lead-free bullets would be to reduce the shooting distance. The shooting distances in our study were typical of professional and recreational rabbit shooting in Australia (Hampton et al. 2015, 2016), and the flight initiation distances of rabbits (distances at which rabbits flee from an approaching vehicle) would have seldom enabled shots to be taken at stationary rabbits at shorter distances.

The terminal ballistics of the lead-free bullets manifested in a majority (52%) of pass-through shots and less fragmentation and deformation than observed for lead-based bullets. A bullet that passes through an animal with much of its kinetic energy remaining tends to produce less wound trauma than one that is frangible or malleable and transfers all (or most) of its kinetic energy to the animal (Caudell et al. 2012, DeNicola et al. 2019). Bullets are designed to maximize wound trauma (and hence the likelihood of ‘instant incapacitation’) by maximizing their kinetic energy transfer through fragmentation or deformation, which both increase the diameter of the wound channel. However, a bullet that loses all of its kinetic energy in an animal may not achieve deep penetration (Caudell 2013), which is a concern for shooting large mammals (e.g., ungulates) but less of a concern for mammals the size of European rabbits. A logical addition to our study would have been testing lead-free bullets terminal performance in ballistic gel prior to cadaver trials (Caudell et al. 2013). For a more detailed discussion of the mechanisms of wound ballistics, see Caudell (2013).

The magnitude of kinetic energy transfer is related to the likelihood of 'instant incapacitation,' with greater kinetic energy levels associated with more rapid incapacitation (Hampton et al. 2016). The kinetic energy values of the 2 ammunition types differed, but our aim was not to match all variables other than bullet construction. Rather, we compared the only commercially available .22 LR lead-free cartridges at the time of the study with a commonly used lead-based .22 LR cartridge that has been previously studied (Hampton et al. 2015, 2016).

The lead-free bullets assessed either displayed complete pass-through or were retained without fragmentation or deformation, limiting their ability to maximize transfer of kinetic energy. Any bullet that does not expand, fragment, or reliably transfer its kinetic energy to the target relies on optimal shot placement to kill an animal and provides minimal room for error (Caudell et al. 2013). The sintered construction of the lead-free bullets assessed in our study could reduce their precision and also the killing potential of their terminal ballistics when compared with solid copper (monolithic) bullets (Stokke et al. 2017). Sintered bullets are intended to have nearly no penetrating power and disintegrate upon contact with solid objects but there is limited research available to examine their behavior when striking the soft tissues of an animal (Whiting and Will 2019). However, there is an important relationship between bullet velocity and terminal performance: it is possible that impact velocities in our study were insufficient to cause the bullets to reliably disintegrate upon impact (Caudell et al. 2012), but we did not experiment with firing bullets at different velocities and there is limited research available to evaluate the efficacy of sintered bullets for killing animals (Whiting and Will 2019). We are unaware of any other studies quantifying animal welfare effects for sintered bullets, and do not believe that the results of this study are indicative of all lead-free ammunition or all lead-free rimfire ammunition.

Our results differ from other studies assessing lead-free ammunition in several ways. First, we assessed a sintered copper bullet, whereas other studies have assessed monolithic copper bullets. Second, we assessed a small caliber (0.22) and a relatively nonpowerful cartridge (0.22 LR), factors known to be problematic for lead-free bullet performance (Caudell et al. 2012). Third, the testing protocol we used could have captured more adverse events than the design of other studies allowed. Some such studies have either used only antemortem (before death) data (e.g., flight distance after shooting; Kanstrup et al. 2016, Stokke et al. 2019), and other studies have used only postmortem data (e.g., radiography; Trinogga et al. 2019). Few studies of lead-free ammunition have combined antemortem and postmortem data as per contemporary approaches in animal welfare (Hampton et al. 2015) and as lead-free shot has been assessed (Pierce et al. 2015). This is exemplified by few studies quantifying the frequency at which animals are missed or wounded (McCann et al. 2016). Additionally, much of these data were collected by hunter questionnaires rather than direct observation. Other studies have used tissue simulants such as ballistic gel or soap rather than live animal trials (Gremse et al. 2014). We suggest that combined antemortem and postmortem data provide a robust template for assessing all aspects of the performance of ammunition, including precision and terminal ballistics.

The main argument for the use of lead-free ammunition is to prevent harm to scavenging wildlife through lead exposure, and to a lesser extent, to human consumers of game meat (Arnemo et al. 2019, Schulz et al. 2019). Poisoning of scavenging wildlife is an example of an indirect and unintentional harm to animals (Fraser and MacRae 2011), whereas wounding during shooting is a direct and intentional harm. Any reduction in indirect harms to wild scavengers of rabbits in Australia (e.g., wedge-tailed eagles [*Aquila audax*]; Lohr et al. 2020, Woodford et al. 2020), and by humans eating the meat, would need to be considered against increased direct harms incurred on animals shot at, as well as greater costs of ammunition per animal killed.

We do not suggest that results of our study are indicative of all lead-free ammunition performance. The specific lead-free product we tested could be an anomaly. Our study had several limitations, including small sample size, shooting at a single species, using a single rifle, using a single type of lead-based and lead-free ammunition, and observing a single shooter. McTee et al. (2017) demonstrated that different lead-based .22 LR bullets have vastly different abilities to instantly incapacitate. Had we used a lead-based bullet with poor terminal ballistics, the conclusions of our study may have been different. There may have been a discrepancy in trajectory and points of impact for shooting distances other than 50 m (at which the rifle was sighted) due to differences in bullet mass and velocity (390 m/sec and 40 gr for lead-based vs. 564 m/sec and 21 gr for lead-free), which may have contributed to the observed results. We present our results as a cautionary case study to encourage other researchers and wildlife managers, not to assume that animal welfare outcomes will necessarily be equivalent for all lead-free and lead-based ammunition. To ensure that wildlife management prioritizes the welfare of wildlife that are the subject of shooting practices, as well as human health and conservation of scavengers, it is important that any products advocated in a lead-free transition are capable of maintaining, or improving, animal welfare standards (Hampton et al. 2018).

The only commercially available lead-free .22 LR ammunition available for shooting European rabbits in Australia at the time of our study produced lower precision, poorer animal welfare outcomes, poorer terminal ballistics, and were more expensive than commonly used lead-based ammunition. Any benefits to humans and scavenging wildlife derived from using lead-free bullets in this context would need to be weighed against animal welfare costs borne by animals targeted by shooting. Our results emphasize the importance of considering small mammal species and rimfire ammunition when promoting a transition to lead-free bullets. Researchers and wildlife managers should assess the performance of lead-free ammunition in terms of animal welfare and cost prior to recommending them for widespread use.

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Figures

Figure 1. Methods and outcomes of shooting at European rabbits with lead-based and lead-free ammunition in southeastern Australia, August 2019. Lead-based (left) and lead-free (right) .22 LR ammunition (a), shooting configuration used by a commercial rabbit harvester (b), radiograph of a rabbit shot with a lead-based bullet (c), and radiograph of a rabbit shot with a lead-free bullet (d).

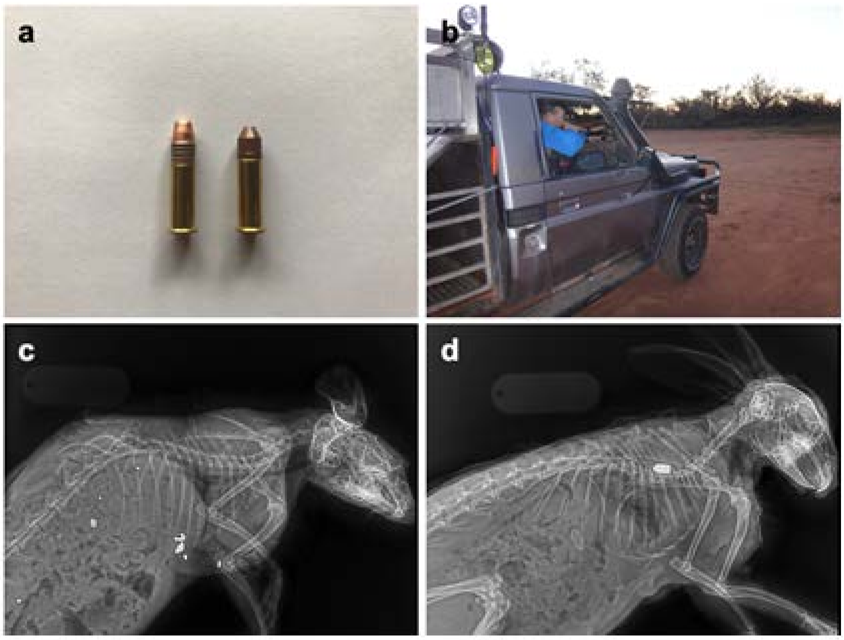

Figure 2. Initial shooting distances used for lead-based (black) and lead-free (grey) .22 LR bullets fired at European rabbits in southeastern Australia, August 2019.

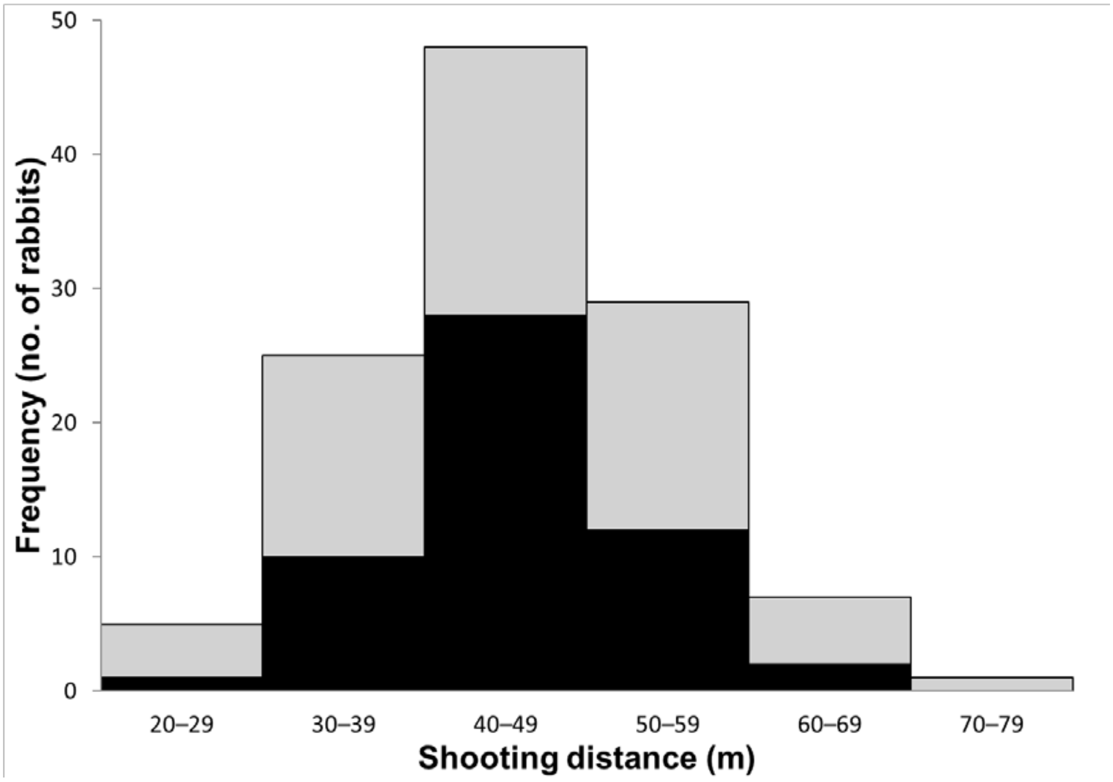

Table 1. Summary of data collected from shooting at 53 and 115 European rabbits with lead-based and lead-free .22 LR bullets, respectively, in southeastern Australia, August 2019. Values are percentages (95% CIs).

Category	Lead-based (%)	Lead-free (%)
Rabbits hit	92 (82–98)	57 (47–66)
Rabbits killed	91 (79–97)	45 (36–55)
Rabbits instantly incapacitated	58 (44–72)	16 (10–24)

Rabbits escaping unwounded	8 (2–18)	43 (34–53)
Rabbits escaping wounded	2 (0–10)	11 (6–19)

Summary for online Table of Contents: The efficacy of lead-free rimfire .22 LR bullets was compared with lead-based bullets for shooting European rabbits in Australia. Lead-free bullets were less effective, emphasizing the need for animal welfare testing for new ballistic technology.