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Are lead-free hunting rifle bullets as effective at killing wildlife as conventional lead bullets? A comparison based on wound size and morphology

Anna Trinogga [*], Guido Fritsch, Heribert Hofer, Oliver Krone

Leibniz Institute for Zoo and Wildlife Research, P.O. 601103, D-10252 Berlin, Germany

HIGHLIGHTS

- ► Wound diameters do not differ between lead-free and lead-based hunting rifle bullets.
- ► The size of the wound's maximum cross-sectional area does not depend on bullet material.
- ► Lead-free rifle bullets represent a suitable alternative to conventional bullets.
- ► The use of non lead bullets is appropriate to prevent lead deposit in the ecosystem.

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ABSTRACT

Fragmentation of the lead core of conventional wildlife hunting rifle bullets causes contamination of the target with lead. The community of scavenger species which feed on carcasses or viscera discarded by hunters are regularly exposed to these lead fragments and may die by acute or chronic lead intoxication, as demonstrated for numerous species such as white-tailed eagles (*Haliaeetus albicilla*) where it is among the most important sources of mortality. Not only does hunting with conventional ammunition deposit lead in considerable quantities in the environment, it also significantly delays or threatens the recovery of endangered raptor populations. Although lead-free bullets might be considered a suitable alternative that addresses the source of these problems, serious reservations have been expressed as to their ability to quickly and effectively kill a hunted animal. To assess the suitability of lead-free projectiles for hunting practice, the wounding potential of conventional bullets was compared with lead-free bullets under real life hunting conditions. Wound dimensions were regarded as good markers of the projectiles' killing potential. Wound channels in 34 killed wild ungulates were evaluated using computed tomography and post-mortem macroscopical examination. Wound diameters caused by conventional bullets did not differ significantly to those created by lead-free bullets. Similarly, the size of the maximum cross-sectional area of the wound was similar for both bullet types. Injury patterns suggested that all animals died by exsanguination. This study demonstrates that lead-free bullets are equal to conventional hunting bullets in terms of killing effectiveness and thus equally meet the welfare requirements of killing wildlife as painlessly as possible. The widespread introduction and use of lead-free bullets should be encouraged as it prevents environmental contamination with a seriously toxic pollutant and contributes to the conservation of a wide variety of threatened or endangered raptors and other members of the guild of scavengers.

1. Introduction

1.1. Lead intoxications in birds of prey

The impact of lead on the ecosystem represents an important challenge in terms of nature conservation. As lead is a highly toxic heavy metal, efforts have been made for years in order to eliminate it from the environment. Nevertheless, considerable quantities of lead are deposited in the ecosystem by hunting. Conventional hunting rifle bullets contain a lead core partially enclosed by a copper or brass jacket, a type of bullet that is called semi-jacketed. These projectiles fragment on impact on a body, leaving behind a large number of small lead particles (Cornicelli and Grund, 2008; Hunt et al., 2006, 2009b). The oral uptake of such lead fragments may result in severe and often fatal lead poisoning in raptors (Fisher et al., 2006; Hunt et al., 2006; Kenntner et al., 2001; Kramer and Redig, 1997; Krone et al., 2009; Scheuhammer and Templeton, 1998). It is a common practice among hunters to eviscerate hunted wildlife in the field, leaving

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[*] Corresponding author at: Food and Feed Control Authority of the county of Havelland (Landkreis Havelland, Amt für Landwirtschaft, Veterinär- und Lebensmittelüberwachung), Goethestr. 59/60, D-14641 Nauen, Germany. Tel.: +49 3321 4035516; fax: +49 3321 40335516.

E-mail address: anna_trinogga@gmx.de (A. Trinogga).

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behind the viscera which then are available for many scavenging species. Wounded animals represent an additional source of lead for predators. Nadjafzadeh et al. (2012) showed that not only raptors are affected but also corvids and terrestrial carnivores. Lead from spent ammunition may alter the population dynamics of these species and threaten the recovery of some highly endangered raptors such as the California condor (*Gymnogyps californianus*), Steller's sea eagle (*Haliaeetus pelagicus*), bearded vulture (*Gypaetus barbatus*) and griffon vulture (*Gyps fulvus*) (Church et al., 2006; Hunt et al., 2009a; Kim et al., 1999; Mateo, 2009; Pain et al., 2009; Saito, 2000). In Germany, the white-tailed eagle (*Haliaeetus albicilla*) represents the best studied raptor species regarding the accumulation of toxic elements. Krone et al. (2003) identified lead poisoning as the primary cause of death in white-tailed eagles found dead or moribund in Germany. Sulawa et al. (2010) demonstrated that lead intoxication is responsible for a significant reduction in the growth rate of the German white-tailed eagle population.

1.2. Lead-free bullets as one solution

In this context the question arose whether there are suitable alternatives to conventional lead-based hunting rifle bullets. Lead-free bullets made of copper or copper alloys have existed since the 1990s but their use is still highly controversial in Germany (Beyer, 2005; BfR, 2012; Grieder, 2006; Klups, 2005a–g, 2006a–f; Liese, 2012). Typically, reservations are expressed about the wounding capacity of lead-free constructions; they are said to be inferior to standard lead-based ammunition. As national and European legislation (e.g., in Germany, the Tierschutzgesetz der Bundesrepublik Deutschland, 2006) and the ethical codices of hunters in many countries claim that no unnecessary pain is to be inflicted upon a hunted and shot animal, new bullets are only accepted if their wounding and killing potential at least equals those of conventional projectiles.

1.3. Comparing the wounding potential of rifle bullets

Under comparable conditions, a similar wounding potential of different bullets should be reflected by a comparable wounding pattern. Rifle shots kill by tissue destruction (Karger, 2004; Kneubuehl et al., 2008; Sellier and Kneubuehl, 2001). The size and morphology of wounds are therefore good indicators of the killing capacity of bullets. Another method to assess the adequacy of a certain bullet or bullet type for hunting purposes is the analysis of flight distances. Stokke et al. (2012) defined maximum acceptable flight distances for several species such as moose and brown bear.

We chose the evaluation of tissue damage patterns as this approach allows for the direct comparison of the wounding potential of different bullet types even if both types meet the minimum requirements. If the performance of lead-free bullets was inferior to conventional lead-core bullets this should be reflected in the dimensions of the wounds they cause. In such a case, the wound channel diameters should be smaller than those caused by conventional lead bullets. Computed tomography (CT) and necropsy are both appropriate methods to evaluate gunshot wounds (Donchin et al., 1994; Oliver et al., 1995; Thali and Dirnhofer, 2004; Thali et al., 2003; Thali et al., 2007). Wound dimensions can easily be measured using modern CT software. Conclusions as to the actual cause of death can be drawn from the organ injuries and from typical alterations such as organ anaemia in cases of exsanguination. Evaluating wound dimensions and morphology represents the basis for the assessment of a bullet's ability to quickly and effectively kill a hunted animal. The present study was therefore designed to use such measures to answer the question whether lead-free hunting rifle bullets are an adequate surrogate for the conventional but toxic lead-based bullets and whether the use of currently available lead-free bullets can be recommended.

We were particularly interested in evaluating this question under real life practical hunting conditions. In Germany, our study area, this means hunting small to medium-sized wild ungulates shot at distances of up to 150 m with bullets having an impact energy of approximately 1500 to 3500 J. It was the aim of the present study to analyse whether lead-free hunting rifle bullets are adequate for hunting which means that they have to function properly under a variety of conditions. Evaluating the bullet potential under real life conditions implies refraining from a standardised shooting situation but taking advantage of the fact that the lead-freed bullets were used by hunters trained to make their shooting decisions using lead bullets throughout their hunting career. Shots under standardised conditions were performed as another part of the project using ballistic soap as a tissue simulant. Their results are to be presented in a subsequent paper.

2. Materials and methods

2.1. Study animals

The bodies of 65 shot wild ungulates were provided by private hunters and the forest management units of the Federal Republic of Germany and the federal states of Bavaria, Brandenburg and Schleswig–Holstein. The animals were shot during stalking and drive hunts between December 2006 and January 2009. Of these, 22 were shot into abdominal viscera, seven into the head or neck, two in the lumbar spine and 34 into the thoracic cavity.

To ensure comparability, only animals with wound channels through the thoracic cavity were included in the study, resulting in a subsample of 34 carcasses — 15 wild boar (*Sus scrofa*), 13 roe deer (*Capreolus capreolus*), four chamois (*Rupicapra rupicapra*), one red deer (*Cervus elaphus*) and one fallow deer (*Cervus dama*). Each animal was placed in a cooling chamber (4 °C) immediately after the hunt and frozen at −20 °C as soon as possible.

2.2. Ammunition

Hunters gave detailed information on the ammunition and the rifle used as well as the shooting distance using a standardised shooting report. Bullets were classified on the basis of manufacturers' information and the evaluation of radiographs of shot wildlife (Cornicelli and Grund, 2008; Hunt et al., 2006, Trinogga et al., unpublished data). Bullets were assigned to three different classes according to their terminal ballistic behaviour: type 1 were lead-free deforming bullets, type 2 were lead-free partially fragmenting bullets and type 3 were bullets containing one or two lead-core(s). Ballistic data such as bullet mass and bullet velocity at different shooting distances were provided by bullet manufacturers. If available, information on impact energy was directly taken from these data. Otherwise impact energy (with units J) was calculated as $E_{\mathrm{kin,i}} = (1/2000)\ mv_i^2$ with m being the bullet mass (with units g) and v_i being the impact velocity (with units m s^{-1}) at the relevant distance. Information on shooting distances was given in the hunters' reports using the following categories: up to 50 m, 51 to 100 m, 101 to 150 m, 151 to 200 m, and 201 to 250 m. For calculating $E_{\mathrm{kin,i}}$ the upper limit of the indicated distance interval was used. Sectional density was calculated from manufacturers' data as $SD = m/A$, m being the original bullet mass (with units g) and A being the cross sectional area of the undeformed bullet (with units mm^2) in direction of flight. A was calculated as $(d/2)^2\ \pi$ with d being the bullet diameter (with units mm). Eight different brands were tested (Table 1).

2.3. Computed tomography

We conducted CTs of the shot wildlife bodies using a 4-slice-spiral-CT scanner (Lightspeed QXi, General Electric Medical Systems, USA) and the workstations ADW 4.2 and 4.4 (General Electric) and Vitrea (Toshiba, Japan). Data were acquired with a collimation of 4 × 1.25 mm. The analysis of the wound channel included the shot

Table 1
Bullets employed by hunters in the present study.

Manufacturer and brand name	Bullet type	N
Barnes XLC or TSX	Lead-free deforming bullet	5
Lapua Naturalis	Lead-free deforming bullet	5
RWS Bionic Yellow	Lead-free partially fragmenting bullet	4
Moeller KJG	Lead-free partially fragmenting bullet	2
Reichenberg HDBoH	Lead-free partially fragmenting bullet	5
Norma Vulkan	Bullet with one or two lead-core(s)	1
RWS Evolution	Bullet with one or two lead-core(s)	5
RWS UNI classic	Bullet with one or two lead-core(s)	2
Semi-jacketed	Bullet with one or two lead-core(s)	5

placement, the length of the wound channel (with units mm) and the number of bones crossed by the wound channel. The diameter of identifiable tissue damage was measured at a penetration depth of 0 mm (entry wound) and at distances of every 50 mm along the wound channel (Fig. 1) in units of mm. The size of the maximum diameter (with units mm) of damaged tissue was also determined. The maximum cross-sectional area of the wound channel A_{max} was calculated using the formula for the area of an ellipsis as π*ab*, with *a* and *b* being the major and minor axes (with units mm) of the ellipsis, respectively.

2.4. Necropsy

After CT, the animals were thawed and a necropsy was conducted. The locations of entry and exit wounds were noted, the wound channel was examined macroscopically; and injuries were described and documented by photographs (Figs. 2 and 3). We measured the diametres of entry and exit wounds in proximodistal and craniocaudal directions. To calculate the cross-sectional areas A_{entry} and A_{exit} of the wounds we treated them as being elliptic and calculated them as π*ab* with *a* and *b* denoting, as before, the major and minor axes of the ellipsis (measured in units of mm). During the preparation of the wound channel, special attention was paid to the colour of mucous membranes and inner organs as well as to the degree to which hypostasis had occurred. These criteria were regarded as markers of the intensity of blood loss (Betz, 2004). We refrained from estimating the angle of bullet entry or grouping cases according to angles of bullet entry as we wanted to evaluate whether lead-free bullet types work well in those situations in which German hunters normally decide to shoot. We also did not expect the angle of the shot to systematically vary with bullet type, so neglecting this factor would not have introduced any kind of bias to the subsequent data analysis.

Fig. 1. Axial CT image of a roe deer with measurement of destroyed lung tissue (see inset for orientation).

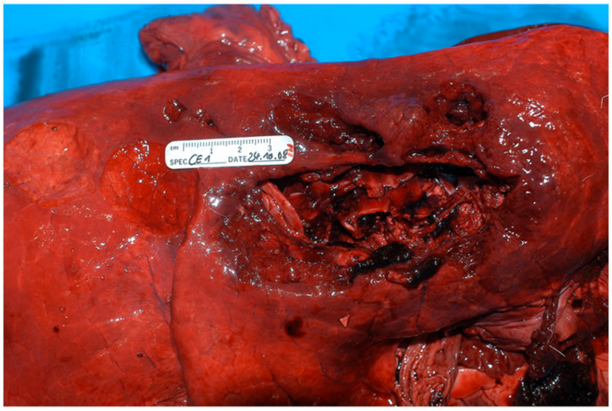

Fig. 2. Lateral view of the lung of a red deer (*Cervus elaphus*) wounded by a conventional lead-core bullet (RWS UNI Classic).

2.5. Statistical analyses

Statistical analyses were conducted in SPSS 18 (SPSS Inc., Chicago, Illinois) and SYSTAT 13 (Systat Inc., Chicago, Illinois). Descriptive statistics are reported as means ± S.E.M, the median, the range of values and the coefficient of variation, a measure of the relative spread of variation as it is estimated as the standard deviation divided by the mean. The significance threshold was set at 0.05 and all tests were two-tailed. Variation between bullet types in terms of sectional density and impact energy were tested with the nonparametric Kruskal–Wallis test, post hoc multiple comparisons performed using the Dwass–Steel–Critchlow–Fligner test. To assess the question whether the type of bullet influences A_{max} we analysed tissue damage measurements with a general linear model (GLM) with A_{max} as the dependent variable and bullet type and the number of bones in the wound tract as independent variables. With regard to wound diameters measured at several defined

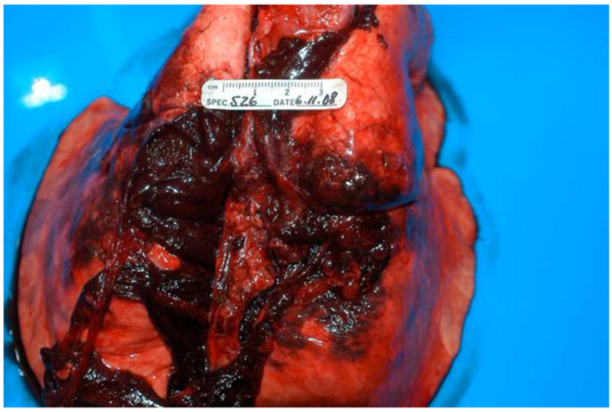

Fig. 3. Lacerations in the lung of a wild boar killed by a lead-free deforming copper bullet (Barnes XLC) (wound channel in laterolateral direction).

depths of penetration a GLM for repeated measures was used, tissue damage diameter being the dependent variable and bullet type being the independent variable. The null hypothesis was that there was no difference between bullet types with regard to the extent of tissue damage. We tested and confirmed that the requirements of the general linear model were met: amongst residuals there was no significant deviation from normality, variance was homoscedastic and there was also no significant deviation from the assumption of sphericity. For multiple comparisons in this model the Šidák correction was used.

In 33 cases measures could be carried out at depths of penetration of 0 cm, 5 cm and 10 cm. Measurements at a depth of penetration of 15 cm were available for 27 animals. An exploratory repeated measures analysis of variance of the 27 animals with four measures per wound channel did not reveal any differences to a model using only three measures per wound channel for the full set of animals. We also checked that the exclusion of animals, for which measures at 15 cm depth of penetration were not available, did not change test results with regard to the mean estimates of sectional density and impact energy. The classification of bullets (bullet type) was therefore considered to be an appropriate summary of these parameters in both models. As the model with measurements at three depths of penetration had a larger sample size and hence greater statistical power, we report its results in detail below.

3. Results

Shooting distances ranged from under 50 m to about 150 m. 33 of 34 animals were shot at distances of less than 100 m.

Descriptive statistics for sectional density and estimated impact energy of the projectiles employed by hunters in this study under actual shooting conditions are listed in Table 2. Bullet types varied in their initial sectional density (Kruskal–Wallis test: H = 23.600, df = 2, $p<0.0001$; post hoc multiple comparisons: lead-free deforming bullet > lead-free partially fragmenting bullet, p = 0.023; lead-free deforming bullet < bullet with one or two lead-core(s), $p<0.0001$; lead-free partially fragmenting bullet < bullet with one or two lead-core(s), $p<0.0001$; Table 2). Impact energy also differed significantly between bullet types (Kruskal–Wallis test: H = 9.509, df = 2, p = 0.0086; post hoc multiple comparisons: lead-free deforming bullet = lead-free partially fragmenting bullet, p = 0.45; lead-free deforming bullet < bullet with one or two lead-core(s), p = 0.00053; lead-free partially fragmenting bullet < bullet with one or two lead-core(s): p = 0.00006; Table 2). For the detailed analysis of the wound channel, bullet type was therefore regarded as an appropriate parameter to represent these physical characteristics of the projectiles in actual shooting conditions.

3.1. Measurements with computed tomography

Wound channel length was similar between bullet types (general linear model, F = 0.057; df = 2, 31; p = 0.945). There was no significant influence of the bullet type (general linear model, F = 1.248; df = 2, 25; p = 0.304) or the number of bones in the wound tract (general linear model, F = 0.584; df = 2, 25; p = 0.565) on $A_{max.}$ Mean values of A_{max} tended to be highest for lead-free deforming bullets (Fig. 4).

The diameter of identifiable tissue damage was significantly influenced by the depth of penetration (repeated measures analysis of variance, F = 92.721; df = 2, 60; $p<0.0001$). In the analysis of contrasts, linear and quadratic trends were both significant (linear: F = 169.031; df = 1, 30; $p<0.0001$, quadratic: F = 24.493; df = 1, 30; $p<0.0001$). Post hoc multiple comparisons of the estimated marginal means demonstrated a significant difference between the entry wound diameter and the diameters at 5 and 10 cm, respectively (both $p<0.0001$) (Fig. 5).

Bullet type significantly influenced wound diameters at 0, 5 and 10 cm penetration depths (repeated measures analysis of variance, F = 3.644; df = 2, 30; p = 0.038). The estimated marginal diameter means were significantly (p = 0.035) higher for lead-free deforming bullets (type 1) than for lead-free partially fragmenting bullets (type 2). No significant differences were found between lead-free types and conventional bullets (lead-free deforming bullet = conventional bullet, p = 0.601; lead-free partially fragmenting bullet = conventional bullet, p = 0.301) (Fig. 5).

Table 2
Sectional density of bullets employed, the impact energy generated by the actual shots, and entry and exit wound cross-sectional areas in free-ranging ungulates killed by hunters in this study with three different types of bullets.

Parameter	Lead-free deforming bullet	Lead-free partially fragmenting bullet	Bullet with one or two lead-core(s)
N	10	11	13
Sectional density [g/mm^2]			
Mean ± S.E.M. [g/mm^2]	0.245 ± 0.0051	0.185 ± 0.011	0.266 ± 0.0053
Median [g/mm^2]	0.250	0.176	0.261
Range [g/mm^2]	0.21–0.26	0.15–0.23	0.22–0.29
Coefficient of variation [%]	6.6%	19.9%	7.1%
Impact energy [J]			
Mean ± S.E.M. [J]	3260.4 ± 163.8	2426.7 ± 319.5	3477.5 ± 138.9
Median [J]	3239	2415	3751
Range [J]	2757–4436	1155–4522	2567–3920
Coefficient of variation [%]	15.9%	43.7%	14.4%
Cross-sectional area of wound channel [cm^2] at point of bullet entry A_{entry}			
Mean ± S.E.M. [cm^2]	4.44 ± 1.78	5.04 ± 1.81	7.16 ± 2.64
Median [cm^2]	8.35	7.00	8.10
Range [cm^2]	0.47–18.79	1.10–18.06	0.28–28.90
Coefficient of variation [%]	65.7%	69.3%	56.9%
Cross-sectional area of wound channel [cm^2] at point of bullet exit A_{exit}			
Mean ± S.E.M. [cm^2]	22.39 ± 8.89	18.58 ± 9.59	20.83 ± 5.97
Median [cm^2]	33.65	21.66	36.90
Range [cm^2]	2.50–94.90	0.00–103.7	0.50–62.80
Coefficient of variation [%]	60.6%	105.4%	57.2%

3.2. Necropsy

All animals showed signs of extensive blood loss. Large amounts of coagulated and liquid blood were located in the thoracic cavities. The mucous membranes and inner organs were pale to very pale in all cases. Hypostasis was developed indistinctly. Tissue disruption was extensive in all dissected animals. Tissue surrounding the permanent

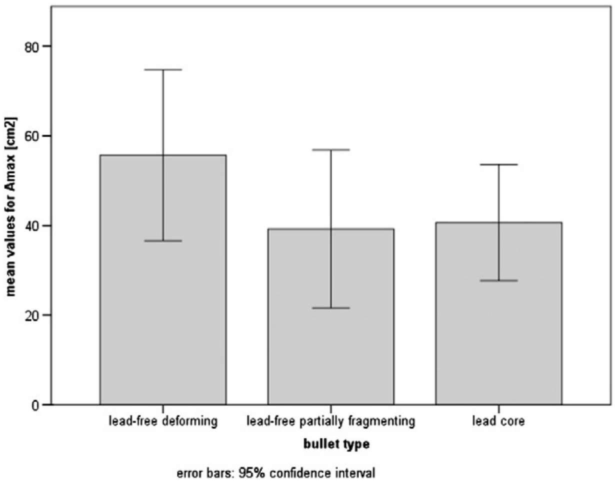

Fig. 4. Mean values ± 95% confidence limits for the maximum cross sectional area of the wound channel. Differences between bullet types are not significant.

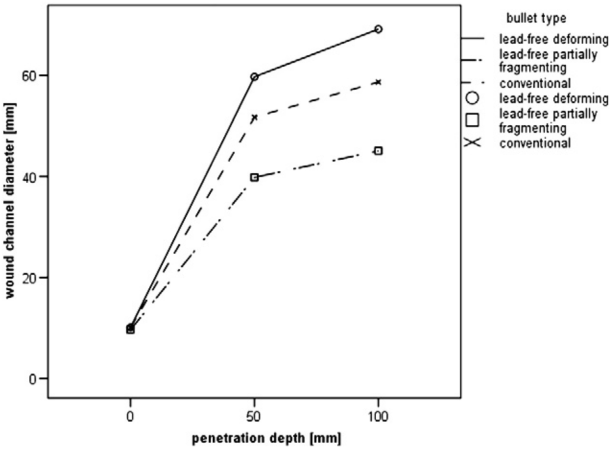

Fig. 5. Estimated marginal means of the wound diameters at three different penetration depths. Wound diameters are significantly larger after 5 and 10 cm penetration than at the entry point. Differences between lead-free types and conventional bullets are not significant.

wound channel was torn and bloody at distances of several centimetres from the wound cavity (Figs. 2 and 3). All animals had injuries to the lungs, 16 had additional injuries to major blood vessels such as the aorta or the *Truncus pulmonalis* and in 17 cases the heart was injured. Eight animals were injured in all three locations.

Except for one case – a wild boar shot with a partially fragmenting lead-free bullet – all bullets exited the bodies. There were no significant differences of the size of entry wounds (Kruskal–Wallis test, $H = 1.087$, $df = 2$, $p = 0.581$) or exit wounds (Kruskal–Wallis test, $H = 2.876$, $df = 2$, $p = 0.237$) between bullet types (Table 2).

4. Discussion

4.1. Wound dimensions and morphology

Our findings show that under real life normal German hunting conditions, with bullets having an impact energy of 1500 to 3500 J, the decision whether a conventional lead-core bullet or a lead-free variety is used does not significantly influence the wounding potential of the shot. According to Spencer (1908), the wounding potential of a projectile depends on its kinetic energy and on its ability to transfer this energy onto the target. The latter is strongly influenced by the sectional density of a bullet which is given by the ratio of its mass to its cross-sectional area. Kneubuehl (2004) states that sectional density is the crucial parameter in ballistics and more important than bullet mass or calibre. As sectional density decreases, wounds become wider and shorter (Sellier and Kneubuehl, 2001). The initial sectional density is lower in lead-free partially-fragmenting bullets than in the other types. As lower sectional density results in wider wounds this might mask the effect of the lower kinetic energy. On the other hand, sectional density changes during the interaction of the bullet with the tissue. In this study it was not possible to assess the shape of the residual bullet. The extent to which sectional density changed in the actual shots could therefore not be evaluated. Data obtained by simulation experiments with ballistic soap (Trinogga et al. unpublished), however, suggest that sectional density in lead-free partially-fragmenting bullets often does not decrease as much by the interaction with the target as in the other bullet types. This may be reflected by the smaller wound diameters caused by this type of projectile. This hypothesis is further supported by the fact that despite of intermediate-sized entry wound surfaces the exit wound surfaces caused by lead-free partially fragmenting bullets tended to be the smallest of all three bullet types, although the differences between bullet types were not significant. The non-significant difference in tissue damage between the lead-free deforming bullets (type 1) and conventional bullets (type 3) – slightly larger diameters with type 1 – may also be a consequence of their different sectional densities.

As our results show, the maximum cross-sectional area of the wound channel is not affected by the choice of bullet type. Wound morphology also does not depend on projectile type, as no significant interaction effect between penetration depth and bullet type could be detected. The diameter of tissue destruction significantly increased between the point of entry and a depth of 5 and 10 cm, respectively. We conclude that each of the three missile types starts dissolving its kinetic energy on target quickly after first contact. These kinetic properties are desirable for hunting small to medium-sized wildlife because wound channels are likely to be short in these animals as body dimensions are small.

Bullets with a lead core did not cause wider wounds at 0, 5 and 10 cm penetration depth than their lead-free counterparts. The only significant difference in this respect concerned the two types of lead-free projectiles. Wounds caused by deforming bullets (type 1) had a larger diameter than those created by partially fragmenting varieties (type 2). Although the difference in impact energy between lead-free deforming bullets (type 1) and lead-free partially fragmenting bullets (type 2) was not statistically significant, the higher energy of the deforming projectiles might be reflected in larger wounds. In contrast, the significantly higher impact energy of conventional lead core bullets (type 3) than lead-free bullets (types 1 and 2) did not induce a significant difference in tissue damage.

4.2. Temporary cavitation and hit placement

The interaction between a bullet and a body is characterised by the phenomenon of the temporary wound cavity (Karger, 2004; Kneubuehl et al., 2008; Sellier and Kneubuehl, 2001). The penetrating bullet causes a radial acceleration of body tissue which is displaced as a consequence and subjected to elongation and shearing forces. The amount of tissue destruction caused by the temporary cavity depends on the elasticity of the organs which are struck — less elastic tissue such as liver (Amato et al., 1974a, 1974b) or brain (Oehmichen et al., 2000) is more severely damaged than muscle or lung, for example, which have a higher elasticity. For this reason we restricted the analysis to shots through the chest. Owing to its high elasticity, the lung is relatively insensitive to damage by the temporary cavity (Karger, 2004). As it collapses when air enters the thorax, measurements in lung tissue are difficult to compare with measurements made in other organs.

An unambiguous differential diagnosis separating the direct impact of the shot from putrefaction and autolysis which arose because of the unavoidable delay between the death of the animal and its freezing can be difficult in abdominal organs (Jackowski et al., 2006) and often was impossible in our study. We therefore refrained from conducting measurements on abdominal viscera. Other shot placements such as the head or the neck were not represented as frequently as would have been necessary for statistical evaluation. We consider that the value of the current study was not restricted by this constraint. A comparison of the wounding potential of bullet types should be based on the analysis of thorax shots because hunters normally aim at the chest since this shot placement allows a rapid killing of the animal and at the same time implies a considerably lower risk of missing and wounding than a shot through the head or neck which theoretically is even more potent. As our study was meant to evaluate real life hunting situations it seems legitimate to confine the analysis to the desired hit placement.

4.3. Cause of death

Schmidt and Madea (1994) report cases of death via vaso-vagal reflexes caused by contusion of the cervical spinal cord through the formation of the temporary cavity. Sellier and Kneubuehl (2001) also mention the theoretical possibility of baroreceptor-mediated reflex death caused by the pressure changes during the pulsation of the temporary cavity. All animals in this study showed injuries that were severe enough to support the theory of a rapid death by extensive blood loss alone, followed by consecutive hypoxia of essential brain regions. As wound dimensions measured with CT did not depend on bullet type we conclude that this is also the case for the temporary cavity. If temporary cavitation does cause a reflex death, this mechanism should be present independent of the bullet type.

4.4. The role of bullet fragmentation

Fackler et al. (1984) claim that missile fragments weaken tissue by cutting through it and creating points of least resistance, thus making the stretch exerted by temporary cavitation more effective. They compared the effects of non-fragmenting, non-expanding solid brass bullets to those of standard fragmenting soft-point bullets. Projectiles that deform without losing mass were not included in the experiments. Our findings do not suggest a superiority of fragmenting hunting bullets over non-fragmenting expanding varieties. This is consistent with the findings of Coupland (1999) who assessed the relation between projectile fragmentation and wound size in wounds caused by military bullets. Based on the Red Cross wound classification, he came to the conclusion that “Fragmentation of bullets is neither a necessary nor sufficient cause of large wounds”. In our study, neither size nor morphology of the wound tract differed significantly between conventional fragmenting and unleaded non-fragmenting projectiles, nor did we find any additional injuries such as separate wound channels caused by fragments. If anything, mean wound diameters caused by non-fragmenting varieties tended to be the largest of all bullet types (Figs. 4 and 5).

4.5. Exit wound production

Sufficiently large exit wounds are important for hunters in case a wounded animal manages to escape. Without an exit wound or with only a very small one it will be much more difficult to find blood, hair, bone fragments or parts of the viscera on the track. These signs provide important information about the shot placement. The animal's behaviour thus can be better anticipated and, as a consequence, the effectiveness of a search is increased. This is directly linked to the question whether a bullet is adequate for hunting effectively as a short search reduces the duration of pain and suffering inflicted to the wounded animal. Apart from one lead-free partially-fragmenting bullet all projectiles exited the bodies. In the case of the non-exiting bullet, the impact energy was comparatively low (1392 J) and the wound channel was the longest channel measured in our study (41 cm). So, in general, all three bullet types met the requirements in terms of exit wound production.

5. Conclusions

As bullet material did not exert a significant influence on wound dimensions under real life hunting conditions, this study clearly demonstrates the equality of lead-free bullets to conventional hunting bullets in terms of killing effectiveness. Lead-free hunting rifle bullets thus meet the welfare requirements of killing wildlife without superfluous pain as good as do conventional bullets.

The present study evaluated real life hunting conditions, accepting that not all details of the actual shots can be known with certainty. Our results show that in those situations that hunters judge as appropriate for shooting, lead-free hunting rifle bullets function as well as conventional bullets.

In 2008 reservations arose as to the allegedly unpredictable behaviour of ricocheting lead-free bullets. A study evaluated by Kneubuehl (Kneubuehl, 2011; Rottenberger, 2011) did not confirm these speculations. The widespread introduction and use of lead-free bullets should therefore be encouraged as it prevents environmental contamination with a seriously toxic pollutant and contributes to the conservation of a wide variety of threatened or endangered raptors and other members of the guild of scavengers.

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