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LEAD USE IN HUNTING

Fragmentation of lead-free and lead-based hunting rifle bullets under real life hunting conditions in Germany

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Abstract As lead is a heavy metal showing high toxicity for many organisms, its entry in the ecosystem should be minimised. Nevertheless, considerable quantities are deposited in the environment via hunting ammunition. Such practice is responsible for the occurrence of lead poisoning in many wildlife species and represents a health risk to humans. We assess the differences in the fragmentation patterns of lead-based and lead-free hunting rifle bullets using the radiographic characteristics of gunshot wounds. We took radiographs of 297 wild ungulates shot during regular hunting events in Germany. Compared to lead-free ammunition, both the number of bullet fragments and the maximal distance between fragments and the wound channel increased when bullets were lead-based. Under normal German hunting conditions, the use of lead-based bullets causes a broad contamination of the carcass and the viscera with bullet material. The wide-spread substitution of lead-based bullets through non-lead alternatives should therefore be further encouraged.

Keywords Bullet fragmentation · Game animals · Lead poisoning · Radiography · Rifle bullets · Sustainable hunting

INTRODUCTION

As the high toxicity of lead to both humans and animals is well known, it seems desirable to eliminate human spread of lead in the environment. Considerable efforts have been made to reach this goal for years. The European Commission regulated the use of lead in many applications during the last years (Krone 2018). The use of lead-based hunting ammunition, though, still represents a significant source of lead in the ecosystem. For example, Stokke et al. (2017) estimate that 215 kg of ammunition lead are deposited in the ecosystem of Fennoscandia via gutpiles, offal and non-retrieved carcasses of moose (*Alces alces*) in 1 year.

Fragments of lead-based bullets pose a particular risk to many scavenging raptors as they can cause fatal lead intoxications when ingested orally with tissues of shot game animals. The impact of lead-based bullets on a broad variety of wildlife species has been well documented and Krone (2018) provides a recent summary of the literature concerning this issue.

Lead bullet fragments may also present a risk to humans, when the increase in the lead content of venison is such that the consumption of this meat can pose a risk to consumer health. Lindboe et al. (2012) found high mean lead levels in meat from moose (*Alces alces*) shot with lead-based bullets. Accordingly, the consumption of game meat derived from animals killed with lead-containing ammunition has been shown to increase lead exposure and the health risks associated with lead in humans (Fachehoun et al. 2015). Authority (EFSA 2013) have stated that even low intake levels of lead can cause severe and irreversible damage to humans, especially concerning the neurological development of foetuses, infants and children, and that therefore no tolerable intake can be defined. Several European food safety agencies also recommend vulnerable consumers such as pregnant women, women of fertile age and children to refrain from eating meat of game animals shot with lead-based ammunition (Knutsen et al. 2015).

It is known from several studies that lead-based rifle bullets fragment more upon impact than alternative materials. Hunt et al. (2006) described numerous small metallic particles on radiographs of offals of white-tailed deer (*Odocoileus virginianus*) and mule deer (*O. hemionus*) killed with lead-based bullets. Knott et al. (2010) radiographed carcasses and viscera of twelve deer shot with standard lead-core bullets. They reported an average of 356 metallic particles in the carcasses and 180 particles in the viscera. Grund et al. (2010) and Cruz-Martinez et al. (2015) found high numbers of bullet fragments on radiographs of domestic sheep (*Ovis aries*) and white-tailed deer shot with lead-based projectiles designed for rapid or controlled expansion, respectively. Ballistic simulation tests using soap as a tissue simulant revealed significantly more fragments for the tested lead-based bullet than for the non-lead alternatives (Gremse et al. 2014). Hunting rifle bullets made of copper which represent an alternative to lead-based constructions have been shown to resist fragmentation or to produce a smaller number of fragments than lead-based bullets (Hunt et al. 2006; Grund et al. 2010; Irschik et al. 2013; Cruz-Martinez et al. 2015).

The present study aimed at evaluating the fragmentation patterns of commonly used lead-based and lead-free hunting rifle bullets under normal hunting conditions. In Germany, this means the hunting of small to medium-sized game with bullet diameters ranging from 5.6 to 9.3 mm. The examination of animals shot under field conditions, as presented here, allows for investigating bullet fragmentation over the range of conditions in which hunters decide to shoot. We were particulary interested in knowing to which extent commonly used rifle bullets fragment in real life hunting situations and at which distance apart from the wound channel fragments can be found. This knowledge has practical importance regarding the trimming of game animal carcasses as all meat that contains lead fragments should be discarded to obtain safe venison (BfR 2010). If bullet fragments are spread widely into muscle tissue, large amounts of meat have to be excluded from human consumption. Game meat is a high-quality foodstuff and hunters should strive to discard as little as possible. In addition, the rejection of meat that would otherwise be edible implies the need to kill a higher number of animals to derive a given amount of venison.

Radiography represents a well implemented method for the evaluation of gunshot wounds and the identification of bullet fragments (Hollerman et al. 1990; Brogdon and Messmer 2011). This technique has been previously used in several studies investigating the behaviour of rifle bullets in animal carcasses (Hunt et al. 2006; Hunt et al. 2009; Grund et al. 2010; Knott et al. 2010; Cruz-Martinez et al. 2015). For this study, we decided to radiograph non-eviscerated game animals as we wanted to evaluate the distribution of fragments in relation to the wound channel.

MATERIAL AND METHODS

Study animals

We radiographed the bodies of 297 shot wild ungulates (5 chamois (*Rupicabra rupicabra*), 87 fallow deer (*Cervus dama*), 23 red deer (*Cervus elaphus*), 103 roe deer (*Capreolus capreolus*), 79 wild boars (*Sus scrofa*)) during regular stalking and drive hunts in Germany between 2006 and 2009. The animals were provided by private hunters and by the forest management units of the Federal Republic of Germany, the federal states of Bavaria, Berlin, Brandenburg, Lower Saxony and Schleswig–Holstein, the city of Rostock and the Müritz National Park.

Ammunition and shooting distance

The ammunition used was chosen by the hunters or prescribed by the forest management. A large variety of bullet brands was employed. We assigned the bullets to five classes depending on their material and terminal ballistic behaviour as described by the manufacturers: type 1 were lead-free deforming bullets, i.e. bullets made of copper or copper alloys that shall resist fragmentation but deform upon impact into a mushroom-like shape; type 2 were lead-free partially fragmenting bullets, i.e. copper or brass bullets whose front part is designed to fragment; type 3 were simple semi-jacketed lead-core bullets, i.e. projectiles with a lead core partially enclosed by a copper jacket; type 4 were semi-jacketed bullets with two lead cores of different hardness that are designed for controlled fragmentation; type 5 were bullets whose lead core is bonded to the jacket in order to prevent separation of the two components. The calibres used were common calibres for hunting medium-sized game in Germany, most frequently .30–06 Springfield, 9.3 × 62, 8 × 57 IS and .308 Winchester. Shooting distances were given as categories of 50 m in a standardised shooting report filled up by the hunters; 102 out of 297 shots were done at a distance of up to 50 m, further 161 shots were done at a distance ranging between 51 and 100 m. In the remaining 34 cases, shooting distances were longer than 100 m.

Radiographic examinations and processing of radiographs

Radiographs were taken before evisceration, no later than 90 min after death. Two mobile X-ray units (Vet Ray Gamma 2000, Acoma Xray, South Korea, and Vet Ray Gamma Titan, Poskom, South Korea) with imaging plates

Fuji CR ST-VI (Fujifilm, Japan) and a drum scanner (VetRay® CR35 V, VetRay GmbH, Pfaffenhofen, Germany) were used. We took two radiographs of each animal, one in latero-lateral and one in ventro-dorsal direction. Processing of the radiographs was done by means of the medical image processing software VetRay® Vision 4.4 (VetRay GmbH). For counting the number of metallic fragments in the carcass, a grid was placed on the picture. If the number of fragments differed between the latero-lateral and the ventro-dorsal view, the higher number was considered for the analysis. The maximal distance of a bullet fragment to the centre of the wound channel was measured on the latero-lateral and on the ventro-dorsal radiograph, and again the largest distance from both views was retained. Concerning a given fragment, we measured the distance along the shortest line to the wound channel. Fragments situated in limbs were excluded from this analysis as the positioning for radiography may have altered the position of the limb—and thus the fragment—in relation to the wound channel. Distances are given with an accuracy of 0.5 cm. As in some cases the exact course of the wound channel was difficult to characterise exactly, especially in the abdominal viscera, we approximated the location of the wound channel by the linear course of the bullet path.

Statistical analyses

Statistical analyses were conducted in IBM SPSS Statistics Version 23.0 (IBM Corp., Armonk, NY, USA) and R Version 3.5.2 (R Core Team, 2019).

We analysed the relationship between the lead content of the bullets (lead-free vs. lead-based) and two variables—the number of bullet fragments and the maximal distance of the fragments in relation to the wound channel (hereafter referred to as "number of fragments" and "maximal distance from wound channel", respectively) using two statistical frameworks. First, we applied non-parametric tests assessing differences in ranks between groups. Specifically, we compared whether the number of fragments and the maximal distance from wound channel differed between the 5 types of bullets using the Kruskal–Wallis rank sum test as implemented in the function kruskal.test() in R. Since the outcomes of both Kruskal–Wallis tests were significant, we further performed a post-hoc comparison of all possible pairwise comparisons between the bullet types using the Dunn's test as implemented by the function dunn.test() from the package dunn.test version 1.3.5 (Dinno 2017). For the computation of this test, we set the option *method* to"holm" to perform Holm's family-wise error rate correction for multiple testing and the option *altp* to TRUE to obtain *p*-values compatible with other implementations of the same test. As an alternative post-hoc test, we performed the Dwass–Steel–Critchlow–Fligner test as implemented in the R package NSM3 version 1.12 (Schneider et al. 2018). However, since we obtained results qualitatively similar to those obtained using the Dunn's test, we only report the former for the sake of simplicity. We also compared whether the number of fragments and the maximal distance from wound channel differed between the lead-free and lead-based bullets using the

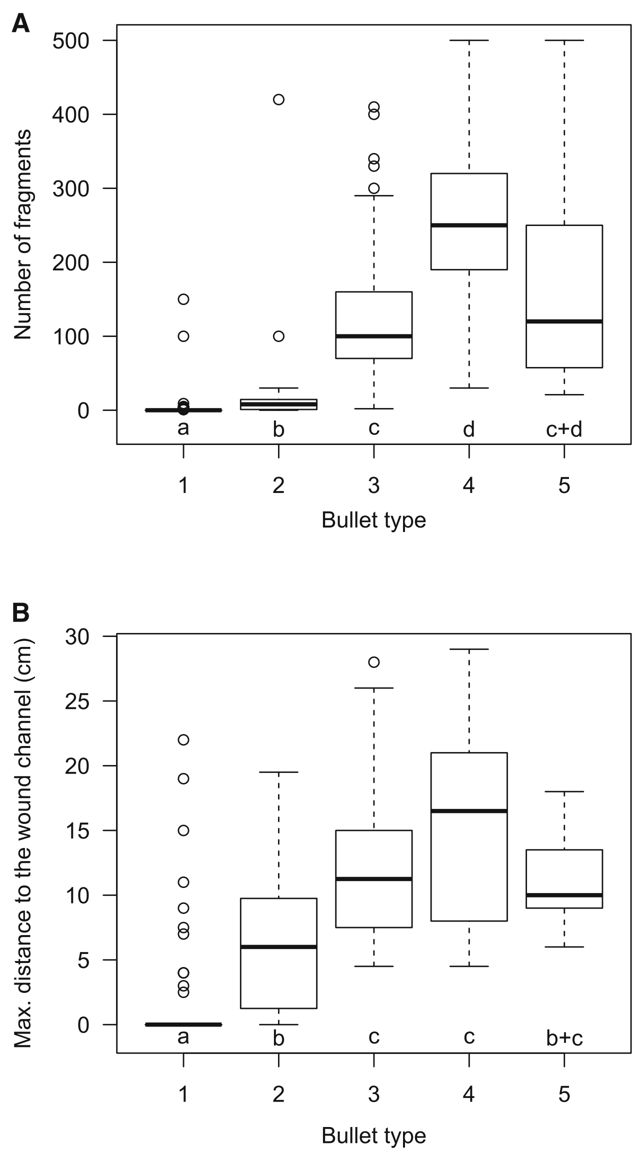

Fig. 1 Relationship between the bullet type and the number of bullet fragments (**a**) or the maximal distance of fragments to the wound channel (**b**). Data are presented as box plots with the box showing the interquartile range and the central line indicating the median. The ends of the whiskers represent the last data point lying within a distance of no more than 1.5 times the interquartile range away from the box. Groups sharing a common letter (below each box plot) did not significantly differ ($p > 0.05$) as assessed by the Dunn's test, and those not sharing a letter did ($p \leq 0.05$)

Mann–Whitney U test as implemented in the function wilcox.test() in R.

Second, we used the framework of logistic regressions to characterise more finely the relationship between the use of lead and the number of fragments or the maximal distance from wound channel. The distributions of the two latter variables in relation to the bullet type (see Fig. 1) prevented us from using them as response variables. Instead, we thus chose to predict the lead content of the bullets (a binary response variable) from the number of fragments and the maximal distance from wound channel. We recall that linear regression models make no assumption with respect to causality but only about exogeneity. So, albeit somewhat less intuitive, this way of analysing the data is correct and justified by the trade-off between the respect of model assumptions vs cognitive simplicity. Each of the two predictors was considered in separate models due to the large collinearity between them. The two models controlled for the effect of the shooting distance as a covariate with 3 categories (0 to 50 m, 51 to 100 m or more than 100 m) and were fitted using the function glm() in R with family argument set to binomial(link = "log"). The model assumptions were evaluated using the R package DHARMa version 0.2.2 (Hartig 2019).

Because the sample size differed between bullet types, we subsampled our dataset by drawing a number of observations equal to the minimal number of observations observed among bullet types (i.e. 19 per bullet type once we have discarded missing values, so 95 in total). As an alternative, we also fitted the same models as generalised linear mixed-effect models in the R package spaMM version 2.6.1 (Rousset and Ferdy 2014), considering the bullet model (21 levels) as a random effect. The benefit of such model is that it controls for the pseudo-replication in the data without having to discard any observation. However, since the conclusions were very similar to those obtained using simple generalised linear models, we only present the results of the simplest approach.

RESULTS

We found clear differences in the number of fragments and in the maximal distance from wound channel depending on the five types of bullets we investigated (number of fragments: Kruskal–Wallis test, $\chi^2 = 238.04$, $df = 4$, $p < 0.001$; maximal distance: $\chi^2 = 179.67$, $df = 4$, $p < 0.001$; see Fig. 1 for post-hoc tests). Both the number of fragments and the maximal distance from wound channel were clearly higher in lead-based than in lead-free bullets (number of fragments: Mann–Whitney U test, $W = 397$, $p < 0.001$; maximal distance: $W = 1022$, $p < 0.001$; Fig. 1; Tables 1 and 2).

Table 1 Number of bullet fragments identified on radiographs of wild ungulates killed by hunters in this study with five different types of bullets

Bullet type	*N*	Minimum	Maximum	Median	Mean	S.E.M.	S.D.
1	126	0	150	0	2	1	16
2	31	0	420	8	25	14	76
3	93	2	410	100	124	8	81
4	24	30	500	250	252	21	101
5	23	21	500	120	167	29	140

Table 2 Maximal distance [cm] of bullet fragments to the wound channel measured on radiographs of wild ungulates killed by hunters in this study with five different types of bullets

Bullet type	*N*	Minimum	Maximum	Median	Mean	S.E.M.	S.D.
1	117	0.0	22.0	0.0	0.9	0.3	3.4
2	20	0.0	19.5	6.0	6.6	1.3	6.0
3	82	4.5	28.0	11.3	11.7	0.6	5.2
4	22	4.5	29.0	16.5	15.6	1.5	7.2
5	19	6.0	18.0	10.0	11.3	0.8	3.3

We detected metallic particles of different size and morphology in the wound channel and its surroundings on all radiographs of animals shot with lead-based bullets. Small fragments clustering together to clouds of radiodense particles were predominating. Bone hits were not required for the production of a large number of fragments. This fragmentation pattern was similar for all three types of lead-based bullets, including bonded bullets (Figs. 2, 3).

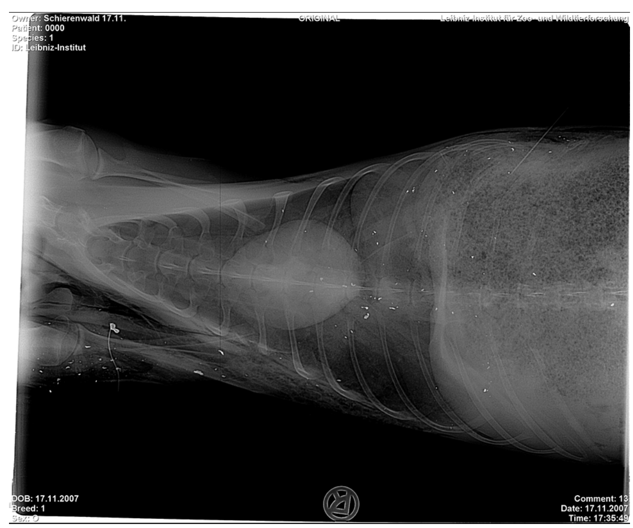

Fig. 2 Radiograph (ventro-dorsal view) of a roe deer shot with a semi-jacketed bullet. Bullet fragments are visible as white particles. Medical cannulas mark the entry and exit wounds

Fig. 3 Radiograph (ventro-dorsal view) of a wild boar shot with a controlled expansion bullet with two lead cores. See Fig. 2 for legend details

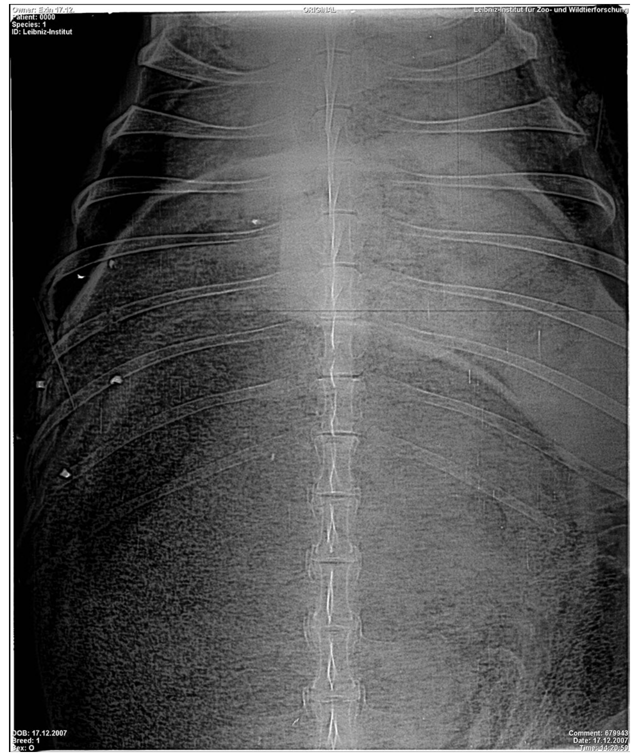

Fig. 4 Radiograph (ventro-dorsal view) of a fallow deer shot with a partially fragmenting lead-free bullet. See Fig. 2 for legend details

Average fragment numbers were highest for bullets with two lead cores (type 4) (Table 1, Fig. 1a).

The bodies of animals shot with lead-free projectiles did not always contain fragments (Table 1). When hunters used lead-free deforming bullets (type 1) no fragments were detectable on the radiographs in most 106 out of 126 cases (Fig. 1a). In 18 out of the 20 remaining cases, the number of bullet fragments on the radiographs did not exceed 10. The two remaining cases of fragmentation corresponded to a large number of fragments (100 and 150 particles) and concerned two different brands of bullets.

Radiographs of animals shot with lead-free partially fragmenting bullets (type 2) revealed less and larger fragments than those of lead-based bullets (Table 1, Figs. 1a, 4). Because fragmentation patterns of lead-free bullets have not been widely documented, we provide here a summary of our measurements. The majority of the fragments given off by lead-free partially fragmenting bullets were larger in size than those of lead-based bullets. With respect to the number of fragments we observed marked differences between bullet brands belonging to this bullet type. Descriptive statistics for the number of fragments of the three most common brands of this type (referred to as bullet "a" to "c") are listed in Table 3. Bullet "b" left 1–4 relatively large fragments (petals) in 11 out of 13 cases. Concerning the remaining two cases, it fragmented to an unexpected extent (100 fragments and 420 fragments).

Table 3 Number of bullet fragments identified on radiographs of wild ungulates killed by hunters in this study with three different brands of lead-free partially fragmenting bullets (type 2)

Bullet brand	*N*	Minimum	Maximum	Median	Mean	S.E.M.	S.D.
a	7	8	30	14	17	3	8
b	13	0	420	1	41	32	117
c	10	0	25	10	11	2	7

Lead-based bullets left back fragments along the entire length of the wound channel (Figs. 2, 3). Fragments could be seen in the skin and subcutaneous tissue as well as in muscles and in the viscera.

Average maximal distances of fragments in relation to the wound channel were highest for lead-based bullets with two lead cores (type 4) and smallest for the two types of lead-free bullets (type 1 and type 2) (Table 2, Fig. 1b). For all three types of lead-based bullets (types 3, 4 and 5) the mean maximal distance of fragments to the wound channel exceeded 10 cm (11.7 cm for type 3, 15.6 cm for type 4, and 11.3 cm for type 5).

The fit of the two statistical models confirmed that the use of a lead-based bullet was strongly associated with the

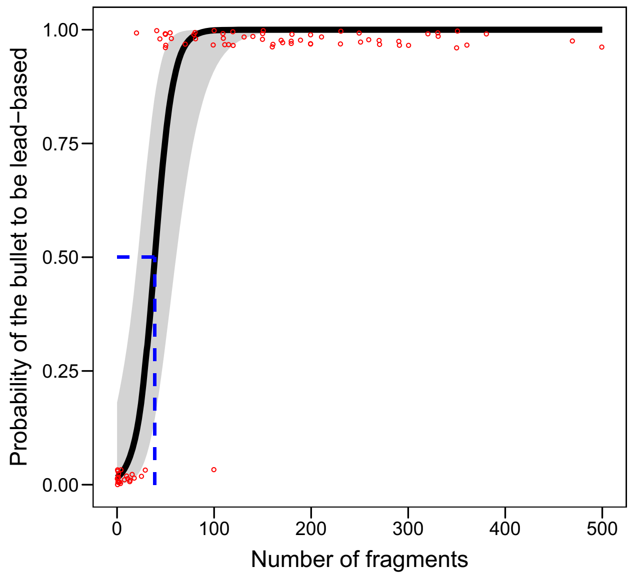

Fig. 5 Predicted probability for the bullet to be lead-based as a function of the number of fragments. The black curve depicts the mean prediction and the grey ribbon depicts the 95% confidence interval (predictions and CI were computed at the scale of the logit link and then back-transformed using the logistic function). The predictions have been computed for a short shooting distance (lower than 51 m) but the effect of the shooting distance is not significant and has little influence on predictions. The blue dashed segment indicates the value of the predictor leading to a probability of 0.5. The red points show the (jittered) raw data (for all shooting distances) from the sub-sampled dataset. Predictions for higher number of fragments are not depicted as we lack data for a reliable inference

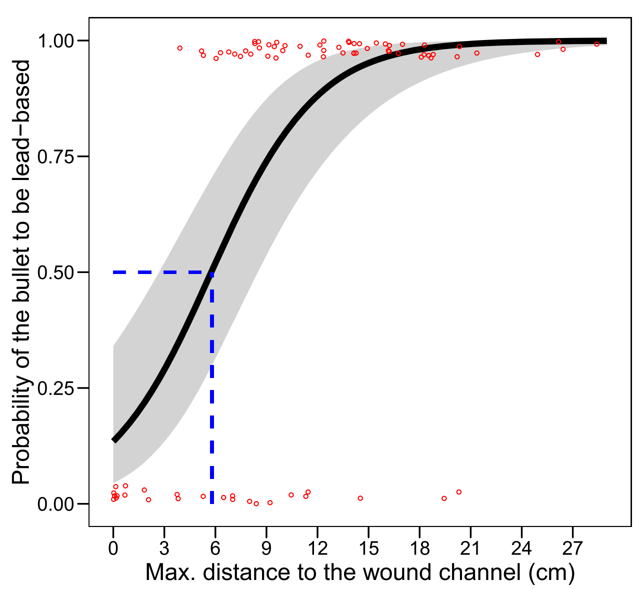

Fig. 6 Predicted probability for the bullet to be lead-based as a function of the maximal distance of fragments to the wound channel. As for the number of fragments, the predictions have been computed for a short shooting distance but the effect the shooting distance is not significant and has little influence on predictions. See Fig. 5 for legend details

number of bullet fragments in the carcass as well as the maximal distance between these fragments and the wound channel (Figs. 5, 6). Indeed, the probability for the bullet to be lead-based became higher than 50% (for short shooting distance) as soon as the number of fragments was higher than 39 (Fig. 5) or that the maximal distance of fragments to the wound channel was higher than 5.8 cm (Fig. 6). The relationship between the presence of lead in the bullet and the number of fragments or the maximal distance from the wound channel were both strongly significant (number of fragments: Likelihood Ratio Test, $\chi^2 = 104.2$, $df = 1$, $p < 0.001$; maximal distance from wound channel: LRT, $\chi^2 = 52.6$, df = 1, $p < 0.001$), but the effect of the shooting distance did not reach significance in either models (LRT, $\chi^2 = 1.46$, $df = 2$, $p = 0.48$; LRT, $\chi^2 = 1.68$, $df = 2$, $p = 0.43$).

DISCUSSION

Our data show that it is possible to predict the probability of the bullet used to be lead-based on the basis of the fragmentation pattern alone. The thresholds for having a probability of more than 50% for the bullet to be lead-based (number of fragments $\geq$ 39, maximal distance to the wound channel $\geq$ 5.8 cm) are particularly small when considering that the average number of fragments for lead-based bullets was 153 ± 107 (mean ± SD) and the average maximal distance of lead-based bullets' fragments from the wound channel was 12.3 ± 5.55 cm. We were able to illustrate that a large fragmentation pattern which is neither desirable in terms of a responsible handling of meat nor from the toxicological point of view is clearly linked to the use of bullets containing lead.

The radiographic appearance of the wounds produced by lead-based hunting ammunition and evaluated in this study match the "snowstorm" pattern described in forensic literature (Brogdon and Messmer 2011): large clouds of small radiodense particles. Our results are consistent with those of previous studies in game animals (Hunt et al. 2009; Grund et al. 2010; Knott et al. 2010) or viscera (Hunt et al. 2006; Knott et al. 2010; Cruz-Martinez et al. 2015) as well as in ballistic soap (Gremse et al. 2014) which found high numbers of fragments associated with lead-based bullets. Knott et al. (2010) estimated an average weight of metal fragments, mostly lead, of 1.2 g in the carcass and 0.2 g in the viscera. Furthermore, they showed that the majority of fragments produced by lead-based bullets were very small. We did not measure fragment size, but also found that clusters of small particles were typical for lead-core bullets. Considering the results of Kollander et al. (2017) who detected lead nanoparticles surrounding the wound channel in game animals shot with lead-based bullets, we assume that there are, yet, much smaller fragments which could not be identified by radiography.

According to our data, the overall fragmentation pattern is similar for all types of lead-core bullets tested. Our results are consistent with those of Stokke et al. (2017) who reported average rates of metal loss of 18–26 and 10–25% for lead-core and bonded lead-core bullets in bodies of moose. For hunters who prefer deforming bullets with no or little loss of bullet mass, bonded lead-core bullets do not seem to be a reliable choice. In our study, the highest fragment counts and largest distances of fragments in relation to the wound channel belonged to bullets with two lead cores of different hardness (type 4). This is probably due to the fact that the front core disassembles completely.

Lead-free deforming bullets (type 1) resisted fragmentation in most cases. There were two cases of unexpectedly high fragment counts showing 100 and 150 bullet fragments, respectively. For one of the brands concerned, a companion study showed a tendency to fragment at high impact velocities in blocks of ballistic soap (Trinogga et al., unpublished). Yet, we cannot preclude mislabelling in the shooting report concerning both cases. The untypical fragmentation found here might also be the result of obstacles in the bullets' trajectory before impact.

The extent to which lead-free partially fragmenting bullets (type 2) undergo fragmentation seems dependent on the actual bullet construction and the properties of the bullet material. We found marked differences between three bullet brands belonging to this bullet type. The fragmentation pattern, yet, strongly differed from the "lead snowstorm" found for all types of lead-core bullets. We did not see clusters of small metallic particles on the radiographs of animals shot with lead-free partially fragmenting bullets except for two cases of untypical fragmentation with 100 and 420 fragments both concerning the same brand. Again, mislabelling cannot be precluded. Regarding the case of 420 fragments, the hunter reported an obstacle (a branch of a tree) within the bullet's trajectory. The fragmentation process is likely to have been altered by the collision with this obstacle. Nevertheless, we decided not to exclude the shots with surprisingly high fragment counts from the analysis because their exclusion would not alter the results. Moreover, an exclusion of these cases would not change the conclusions regarding the number of fragments because the differences between lead-free and lead-core bullets would then be even larger.

Our findings with respect to the fragmentation patterns of lead-free bullets match those described by Hunt et al. (2006), Grund et al. (2010), Irschik et al. (2013) and Cruz-Martinez et al. (2015) as well as the results of Gremse et al. (2014) in ballistic soap. Stokke et al. (2017) found a relative loss of bullet mass of 0 to 15% concerning copper bullets which also is consistent with the results of our study. To our knowledge, there is no published study assessing whether the use of copper bullets results in the presence of copper nanoparticles as examined by Kollander et al. (2017) with regard to lead-based bullets and lead nanoparticles.

Fragments of all three types of lead-core bullets were found distant from the wound channel. The mean maximal distances found in this study were lower than the average of 24 cm reported by Hunt et al. (2009), but still corresponded to a large distance with respect to meat preparation. Fragments of non-lead bullets, too, can travel considerable distances through the animal's body as shown by the extreme values of 22 cm and 19.5 cm for lead-free deforming bullets (type 1) and lead-free partially fragmenting bullets (type 2), respectively. They should, however, be much easier to find and remove during the process of trimming the carcass because of their larger size.

Lead concentrations in venison derived from game animals shot with lead-based bullets vary considerably (Lindboe et al. 2012; Fachehoun et al. 2015; Gerofke et al. 2018). Extremely high values have been reported for some samples (Gerofke et al. 2018). The fragmentation patterns shown by lead-based bullets in this study support the opinion that large amounts of meat have to be discarded during trimming if lead-core bullets are used (BfR 2010). Fragments situated distant to the wound channel (and therefore not being removed from the carcass) can result in intolerable high lead contents of the meat. Moreover, small bullet fragments may be spread throughout the carcass by rinsing as was shown by Grund et al. (2010). Our results therefore go in line with the recommendations of several European Food Safety Authorities recommending vulnerable consumers not to eat meat of lead-killed game (Knutsen et al. 2015).

A study using ballistic soap as a tissue simulant showed an effect of the impact velocity on the number of fragments for both lead-based and lead-free bullets (Gremse et al. 2014). Our data did not allow to control for the this as the actual impact velocity of the bullets was not known. Hunters reported their shooting distance—which influences the impact velocity—in categories of 50 m resulting in a considerable uncertainty when computing impact velocity. We therefore refrained from studying its effect. Shooting distance was included in the model as a covariate but did not have a significant effect. A potentially existing effect may have been masked by the broad variety in calibres and thus in bullet mass and velocity at a given distance. Nevertheless, the goal of our study was to illustrate the fragmentation pattern under normal hunting conditions covering the broad range of situations in which trained hunters take the decision to harvest an animal.

We also did not control for the length of the wound channel. If the bullet travels a longer distance through a body the probability of releasing more fragments may increase. Differences in wound channel length among the bullet types cannot be precluded. Yet, the effect demonstrated by our evaluation is so clear that the overestimation of fragment counts for lead-based bullet types would not alter the conclusions.

The role of bullet fragmentation in wounding mechanisms is controversial. Some authors claim that fragmentation augments the damage done by the bullet to the tissue and results in a stronger wounding effect (Fackler et al. 1984; Caudell et al. 2012). On the contrary, no hint to a higher efficiency of fragmenting bullets was found in a study comparing wound size and morphology by the means of computed tomography and post mortem macroscopical examination (Trinogga et al. 2013), nor by the evaluation of simulation tests with ballistic soap as a tissue surrogate (Gremse et al. 2014). Several field tests also did not reveal a superiority of fragmenting bullets (Knott et al. 2009; Kanstrup et al. 2016; Martin et al. 2017).

CONCLUSION

Under normal German hunting conditions, lead-based bullets commonly contaminate the harvested carcass on a large scale, as well as the viscera. This study illustrates that the use of lead-based hunting rifle bullets induces public health and ethical issues. Besides the fact that it can threaten wildlife and human health, using lead-based bullets augments the probability of having to remove and discard large portions of meat, resulting in substantial food waste. The adequacy of lead-free hunting bullets in terms of animal welfare (Knott et al. 2009; Trinogga et al. 2013; Gremse et al. 2014; Kanstrup et al. 2016; Martin et al. 2017), toxicity (Irschik et al. 2013; Schlichting et al. 2017) as well as regarding security aspects (Kneubuehl 2011) has been shown. Consequently, with regard to nature conservation, consumer health and a responsible handling of food, the replacement of lead-based hunting rifle bullets by non-lead alternatives should be further encouraged.

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