Aus dem Leibniz-Institut für Zoo- und Wildtierforschung

eingereicht beim Fachbereich Veterinärmedizin
Professur für interdisziplinäre Zoo- und Wildtierkunde
Freie Universität Berlin

Comparison of the performance and fragmentation of common lead-free and lead-based hunting rifle bullets in shot wild ungulates and in ballistic soap

Inaugural-Dissertation
zur Erlangung des Grades eines
Doktors der Veterinärmedizin
an der
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vorgelegt von
Anna Lena Trinogga
Tierärztin
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Abbreviations

A	cross-sectional area
A_{entry}	cross-sectional area of the entry wound [unit: square centimeters]
A_{exit}	cross-sectional area of the exit wound [unit: square centimeters]
A_{max}	maximum cross-sectional area of damaged tissue [unit: square millimeters]
Amtsbl.	official legal gazette of the German Federal State of Saarland (*Amtsblatt des Saarlandes*)
BfR	German Federal Institute for Risk Assessment (*Bundesinstitut für Risikobewertung*)
BgBl. I	part I of the official legal gazette of the Federal Republic of Germany (*Bundesgesetzblatt Teil I*)
BMBF	German Federal Ministry of Education and Research (*Bundesministerium für Bildung und Forschung*)
DEVA	*Deutsche Versuchs- und Prüfanstalt für Jagd- und Sportwaffen e. V.*
df	degrees of freedom
DJZ	*Deutsche Jagdzeitung*
E	kinetic energy [unit: Joule]
E_{dis}	kinetic energy dissipated into the target [unit: Joule]
$E_{dis,rel}$	relative amount of kinetic impact energy dissipated into the target (dimensionless, in %)
E_{imp}	kinetic energy at impact [unit: Joule]
E_{res}	residual kinetic energy [unit: Joule]
EC	European Commission
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
fig.	figure

FU	*Freie Universität Berlin*
GBl.	official legal gazette of the German Federal State of Baden-Württemberg (*Gesetzblatt für Baden-Württemberg*)
GVBl.II	official legal gazette of the German Federal State of Brandenburg (*Gesetz- und Verordnungsblatt für das Land Brandenburg, Teil II – Verordnungen*)
GV. NRW	official legal gazette of the German Federal State of North Rhine-Westphalia (*Gesetz- und Verordnungsblatt für das Land Nordrhein-Westfalen*)
GVOBl.	official legal gazette of the German Federal State of Schleswig-Holstein (*Gesetz- und Verordnungsblatt für Schleswig-Holstein*)
IZW	Leibniz Institute for Zoo and Wildlife Research (*Leibniz-Institut für Zoo- und Wildtierforschung*)
m	mass [unit: gram]
m_0	original mass [unit: gram]
m_{res}	residual mass [unit: gram]
MLUV	Ministry for Rural Development, the Environment and Consumer Protection of the German Federal State of Brandenburg (*Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz des Landes Brandenburg*)
PtJ	Project Management Jülich (*Projektträger Jülich*)
n	number of cases
SD	sectional density [unit: gram per square millimeters]
S.D.	standard deviation
S.E.M.	standard error of the mean
v	velocity [unit: meters per second]
v_{imp}	impact velocity [unit: meters per second]
v_{res}	residual velocity [unit: meters per second]

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1 General introduction and thesis outline

Hunting wildlife with firearms is a widespread tool for wildlife management and for food production. The adequacy of this harvesting method has to be judged regarding animal welfare aspects and its consequences for biological conservation. In this thesis, the word “hunting” is used in terms of shooting of wildlife.

1.1 Purpose and framework of this thesis

In 2005, the Leibniz Institute for Zoo and Wildlife Research (IZW) organised a stakeholder meeting in order to discuss lead-poisoning in white-tailed eagles (*Haliaeetus albicilla*) and to identify further research necessities related to this problem (Krone and Hofer 2005). Besides scientists from the fields of wildlife biology and veterinary medicine, representatives from hunter associations, forest management agencies, ammunition manufacturers as well as nature conservation organisations participated in this meeting. As a consequence, the IZW initiated the interdisciplinary project “Lead poisoning in white-tailed eagles – causes and approaches to solutions” funded by the German Federal Ministry of Education and Research (*Bundesministerium für Bildung und Forschung*, BMBF). This project included three stakeholder conferences to share the results and discuss further approaches to the problem of lead poisoning in birds of prey (Krone 2011 and 2008). The present thesis represents the results of one part of this project focusing on the adequacy of lead-free rifle bullets for hunting purposes in terms of animal welfare. Data were collected between 2006 and 2009.

1.2 Structure of the thesis

Chapter two (Literature review) provides an overview to the literature available with regard to the subject of this thesis.

The results of the thesis are presented in chapters three to five:

Chapter three (*Trinogga AL, Courtiol A, Krone O. Fragmentation of lead-free and lead-based hunting rifle bullets under real life hunting conditions in Germany, published in Ambio 48 (9), 2019: 1056-1064*) describes and discusses the fragmentation pattern of lead-free and lead-based hunting rifle bullets in game animals. This part of the study is based on the evaluation of radiographs taken during regular hunts in several 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. Knowledge about the fragmentation characteristics of bullets is important for the understanding of their wounding ability as well as for the understanding of the degree to which bullet fragments contaminate the carcass and the offal.

Chapter four (*Trinogga A, Fritsch G, Hofer H, Krone O. Are lead-free hunting rifle bullets as effective at killing wildlife as conventional lead bullets? A comparison based on wound size and morphology, published in Science of the Total Environment 443, 2013: 226-232*) compares wound channel characteristics in bodies of wild ungulates shot with lead-free and lead-based bullets during regular hunts. Computed tomography (CT) and postmortem macroscopic examinations were used in order to quantify wound diameters which can be regarded as a measure of the wounding ability of a given bullet. The animals were donated by participating forest management units of the Federal Republic of Germany and the federal states of Bavaria, Brandenburg and Schleswig-Holstein. Computed tomography was done at the Small Animal Clinic of the Faculty of Veterinary Medicine of *Freie Universität Berlin*, necropsies were performed at the IZW.

Chapter five (From ballistic soap to animal welfare – do lead-free hunting rifle bullets have a lower wounding potential than lead-based bullets?) presents the results of wound ballistic simulation experiments. The ballistic simulation testing was conducted by the Deutsche Versuchs- und Prüfanstalt für Jagd- und Sportwaffen (DEVA) in 2007 on behalf of the IZW. In this chapter, cavity diameters in blocks of ballistic soap are compared for lead-free and lead-based bullets. Cavity dimensions in a simulant medium display the potential of a bullet to interact with a target and therefore can be regarded as a measure of the wounding potential. This chapter represents an unpublished manuscript prepared for submission to a peer-reviewed journal.

In Chapter six (General discussion) I draw the results of the preceding chapters together and discuss the significance of these results for the evaluation of hunting rifle bullets in terms of killing efficacy and therefore animal welfare.

1.3 References

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Krone O (ed.) (2011): Bleivergiftungen bei Greifvögeln. Ursachen, Erfahrungen, Lösungsmöglichkeiten. Der Seeadler als Indikator. Berlin: Leibniz Institute for Zoo and Wildlife Research – ISBN 978-3-00-033402-3. (in German)

2 Literature review

2.1 Hunting as a source of lead in the ecosystem

During the last years, considerable information has been accumulated as to the risks imposed to wildlife and humans by the use of lead-based hunting ammunition. Lead is toxic to both humans and wild vertebrates and its use has been restricted in many sectors especially with regard to paints and petrol (Treu et al. 2020; UNEP 2016). As even a low dosage of lead intake is likely to harm human health, especially the neurological development of children, tolerable intake levels for lead do not exist and cannot be defined (EFSA 2013). The shooting of wildlife during hunting, however, still results in the deposition of remarkable quantities of lead in the ecosystem (Treu et al. 2020). It has been well documented that lead fragments of hunting ammunition represent a serious threat to many scavenging wildlife species such as the white-tailed eagle (*Haliaaetus albicilla*), the endangered California Condor (*Gymnogyps californianus*) and many others (Pain et al. 2019; Krone 2018; Cruz-Martinez et al. 2015; Hunt et al. 2009a; Hunt et al. 2006; Krone et al. 2003; Saito 2000; Kim et al. 1999; Scheuhammer and Templeton 1998). In addition, lead fragments in venison derived from rifle-killed ungulates may harm consumers' health (Green and Pain 2019; Gerofke et al. 2018; BfR 2012 and 2010; Hunt et al. 2009b).

Until now, restrictions on the use of lead-based hunting ammunition are inconsistent. While the use of lead shot in wetlands has been restricted in many countries for several years, legal restrictions on lead-based rifle bullets have not been implemented except for some German states[1], in California, in parts of Japan (Hokkaido) and in Mauretania (Treu et al. 2020; Mateo and Kanstrup 2019; Saito 2009). Following a request of the European Commission (EC), the European Chemicals Agency (ECHA) has assessed the risks related to the use of lead-based hunting bullets and other applications (sport shooting, fishing weights). In February 2021, ECHA brought forward a proposal including EU-wide restrictions on the use of lead in hunting ammunition (ECHA 2021).

2.2 Concerns about the use of lead-free bullets

Since the beginning of the twentieth century lead-based semi-jacketed rifle bullets have been used for hunting wildlfe (Kneubuehl 2008; Karger 2004). Their lead core is surrounded by a copper, brass or steel jacket which is open at the bullet's tip. So, upon impact on a target, the lead core is directly exposed to high pressure causing a rapid deformation and fragmentation

[1] cf. hunting laws and regulations of the federal states of Baden-Württemberg [section 31 (1) number 4 *Jagd- und Wildtiermanagementgesetz des Landes Baden-Württemberg*], Brandenburg [section 4 (11) *Verordnung zur Durchführung des Jagdgesetzes für das Land Brandenburg],* North Rhine-Westphalia [section 19 (1) number 3 *Landesjagdgesetz Nordrhein-Westfalen*], Saarland [section 32 (1) number 7 *Saarländisches Jagdgesetz*] and Schleswig-Holstein [section 29 (5) number 2 *Jagdgesetz des Landes Schleswig-Holstein*]

of the bullet (Kneubuehl 2008). Typically, a high number of fragments - mostly lead - is distributed within and beyond the wound channel (Menozzi et al. 2019; Cruz-Martinez et al. 2015; Brogdon and Messmer 2011; Grund et al. 2010; Hunt et al. 2006). These fragments may contaminate venison (Green and Pain 2019; Menozzi et al. 2019, BfR 2012 and 2010; Hunt et al. 2009b) and are accessible to scavengers feeding on the remains of rifle-killed wildlife if the carcass or parts of it are left in the environment (Pain et al. 2019; Krone 2018; Hunt et al. 2006; Saito 2000). Therefore, from the point of view of biological conservation as well as from the perspective of consumer protection, it appears obvious to strive for a replacement of lead-based hunting bullets. Lead-free projectiles – mostly made of copper or copper alloys - have existed for at least two decades, but their appropriateness for hunting purposes has been the subject of controversial discussions (BfR 2012; Zieschank 2008; Klups 2006a-f and 2005a-g). Concerns have been raised about the wounding capacity of lead-free hunting rifle bullets. The lower specific weight of copper and other substitutes, resulting in either lighter or longer projectiles, and differences regarding the deformation and fragmentation processes were mentioned as possible causes for a potentially lower killing efficacy of lead-free bullets. In 2006, when the IZW started the interdisciplinary project to which the part in which I obtained the results for this thesis belongs, only few data were available with regard to the adequacy of lead-free bullets for hunting wildlife. Since then, several field studies were conducted - for instance in Great Britain (Knott et al. 2009), Denmark (Kanstrup et al. 2016), Germany (Martin et al. 2017), Scandinavia (Stokke et al. 2019) and Australia (Hampton et al. 2021), none of which found significant differences between the killing efficacies of lead-free and lead-based bullets.

2.3 Animal welfare requirements regarding shooting wildlife during hunts

In Germany, animal welfare has been defined as a national objective in article 20a of the German Basic Law (*Grundgesetz der Bundesrepublik Deutschland*) in the year 2002. Section 4 (1) of the German Animal Welfare Act (*Tierschutzgesetz der Bundesrepublik Deutschland*) defines requirements for an acceptable reason to kill vertebrates as it states that the infliction of every superfluous pain to the animal has to be avoided. This is in line with ethic codices of hunters claiming that hunting practices have to protect shot animals from avoidable pain (DJV 2020). Nevertheless, further regulations only provide a few technical details concerning the legitimacy of rifle ammunition applied to shooting wildlife for hunting. So, section 19 (1) of the German Hunting Law (*Bundesjagdgesetz*) demands certain minimum calibres with minimum impact energies to be used for killing wild ungulates but requires no formal standardised licensing procedure by government authorities regarding the characteristics of hunting bullets in terms of their wounding potential prior to their entry to the commercial market. Whereas the effects of military bullets on tissues have been widely studied (Jussila 2005; Coupland 1999;

Fackler 1996; Janzon 1982a; Scepanovic and Ahlbreht 1982; Tikka et al. 1982; Berlin et al. 1977), few data on wound ballistics of different hunting bullet constructions have been published.

2.4 Wound ballistics of rifle bullets

Wound ballistic research is meant to describe the interaction of bullets with living tissue. Knowledge on what happens when a bullet strikes a body is important for surgery as well as forensic medicine. Consequently, most wound ballistic studies have focussed on the effect of military and police ammunition (Jussila 2005; Coupland 1999; Janzon 1982a; Scepanovic and Albreht 1982; Tikka et al. 1982; Berlin et al. 1977; Amato 1974a and b).

Spencer (1908) states that a bullet's wounding potential is influenced by its kinetic energy and by the ability to transfer this energy to the target. Kneubuehl et al. (2008) and Karger (2004) describe the wounding effects of bullets as being determined by bullet traits as well as by the characteristics of the target tissues. They mention different mechanisms by which the transition of a bullet causes damage to living tissue: stretch and shearing of tissues as well as pressure changes due to the formation of the temporary wound cavity, direct crushing of tissues and shock waves.

The temporary wound cavity is caused by radial acceleration of tissues adjacent to the wound tract. The cavity can be regarded as a kind of hollow cylinder. It opens and collapses several times when the bullet passes through tissue (Kneubuehl et al. 2008). Tissues are stretched and sheared due to displacement. As the resistance to elongation and shearing differs between tissues, the effects of temporary cavitation depend on the anatomical structures hit by the bullet. Elastic tissues such as the lungs are thought to be less damaged by temporary cavitation than organs of lower elasticity such as the liver or the brain (Karger 2004; Oehmichen et al. 2000; Amato 1974a and b). The formation of the temporary cavity causes abrupt pressure changes within the tissue, which can activate baroreceptors in blood vessels and therefore instigates reactions by the vegetative nervous system. Kneubuehl et al. (2008) mention the possibility of reflex death by excitation of baroreceptors. Theoretically, these receptors in the Sinus caroticus could be activated by pressure changes in blood vessels following the formation of the temporary wound cavity. These authors state themselves that this view is derived from plausibility arguments how in theory physical forces might develop during the interaction between the bullet and tissues and should be treated as a hypothesis.

Direct crushing of tissues due to very high pressure on the front side of the projectile is said to be a cause of tissue damage, too. According to Karger (2004) this mechanism directly induces the permanent wound cavity. Kneubuehl et al. (2008), in contrast, describe the permanent wound channel and an adjacent zone of extravasation to be resulting from the formation of the temporary wound cavity. Regardless of the underlying mechanism, the permanent wound channel is displayed in practice as a zone of complete tissue disruption and destruction.

Another phenomenon caused by the impact of a bullet on a body is the formation of a shock wave. A shock wave is a special type of acoustic wave whose wavefront is very steep (Kneubuehl et al. 2008). Because of its short duration – Karger (2004) mentions an exposure time of 0,5 µs – it is not able to transport matter (Kneubuehl et al. 2008). The role of shock waves in bullet trauma is discussed by several authors (Kneubuehl et al. 2008; Suneson et al. 1988; Wehner and Sellier 1981). Karger (2004) concludes that a traumatising effect of shock waves has not been proven and that the relevance of such waves for wound ballistics is questionable.

In summary, the effects of rifle bullets on animals can be explained by the degree and location of tissue destruction. Hits to most brain regions or to the upper spinal cord are expected to be fatal immediately. Other hit placements - as the thoracic region which is favoured in shooting practice during hunts - cause death via blood loss and subsequent cerebral hypoxia (Karger 2004).

With regard to bullet properties influencing a bullet's ability to interact with tissues, Kneubuehl et al. (2008) mention the sectional density as an important factor. Sectional density is calculated as $SD = \frac{m}{A}$, *m* being the original bullet mass and *A* being the cross-sectional area of the bullet in direction of flight. Wounds caused by bullets of comparable kinetic energy can differ strongly because of differences in the sectional density which is defined as the relation of bullet mass and the cross-sectional area of the bullet front. The amount of energy transfer is inversely linked to the sectional density (Kneubuehl et al. 2008). Consequently, deformation and fragmentation processes influence the transfer of energy – and therefore the degree of wounding – by altering the sectional density.

2.5 Approaches to measure the wounding capacity of hunting rifle bullets

Considering the above, the adequacy of a hunting bullet should be judged on the basis of its ability to damage tissue immediately. To do so, different approaches can be chosen.

Tests with live animals have been conducted in the past (for instance Suneson et al. 1988 and 1987). According to section 7a (3) of the German Animal Welfare Act (*Tierschutzgesetz der Bundesrepublik Deutschland*) animal experiments in order to develop or test ammunition are prohibited in Germany. Even if this prohibition did not exist, they would not be acceptable from an ethical point of view. Other methods for ammunition testing include wound ballistic simulation by shooting at test media (Kneubuehl et al. 2008; Karger 2004; Berlin et al. 1982, Scepanovic and Albreht 1982; Tikka et al. 1982) and the assessment of gunshot wounds of animals harvested during regular hunting activities via post-mortem examination. The reaction of the animal to the bullet hit, which means the resulting flight distance, can be used as a measure of the bullet's wounding capacity, as well (Stokke et al. 2019; Martin et al. 2017; Kanstrup et al. 2016; Stokke et al. 2012; Knott et al. 2009).

2.6 Visualisation of wound channels/bullet tracts

Radiography represents a well implemented method for the visualisation of gunshot wounds and bullet fragments (Brogdon and Messmer 2011; Thali and Dirnhofer 2004). Due to the high radiodensity of metal, metallic bullet fragments can easily be detected on radiographs. By evaluating two orthogonal projections, the analysis of fragment distribution in a target is possible. Radiographic examination of animal carcasses shot during hunts has been used to document fragmentation of hunting bullets (Menozzi et al. 2019; Grund et al. 2010; Hunt et al. 2006).

Computed tomography as a special application of radiography has become an important tool of forensic medicine and allows for the three-dimensional reconstruction of bullet channels (Thali et al. 2005 and 2003; Donchin et al. 1994). In Switzerland, computed tomography was used (Thali et al. 2007) to examine a case of illegal shooting of a lynx (*Lynx lynx*).
Another way to examine the characteristics of bullets in a target is the use of simulant media. Wound ballistic simulation has been frequently used in forensic medicine and research, especially with regard to military and police ammunition (Jussila 2005; Janzon 1982a and b; Scepanovic and Albreht 1982; Tikka et al. 1982). Kneubuehl et al. (2008) and Karger (2004) mention glycerine soap and gelatine as the two most common simulants and describe their use. Both substances strongly resemble muscle tissue because of a similar density, viscosity and fluidity (Kneubuehl et al. 2008). Gelatine reacts in an elastic way when it is deformed by a traversing bullet. The temporary cavity collapses in a similar way as does living tissue, leaving behind fissures in the gelatine block which allow conclusions as to the dimensions of the temporary cavity (Kneubuehl et al. 2008). Fackler et al. (1988) and Fackler and Malinowski (1985) described wound profiles derived from ballistic gelatine and Jussila (2005) reported the use of gelatine for testing police ammunition. On the other hand, several publications describe the use of glycerine soap (Gremse et al. 2014; Janzon 1982a and b; Scepanovic and Albreht 1982; Tikka 1982). In contrast to gelatine, soap conserves the temporary cavity in a plastic manner, displaying almost its maximal dilatation (Karger 2004). Methods to evaluate bullet channels in soap blocks are given by Kneubuehl et al. (2008) and by Janzon (1982a and b). Because of the plastic deformation of soap, measurements of bullet-induced changes in soap are more feasible than in gelatine.

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

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Dr. Oliver Krone: funding acquisition, project administration, conceptualisation of the study, supervision, revision of manuscript

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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

Anna Lena Trinogga, Alexandre Courtiol, Oliver Krone

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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 particularly 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

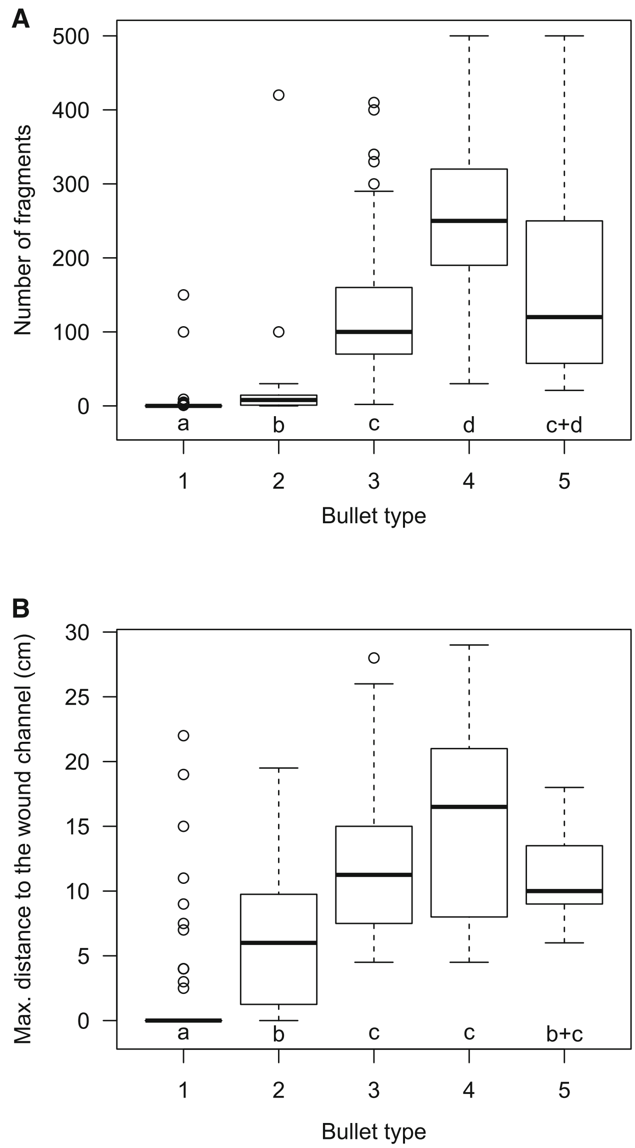

Fig. 1 Relationship between the bullet type and the number of bullet fragments (**a**) or the maximal distance of fragments to the wound channel (**b**). Data are presented as box plots with the box showing the interquartile range and the central line indicating the median. The ends of the whiskers represent 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).

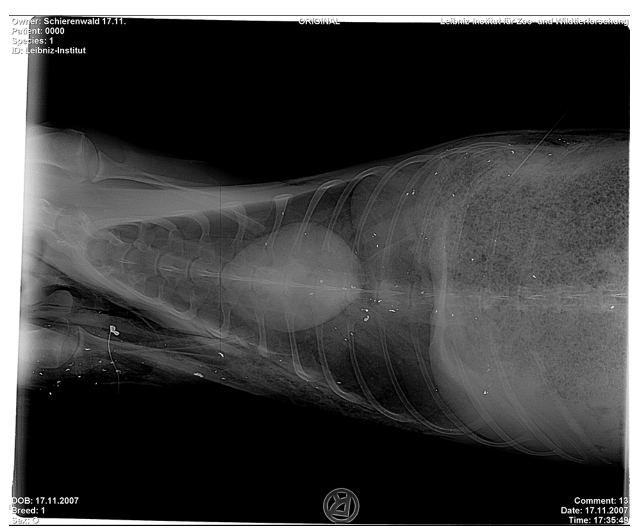

Fig. 2 Radiograph (ventro-dorsal view) of a roe deer shot with a semi-jacketed bullet. Bullet fragments are visible as white particles. Medical cannulas mark the entry and exit wounds

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

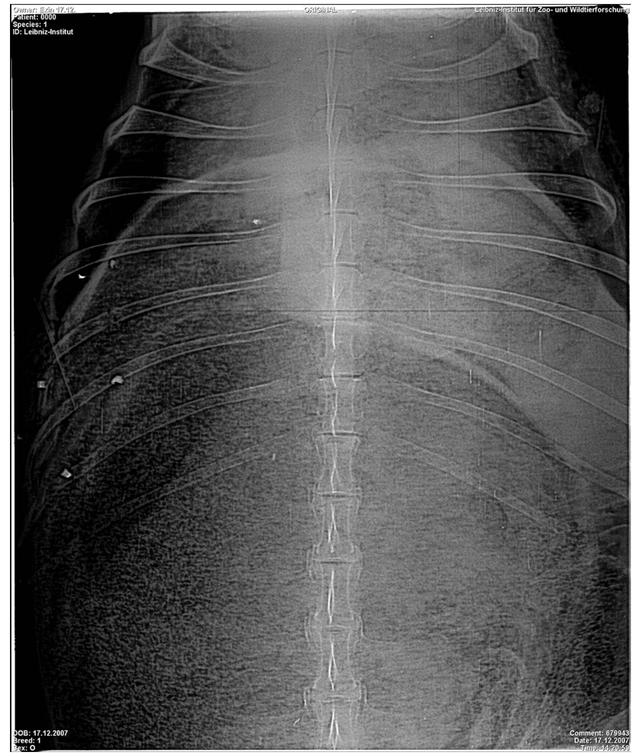

Fig. 4 Radiograph (ventro-dorsal view) of a fallow deer shot with a partially fragmenting lead-free bullet. See Fig. 2 for legend details

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.

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

Concerning the remaining two cases, it fragmented to an unexpected extent (100 fragments and 420 fragments).

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

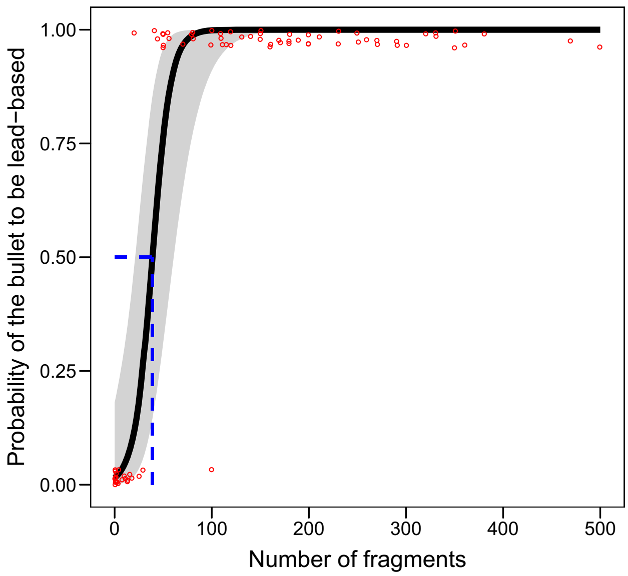

Fig. 5 Predicted probability for the bullet to be lead-based as a function of the number of fragments. The black curve depicts the mean prediction and the grey ribbon depicts the 95% confidence interval (predictions and CI were computed at the scale of the logit link and then back-transformed using the 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

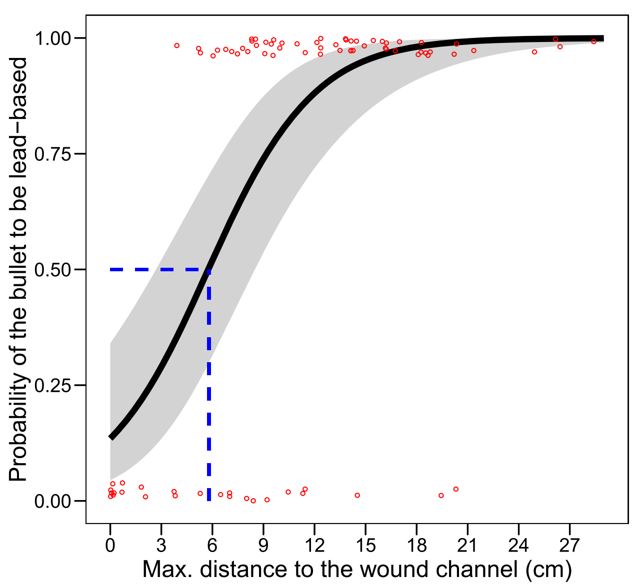

Fig. 6 Predicted probability for the bullet to be lead-based as a function of the maximal distance of fragments to the wound channel. As for the number of fragments, the predictions have been computed for a short shooting distance but the effect the shooting distance is not significant and has little 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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4 Are lead-free hunting rifle bullets as effective at killing wildlife as conventional lead bullets? A comparison based on wound size and morphology

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Anna Trinogga: conceptualisation of the study design, data acquisition, evaluation, writing of the manuscript

Guido Fritsch: conduction of CT-scans

Prof. Dr. Heribert Hofer: statistics, revision of manuscript, supervision

Dr. Oliver Krone: funding acquisition, project administration, conceptualisation of the study, revision of manuscript, supervision

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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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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 $E_{kin,i} = (1/2000)\, mv_i^2$ 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 $E_{kin,i}$ 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 πab, 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 πab 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

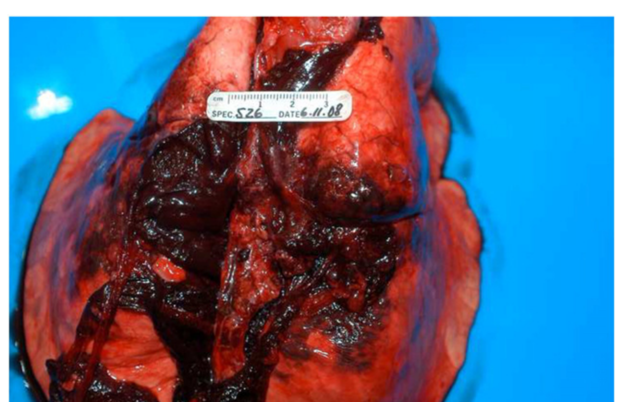

Fig. 3. Lacerations in the lung of a wild boar killed by a lead-free deforming copper bullet (Barnes XLC) (wound channel in laterolateral direction).

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/mm²]			
Mean ± S.E.M. [g/mm²]	0.245 ± 0.0051	0.185 ± 0.011	0.266 ± 0.0053
Median [g/mm²]	0.250	0.176	0.261
Range [g/mm²]	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 [cm²] at point of bullet entry A_{entry}			
Mean ± S.E.M. [cm²]	4.44 ± 1.78	5.04 ± 1.81	7.16 ± 2.64
Median [cm²]	8.35	7.00	8.10
Range [cm²]	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 [cm²] at point of bullet exit A_{exit}			
Mean ± S.E.M. [cm²]	22.39 ± 8.89	18.58 ± 9.59	20.83 ± 5.97
Median [cm²]	33.65	21.66	36.90
Range [cm²]	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

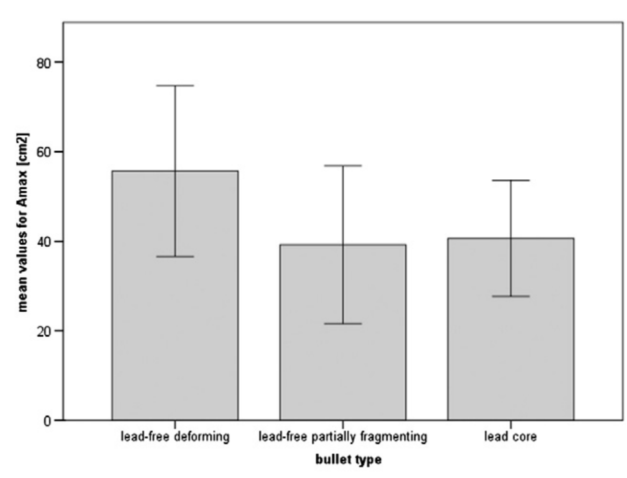

Fig. 4. Mean values ± 95% confidence limits for the maximum cross sectional area of the wound channel. Differences between bullet types are not significant.

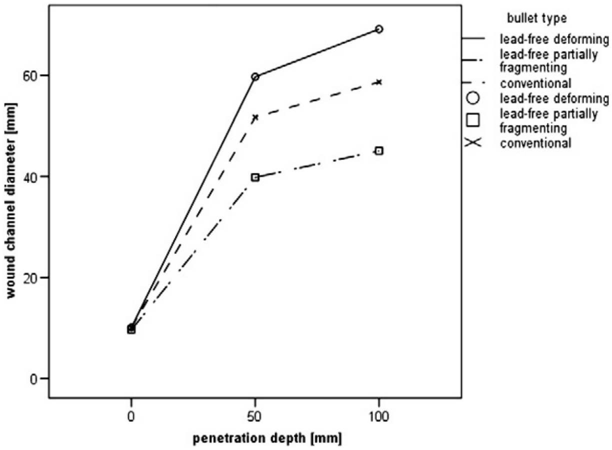

Fig. 5. Estimated marginal means of the wound diameters at three different penetration depths. Wound diameters are significantly larger after 5 and 10 cm penetration than at the entry point. Differences between lead-free types and conventional bullets are not significant.

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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5 From ballistic soap to animal welfare – do lead-free hunting rifle bullets have a lower wounding potential than lead-based bullets?

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5 From ballistic soap to animal welfare – do lead-free hunting rifle bullets have a lower wounding potential than lead-based bullets?

Abstract

The suitability of lead-free hunting rifle bullets as an alternative to toxic lead-based bullets has been discussed from the point of view of animal welfare and biological conservation for years. High animal welfare standards demand that hunting bullets should kill an animal quickly. Data on the efficacy of wounding potential (killing efficacy) for different construction types and materials of lead-based and lead-free hunting bullets are limited because experiments with live animals are unethical, cumbersome and difficult to standardise. A simple, ethical and viable alternative to assess bullet performance are simulation experiments by shooting rifle bullets at tissue simulants. We assessed energy transfer rates and cavity diameters of eight lead-free and three lead-based bullets from different manufacturers shot at blocks of ballistic soap from distances of 50 m, 100 m and 200 m. Energy transfer rates differed significantly between bullet types, with lead-free partially fragmenting bullets transferring a lower percentage of initial kinetic energy to the target than deforming lead-free or lead-based bullets. Bullet type did not affect maximum cavity diameter, but cavities of lead-free partially fragmenting bullets reached their maximum diameter significantly closer to the entry point than those of the other bullet types. Our results demonstrate that the construction principle (*fragmenting vs deformation*) of a projectile has more influence on wounding potential than bullet material (lead or non-lead). As the maximum cavity diameter was situated close to the entry point of the soap blocks for all bullet types, we conclude that they are all suitable for hunting small to medium target species. In summary, lead-free bullets did not perform worse than lead-based bullets, had a similar wounding potential as lead-based bullets and are an adequate alternative to lead-based bullets.

Key words

hunting rifle bullets, wound ballistic simulation, cavity diameter, energy transfer, lead, animal welfare

5.1 Introduction

The use of firearms to harvest wildlife is a widespread tool of wildlife management and necessary to produce venison. Every human action of killing of animals should be evaluated on the basis of protecting animals against superfluous suffering. European and national legislation acts such as section 4 (1) of the German Animal Welfare Act insist that vertebrate animals must not be killed unless they are first made unconscious. Hunting wildlife by shooting is a legal exception. In accordance with the law hunters do not stun game animals before killing them. Consequently, hunting by shooting is particularly responsible to meet high welfare standards. There is currently no official standardised testing procedure of hunting rifle bullets with respect to their wounding potential. Conducting simulation experiments by shooting at tissue simulants is a simple and ethically acceptable manner to assess bullet performance. Several studies assessing the terminal effects of military bullets in tissue simulants are available (Jussila 2005; Berlin et al. 1982; Janzon 1982a and1982b; Scepanovic and Albrecht 1982; Tikka et al. 1982; Berlin et al. 1977) but data from laboratory tests of hunting bullets are limited, particularly with respect to bullet material (lead-based or lead-free) and construction principle (partially fragmenting or deforming). As a consequence, hunters have little options but choosing a projectile based on experiences made or reported by others.

The debate on the suitability of lead-free projectiles for hunting displays this lack of evidence. The use of lead-free hunting rifle bullets has been discussed from the point of view of animal welfare and biological conservation for years. Lead intoxication caused by spent ammunition is a threat to many raptors (Krone, 2018). Radiographs of wildlife shot with standard lead-based bullets document large numbers of tiny fragments dispersed widely around the wound channel (Menozzi et al. 2019; Trinogga et al. 2013; Grund et al. 2010; Hunt et al. 2006). Fragments of lead bullets in venison can pose a risk to consumer safety and result in considerable waste of high-quality food (Trinogga et al. 2019; BfR 2010; Knott et al. 2010). While it is a commonly accepted fact that the use of non-lead bullets for hunting wildlife can prevent scavengers from taking up lead fragments with carrion (Trinogga et al. 2019; Stokke et al. 2017; Nadjafzadeh et al. 2015; Gremse et al. 2014; Hunt et al. 2006) and strengthens food safety (Gerofke et al. 2018; BfR 2010), neither the voluntary replacement of lead-based bullets nor their ban by legislative measures have been widely introduced throughout Europe or beyond (Mateo and Kanstrup 2019).

In a companion paper (Trinogga et al. 2013) we compared lead-based and lead-free rifle bullets in terms of the morphology of wound channels in ungulates shot in real life hunts. Here we are presenting tests under standardised conditions using a tissue simulant. Wound ballistic simulation is a means to compare the wounding potential of different bullet constructions. It has been frequently used to analyse terminal ballistics of military or police ammunition (Jussila

2005; Berlin et al. 1982; Janzon 1982a and 1982b; Scepanovic and Albreht 1982; Tikka et al. 1982; Berlin et al. 1977). Gremse et al. (2014) assessed the characteristics of hunting bullets in soap blocks using computed tomography.

According to Spencer (1908) the wounding potential of a bullet is determined by the bullet's kinetic energy and its ability to transfer this energy to the target. Methods to evaluate bullet channels in simulants, as given in Kneubuehl et al. (2008) and Berlin et al. (1982) are based on the proportionality between the volume of the bullet channel and the energy transferred to the simulant. Common tissue simulants are ballistic soap or ordnance gelatine (Kneubuehl et al. 2008; Jussila 2005; Berlin et al. 1977). Ballistic soap has a density very close to muscle tissue. It conserves the bullet channel at almost its maximal dilatation (Kneubuehl et al. 2008; Jussila 2005). As this deformation allows for a simple assessment and comparison of "wound" cavity dimensions we decided to use soap for this study. The aim of the present study was to assess whether lead-free hunting rifle bullets have a lower potential for energy transfer than lead-based bullets by comparing the cavity volumes produced by the projectiles in blocks of ballistic soap.

5.2 Materials and methods

Ballistic testing was conducted by the DEVA (*Deutsche Versuchs- und Prüfanstalt für Jagd- und Sportwaffen*, Altenbeken, Germany) on behalf of the Leibniz Institute for Zoo and Wildlife Research. The mandate included the preparation and implementation of shooting experiments, the documentation of cavities by photographs and the measurement of the kinetic energy and the mass loss of bullets.

5.2.1 Ballistic simulant medium

Glycerin soap of commercial grade was used (Permatin AG, Switzerland). Blocks had a cross-sectional area of 250 x 250 mm and a length of 400 mm. Material density was tested by airgun shots at the soap blocks: Diabolo bullets (calibre 4.5 mm) with an impact velocity of 300 m/s were required to penetrate by 90 ± 10 mm (Dr. Beat Kneubuehl, personal communication). Blocks that did not conform to this rule were discarded.

5.2.2 Ammunition

Eight different lead-free bullets (made of copper or copper alloys) and three lead-based bullets were tested from different manufacturers. They were chosen because of their popularity among hunters during the study period. Bullets were classified regarding construction principles in terms of terminal ballistics (partially fragmenting or deforming without considerable mass loss) based on manufacturer information (table 5.1). For the remainder we classify bullets as type 1 if they were lead-free deforming bullets, as type 2 if they were lead-free partially fragmenting bullets and as type 3 if they were lead-based bullets.

As to cartridge size the calibre .30-06 Springfield (7,62 x 63 mm) was chosen because of its high popularity among hunters. If available, industrially-loaded cartridges were used. This was the case for all bullets except for two partially fragmenting constructions (Möller KJG and Reichenberg HDBoH). Ammunition with these two projectiles therefore was obtained from commercial reloaders.

Table 5.1: Classification of bullets tested in this study according to manufacturer information, with the initial bullet mass in g for each construction

classification in terms of terminal ballistic characteristics	**lead-free**	**lead-based**
deforming bullets	*Type 1:* Barnes XLC: 11.7 g Barnes TSX: 11.7 g Lapua Naturalis: 11.7 g RWS Bionic Black: 10.0 g Sauvestre FIP: 11.3 g	*Type 3:* RWS Evolution: 11.9 g
(partially) fragmenting bullets	*Type 2*: Möller KJG: 8.0 g Reichenberg HDBoH: 10.7 g RWS Bionic Yellow: 10.0 g	*Type 3:* RWS UNI Classic: 11.7 g Geco Teilmantelrundkopf: 11.0 g

5.2.3 Testing arrangement

All shots were fired from a shooting device for gas pressure testing with a barrel length of 600 mm. A gunsight was fitted to the shooting device allowing a precise aim at the centre of the frontal area of the block soap.

Soap blocks were positioned 50 m behind the barrel mouth for all shots (fig. 5.1). Testing was done under outdoor conditions during summer 2007 at the DEVA shooting range in Altenbeken (North Rhine-Westphalia, Germany). We were particularly interested in assessing projectile performance at shooting distances similar to real hunting situations. Therefore, we decided to include as shooting distances 50 m, 100 m and 200 m. Three shots per bullet and distance were fired. As central hits are essential for preventing edge effects (Berlin et al. 1982; Janzon 1982b) and scatter is positively correlated to shooting distance, all shots were performed with the soap block positioned 50 m behind the shooting device. To simulate distances of 100 and 200 m, the propellant charge of three cartridges per bullet and distance was adjusted as to simulate the impact velocity given in manufacturers' tables with respect to these two distances.

Impact and exit velocities (v_{imp} and v_{res} in m/s) of bullets were determined with the help of photoelectric barriers in front of and behind the blocks. A paper screen was placed between the soap blocks and the second barrier in order to hold back soap particles and thus prevent false measurements. Three cotton-filled boxes behind the second photoelectric barrier allowed retrieval of the exiting bullets. A few bullets could not be found in the boxes because of large exit angles. These shots were repeated.

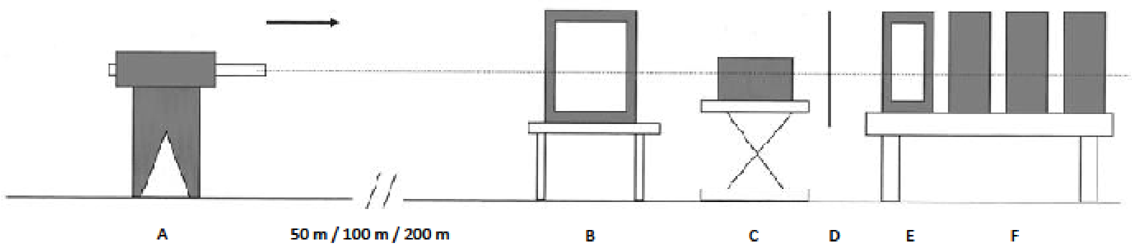

Figure 5.1: Testing arrangement (modified from an original cartoon by DEVA).
A: shooting device
B: first photoelectric barrier (v_{imp})
C: soap block
D: paper screen
E: second photoelectric barrier (v_{res})
F: three cotton-filled boxes

According to manufacturer information, three lead-free bullets (Lapua Naturalis and Sauvestre FIP of type 1, and Reichenberg HDBoH of type 2) were designed for short to medium shooting distances only. For this reason, we decided not to analyse shots at a distance of 200 m for these bullets.

5.2.4 Evaluation

The original bullet mass m_0 [g] was obtained by weighing ten bullets per bullet variety on a scale by Sartorius (Göttingen, D) with an accuracy of 0.1 mg. The mean value of these measurements was used for further calculations in this study because determining the individual original bullet mass of each single bullet would have meant separating the bullets from the cartridges. Each residual bullet was weighed to obtain its mass m_{res} [g] and assess the bullet's loss of mass from fragmentation (mass loss = $m_0 - m_{res}$).

The impact energy E_{imp} [J] is the kinetic energy ($E_{kin} = \frac{1}{2} mv^{2)}$ of the bullet at the moment of impact on the soap block. In this study it was calculated by using the (mean) original bullet mass m_0 [g] and the impact velocity v_{imp} [m/s] measured by the first photoelectric barrier placed in front of the ballistic soap block ($E_{imp} = \frac{1}{2} \frac{m0}{1000} v_{imp}^2$). Likewise, the residual energy E_{res} [J] was calculated from the residual bullet mass m_{res} [g] and the residual bullet velocity v_{res} [m/s], measured by the second photoelectric barrier placed behind the ballistic soap block, as $E_{res} = \frac{1}{2} \frac{mres}{1000} v_{res}^2$. Hence, the total amount of energy dissipated into the soap block is $E_{dis} = E_{imp} - E_{res}$, the relative amount of energy dissipated is $E_{dis,rel} = \frac{Edis}{Eimp}$.

Block storage and evaluation took place under normal indoor conditions (20° C). Blocks were cut in two halfs along the middle axis of the bullet channel in shooting direction. We assumed a symmetrical shape of the cavities, in line with Kneubuehl et al. (2008), Janzon (1982b) and Berlin et al. (1977). Photographs were taken of each block's cutting surface. Cavity diameters were measured at penetration depths of 50 to 300 mm from the block's front surface in steps of 50 mm using the software k-analyzer 1.4 (author Stefan Kneubuehl, Bern). In addition, we measured the maximum diameter of the cavity and the corresponding penetration depth. We refrained from measuring cavity diameters at block entry and deeper than 300 mm in the soap block because previously considerable edge effects were reported in the literature at these positions (Janzon 1982b).

We decided not to include the proportionality factor µ [cm^3/J] described by Kneubuehl et al. (2008). This proportionality factor gives the ratio of the total cavity volume [cm^3] to the energy [J] transferred to the soap block. According to Kneubuehl et al. (2008), µ is meant to eliminate influences of the composition of soap blocks on the cavity and depends on the impact velocity. Gremse et al. (2014) reported an effect of the actual bullet construction principle on the interaction between impact velocity and µ. They therefore concluded that a comparison of different bullets should be based on the actual cavity dimensions without inclusion of µ. The testing of soap density for each block as described above (see section 2.1) should ensure comparable results in this respect.

5.2.5 Statistical analyses

Descriptive statistics are reported as minimum and maximum values, the mean ± S.E.M, the median and the standard deviation. The significance threshold was set at 0.05 and all tests were two-tailed. Variation between bullet types in terms of energy transfer rate, mass loss and penetration depth corresponding to the maximum cavity diameter were tested with the nonparametric Kruskal-Wallis test, post hoc multiple comparisons performed using the Dwass-Steel-Critchlow-Fligner test. To assess whether the bullet type affected maximum cavity diameter we used univariate analysis of variance. As Levene's test revealed heterogeneity of variances (Levene's test based on the median: $F = 10.917$; $df = 2, 87$; $p < 0.001$) Welch's ANOVA was interpreted instead of classic ANOVA.

We also assessed whether bullet type affects the relationship between cavity diameter and penetration distance in the soap block. This was done by testing the effect of the interaction between bullet type and distance (modelled as a factorial variable with 6 categories: 50, 100...) in a linear mixed effect model predicting the cavity diameter. This model estimated 24 fixed effect parameters (1 for the intercept that corresponds to a given bullet type and distance category, 5 for each additional categories of distance, 2 for the additional bullet types, 1 for the impact velocity, 10 for the interaction between the additional bullet types and the additional distance categories, and 5 for the interaction between the additional distance categories and the impact velocity), as well as three variance components (the variance between bullet models, the variance between bullets within a bullet model and the residual variance).

This linear mixed effect model was fitted using the function HLfit from the package spaMM version 1.6.15 (Rousset and Ferdy, 2014) in R (R Core Team, 2015). The effect of the interaction between bullet type and distance was tested by comparing the likelihood of the aforementioned model to the likelihood of the same model after excluding this interaction (10 fewer parameters). This likelihood ratio test was performed by parametric bootstrap using the function LRT from the same package (using 99 bootstrap replicates).

Statistical analyses were performed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA), SYSTAT 13 (Systat Inc., Chicago, Illinois, USA) and R (R Core Team, 2015).

5.3 Results

5.3.1 Impact energy

Impact energies ranged from 1966 J to 3914 J (fig. 5.2).

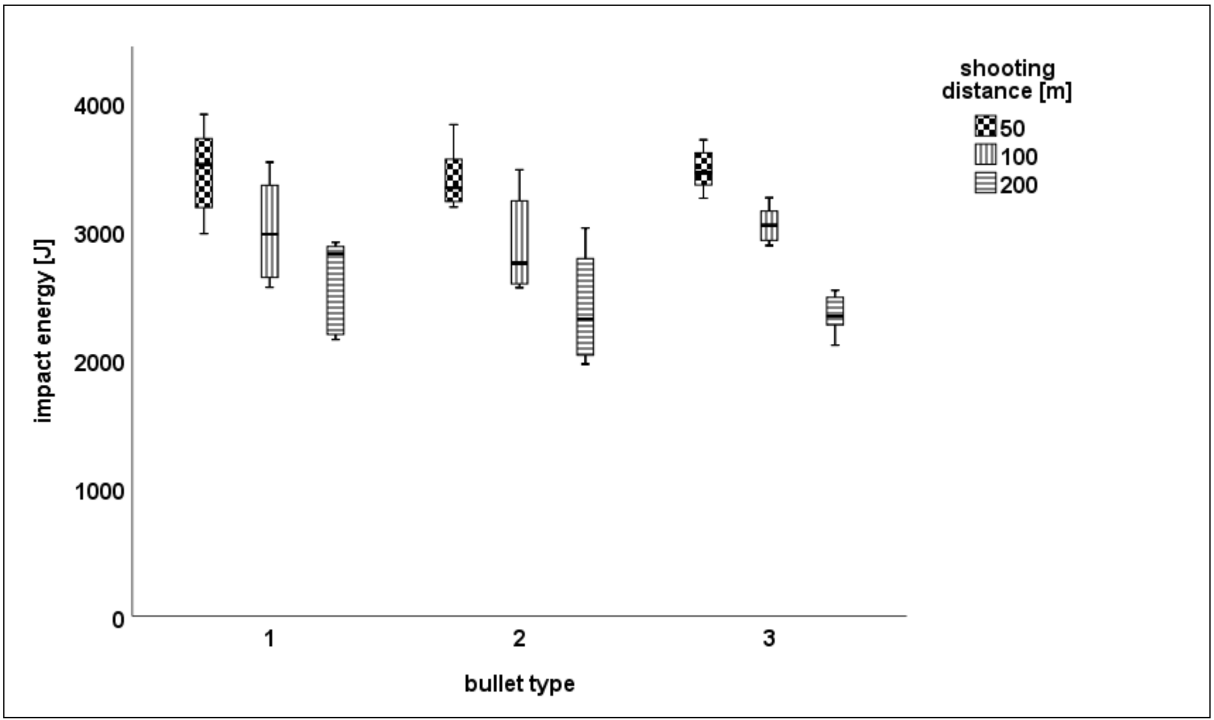

Figure 5.2: Impact energies [J] of the bullet types used in this study as a function of shooting distance; boxes denote the interquartile range, horizontal black lines are median values [type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-core bullets]

5.3.2 Cavity diameters in soap blocks in relation to the penetration depth

The analysis of data using a linear mixed effect model showed that the effect of penetration distance on cavity diameter differed between all three types of bullet, even after accounting for differences in impact velocity (LRT = 181.9, df = 10, $p < 0.01$, fig. 5.3). Cavities associated with lead-free deforming bullets (type 1) and lead-based bullets (type 3) opened close to the front surface of the block and expanded until about 10 cm penetration depth. Lead-free partially fragmenting projectiles (type 2), on the contrary, created bullet channels which expanded faster and with a diameter already diminishing at about 5 cm penetration into the soap. This effect was also noticeable in the raw data (fig. 5.4) and easily recognisable on the soap block cutting surfaces (fig. 5.5 – 5.9).

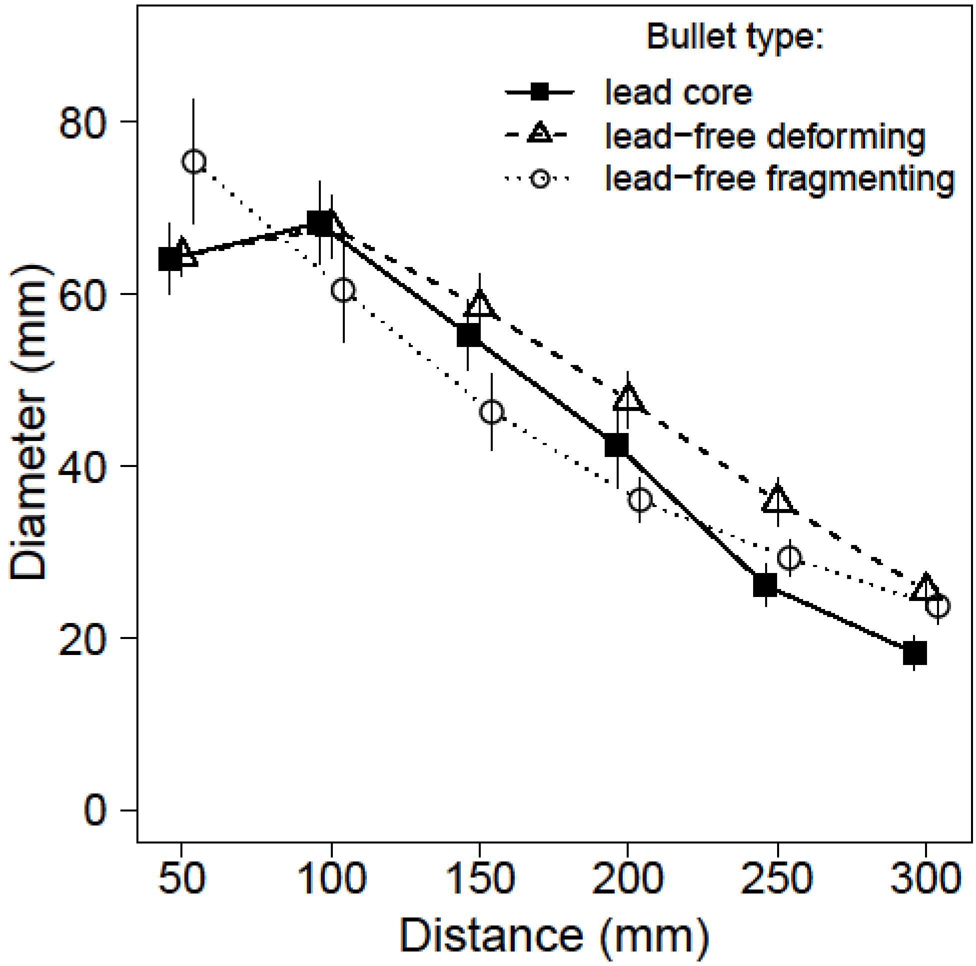

Figure 5.3: Cavity diameter depended on the distance travelled by the projectile within the soap block (= penetration depth). Error bars denote ±S.D.

Bullet types: lead core = type 1 (lead-based); lead-free deforming = type 2; lead-free partially fragmenting = type 3.

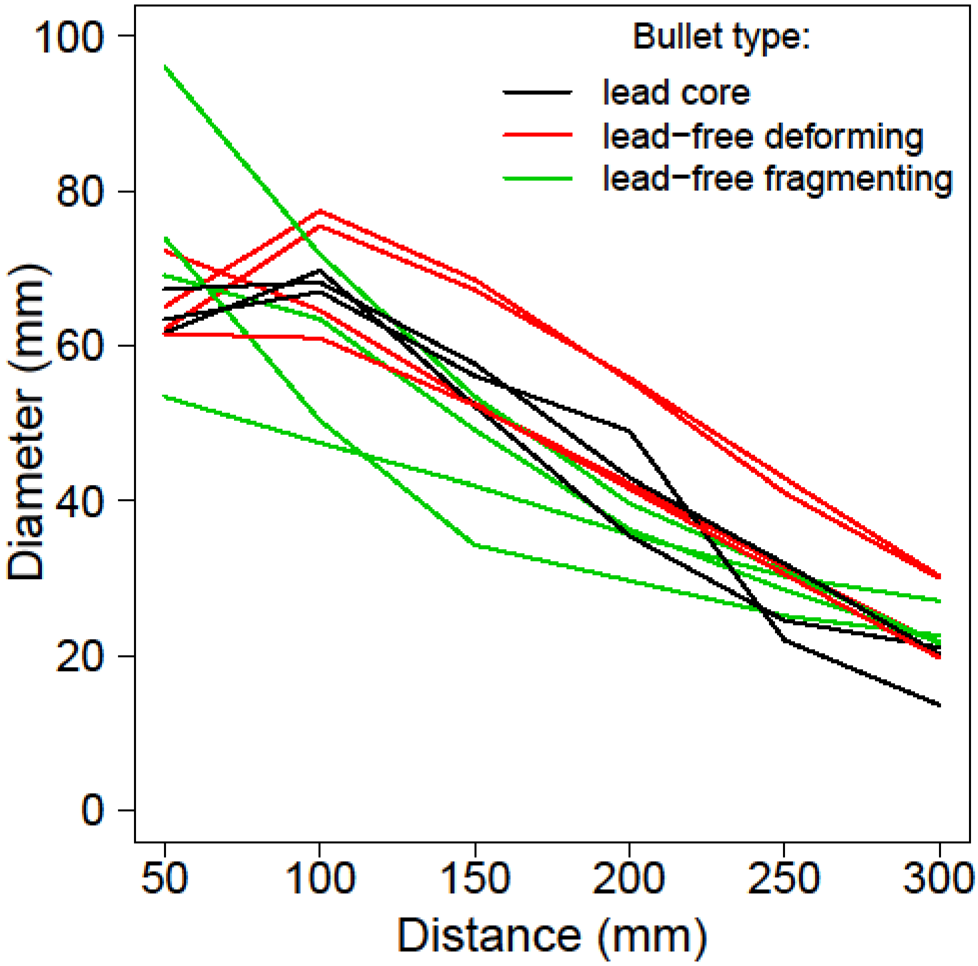

Figure 5.4: Cavity diameter depended on the penetration depth. Every line represents one bullet (= one product).

Bullet types: lead core = type 1 (lead-based); lead-free deforming = type 2; lead-free partially fragmenting = type 3.

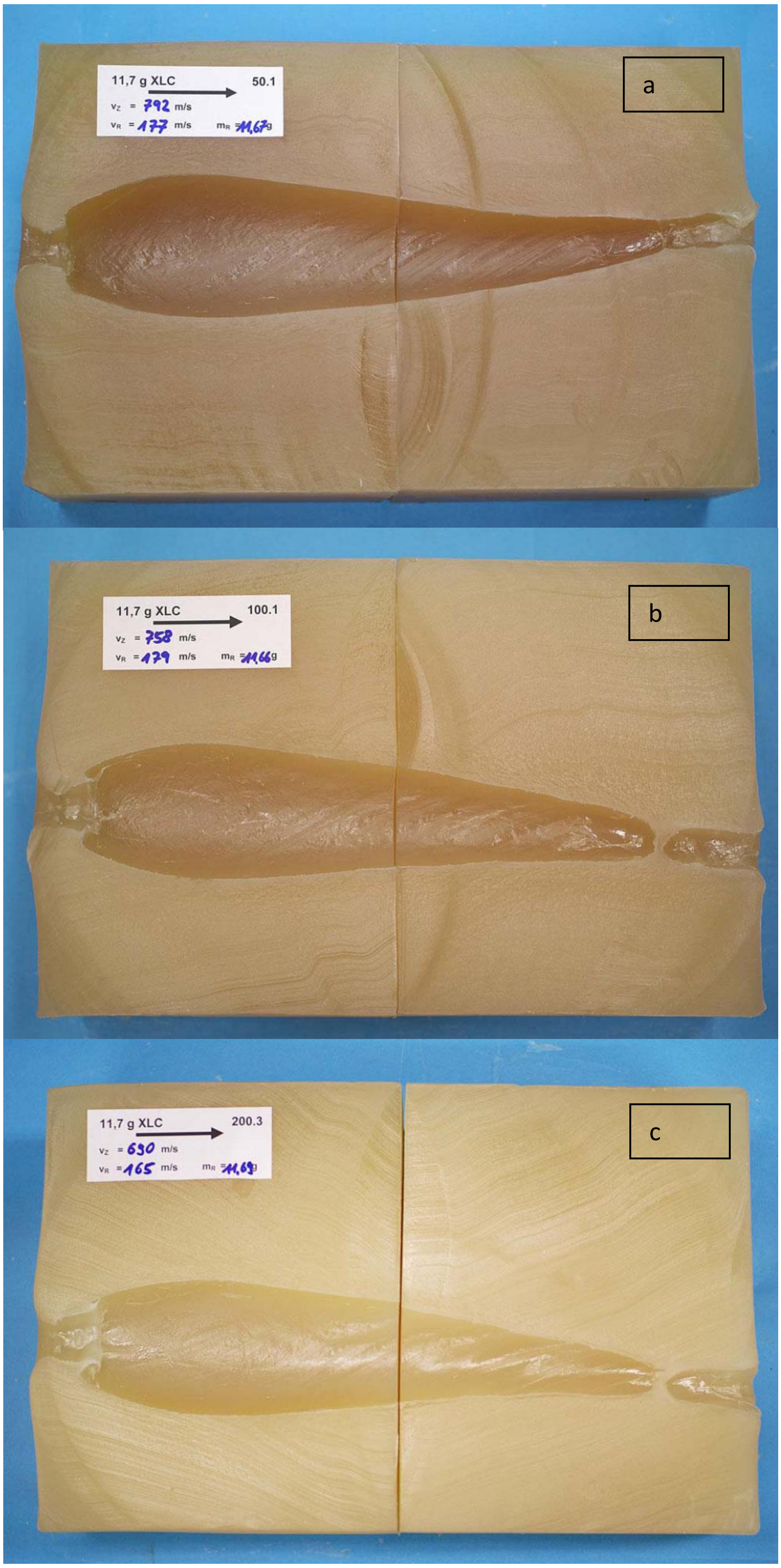

Figure 5.5: Cavities associated with a lead-free deforming bullet (Barnes XLC) at (a) 50 m, (b) 100 m and (c) 200 m

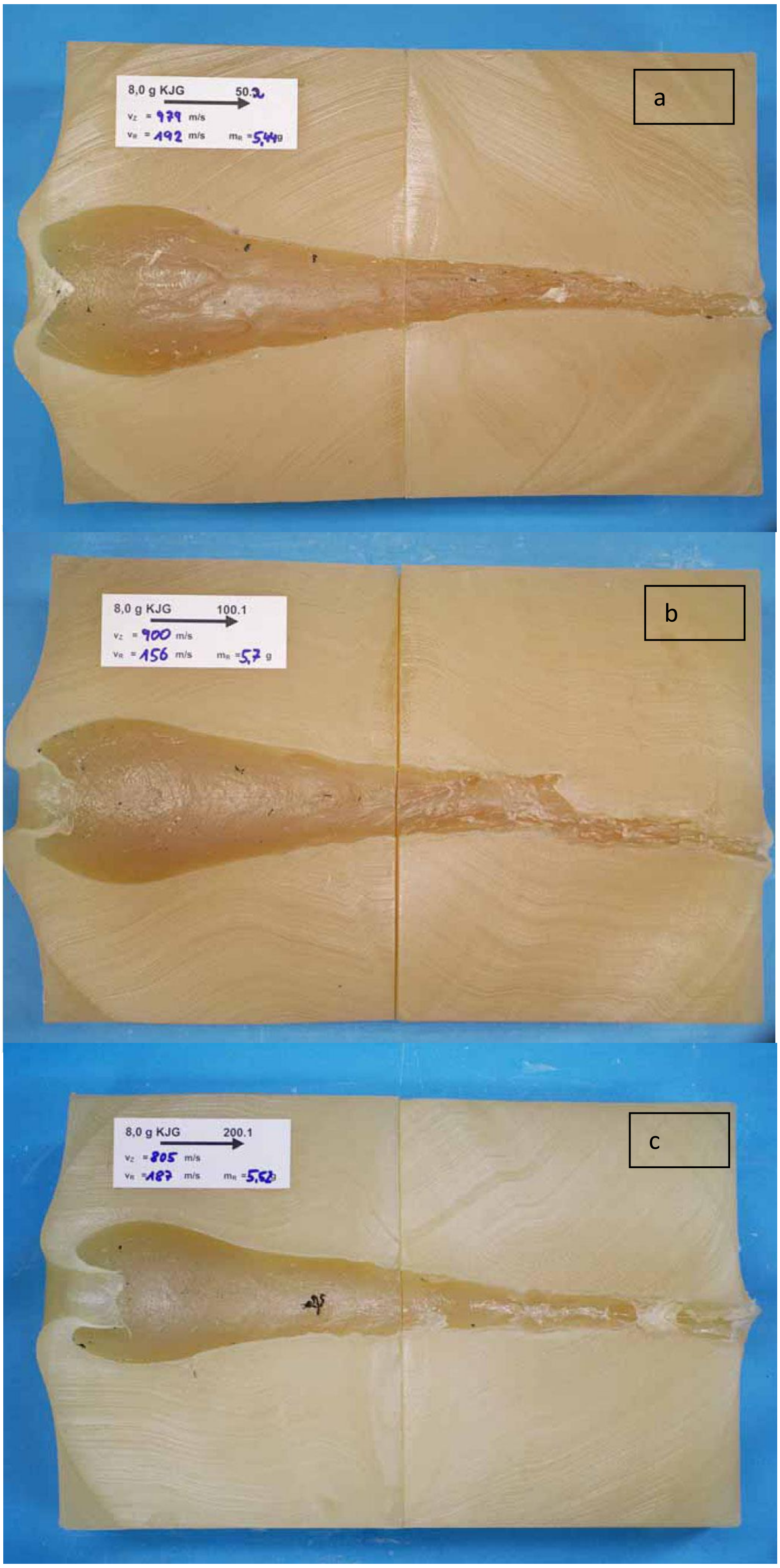

Figure 5.6: Cavities associated with a lead-free partially fragmenting bullet (Möller KJG) at (a) 50 m), (b) 100 m) and (c) 200 m. Note the pronounced transfer of soap material towards the front surface of the block.

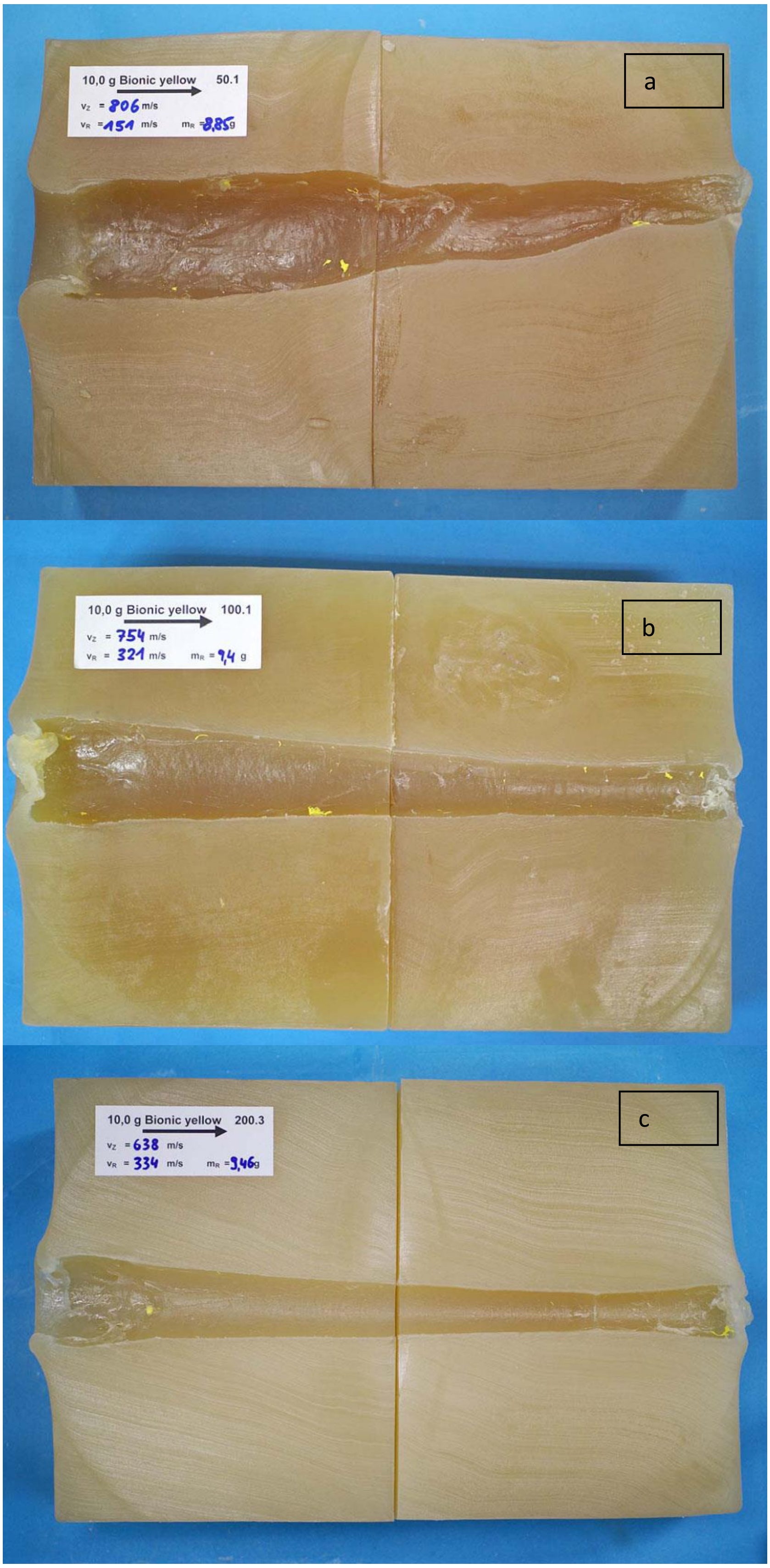

Figure 5.7: Cavities associated with another lead-free partially fragmenting bullet (RWS Bionic Yellow) at (a) 50 m, (b) 100 m and (c) 200 m

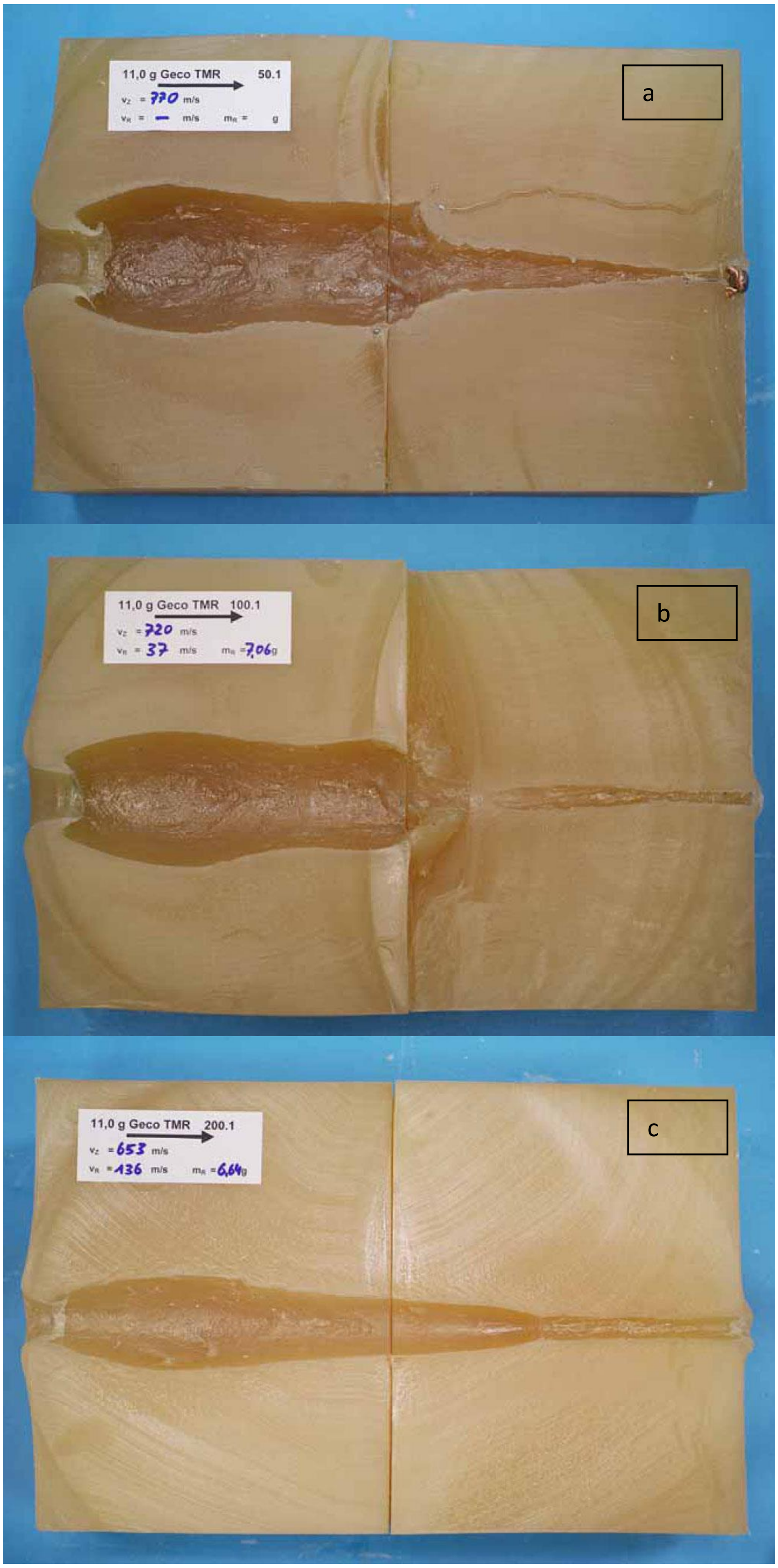

Figure 5.8: Cavities associated with a standard lead-based bullet (Geco Teilmantelrundkopf) at (a) 50 m, (b) 100 m and (c) 200 m

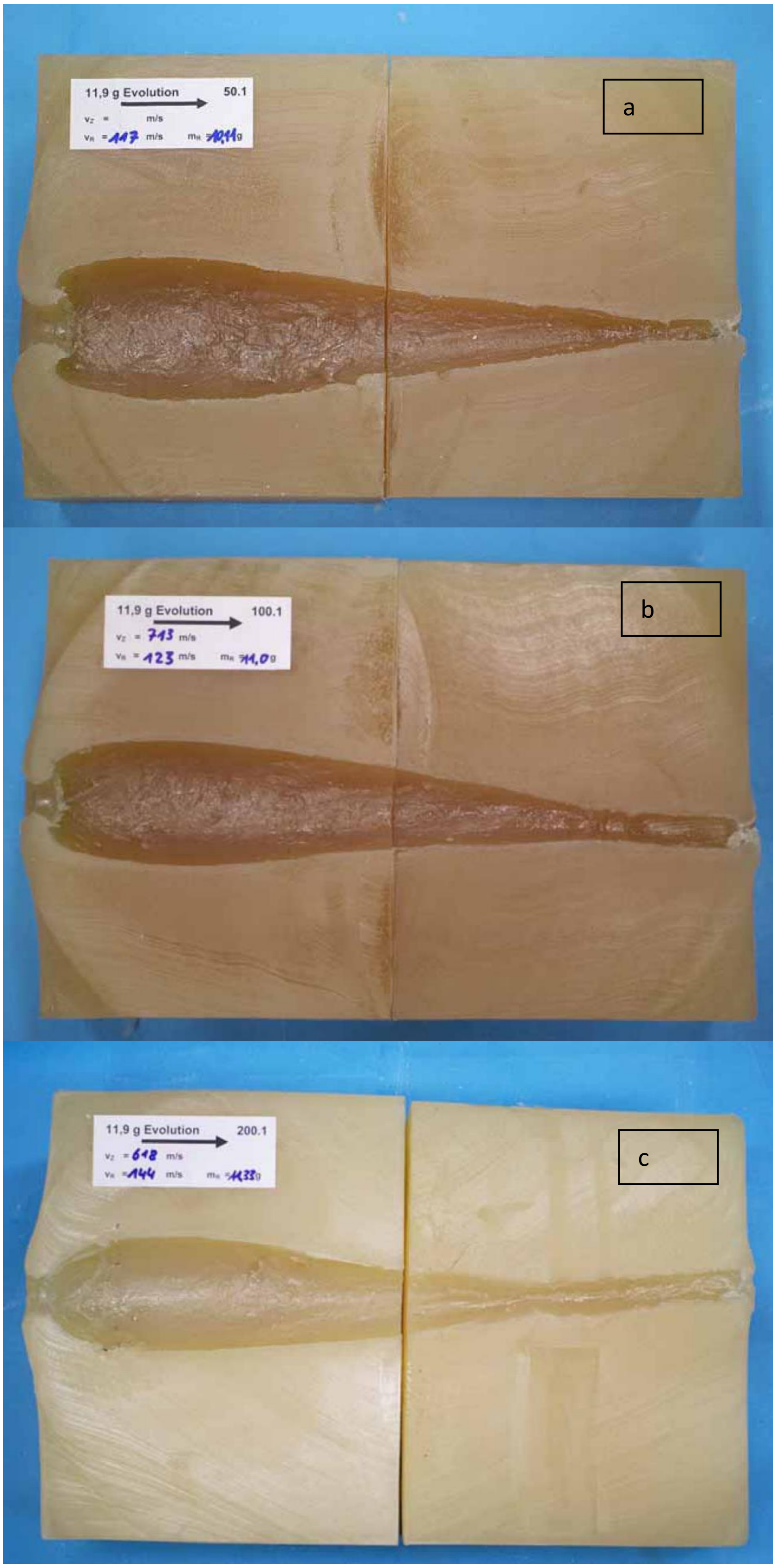

Figure 5.9: Cavities associated with a bonded lead core (= lead-based) bullet (RWS Evolution) at (a) 50 m, (b) 100 m and (c) 200 m

The maximum dilatation of the bullet channels occurred in the front part of the soap block for all three types of bullets. The penetration depth corresponding to the maximum diameter of the cavity differed significantly between bullet types (Kruskal-Wallis test: $H = 25.406$, $df = 2$, $p < 0.001$; post hoc multiple comparisons: lead-free deforming bullet > lead-based bullet, $p < 0.001$; lead-free deforming bullet > lead-free partially fragmenting bullet, $p < 0.001$; lead-free partially fragmenting bullet < lead-based bullet, $p = 0.001$, fig. 5.10). Cavities associated with lead-free partially fragmenting bullets reached their maximum diameter significantly nearer to the soap block front surface than did those associated with lead-free deforming and lead-based bullets. The penetration depth corresponding to the maximum cavity diameter was largest for lead-free deforming bullets. No distinct relationship between the location of the maximum cavity dilatation in the soap block and shooting distance was obvious (fig. 5.11).

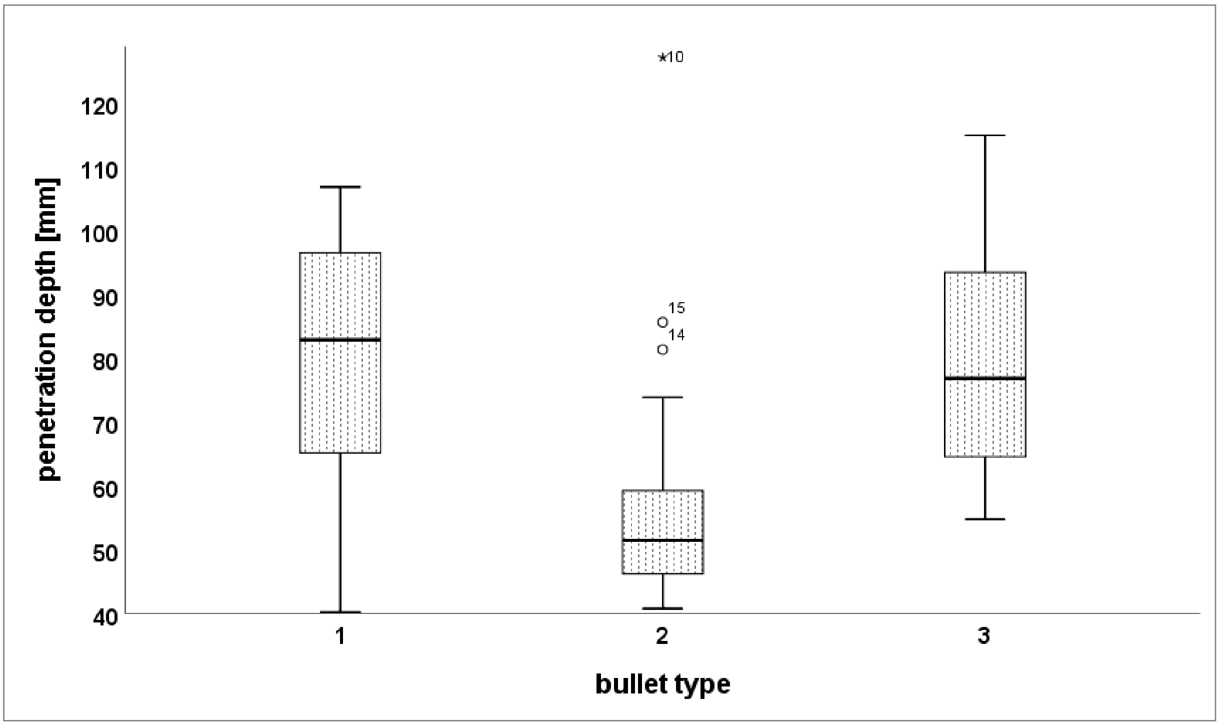

Figure 5.10: Penetration depth at the maximum cavity diameter in different bullet types. Boxes denote the interquartile range, horizontal black lines are medians. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

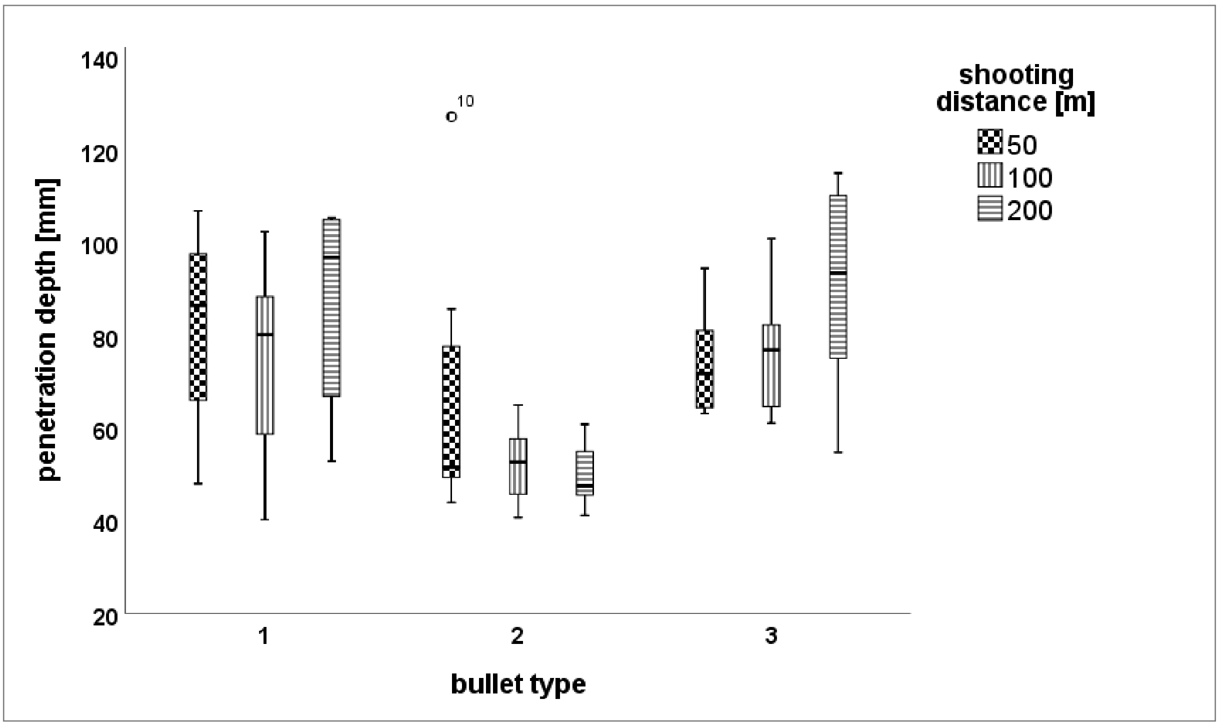

Figure 5.11: Penetration depth [mm] at the maximum cavity diameter as a function of shooting distance. Boxes denote the interquartile range, horizontal black lines are medians. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

5.3.3 Maximum cavity diameter

There was no significant effect of bullet type on maximum cavity diameter (Welch's ANOVA: F = 1.154; df = 2, 46.69; p = 0.32). Empirical cavity diameters considerably varied between bullets of the same type, especially within the lead-free partially fragmenting bullets (table 5.2). Overall maximum cavity diameters were produced by lead-free partially fragmenting bullets at short distances (50 m). Maximum cavity diameters diminished with increasing shooting distance (fig. 5.12).

Table 5.2: Maximum cavity diameter [mm]. Bullet type 1: lead-free deforming bullets, type 2: lead-free partially fragmenting bullets, type 3: lead-based bullets.

bullet type	n	minimum	maximum	median	mean ± S.E.M.	S. D.
1	36	55.2	85.3	72.3	70.8 ± 1.4	8.5
2	27	42.2	107.5	82.5	76.2 ± 3.9	20.1
3	27	50.1	89.0	69.8	69.3 ± 2.4	12.3

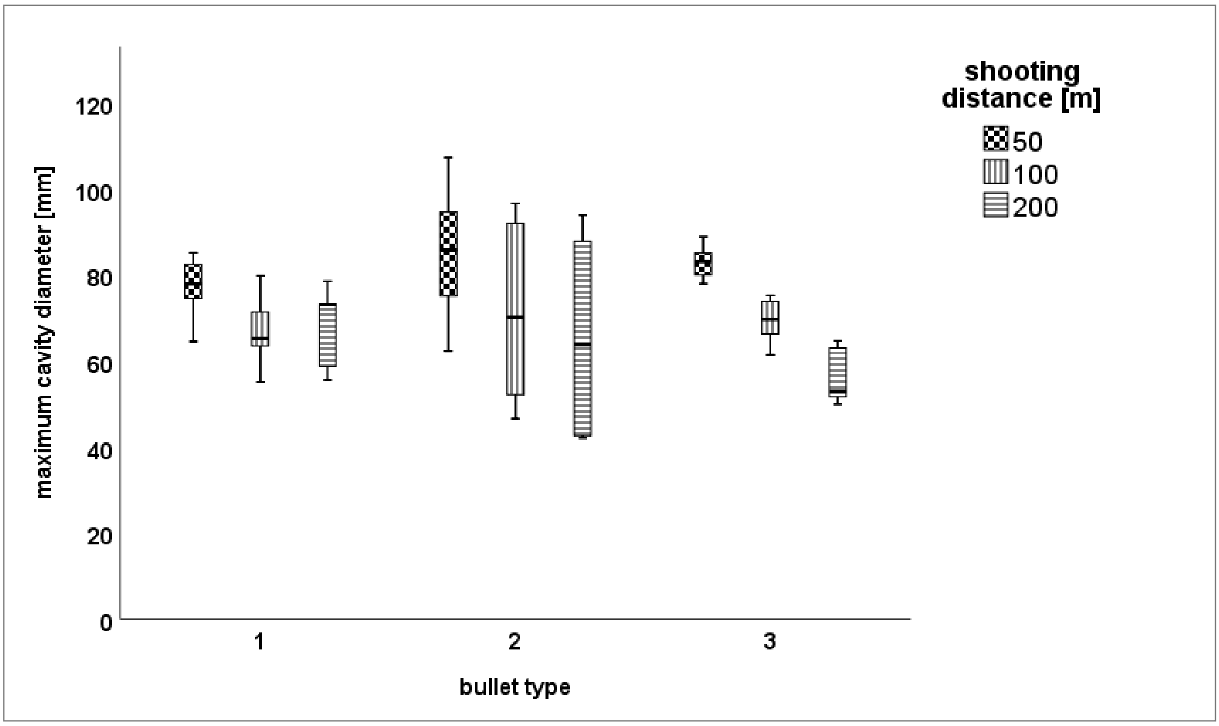

Figure 5.12: Maximum cavity diameter [mm] as a function of shooting distance. Boxes denote the interquartile range, horizontal black lines are medians. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

5.3.4 Energy transfer

Several bullets from all bullet types dissipated at least 90 % of their kinetic energy into the soap blocks (fig. 5.15). The relative amount of kinetic energy transferred to the target was significantly affected by bullet type (Kruskal-Wallis-Test: $H = 15.971$, $df = 2$, $p < 0.001$; post hoc multiple comparisons: lead-free deforming bullet > lead-free partially fragmenting bullet, $p < 0.001$; lead-free deforming bullet = lead-based bullet, $p = 0.818$; lead-free partially fragmenting bullet < lead-based bullet, $p = 0.001$). Lead-free partially fragmenting bullets dissipated a significantly lower percentage of their kinetic energy into the target than lead-free deforming or lead-based bullets (fig. 5.13). Within lead-free partially fragmenting bullets energy transfer rates varied considerably (fig. 5.13, 5.14).

Energy transfer rates of lead-free deforming bullets (type 1) and lead-based bullets (type 3) did not depend on shooting distance. In contrast, energy transfer of lead-free partially fragmenting bullets was markedly affected by shooting distance, with a lower percentage of the impact energy being transferred to the target at longer distances (fig. 5.14).

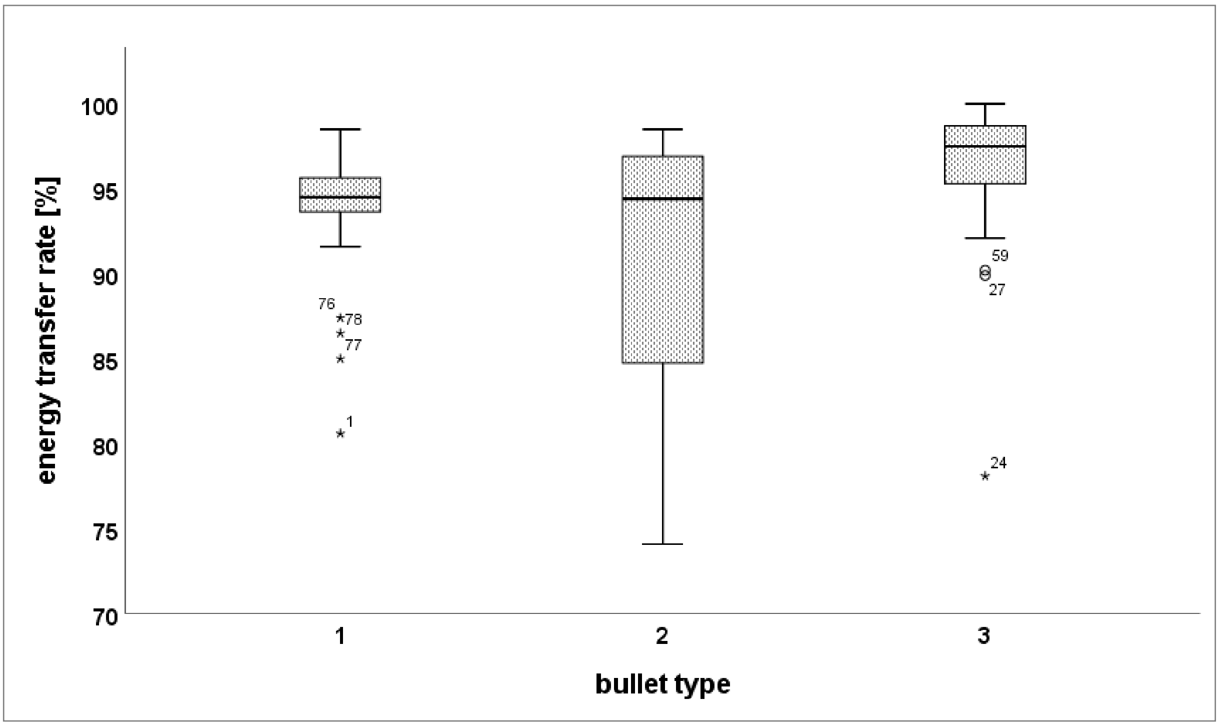

Figure 5.13: Relative impact energy dissipated into the soap block. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

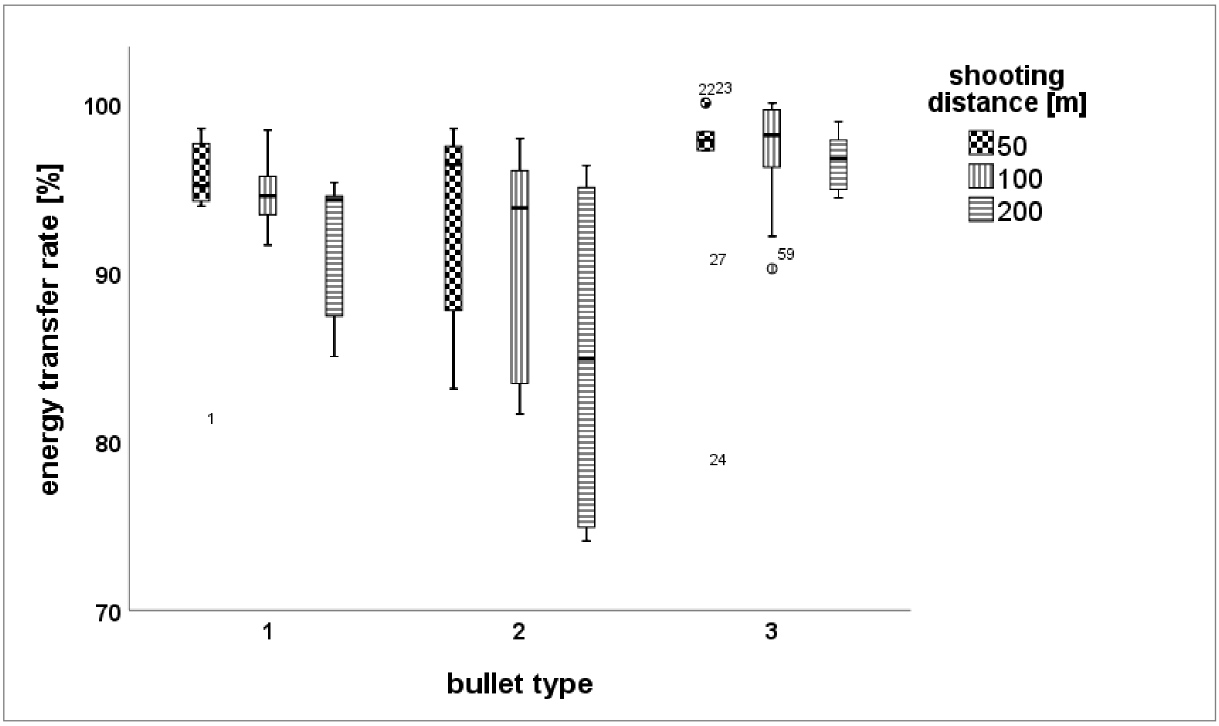

Figure 5.14: Relative impact energy dissipated into the soap block as a function of shooting distance. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

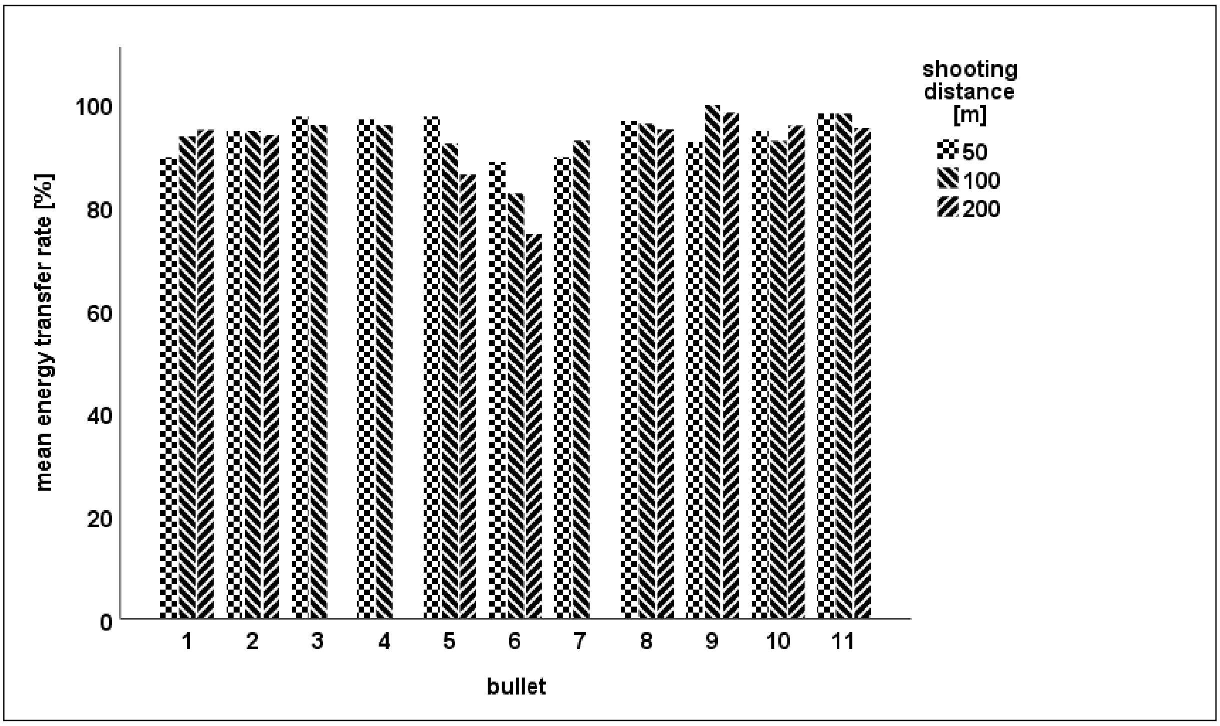

Figure 5.15: Mean relative energy transfer rate (% of kinetic energy at impact on soap block) for each bullet as a function of shooting distance. 1 = Barnes TSX, 2 = Barnes XLC, 3 = Lapua Naturalis, 4 = Sauvestre FIP, 5 = RWS Bionic Black, 6 = RWS Bionic Yellow, 7 = Reichenberg HDBoH, 8 = Möller KJG, 9 = Geco Teilmantelrundkopf, 10 = RWS UNI Classic, 11 = RWS Evolution. Type 1 = lead-free deforming: bullets 1 to 4, bullet 5 at distances of 100 m and 200 m; type 2 = lead-free partially fragmenting: bullet 5 at distances of 50 m, bullets 6 to 8; type 3 = lead-based: bullets 9 to 11

5.3.5 Loss of bullet mass

The relative amount of bullet mass lost during the penetration of the soap block significantly differed between bullet types (Kruskal-Wallis-Test: $H = 65.063$, $df = 2$, $p < 0.001$; post hoc multiple comparisons: lead-free deforming bullets < lead-free partially fragmenting bullets, $p = 0.016$; lead-free deforming bullets < lead-based bullets, $p = 0.016$; lead-free partially fragmenting bullets = lead-based bullets, $p = 0.245$). Lead-free partially fragmenting bullets (type 2) and lead-based bullets (type 3) lost a significantly larger portion of their mass than lead-free deforming bullets (type 1, fig. 5.16). The overall highest loss of bullet mass observed in this study occurred in the semi-jacketed lead-based bullet (Geco Teilmantelrundkopf, bullet 9 in figure 5.17). Considering shots at 100 m and 200 m distance, mean values of relative mass loss were highest in a lead-based bullet (RWS UNI Classic, bullet 10 in figure 5.17). In contrast, two deforming lead-free bullets (Barnes TSX, Barnes XLC) retained more than 99 %

of their original mass, independent of shooting distance. Two other bullets of the same type (Lapua Naturalis, Sauvestre FIP) lost less than 5 % of their original mass in shots at 50 m and 100 m. No analyses for 200 m shots were done for these bullets because of their limited effective shooting range (manufacturer information). The lead-free RWS Bionic Black bullet (bullet 5 in figure 5.17) which should – according to manufacturer information – belong to the deforming type (type 1) fragmented to a considerable extent at the 50 m distance and only retained about 70 % of its original mass (fig. 5.17). For the 50 m distance we therefore classified this bullet as partially fragmenting (type 2). At distances of 100 m and 200 m, this bullet deformed and lost less than 5 % of its original mass. Within the lead-fee partially fragmenting bullets (type 2) there were two bullets (Reichenberg HDBoH, Möller KJG) which retained about 70 % of their original mass whereas a third one (RWS Bionic Yellow) retained approximately 90 %.

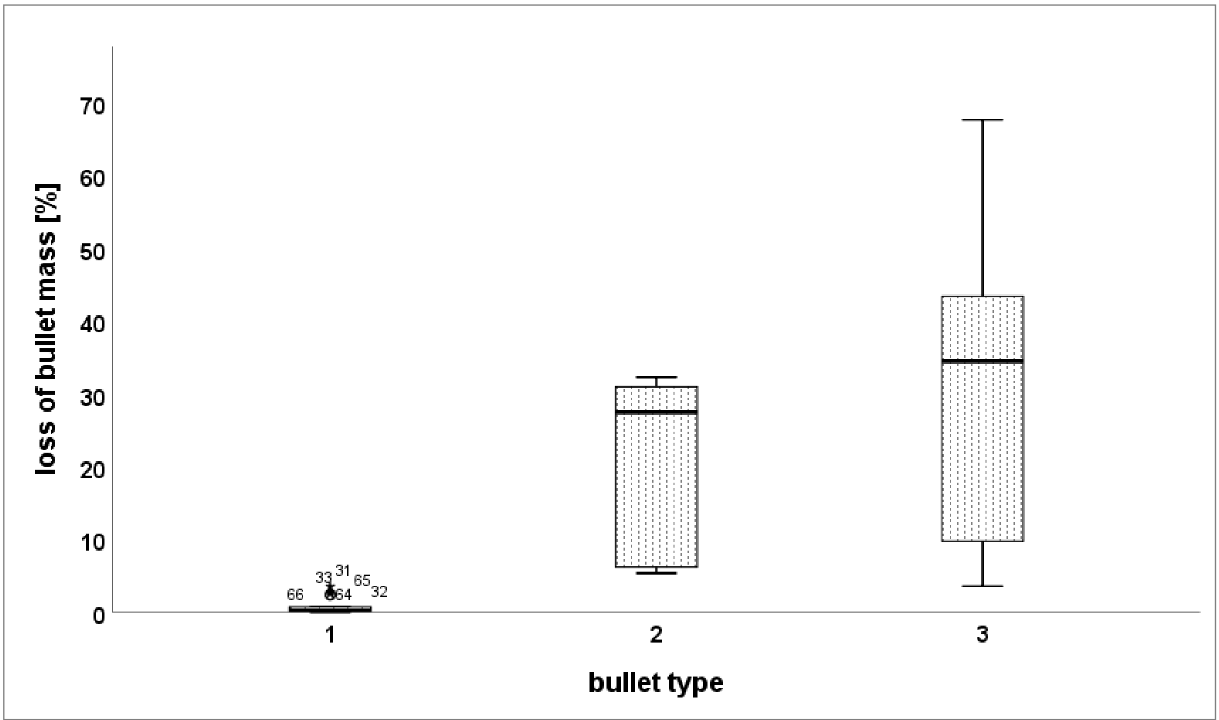

Figure 5.16: Relative loss of bullet mass. Type 1: lead-free deforming bullets; type 2: lead-free partially fragmenting bullets; type 3: lead-based bullets.

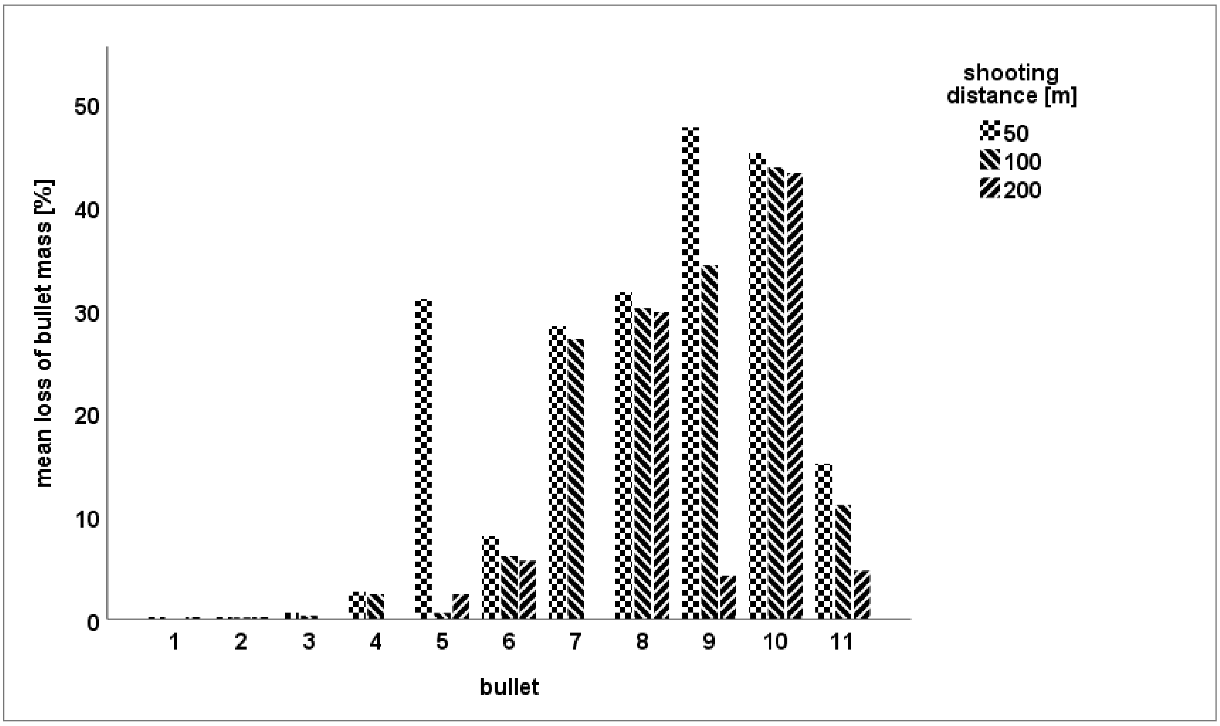

Figure 5.17: Mean relative mass loss (% of original bullet mass) for each bullet as a function of shooting distance. 1 = Barnes TSX, 2 = Barnes XLC, 3 = Lapua Naturalis, 4 = Sauvestre FIP, 5 = RWS Bionic Black, 6 = RWS Bionic Yellow, 7 = Reichenberg HDBoH, 8 = Möller KJG, 9 = Geco Teilmantelrundkopf, 10 = RWS UNI Classic, 11 = RWS Evolution; Type 1 = lead-free deforming: bullets 1 to 4, bullet 5 at distances of 100 m and 200 m, type 2 = lead-free partially fragmenting: bullet 5 at distances of 50 m, bullets 6 to 8, type 3 = lead-based: bullets 9 to 11

5.4 Discussion

5.4.1 Morphology of the cavity

Our data show that the shape and size of the cavity directly depended on the bullet (type). The maximal dilatation of the bullet channel was located in the front part of the soap block for all tested bullets. Cavities produced by lead-free deforming bullets (type 1) and lead-based bullets (type 3) expand until about 10 cm penetration depth. In contrast, lead-free partially fragmenting projectiles (type 2) create bullet channels reaching a maximum dilatation within the first 5 cm. This might be a consequence of different mechanism of increasing their cross-sectional surface and thus decreasing sectional density. The amount of bullet energy transferred to the target is inversely linked to the bullet's sectional density (Kneubuehl et al. 2008). Lead-free deforming bullets (type 1) as well as lead-based bullets (type 3) deformed into a mushroom-like shape with a flattened front surface of clearly increased diameter. In case of lead-free projectiles (type 1) this expansion took place without mass loss whereas bullets (type 3) underwent fragmentation to an extent that depended on their construction and impact velocity.

The pronounced increase of the front area is common to these two bullet types (Kneubuehl et al. 2008) whereas lead-free type 2-projectiles fragmented without a noticeable augmentation of their front diameter (Gremse et al. 2014, consistent with the shape of the residual bullets from this study). Their sectional density was abruptly decreased by segmentation – a process that takes place soon after impact and is the reason for the instantaneous opening of the cavities (Kneubuehl et al. 2008). In addition to this, the lead-free partially fragmenting bullets in our study had a lower bullet weight than bullets of the other two types and therefore a lower initial sectional density. This might also be a cause of the abrupt opening of the cavities produced be lead-free partially fragmenting bullets. The deformation of expanding bullets (types 1 and 3) in contrast seems to be a more continuous process which is displayed in a slower widening of the bullet channel and a longer lasting maximal dilatation (fig. 5.3). Cavities created by lead-free deforming bullets reached their maximum diameter significantly deeper in the target than those created by the other two types. So, if penetration depth is an important criterion for an adequate killing efficacy, for instance when hunting rather big ungulates, lead-free deforming bullets should be advantageous.

Cavity diameters varied considerably within the three types of bullets. This applied especially to the two lead-free types and was displayed in the standard deviation which is the largest in the case of type 2-bullets (table 5.2). The bullet responsible for the largest maximum cavity diameters (Möller KJG) belonged to bullet type 2 as did the bullet with the smallest maximum diameter (RWS Bionic Yellow). This high variation might be a consequence of differences in alloy composition or originate in construction details. Differences in impact energy might influence cavity dimensions and therefore cause differences between bullets. We did not test for this because we considered the impact energy of a given cartridge to be a characteristic of the bullet construction itself.

There are several lead-free bullets from both types – deforming and partially fragmenting - that caused cavities of at least the same diameters as lead-based projectiles at all three shooting distances. This finding confirms the results of the analysis of wound channels in ungulates shot during real hunting situations which we presented in a companion paper (Trinogga et al. 2013). It is also consistent with the results of Gremse et al. (2014) who report similar cavity shapes in soap blocks for a lead-free deforming and a lead-based hunting rifle bullet. As cavity dimensions in soap display the maximum dilatation of the temporary cavity caused by the bullet transit, we conclude that under similar circumstances temporary cavities caused by lead-free and lead-based hunting bullets are of comparable diameters. If bullets of similar impact energies are directed at similar hit placements, wounding should therefore be of comparable intensity for lead-based bullets and lead-free constructions.

5.4.2 Energy transfer rate and its dependence on impact velocity

The ability to transfer impact energy to the target differs between bullet types but also between bullets of the same type. Lead-based bullets and lead-free deforming bullets dissipated a significantly higher percentage of their impact energy into the soap blocks than lead-free fragmenting bullets. This result might be influenced by the fact that one lead-based bullet (Geco Teilmantelrundkopf) did not exit the blocks in three of nine shots, so transferring 100 % of its impact energy in these cases. Perhaps it is also a result of the differences in decreasing sectional density. As described above lead-free partially fragmenting bullets fragment without noticeable increase of their cross-sectional front area, decreasing their sectional density by segmentation only.

For some bullets, the energy transfer is strongly influenced by the impact velocity with a remarkable decline of energy transfer rate at lower velocities. This is the case especially for two lead-free bullets (RWS Bionic Black and Bionic Yellow) and probably contributes to the high variability in energy transfer rates concerning lead-free fragmenting bullets. Material attributes such as the copper alloy used or construction details may be the reason for this distinct velocity dependence.

For the majority of hunters and hunting situations a pronounced dependence of the energy transfer on impact velocity – which means on shooting distance – is not desirable. A hunting bullet should function over a certain range of distances as the actual shooting situation is not fully predictable.

Our data show that several lead-free hunting bullets – including deforming varieties as well as partially fragmenting ones - are capable of transferring a high amount of their kinetic energy to the target under normal German hunting conditions with shooting distances up to 200 meters. This study was restricted to the calibre .30-06 Springfield (7,62 x 63 mm). Potentially, the situation may not be fully transferable to other calibres whose impact energies differ markedly. This does, however, not compromise our results because we wanted to analyse bullet characteristics under wide-spread conditions which are well displayed by using this very common calibre. Hunters should carefully address the information given by bullet manufacturers on the recommended shooting range for each bullet and calibre.

5.4.3 Predictability of fragmentation

As expected, lead-free deforming bullets deformed with no or little fragmentation. This characteristic is advantageous for consumer protection as well as biological conservation, as it prevents fragments in venison and in carcasses or offal accessible to scavenging wildlife.
Our results on the relative loss of bullet mass contradict the manufacturer statements in some cases. At the 50 m distance one lead-free bullet which should have deformed (RWS Bionic

Black) fragmented to a considerable extent and retained only 70 % of its original mass. In practice, such departures from expected characteristics can be important for shots from short distances. Dog handlers often chose expanding bullets in order to protect the dog from passing-out fragments when it is located close to the target animal. Similar differences between manufacturer information and our results occurred in the case of the bonded lead core bullet (RWS Evolution). The lead core of this construction is bonded to the jacket – a technique that is supposed to prevent the separation of both parts (RUAG Ammotec GmbH 2020, Stokke et al. 2017). According to the manufacturer the projectile is designed to retain almost all of its mass (RUAG Ammotec GmBH 2020). We found a relative mass loss of about 15 % at 50 m and 11 % at 100 m and almost 5 % at 200 m. Similar findings were reported by Stokke et al (2017) on other bonded lead core bullets. There is no commonly accepted threshold up to which a bullet should be considered as deforming but 15 % certainly should exceed such a threshold. As in this case the discrepancy concerns a lead bullet. An unexpected contamination of venison with lead can occur in real hunting situations. This may pose a risk to food safety if hunters discard too little tissue from the surroundings of the wound channel, assuming the bullet did not fragment considerably.

5.4.4 Implications for animal welfare in real hunting situations

Little information is available in the literature on minimum values of cavity diameters a hunting bullets should produce in glycerin soap in order to be classified as being adequate to kill wildlife. We therefore cannot state with certainty whether every single bullet included in the study really meets the requirements posed by high standards of animal welfare. Our data show that this is likely to be determined by the bullet construction (deformation vs partial fragmentation) rather than the bullet material (lead-based vs lead-free).

The dimensions and shape of bullet channels in a body will not be exactly the same as those in ballistic soap. Soap blocks are made of homogeneous material whereas a real wound tract includes different tissues of various densities and elasticities. The resistance and therefore the force that acts on the projectile may change several times along its penetration path. Often wounds open along fascial structures or between muscle layers (Amato et al. 1974a and b; Berlin et al. 1977). In addition, ballistic soap is a plastic material providing information on the dilatation of the temporary cavity. Damage caused by temporary cavitation strongly depends on tissue characteristics such as elasticity, with less severe injuries experienced by highly elastic organs such as the lungs or muscles than others of little elasticity such as bones (Amato et al. 1974b). Bullet tracts through bodies of animals will therefore be more heterogeneous than the cavities described here. Furthermore, diameters of permanent wound tracts in animal tissues will be much smaller than those of the temporary cavities displayed in ballistic soap (Amato et al. 1974a; Kneubuehl et al. 2008).

The use of ballistic simulants displays the wounding potential of bullets. If the anatomical structures affected in real injuries are comparable among the cases, the degree to which this potential can be converted into high efficacy of killing should be comparable, too. Hunters normally strive for shots at and through the thoracic cavity. Most bullet channels consequently include the lungs which provide less resistance to a projectile than the soap does because of their low specific density. As energy transfer increases with target resistance (Kneubuehl et al. 2008), cavities in the lungs will probably be smaller than those in the simulant. This is consistent with the findings of Amato et al. (1974a) who described smaller wound cavities in the lungs than in liver or muscle tissue.

When taking into account the body dimensions of most European ungulates, well placed shots are expected to reach vital organs within the first 10 to 15 cm. Thus, it is crucial that a hunting bullet dissipates a sufficient amount of its kinetic energy within this range. As all cavities analysed within this study were at a maximum dilatation in the front part of the soap blocks, all bullet types seem to meet this requirement. We did not observe cavities resembling to those reported for military bullets (Janzon 1982a; Scepanovic and Albreht 1982; Tikka et al. 1982) with an initial narrow channel and a subsequent opening of the cavity in the depth of the simulant block. So, all types of hunting rifle bullets tested here should be adequate for hunting smaller ungulates such as roe deer (*Capreolus* capreolus) or young wild boar (*Sus* scrofa) as well as medium sized ungulates such as fallow deer (*Cervus dama*).

Our data also suggest that for hunting rather big wildlife such as red deer (*Cervus elaphus*) or moose (*Alces alces*), lead-free deforming bullets should be a good choice because cavities produced by this bullet type reach their maximum dilatation deeper in the target than is the case for lead-free partially fragmenting bullets.

5.5 Conclusion

The analysis of bullet channel diameters presented here demonstrates that lead-free bullets do not have a lower wounding potential than lead-based hunting rifle bullets. This is consistent with the results of our companion study in which we analysed wound channels in carcasses of ungulates shot with lead-free and lead-based bullets (Trinogga et al. 2013). Our results furthermore demonstrate that the actual construction of a projectile has a bigger effect on cavity diameters than bullet material (lead-based or lead-free). The importance of this result is not reduced by recent developments in the field of lead-free hunting bullets as they are applicable to newly developed bullet constructions as well.

Our findings are consistent with those of Gremse et al. (2014) who performed wound ballistic simulation as well and concluded that construction properties had a more important influence on wounding potential of hunting bullets than bullet material. We conclude that each bullet construction should be tested in a standardised manner by impartial testers before its introduction to the commercial market.

The efficacy of lead-free hunting rifle bullets under field conditions has been shown by several studies (Martin et al. 2017; Kanstrup et al. 2016; Trinogga et al. 2013; Knott et al. 2009). Taking into account the risks that the use of lead-based bullets poses from the perspective of consumer health and biological conservation, the replacement of lead-based bullets for hunting purposes by lead-free alternatives should be strongly encouraged.

5.6 Acknowledgements

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6 General discussion

This study was designed to assess the wounding capacity and hence killing efficacy of lead-free hunting rifle bullets. The question whether the use of lead-free bullets is more likely to cause animal welfare problems by inflicting avoidable pain to animals shot during hunts than the use of lead-based bullets was to be addressed. In order to do so, different approaches to analyse the terminal ballistic characteristics of different hunting rifle bullets were combined.

Radiography represents a simple method to assess the spatial distribution of metallic particles in tissues and is widely used in forensic medicine to document bullet residues (Brogdon and Messmer 2011). By means of radiographic visualisation, the fragmentation of lead-based bullets in living tissues and the subsequent substantial contamination of carcasses and inner organs by bullet fragments was documented. The knowledge of fragmentation patterns of hunting bullets gives a sound basis for recommendations on how to further process carcasses and handle offal from rifle-killed animals. The results of the present study in this respect demonstrate the strong necessity of removing offal from the ecosystem in order to prevent lead poisoning in scavengers in case hunters use lead-based bullets. Nadjafzadeh et al. (2015) report the results of feeding experiments in the field in home ranges of white-tailed eagles and in captive white-tailed eagles. According to their results, scavengers avoided particles with a diameter exceeding 8.8 mm. The authors conclude that the use of deforming bullets or of those fragmenting in particles bigger than 9 mm may prevent metal ingestion and subsequent poisoning in scavengers. The radiographic examinations presented in chapter 3 of this thesis clearly demonstrated that lead-based bullets do not meet these requirements.

Analysing the spatial distribution of fragments in tissues also allows for an assessment of the amount of tissue surrounding the bullet path that has to be debrided in terms of food safety (BfR 2010). The production of high-quality meat represents an important and legally sanctioned justification for the shooting of animals by hunters. If hunting is meant to be sustainable, food waste resulting from unnecessarily large zones of contamination by bullet material should be avoided. Hunters therefore should strive to use bullets that minimise the amount of meat which has to be discarded. The use of radiography allows for an impressive visual representation of the fragmentation characteristics of bullets. It clearly demonstrates the superiority of lead-free rifle bullets in terms of protecting wildlife as well as human health. Hunters that were shown the X-ray pictures of “their” shots with lead-based bullets often reacted seriously surprised when confronted with the high number and wide distribution of fragments. Especially the fact that hits without any bone contact resulted in severe fragmentation of the bullet and that bonded lead core bullets did fragment, too, caused astonishment in many participating hunters.

Computed tomography allows for three-dimensional reconstruction of gunshot wounds and for measurements of tissue destruction diameters on different planes. Thus, dimensions of gunshot wounds can be compared. As the extent of tissue destruction is influenced by tissue characteristics (Kneubuehl et al. 2008; Karger 2004; Oehmichen et al. 2000; Amato 1974a and b) comparisons of measurements should be restricted to comparable wound channel localisations. We assured comparability by focussing the analysis on shots through the thoracic cavity. Post mortem macroscopic examination allows the evaluation of wound characteristics and conclusions as to the actual cause of death can be drawn. Both CT and necropsy findings did not show a superiority of lead-based bullets to lead-free projectiles in this respect.

We decided to concentrate our evaluation on wound characteristics rather than on flight distances which are another common parameter to assess killing efficacy (Hampton et al. 2021; Stokke et al. 2019; Martin et al. 2017; Kanstrup et al. 2016; Knott et al. 2010). The reaction of an animal hit by a bullet does not only depend on factors such as choice of bullet type (and manufacturer) and hit placement, but is also strongly influenced by intrinsic factors of the target animal itself such as the level of stress. Even if shots were apparently correctly targeted at the ideal body part, animals may still run a considerable distance because blood supply to the brain does not stop immediately (Kneubuehl et al. 2008). With regard to humans, Karger (2004) mentions that incapacitation time following fatal gunshot wounds to the chest is strongly affected by the mental status of the victim. Thus, flight distance results are likely to be altered by internal characteristics of the animals, too. Wounding patterns, though, are supposed to be dependent on the characteristics of the bullet and the tissues in its way only (Kanstrup et al. 2016; Kneubuehl et al. 2008; Karger 2004). If tissue characteristics are comparable, wound dimensions should reflect the bullet's ability to interact with the target, or in other words its wounding capacity. Large wounds are not necessary to kill animals quickly and without superfluous pain, and unnecessary tissue destruction should be avoided to prevent food waste. A certain minimum wound diameter though is desirable in order to compensate for deviations from the ideal hit placement which is not always possible, particularly under drive hunt conditions. This study, however, was not designed to deduce a minimum value for wound dimensions which are required for efficacious killing by hunting rifle bullets. Regarding the necropsy and CT findings described in chapter 4, it can be concluded that – given that vital organs are hit - all bullets tested in this study are sufficiently efficacious to quickly kill ungulates during hunts. Reflex death due to some kind of shock phenomenon has not been proven to be caused by gunshot wounds (Karger 2004) and hunting bullets of any material should not be expected to compensate for a lack of accuracy by the hunter when targeting a particular body part.

Whereas the radiographic methods and macroscopic examinations of wounds can be used to assess the performance of bullets in real hunting situations, wound ballistic simulation reflects the wounding potential of a bullet. The extent to which this potential can be transferred to quickly and humanely kill an animal depends on the actual shooting situation. In this thesis, both aspects – performance in real hunting situations and wounding potential – were combined. The dimensions and the shape of bullet channels in ballistic soap resemble those in muscle tissue (Kneubuehl et al. 2008). By combining the assessment of real gunshot wounds inflicted to hunted animals with the evaluation of wound ballistic simulation, we were able to show that lead-free hunting rifle bullets have a comparable wounding potential as lead-based bullets and that they are able to realise this potential under normal hunting conditions as good as their lead-based counterparts.

As wound channels through the thorax pass through several tissues and hence heterogenous material, we refrained from direct comparisons of empirical diameters measured in bodies and in soap. By using both techniques, however, we were still able to demonstrate that wounds caused by all tested types of hunting rifle bullets open during the first centimetres of the wound tract and thus are likely to cause damage in vital organs in most European ungulates if the thorax is hit. The characteristics and effects of lead-free partially fragmenting bullets seem to differ from lead-free deforming and lead-based constructions. This might be induced by differences in the mechanism of decreasing the bullet's sectional density.

As a side effect, the results of the present study revealed that the actual terminal ballistic properties of some bullets differed from the information given by the manufacturers. The bonded lead core bullet tested in ballistic soap fragmented to a surprisingly high extent. Radiographs of animals shot with bonded lead core bullets showed large numbers of fragments, too. These findings contradict the manufacturers who advertise the bullet as being a deforming projectile. One lead-free bullet was also found to fragment in soap blocks at high impact velocities although it was classified as a deforming bullet by the manufacturer. Such misleading information may impose risks on hunters or their dogs who rely on the absence of bullet fragments. They might also mislead hunters to think that it is safe to leave (contaminated) offal in the field or to discard too little meat from the surroundings of the wound channel because they are not aware of the extent of the space covered by fragments of the bullet.

The results obtained in this study are necessarily limited to the types and specific bullets used. It cannot be fully precluded that bullets of similar types made by other manufacturers not tested here might produce differing results. The aim of this project was to draw principal conclusions referring to the adequacy of lead-free bullets compared to lead-based bullets. For this purpose, we selected bullets with regard to their popularity among hunters in the study area and their availability at the time of data collection and included the main constructional principles. For this reason, I consider it unlikely that the choice of bullets will severely limit the applicability of our results.

The conclusions drawn from this project might not be fully applicable to different hunting conditions. Some of these include long distance shots, small calibres with clearly different impact energy, or very small target species such as rabbits. Hampton et al. (2020) report a low killing efficacy of lead-free .22 LR bullets for shooting European rabbits (*Oryctolagus cuniculus*). Although their findings are based on the testing of two bullet varieties only, further research with regard to small calibres and small target species should be carried out.

By a combination of different approaches, this study documents the adequacy of lead-free hunting rifle bullets in terms of animal welfare and their superiority regarding the contamination of the carcass. Its results are consistent with many other studies which demonstrated the suitability of lead-free hunting rifle bullets (Stokke et al. 2019; Martin et al. 2017; Kanstrup et al. 2016; Gremse et al. 2014; Knott et al. 2010). Thus, animal welfare aspects should no longer be cited as a reason to refuse the phasing-out of lead-based bullets for hunting purposes, at least not for the common types of hunts, rifles and bullets which my results cover. The results presented in this thesis show that the actual construction principle exerts more influence on the performance of a bullet than the presence or absence of a lead core. This is consistent with the findings of Gremse et al. (2014) and underlines the importance of introducing a standardised testing procedure of bullet constructions prior to their introduction to the commercial market. It is up to the ammunition industry to concentrate on the development of high-performance lead-free rifle bullets. This study shows that such bullets already exist and that they are successfully used for hunting. Moreover, the development of lead-free bullets makes continuous progress and refined constructions have become available on the market since the start of this project. Especially with regard to lead-free partially fragmenting bullets, new construction principles have been established which include bullets with tin cores and mantled varieties. So, deficits shown here by individual lead-free bullet constructions are likely to be remedied by further technical developments. The ECHA proposal on restricting the use of lead bullets (ECHA 2021) therefore marks the logic turning point in European policy concerning lead-based hunting ammunition.

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Summary

Comparison of the performance and fragmentation of common lead-free and lead-based hunting rifle bullets in shot wild ungulates and in ballistic soap

Anna Lena Trinogga

The present thesis was designed to assess the question whether commonly used lead-free hunting rifle bullets represent an adequate surrogate for conventional lead-based bullets in terms of animal welfare. The study was initiated as a result of the stakeholder conference on lead intoxications in white-tailed sea eagles organised by the IZW in 2005. Fragments of conventional lead core hunting bullets had been recognised as a major source of lead poisoning in white-tailed sea eagles and many other wildlife species. Reservations concerning the alleged reduced killing efficacy of lead-free bullets as an alternative to lead bullets were widely raised by hunters and the ammunition industry.

For this study different approaches were used in order to assess the wounding capacity – the killing efficacy – and to describe fragmentation patterns of lead-free deforming and lead-free partially fragmenting bullets compared to lead-based bullets:

297 wild ungulates shot during regular hunting events in Germany were radiographed between 2006 and 2009 and the number of fragments as well as the maximum distance of fragments to the wound tract were evaluated. Fragmentation patterns significantly differed between lead-free and lead-based bullets. The use of lead-based bullets was associated with both a significantly higher number of fragments and a significantly larger maximum distance of fragments in relation to the wound tract. We showed that the use of lead core bullets results in a broad contamination of the carcass and the offal from shot ungulates and therefore should be avoided with regard to biological conservation, consumer protection and the prevention of food waste (chapter 3).

The amount of tissue destruction in bodies of shot ungulates displays the wounding capacity associated with a bullet under field conditions. Comparable locations of the wound tract within the body should result in comparable wound dimensions. To answer the question whether wounds caused by lead-free bullets are less severe, thereby potentially causing superfluous pain to the animal by delayed entry of death, we conducted CT scans and post-mortem macroscopic examinations of 34 shot wild ungulates. The comparison of wound channel diameters along the bullet path and the determination of the maximum cross-sectional area of the wound tract did not reveal significant differences between lead-free and lead-based bullets. Additionally, we assessed the morphology of the wounds. All animals showed severe injuries to vital organs, which were likely to have caused rapid death due to exsanguination. No hints were found that lead-free bullets would produce less severe or smaller wounds. We conclude that lead-free rifle bullets perform as good as conventional lead core bullets under normal German hunting conditions (chapter 4).

Wound ballistic simulation using glycerine soap as a tissue surrogate is widely used in ballistic research. The wounding potential of a given bullet corresponds to the cavity volume in the soap block. In order to compare lead-free and lead-based hunting rifle bullets under standardised conditions we analysed the cavities associated with three lead core and eight lead-free bullets. We did not find a superiority of lead core bullets in terms of cavity diameters in ballistic soap. The shape of the cavity, though, was significantly influenced by the bullet type. The maximum cavity diameter was positioned within the front part of the block for all bullets but situated significantly more distant to the target surface ("deeper") for lead-free deforming bullets than lead core bullets or lead-free partially fragmenting bullets. So, the first bullet type might be more suitable for hunting larger wildlife species. Bullet-tissue-interaction varied substantially within bullet types, especially within the lead-free partially fragmenting bullets. Our results clearly showed that the actual bullet construction exerts a stronger influence on the wounding potential than the presence or absence of a lead core. This suggests that a standardised regime for official testing of all hunting bullet constructions prior to their licencing as official hunting bullets is desirable (chapter 5).

Technical enhancement of bullet construction is making continuous progress. New constructional details such as tin cores and steel mantles may remedy deficits shown by individual lead-free bullet varieties in this study and improve the availability of high-performance lead-free partially fragmenting bullets.

Taking into consideration the results of all three parts of this thesis, lead-free hunting rifle bullets have to be regarded as an adequate surrogate for conventional lead-based bullets in terms of animal welfare. As the toxicity of lead for both humans and wildlife is well known and safety concerns have been shown to be unfounded, the phasing-out of conventional lead core bullets for hunting purposes should be strongly encouraged.

Zusammenfassung

Vergleich der Wirksamkeit sowie der Fragmentierung gängiger bleifreier und bleihaltiger Jagdbüchsengeschosse in erlegten wildlebenden Huftieren und in ballistischer Seife

Anna Lena Trinogga

Unter Tierschutzgesichtspunkten ist der Schuss auf Wild im Rahmen der Jagdausübung nur dann akzeptabel, wenn er dem beschossenen Tier nicht mehr als die unvermeidbaren Schmerzen zufügt. Vor dem Hintergrund der Erkenntnisse über die Rolle bleihaltiger Jagdgeschosse als Verursacher von Bleivergiftungen bei Greifvögeln wird zunehmend der Einsatz bleifreier Geschossvarianten gefordert. Letztere sind allerdings hinsichtlich ihrer Tötungswirkung umstritten. Ziel der vorliegenden Doktorarbeit war es daher zu beurteilen, ob gängige bleifreie Jagdbüchsengeschosse in Hinblick auf den Tierschutz einen adäquaten Ersatz für konventionelle bleihaltige Geschosse darstellen.
Um die Verwundungswirkung – und folglich die Tötungswirkung – von Geschossen zu untersuchen und um das Splitterverhalten der Geschosse darzustellen, nutzten wir verschiedene Ansätze:

Zwischen 2006 und 2009 fertigten wir Röntgenaufnahmen von 297 im Rahmen der regulären Jagdausübung in Deutschland erlegten wildlebenden Paarhufern an und ermittelten die Zahl der Geschossfragmente im Wildkörper sowie die maximale Distanz zwischen den Fragmenten und dem Schusskanal. Es zeigten sich signifikante Unterschiede im Splitterverhalten zwischen den bleifreien und den bleihaltigen Geschossen. Die Verwendung bleihaltiger Geschosse ging sowohl mit einer signifikant höheren Splitterzahl als auch mit einer signifikant größeren maximalen Entfernung der Splitter vom Schusskanal einher. Wir konnten zeigen, dass der Einsatz bleihaltiger Büchsengeschosse eine weitflächige Kontamination des Wildkörpers und des Aufbruchs mit sich bringt. Er sollte daher sowohl aus Naturschutz- wie auch aus Verbraucherschutzgründen vermieden werden (Kapitel 3).

Die Tötungswirkung eines Geschosses ist direkt abhängig von der Gewebezerstörung, die es innerhalb des Wildkörpers verursacht. Im Rahmen der Jagdausübung sollten vergleichbare Trefferplatzierungen zu vergleichbaren Wunden führen. Um die Frage zu beantworten, ob bleifreie Geschosse zu weniger schweren Wunden führen und folglich den beschossenen Tieren vermeidbare Schmerzen zufügen, führten wir Computertomographien und pathologisch-anatomische Untersuchungen an 34 Stück Schalenwild durch. Der Vergleich der Wunddurchmesser entlang des Schusskanals und der maximalen Querschnittsfläche der Wundhöhle ergab keine signifikanten Unterschiede zwischen bleihaltigen und bleifreien

Geschossen. Alle untersuchten Tiere zeigten schwere Verletzungen lebenswichtiger Organe, die einen schnellen Todeseintritt durch Verbluten wahrscheinlich machen. Wir fanden keine Hinweise darauf, dass die Verwendung bleifreier Geschosse mit weniger schweren oder kleineren Wunden verbunden wäre (Kapitel 4).

Die Simulation wundballistischer Prozesse mit Glyzerinseife als Gewebeersatz ist eine gängige Methode, um das Verhalten von Geschossen in einem Zielmedium darzustellen. Sie erlaubt einen Vergleich des Wirkungspotentials unterschiedlicher Geschosse. Für diese Arbeit wurden unter standardisierten Bedingungen Seifenblöcke beschossen. Wir analysierten die von acht bleifreien und drei bleihaltigen Geschossen verursachten Kavernen. Eine Überlegenheit bleihaltiger Geschosse in Bezug auf die Kavernendurchmesser in ballistischer Seife fanden wir nicht. Allerdings beeinflusste der Geschosstyp die Form der Kaverne signifikant. Der maximale Kavernendurchmesser befand sich bei allen Geschossen im vorderen Teil des Seifenblocks, jedoch lag er bei bleifreien Deformationsgeschossen signifikant tiefer innerhalb des Blockes als bei bleihaltigen Geschossen oder bei bleifreien Teilzerlegungsgeschossen. Der erstgenannte Geschosstyp scheint folglich für die Jagd auf schwereres Wild besser geeignet zu sein. Hinsichtlich der Wechselwirkungen zwischen Geschoss und Gewebe fanden wir deutliche Unterschiede innerhalb der Geschosstypen, insbesondere zwischen den einzelnen bleifreien Teilzerlegungsgeschossen. Unsere Ergebnisse zeigen deutlich, dass die Geschosskonstruktion einen stärkeren Einfluss auf das Potenzial eines Geschosses hat als die An- oder Abwesenheit eines Bleikerns. Ein einheitlicher Zulassungstest vor dem Inverkehrbringen erscheint daher für alle Jagdgeschosskonstruktionen sinnvoll (Kapitel 5).

Angesichts der laufenden Weiterentwicklung der Geschosskonstruktionen durch die Munitionsindustrie ist davon auszugehen, dass die im Rahmen dieser Studie bei einzelnen Fabrikaten zu Tage getretenen Defizite durch Veränderungen des Geschossaufbaus behoben werden. Unter anderem könnte sich durch die Etablierung von Varianten mit Zinnkernen und Stahlmantel die Verfügbarkeit leistungsfähiger bleifreier Teilzerlegungsgeschosse deutlich erhöhen.

Zusammengefasst zeigen die Ergebnisse dieser Arbeit, dass bleifreie Jagdbüchsengeschosse mit Blick auf den Tierschutz als adäquater Ersatz für konventionelle bleihaltige Geschosse anzusehen sind. Da die Toxizität von Blei sowohl für den Menschen als auch für die Tierwelt hinreichend bekannt ist und Sicherheitsbedenken inzwischen ausgeräumt wurden, sollte der Verzicht auf bleihaltige Geschosse dringend empfohlen werden.

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Poster

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Selbstständigkeitserklärung

Hiermit bestätige ich, dass ich die vorliegende Arbeit selbstständig angefertigt habe. Ich versichere, dass ich ausschließlich die angegebenen Quellen und Hilfen in Anspruch genommen habe.

Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen und wurde bisher nicht veröffentlicht.

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Anna Trinogga