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LEAD USE IN HUNTING

Unleaded hunting: Are copper bullets and lead-based bullets equally effective for killing big game?

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Abstract Semi-jacketed lead-cored or copper-based homogenous rifle bullets are commonly used for hunting big game. Ever since their introduction in the 1990's, copper-based bullets have not been widely accepted by hunters due to limited supply, higher expense, and the perception that they exhibit inferior killing efficiency and correspondingly higher wounding rates. Here, we present data showing that animal flight distances for roe deer, red deer, brown bear, and moose dispatched with lead- or copper-based hunting bullets did not significantly differ from an animal welfare standardized animal flight distance based on body mass. Lead-cored bullets typical fragment on impact, whereas copper-based bullets retain more mass and expand more than their leaden counterparts. Our data demonstrate that the relative killing efficiency of lead and copper bullets is similar in terms of animal flight distance after fatal shots. Hunters that traditionally use lead bullets should consider switching to copper bullets to enhance human and environmental health.

Keywords Animal flight distance · Animal welfare · Hunting bullet expansion · Killing efficiency · Lead and copper ammunition · Wound ballistics

INTRODUCTION

Rifles using modern ammunition are used worldwide to cull or harvest wild mammals in order to manage populations and provide recreational, commercial, and subsistence hunting opportunities. Lead (Pb) has been the metal of choice for making rifle projectiles since the earliest muzzleloaders were used for hunting. The reason is obvious—lead is widely available, easily extracted from ore, simple to purify, and cheap to manufacture when compared to most other non-ferrous metals. It has a notably higher density (11.3 g/cm^3) and much lower tensile strength compared to other metals available for manufacturing bullets. It is highly ductile, which allows for rapid expansion after impact to create large wound channels and is thus well-suited as a material for hunting projectiles (Almar-Næss 1985; MacPherson 1994; Guruswamy 2000).

As a non-toxic alternative to lead, rifle projectiles made of copper (Cu) and copper-zinc (Zn) alloys (tombac and brass) have been available since the 1990's. Copper is an essential element required to maintain homeostasis in vertebrates, even though too high or too low dietary intake can induce adverse health effects (Stern 2010). Copper is more expensive than lead but is less dense (8.96 g/cm^3), although it is denser than most forms of steel (< 8.05 g/cm^3). Lead is about 1.5 times more ductile than copper (Almar-Næss 1985).

Bullet expansion and wound ballistics

Hunting bullets designed to expand or deform will exhibit a mushroom-like anterior enlargement of the cross-sectional area of the bullet at impact. Lead-based hunting bullets (L-bullets) have a lead core covered with a copper jacket except for the leading lead tip. At impact the lead core behaves like an incompressible fluid when the drag forces generated by the stagnation pressure at the leading edge of the bullet exceed the yield limit for lead (Berlin et al. 1988; MacPherson 1994; Kneubuehl et al. 2011). Pressure is thus dispersed within the floating lead and works the jacket from the inside of the bullet, causing it to burst (Berlin

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et al. 1988; Kneubuehl et al. 2011). Expansion is very rapid and stagnates within 0.1 ms (Kneubuehl et al. 2011). Copper-based, homogeneous lead-free hunting bullets (C-bullets) expand according to the same mechanisms if the frontal cavity is large enough for viscous pressure to enter (Kneubuehl et al. 2011).

Bullet penetration is characterized by the temporary cavity caused by tissue impelled radially in relation to the velocity vector as momentum is imparted from the projectile to the soft tissue and it undergoes elastic deformation as it is stretched and compressed (Stefanopoulos et al. 2014). The displaced tissue will rapidly recoil towards its initial position in response to the vacuum and elastic energy conveyed to the tissue, thus generating a brief oscillation (Harvey et al. 1946; Di Maio 1999; Fackler 2001; Kneubuehl et al. 2011). The residual wound channel, which is a cavity filled with blood, damaged tissue, and contaminants sucked in from the outside, is termed the permanent wound cavity (Fackler 1988; Janzon et al. 1997). The extravasation zone is the transition between the permanent wound cavity and intact tissue and is characterized by hemorrhage resulting from distention of the temporal cavity, inflicting damage to blood vessels through overstretching and shearing effects due to heterogeneity of the involved tissues (Kneubuehl et al. 2011; Stefanopoulos et al. 2014). There is a proportional relationship between the kinetic energy of the penetrating bullet and the expansion of the temporary cavity. Thus, the potential energy stored in the tissue equals the work done to create the maximum expansion. MacPherson (1994) states that the potential for this energy to cause wounding depends on four factors: The magnitude of the stored energy in the tissue, the ability of the tissue to sustain strain, the size of the organ structure, and the anatomical constraints to tissue movements. If the energy stored in tissue exceeds the elastic limit of the tissue, it will rupture and permanent wounding results. Tissue elasticity is therefore an important factor as it impairs the extent of permanent damage caused by a bullet. Muscle, skin, blood vessels, and lungs are elastic and can absorb energy generated by a penetrating bullet and tend to recoil towards the wound channel (Fackler 1988; MacPherson 1994; Karger 2008). Other less resilient tissues, such as liver, kidney, and brain, tend to disrupt from penetrating projectiles (Roberts 1988; Caudell 2013; Stefanopoulos et al. 2014).

The size of the organ or body is important because there will be a lower size limit whereby all tissues will be stretched beyond the elastic limit of the organ or body, causing it to rupture. For organs or bodies larger than this critical size, tissue damage primarily occurs by crushing, tearing, and stress (MacPherson 1994). Thus, the primary factor causing permanent wound cavity in soft tissue like lungs will mainly be crushing rather than radial stretching if the organ size exceeds the critical size (Stefanopoulos et al. 2014). This suggests that the area of the leading edge of the bullet might correlate with the radial dimension of the permanent wound cavity, with larger calibers yielding larger wound channels. Fragmentation is an inherent ability of all lead-based bullets where lead floats and expands in response to the stagnation pressure (Fackler et al. 1984; Cornicelli and Grund 2008; Stokke et al. 2017). Although debated, bullet fragmentation is commonly considered to be a primary cause of increasing the permanent wound cavity by weakening the tissues under tension from the temporary cavity (Fackler et al. 1984; Coupland 1999; Trinogga et al. 2013). In contrast, deforming copper bullets can withstand fragmentation and thus sustain momentum ensuring proper penetration (Hunt et al. 2009; Batha and Lehman 2010; Gremse et al. 2014).

Cause of death for animals dispatched with hunting bullets

Most hunters, in accordance to codes of practice, target the thoracic area. The expanded bullet will penetrate the thoracic cavity, causing trauma to the heart, lungs, and/or major blood vessels causing subsequent fatal hemorrhage (with subsequent hypotension, hypovolemic shock, hypoxia, and brain death) (Stokke et al. 2018). Hemorrhage is the cause of death in hunted animals, unless the bullet traumatizes the brain (brain death) or the spinal cord cranial to C3–C5 (where the phrenic nerves exit). Wounded, immobile animals are dispatched (euthanized) with a head/neck shot and then the cause of death is not fatal bleeding. Impacts to other body parts might cause fatal hemorrhaging if large blood vessels are lacerated or a well-perfused organ such as a kidney or the liver is ruptured. Fatal wounds will inevitably be followed by circulatory collapse due to a hypovolemic shock with subsequent brain hypoxia (Vincent and De Backer 2013; Gaieski and Mikkelsen 2017). Death due to blood loss is never instantaneous and the rate of hemorrhaging determines the time from bullet impact to permanent incapacitation. Therefore, animal flight distance conveys information about elapsed time and can be used as a practical indicator for killing efficiency of hunting bullets and cartridges (Stokke et al. 2012; McCann et al. 2016; Kanstrup et al. 2016b; Martin et al. 2017; Stokke et al. 2018).

Lead toxicity and transition to non-lead ammunition

Even though the use of L-bullets is mainstream, there are concerns over health and environmental risks from spent ammunition (Bellinger et al. 2013). Lead has no known biological function in vertebrates and is toxic to most physiological systems (Bellinger et al. 2013). A transition to C-bullets is therefore strongly recommended to avoid lead exposure in humans consuming game meat and in wild animals scavenging on remains from shot game (Krone and Hofer 2005; Grund et al. 2010; Delahay and Spray 2015; Arnemo et al. 2016; Kanstrup et al. 2016a; McTee et al. 2017; Gerofke et al. 2018; Kanstrup et al. 2018). In contrast to lead, copper is an essential element in vertebrates and is generally not considered to be toxic to humans (Stern 2010).

Hunters have raised concerns over the efficiency of C-bullets (Caudell et al. 2012; Bundesinstitut für Risikobewertung 2013), including the perception of limited supply, higher costs, inferior killing efficiency, and correspondingly higher wounding rates compared to ‘traditional’ lead-based ammunition (Southwick Associates Inc. 2014; Thomas et al. 2016). However, C-bullets compare favorably to L-bullets in recent studies. In a controlled experiment, Gremse et al. (2014) used ballistic soap as tissue simulant to show that the terminal ballistics of C- bullets were similar to L-bullets. However, tissue simulants are very different from live tissue and may not be analogous to living animals. Trinogga et al. (2013) examined 34 carcasses of ungulates [wild boar (*Sus scrofa*), roe deer (*Capreolus capreolus*), chamois (*Rupicapra rupicapra*), and red deer (*Cervus elaphus*)] shot with either L- or C-bullets. They used X-ray computed tomography to measure permanent wound cavities in the lungs and concluded that both bullet types should have the same killing potential. However, if hunters are to use C-bullets with confidence, they want to see evidence from actual hunting situations where uncontrolled events may occur. Kanstrup et al. (2016b) conducted a study that included 657 ungulates shot with either L- bullets or C-bullets by recreational hunters. The authors used animal flight distance as the primary response variable and concluded that C-bullets were an effective alternative to L-bullets. Spicher (2008) found that 95% of 247 animals were killed quickly with a single shot from C-bullets. Of the 12 hunters in that survey, eight (66%) were convinced that C-bullets were as suitable as traditional L-bullets, and four (33%) considered that the C-bullets performed better. Knott et al. (2009) studied red deer and roe deer dispatched with either C- or L-bullets. They reported no significant difference between either bullet type regarding killing efficiency or accuracy. Likewise, McCann et al. (2016) found that C-bullets were effective in culling 983 elk (*Cervus elaphus*). Finally, McTee et al. (2017) studied the capacity of L- and C-bullets to instantly incapacitate ground squirrels (*Sciuridae* spp) and found no difference between the two bullet types.

Hypotheses and objectives

We used animal flight distance as a discriminator to study differences in killing efficiency between expanding L- and C-bullets. In doing so, we applied the new model developed by Stokke et al. (2018) to compare observed animal flight distances with animal flight distance welfare standards for Fennoscandia (Stokke et al. 2018). This model estimates an expected animal flight distance for mammals based on body mass. One advantage of using this model is its objective representation of animal welfare outcomes that reflect physiological processes that occur in an animal during and after bullet penetration. Furthermore, the model enables a comparison of animal flight distances without dividing the data into groups based on mammal species, body mass, or age classes. In addition, we developed indices for bullet expansion and degree of asymmetrical expansion to study differences in expansion potential between the two bullet types. We tested the null hypothesis that both bullet types exhibited similar killing efficiency and expansion characteristics.

MATERIALS AND METHODS

Sampling of hunting data

Big game hunting in Fennoscandia is typically performed in hunting teams including around 6 hunters on average in Norway (Solberg et al. 2014). During hunting, team members position themselves at strategic sites where animals predictably pass by when driven by other hunters with or without the aid of hunting dogs. In these circumstances, shooting distances are usually within 100–150 m (Fig. 1).

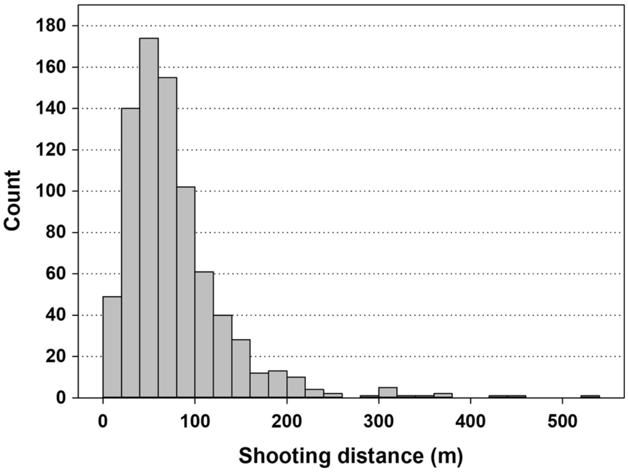

Fig. 1 Frequencies of shooting distances recorded during the present study

We collected data from four mammalian species based on questionnaires distributed to hunters in Fennoscandia: Moose (*Alces alces*: Finland, Sweden, and Norway 2004–2006) $n = 5\,245$; brown bear (*Ursus arctos*: Sweden 2006–2010) $n = 637$; roe deer (Norway 2014–2015) $n = 38$; red deer (Norway 2014–2015) $n = 1$. The hunters completed one form per harvested animal. Live body masses ranged from 9 kg (roe deer) to 662 kg (moose). In addition, hunters provided bullets retrieved from moose carcasses together with the corresponding questionnaire ($n = 1833$, see Online Appendix S1 for summary of bullet types).

In this paper, we used the following information from the questionnaires: animal flight distance (m), number of impacting bullets, whether the bullet exited or stopped in the animal body, the angle of the bullet trajectory in relation to the animal's longitudinal axis, penetrated organs and bones, cartridge, bullet type, whole or slaughter mass, and age class (moose only). We discerned between L-bullets and C-bullets as defined above. To avoid skewness in animal flight distances due to caliber size, we included only calibers with both L- and C-bullets in the analyses. The most commonly used calibers ranged from 6.5 to 8.0 mm.

For all roe deer, red deer, moose, and some bears, we converted slaughter weights (W_s) to estimated live masses (M_l) (kg). For roe deer, red deer, and moose, we estimated this using the following formula (Hjorteviltregisteret 2016):

$$M_l = \frac{100 \cdot W_s}{52}$$

For bears, we estimated live masse (M_b) (Swenson et al. 1995) using the formula

$$M_b = 4.63 + 1.49 \cdot W_s$$

Hunters were asked to locate the spot where the animal was struck by the first bullet and from that point start pacing out along the track of the animal until they arrived at the incapacitated animal. This route, covered by the shot animal, was recorded as animal flight distance in the form.

Comparison of efficiency of lead-based versus homogenous bullets

Concerns have been raised regarding the performance of bullets, in particular C-bullets, when shooting distance exceeds 200 m (Caudell et al. 2012; Caudell 2013). Caudell et al. (2012), firstly draws attention to the possibility of destabilized bullets due to a mismatch between bullet length and twist rate of the rifle barrel, and secondly to reduced expansion potential. Even though shooting distances in the present study rarely exceeded 150 m, we examined if expansion was affected within recorded shooting distances to ensure that our modeling was not influenced by this factor. Due to very few records for shooting distances exceeding 150 m (Fig. 1), we excluded records for longer shooting distances. We applied our expansion indices for this purpose (see next chapter). We regressed the indices against shooting distances and exhibited the result in scatter diagrams with a linear regression per bullet and caliber category.

To enable a sound comparison between animal flight distances shot with C- or L-bullets, we included only records fulfilling the following requirements: (1) the target animal was dispatched with one bullet; (2) the bullet trajectory described an angle of incidence ≤ 45° (in relation to the longitudinal axis of the animal in the horizontal plane), (3) bullet type and caliber were known and, (4) both lungs were penetrated. These criteria reduced the number of records to 710 moose, 71 bears, 1 red deer, and 32 roe deer.

To evaluate if any discrepancies existed between animal flight distances caused by C- or L-bullets, we applied the model designed by Stokke et al. (2018) defining animal welfare standards in hunting (Fig. 2). Based on penetration of the thoracic region, the model estimates an expected

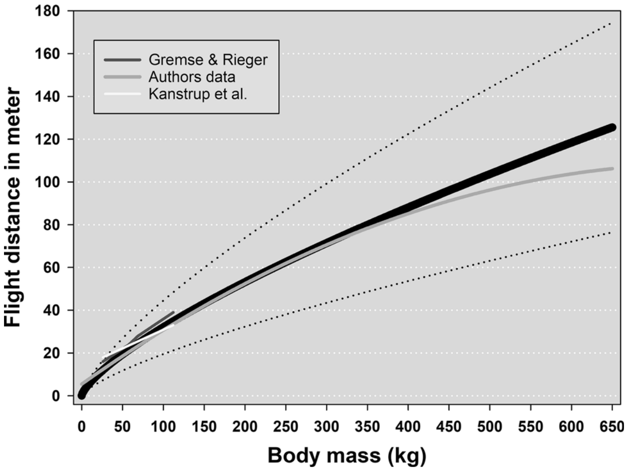

Fig. 2 Expected animal flight distances (efd) predicted by the model for mammals with body masses < 650 kg (reprinted from Stokke et al. 2018). The solid broad black line represents efd in relation to body mass. Dotted lines represent the uncertainty of parameter estimation. A very good accordance with average animal flight distances, recorded from several mammal species under field hunting conditions, exhibits the predictive power of the model. The dark short grey line displays average animal flight distances for four species with increasing body masses: roe deer, fallow deer (*Dama dama*), wild boar (*Sus scrofa*), and red deer (Gremse and Rieger 2014). The short white line shows average animal flight distances for roe and red deer (Kanstrup et al. 2016b). The long light grey line is the regression line representing animal flight distances for red fox, roe deer, brown bear, and moose calves, yearlings, and adults (Stokke et al. 2018)

animal flight distance (efd), for mammals if body mass (M) is known (Stokke et al. 2018).

$$\text{efd} = 1.14M^{0.73}$$

In the applied form the model is calibrated with estimated average traveling speed for adult moose after being shot. However, it is obvious that traveling speed for animals penetrated by expanding bullets may vary. To compensate for this, the model can be calibrated with estimated speed for the species in question. Here we apply four mammalian species. So, the question is, did the animals travel with sufficiently equal speed (i.e., similar deviations from estimated efd-values) to justify a comparison without addressing differences among species? In our case this could partly be tested, because brown bear and moose (calves, yearlings, and adults) had enough overlap of body masses to address this question. We applied records for brown bear and all records from moose except those representing body masses outside the range of brown bear body masses. The data were grouped into 5 body mass classes representing a stepwise increase of 50 kg per class (range 38–250 kg). We exhibited deviations from efd-values with error bars and used a general linear model to test for speed differences between the species.

For all body masses and species, we calculated the discrepancies between expected animal flight distances (efd) and reported animal flight distances and conveyed the differences into two samples (1 and 2) according to bullet class [L (n_1 = 729) vs C (n_2 = 84)]. These samples were compared using a general bootstrap approach with randomized residuals (Ter Braak 1992; Manly 2001). First, we computed the t-statistics for these samples. This t-value was then compared with a bootstrap distribution for which the null hypothesis was made to be true by replacing the sample values with their residuals. A bootstrap population of residuals of size $n_1 + n_2$ could then be used to draw a bootstrap sample 1 by selecting n_1 of these values at random with replacement. Similarly, we obtained a bootstrap sample 2 by selecting n_2 cases from the bootstrap population. These samples were used to compute a bootstrap value for t. By repeating this procedure many times, the bootstrap distribution of t was generated. A two-sided test was applied to see if the $|t|$ value for the observed samples (1 and 2) was significantly larger compared to the distribution of bootstrapped $|t|$ values from randomized residuals. Accordingly, this test does not produce any p value.

To examine if discrepancies between estimated and recorded animal flight distances related to C- or L-bullets differed among body masses, we pooled body masses into weight classes divided per 50 kg body mass up to 200 kg. Due to few samples for C-bullets related to body masses > 200 kg, we applied two weight classes between 200 and 650 kg. The result was exhibited in a grouped vertical error bar graph and tested with a general linear model.

Furthermore, we applied the animal welfare standard model to compare the data against the wounding threshold or maximal animal flight distance (mfd) suggested by the model (Stokke et al. 2018).

$$\text{mfd} = 4.92M^{0.73}.$$

Bullet expansion index and penetration ability

Retrieved bullets were processed according to Stokke et al. (2017). The expanded frontal area of the bullets was measured using a Vernier caliper to obtain two cross-sectional measurements (d_1 and d_2—perpendicularly oriented to each other) to even out asymmetrical expansion. These measurements were used together with bullet diameter (d) to express an index (E) for rate of expansion in relation to original bullet cross-sectional area.

$$E = \left(\frac{d_1 + d_2}{2d}\right)^2.$$

This expansion index was used to explore the expansion potential of C- versus L-bullets and to analyze if caliber and expansion index are correlated. We divided bullets (L and C) into three caliber categories according to diameter (mm): (1) 6.5–7.9, (2) 8.0–9.8, and (3) > 9.9. Variation of expansion among these categories for L- and C- bullets was exhibited with an error bar graph and tested with a general linear model. Due to very low sample size for C-bullets in the largest caliber category, this category was excluded from the statistical model.

In addition, we express asymmetrical expansion with the following index:

$$E_{\text{sym}} = 1 - \left(\frac{d_s}{d_l}\right)^{-1},$$

where d_s represents the smallest and d_l the largest of the two diameters d_1 and d_2. This index equals zero if the diameters are alike and decreases linearly with increasing differences between the diameters. We used this index to compare the levels of asymmetrical expansion between C- and L-bullets and tested for a difference with the Mann–Whitney U test.

Finally, we studied the ability of bullets to fully penetrate and exit moose bodies. This was done by calculating the ratio between bullets that exited the bodies and those that stopped in the bodies. We divided the analyses into two caliber categories: 6.5–7.9 mm and $\geq$ 8.0 mm. Due to reasonable sample sizes for smaller calibers, we were able to divide L-bullets into three categories: bonded core (copper jacked soldered to the lead core), h-mantel (dual lead cores separated with integral partitioning of the copper jacket), and conventional (simple copper jacket with unsoldered lead core). Furthermore, we divided moose body sizes into three age categories for this analysis: calves, yearlings, and adults. We applied a generalized linear model with binomial distribution to analyze penetration ability. This was done only for the smallest caliber category due to very few samples for the larger calibers.

We used Visual FoxPro 9.0 SP2 to handle the data and to program the bootstrap session. We performed standard statistical analyses with IBM SPSS Statistics Version 25 and created graphs with SigmaPlot 13.0.

RESULTS

Comparison of killing efficiency for C- and L-bullets

Apparently, expansion rate of bullets was unaffected by shooting distance within 150 m, except for C-bullets in the > 9.9 mm caliber category (Fig. 3). However, nothing can be deduced from this regression due to lack of datapoints for this category. Since bullets exhibited constant expansion potential within shooting distances shorter than 150 m, we did not regard this factor to have any significant effect on our approach to examine killing efficiency.

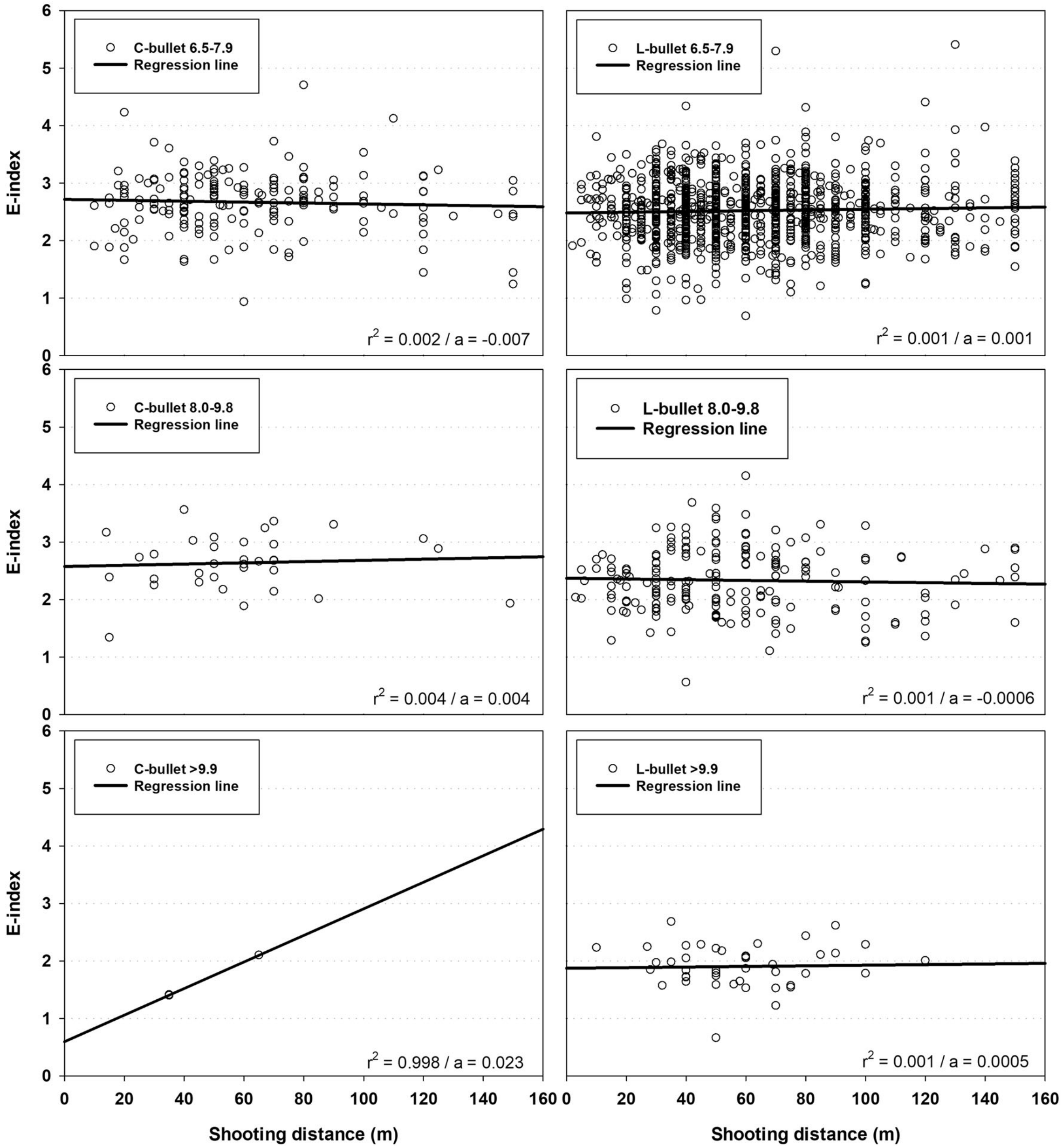

Fig. 3 Expansion indices for C- and L-bullets within three caliber categories in relation to shooting distance, exhibited from top to bottom: (1) 6.5–7.9 mm, (2) 8.0–9.8 mm, and (3) > 9.9 mm. C-bullets are on the left and L-bullets to the right. Values for r^2 and slope (a) are depicted at the bottom of each graph

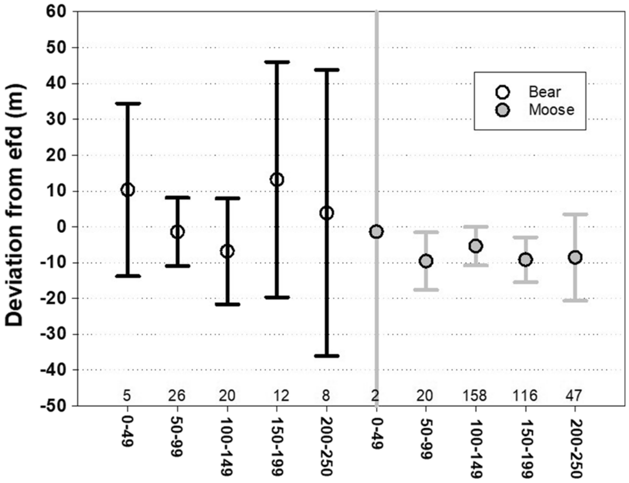

Fig. 4 Deviations from predicted edf-values for recorded animal flight distances from brown bear and moose exhibited in 5 body mass classes (kg). The number of records per body mass class and species is displayed below corresponding error bars

Recorded animal flight distances for brown bear and moose exhibited similar deviations from predicted efd-values among body mass groups (Fig. 4: $F = 0.40$, df = 4, $p = 0.81$). Furthermore, deviations did not differ between brown bear and moose (Fig. 4: $F = 2.12$, df = 1, $p = 0.15$). There was no interaction between deviations for brown bear and moose (Fig. 4: $F = 0.65$, df = 4, $\mathrm{df}_{\mathrm{error}} = 387$, $p = 0.63$). This suggests that traveling speed following bullet impact for these species was analogous and unlikely to skew model output and statistical analyses noticeably.

Measured animal flight distances exhibited a large variation in relation to predicted animal flight distances (Fig. 5). Yet, most records were reasonably evenly distributed around the expected animal flight distances (Fig. 5). Recorded animal flight distances, with one exception, were below the wounding threshold suggested by the model (Stokke et al. 2018). Actual animal flight distances exhibited increasing variability with body mass.

The bootstrap approach suggested that deviations from the expected animal flight distances (efd) did not differ between animals dispatched with L- or C-bullets (Fig. 6). This is because the t-value for the observed data is located within the confidence interval for the bootstrapped t-values from randomized residuals (Fig. 6).

Recorded deviations from predicted animal flight distances did not vary significantly among body masses (Fig. 7: $F = 0.69$, df = 5, $\mathrm{df}_{\mathrm{error}} = 5$, $p > 0.6$). It might be worthwhile noting that C-bullets on average gave shorter animal flight distances for the three smallest body mass categories, whereas the situation was reversed for the next two categories. However, this shift of deviation from efd-values was not significant (Fig. 7: $F = 0.10$, df = 1, $\mathrm{df}_{\mathrm{error}} = 6.87$, $p > 0.7$). There was no interaction between

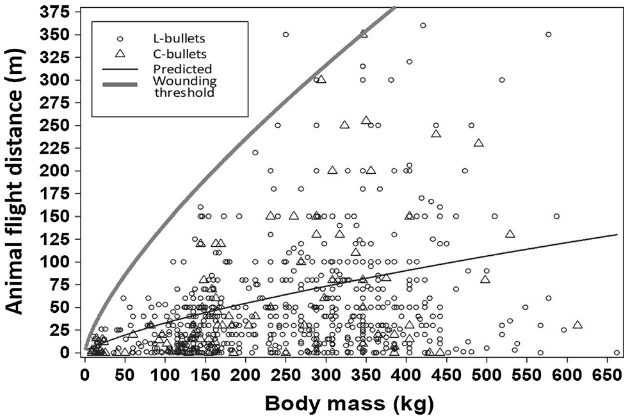

Fig. 5 Distribution of animal flight distances of C- and L-bullets compared to predicted animal flight distances (thin lower line) and wounding threshold (bold upper line) derived from the model (Stokke et al. 2018)

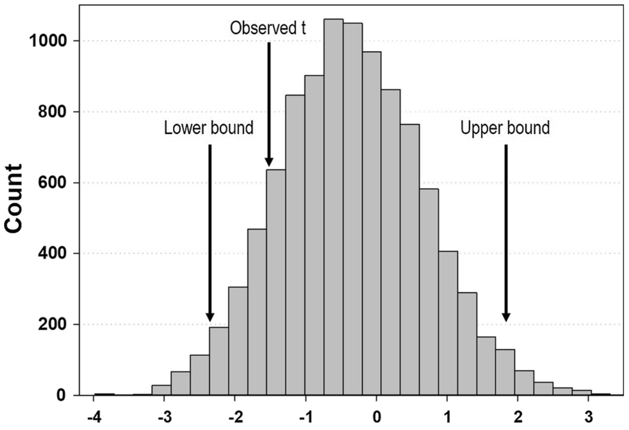

Fig. 6 Randomized residual bootstrap distribution of t-values compared to the t-value (− 1.65) for the observed data. The analysis is performed with 10 000 bootstrap samples with mean = − 0.36, Lower bound = − 2.33 and Upper bound = 1.73

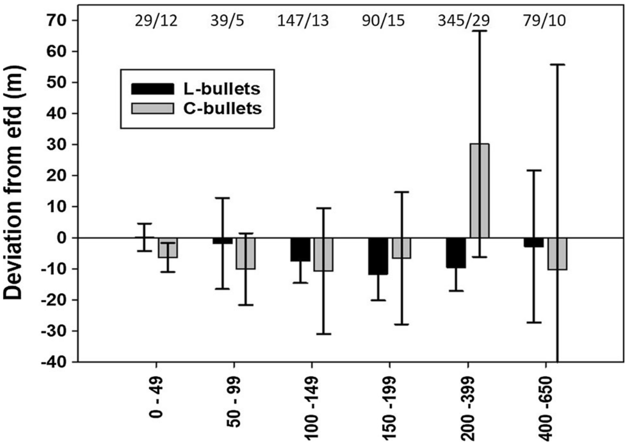

Fig. 7 Deviation from predicted animal flight distances, according to efd-values (Stokke et al. 2018), for C- and L- bullets in relation to 6 body mass classes. Sample sizes are exhibited above the vertical error bars (L-bullets/C-bullets)

Table 1 Range and variance of expansion indices for C- and L-bullets within three caliber categories

Bullet	Caliber category (mm)	*N*	Range	Variance
C	6.5–7.9	183	3.77	0.29
	8.0–9.8	41	3.56	0.40
	> 9.9	3	0.69	0.16
L	6.5–7.9	1187	5.40	0.47
	8.0–9.8	196	4.74	0.42
	> 9.9	45	2.68	0.29

C- and L-bullets and body mass classes regarding deviation from predicted animal flight distance (Fig. 7: $F = 1.43$, df = 5, $\mathrm{df}_{\mathrm{error}} = 801$, $p > 0.2$). However, due to small sample sizes for C-bullets, these results should be treated with caution.

Comparison of expansion indices and penetration ability

Within the three caliber categories, L-bullets appeared to have a wider range of expansion compared to C-bullets (Table 1). This indicates that L-bullets exhibited a more irregular expansion history than C-bullets. This is also reflected in the variance, which is smaller for C-bullets, irrespective of smaller sample sizes (Table 1.). This expansion pattern is supported by the Levene's test, suggesting unequal variances (Levene statistics: mean = 2.52, df1 = 5, df2 = 1604, $p = 0.02$).

The expansion potential was apparently largest for C-bullets as their indices were larger than indices of L-bullets (Fig. 8: $F = 20.3$, df = 1, $\mathrm{df}_{\mathrm{error}} = 1604$, $p < 0.001$ {> 9.9 mm category not included}). In the smallest caliber category, C-bullets expansion index was on average 2.65 compared to 2.52 for L-bullets (Fig. 8). The same trend was evident for the next caliber category with an index of 2.62 for C-bullets versus 2.33 for L-bullets (Fig. 8). For the largest caliber category, the trend was reversed, and C-bullets exhibited an index of 1.64 versus 1.91 for L-bullets. However, sample size for C-bullets in the last category is very small and thus the comparison is unreliable. Another expansion trend was the capacity of C-bullets to maintain expansion index when caliber size increased from the smallest caliber category to the medium one (Fig. 8). This trend was absent for L-bullets as they exhibited a steady decrease of expansion indices for increasing caliber (Fig. 8).

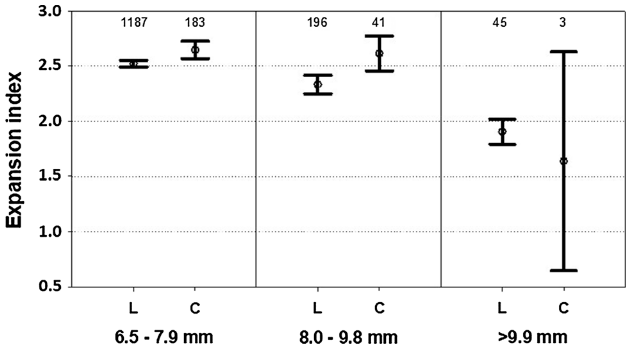

Fig. 8 Expansion indices for C- and L-bullets within three caliber categories. Sample sizes are shown above their respective error bars

The index (E_{sym}) representing the level of asymmetrical expansion showed that L-bullets expanded more asymmetrically than C-bullets (Mann–Whitney $U = 136\,516.5$, $p = 0.002$). Average asymmetrical index for C-bullets was − 0.09, whereas corresponding index for L-bullets was − 1.13.

The tendency of bullets to exit moose bodies did not vary among bullet categories in the smallest caliber category (Fig. 9: Wald Chi-Square = 4.74, df = 3, $p = 0.2$). All bullet types exhibited a clear tendency to increase the amount of seizures with increasing body size (Fig. 9: Wald Chi Square = 46.83, df = 2, $p < 0.001$). This pattern was consistent for all bullet categories in the smallest caliber category as no interaction was present between age classes and bullet categories (Fig. 9: Wald Chi Square = 3.36, df = 6, $p = 0.8$).

DISCUSSION

An evaluation of the efficacy of non-lead versus lead-based ammunition has never been done based on quantified animal welfare outcomes. In this paper, we applied a novel model designed by Stokke et al. (2018) that defines humane killing. The model predicts animal flight distances following penetration of both lungs in relation to body mass of mammals. From an animal welfare perspective, the targeting of vital organs is the optimal and most humane killing strategy because it induces rapid and fatal hemorrhaging (Stokke et al. 2018). In our approach, we measured deviations for animal flight distances recorded by hunters with standardized animal flight distances (efd) suggested by the model in relation to body mass. In contrast to other studies, our approach allows a direct comparison of animal flight distances without any need to classify animals into groups according to body size, age class, or species. This is because the model is mathematically deduced from allometric relationships generally acknowledged to be universal for mammals. However, if studied mammalian game species travel with unequal speeds after bullet impact, the result might be skewed, and corrections should be applied (Stokke et al. 2018). Brown bear and moose had the largest

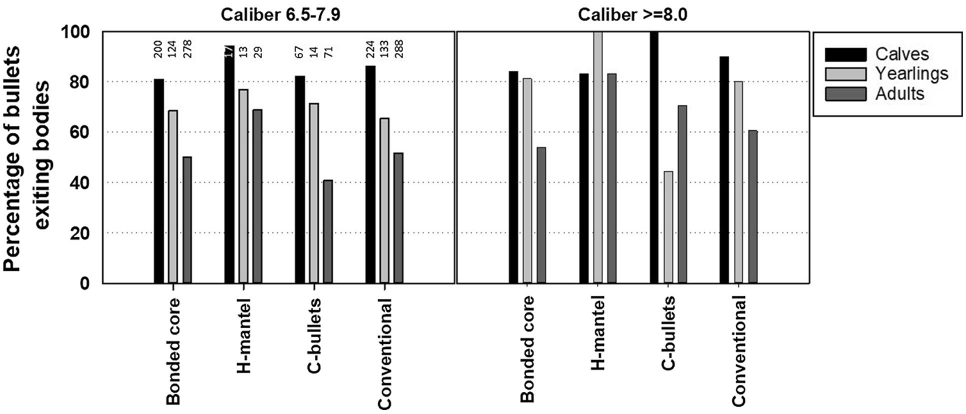

Fig. 9 The percentage of bullets exiting moose bodies in relation to age class, bullet, and caliber category. Bonded core, H-mantel, and Conventional belong to L-bullets. Sample sizes are displayed above their respective bars. Sample sizes for the largest caliber category are too small for statistical analyses

overlap of body masses so we could test for differences between traveling speed for these species. We did not detect significant speed differences (i.e., equal deviations from efd-values) between brown bear and moose, thus indicating no need to differ among species during the analyses.

Our findings showed that animal flight distances varied greatly although we only used cases where bullets penetrated both lungs. Variability also increased with body mass. This pattern is to be expected because (1) total blood volume remains unchanged in relation to body mass, (2) blood circulation time increases with body mass, whereas (3) the radial dimension of the permanent wound cavity remains largely unchanged (Stokke et al. 2018). Thus, bleeding rates will decrease, whereas animal flight distances will increase with increasing body mass. The model estimates animal flight distances relative to body mass when an animal is dispatched with an expanding bullet penetrating both lungs centrally and perpendicularly to its longitudinal axis. Thus, peripheral penetrations of the thorax area will yield diminished hemorrhaging followed by increased animal flight distances because less lung tissue is disrupted. We believe that the model adequately estimates optimal exsanguination rates in relation to body mass. However, target animals of equal body mass after bullet impact may travel at different velocities, which will affect animal flight distances and increase variability of animal flight distances. Interestingly, it appears that the wounding threshold (mfd) defined by the model clearly delineates all cases, except one, from the region defining wounding. This suggests that the model is appropriate to evaluate killing of animals in relation to animal welfare standards.

There was no significant difference in animal flight distances among animals (moose, brown bear, roe deer, and red deer) incapacitated with L- or C-bullets when compared with efd-values in relation to body mass. For all body mass classes, deviations from predicted efd-values for C- and L-bullets were below and close to efd-values. However, for the 200–399 kg body mass class, deviations from predicted efd-values for C-bullets were above predicted efd-values, whereas corresponding deviations for L-bullets were below predicted ones. The difference between the two bullet types was insignificant, but never the less noticeable and might be of interest for hunters, but sample size for C-bullets was low and the discrepancy might as well be coincidental.

Kanstrup et al. (2016b) noticed a similar tendency for animal flight distances recorded from dispatched roe deer when shooting distances exceeded 100 m. There is one obvious difference in expansion history for the two bullet types. L-bullets retrieved from moose carcasses lose on average 2.8 g of lead per bullet, whereas C-bullets loose around 0.5 g of mass (copper) per bullet (Stokke et al. 2017). Fragmentation is therefore much more pronounced for L-bullets. These fragments might enlarge the bleeding surface of the wound cavity by penetrating and weakening tissue in the extravasation zone during cavitation and thus enhance rupturing of tissue (Fackler et al. 1984). The importance of enhanced hemorrhage in the extravasation zone is also noted by Stokke et al. (2018), as they suggested that this zone is a functional part of the wound. So, how can non-fragmenting C-bullets compete so well with L-bullets that have this inherent advantage of fragmentation?

Our results suggest two areas where C-bullets outperformed L-bullets. Firstly, they expanded more and presented a larger frontal surface after tissue penetration than L-bullets. For the most common caliber categories (6.5–7.9 mm and 8.0–9.8 mm), C-bullets exhibited a stable expansion index around 2.6, whereas L-bullets barely reached 2.5 within the smallest caliber category

(6.5–7.9 mm) and diminished strongly for larger caliber categories. Secondly, C-bullets exhibited a more consistent and stable expansion than L-bullets. Both range and variance were consistently less for expansion indices within all caliber categories for C-bullets compared to L-bullets. This clean-cut expansion pattern for C-bullets compared to L-bullets is probably related to their mechanical properties. Copper is relatively ductile and deforms plastically when yielding. However, C-bullets will not expand if not "weakened" by an axial cylindrical hole in the anterior part of the bullet so that the stagnation pressure can enter the cavity and cause the metal to float and burst. C-bullets expand more rapidly than L-bullets and deformation occurs "instantly" when fluid pressure enters the anterior cavity. Thereafter penetration occurs shoulder stabilized without additional deformation. It might happen, though, that petals are lost if heavy bones are penetrated (Kneubuehl et al. 2011). L-bullets on the other hand will be more liable to change their anterior profile after initial expansion because they will be influenced as long as the stagnation pressure exceeds the yield limit for lead (MacPherson 1994). This probably contributes to a greater variability of the anterior surface for the retrieved L-bullets compared to C-bullets. Thus, C-bullets exhibited a more symmetrical deformation history. One advantage of a symmetric anterior leading surface should be less deviation from a strait propagation line in tissue compared to L-bullets with a higher degree of asymmetrical expansion (Kneubuehl et al. 2011). Heterogenous tissues might, however, cause any bullet to deviate substantially from a straight line (Kneubuehl et al. 2011).

Some concern has been raised regarding the potential of C-bullets to expand at longer ranges (Caudell et al. 2012; Caudell 2013). This is because loss of flight speed due to drag will reduce fluid pressure in the frontal cavity of the bullet at impact so that expansion will be reduced or fail to happen et al. Within shooting distances applied in the present study (150 m), we did not detect any sign of such malfunction. Therefore, we did not include shooting distance as a factor influencing killing performance in our approach. Another interesting observation was that relative expansion of bullets decreases with increasing caliber. With increasing caliber, ballistic velocity decreases, whereas the amount of metal increases (lead or copper). This means that there is more metal mass to move during expansion when the stagnation pressure forces the metal to float. As a result, relatively less metal is probably shuffled during expansion resulting in reduced relative expansion.

Since the primary factor causing permanent wound cavity in soft tissues, such as lungs, mainly is crushing rather than radial stretching (Stefanopoulos et al. 2014), there should be a correlation between the radial dimension of the permanent wound cavity and expansion indices. The expansion advantage (larger indices) we registered for C-bullets apparently enables them to compensate for the efficiency of fragmenting so typical for L- bullets. Trinogga et al. (2013) also found that permanent wound cavities caused by deforming copper bullets tended to be the largest of all bullet types.

Even though our study indicates that there is no consistent and significant difference between the efficacy of L- and C-bullets for hunting, we will suggest one possible way for further improvement of the present incapacitation power of C-bullets. Based on our experiences with the present study, one way of improving the incapacitation power of C-bullets is to increase the expansion index by increasing the ability to expand. Energy transfer strongly depends on the size of the frontal area of the expanded bullet (Wolberg 1991). Therefore, penetration depth decreases as bullet expansion increases. So, the question is, will C-bullets manage to retain their penetration ability in combination with increased expansion? Much of the rationale behind the development of C-bullets was to improve bullet mass retention during expansion to maximize the ability of penetration and wounding (Thomas et al. 2016). However, we did not detect any significant difference between the two bullet types regarding penetration ability, so it might be that this ability will restrain further development of expansion indices for C-bullets. The problem might be omitted by making C-bullets heavier. Such a solution may, however, cause problems because it implies increased bullet length making them more liable to lose stability, because the distance between center of gravity and center of pressure (air drag) increases (Carlucci and Jacobson 2014). This applies especially to the smallest calibers (i.e., 6.5 mm and smaller) where barrel twist is insufficient to stabilize longer bullets.

CONCLUSIONS

We found no appreciable difference in killing efficiency between copper and lead-based bullets in our study, which was based on data collected by hunters under normal hunting conditions in Fennoscandia. We evaluated the efficiency of copper versus lead-based ammunition in relation to a quantifiable animal welfare standard. We did not detect any significant difference between reported animal flight distances between copper and lead-based ammunition relative to our standardized predicted animal flight distances based on body mass. Copper ammunition exhibited a larger, more reliable and stable expansion compared to lead-based ammunition. This characteristic seems to offset the advantage lead-based ammunition has in terms of killing efficiency due to fragmentation effects. Given the considerable documentation of harmful health and environmental impacts from lead-based ammunition, hunters should strongly consider using copper-based ammunition based on the results of our study.

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