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Partitioning Human Dietary Exposure to Ammunition-Derived Lead in Meat from Game Animals Between Bullets and Shotgun Pellets

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Abstract
In making recommendations for restricting uses of lead shotgun pellets and bullets for hunting, regulatory agencies, including those of EU and UK REACH, estimate human health risks from dietary exposure to lead from both ammunition types separately and attempt to monetise benefits of restriction options. However, available data from diet surveys are rarely sufficient to allow straightforward partitioning of dietary exposure between game killed with lead bullets and shotgun pellets. Because information on game meat consumption was limited, the UK REACH Agency's draft socioeconomic analysis assigned all health-related economic benefits of lead ammunition restriction to shotgun pellets and none to bullets because a much higher tonnage of shotgun pellets than bullets is used. However, differences between the two ammunition types in exposure pathways make tonnage used an unreliable proxy for dietary exposure. Using primarily data for the UK, we partitioned exposure to lead by estimating tonnages of edible game meat shot with bullets and shotgun pellets separately and the mean lead concentrations in these meats. We estimated that ca.21% of human dietary exposure to ammunition-derived lead in the UK is from bullets and 79% from shotgun pellets. This new partitioning approach could be used to inform cost–benefit analysis in the UK and elsewhere when data from food consumption surveys are lacking.

Keywords Ammunition · Cost–benefit · Dietary exposure · Hunting · Restriction · UK REACH

Introduction

It has been known for centuries that lead is toxic to humans and other animals. Lead is non-essential and impairs the functioning of many body systems, including the nervous, renal, and cardiac systems (EFSA 2010). Associations between blood lead concentration (B-Pb) and health effects are well quantified and independent of the source of the lead. There is no evidence for a threshold B-Pb for lead-induced effects on health (EFSA 2010). In many countries, levels of exposure of humans to lead have been reduced substantially as a result of regulations restricting its use, e.g., in water pipes, paint, and vehicle fuel (EFSA 2010; Stroud 2015). Consequently, most exposure to lead of the general population in the European Union (EU) and the United Kingdom (UK) is now dietary (EFSA 2010). One dietary source of lead is fragments from lead bullets or shotgun pellets that are frequently present in wild-shot game meat (Hunt et al. 2006, 2009; Knott et al. 2010; Pain et al. 2010; Trinogga et al. 2019). This use of lead has remained largely unregulated in many countries, although comprehensive regulations are now being considered in the European Union and UK under their respective REACH chemicals regulations (ECHA 2022a; HSE 2023a, b). Correlative studies show that elevation of B-Pb is associated with the consumption of meat from game animals shot with lead ammunition (Dewailly et al. 2001 (Arctic Canada); Bjerregaard et al. 2004 and Johansen et al. 2006 (Greenland); Iqbal et al. 2009 (USA); Green & Pain 2012 (using published Greenland data); Bjermo et al. 2013 (Sweden); Knutsen et al. 2015 (Norway)). Because of the associated health risks, food and health agencies in the UK (FSA 2017; NHS 2023) and EU (e.g., BfR 2010; ANSES 2018; AESAN 2012) have advised that frequent consumers reduce their consumption of wild

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game shot using lead ammunition and that pregnant women and children minimize or avoid consumption of such meat.

In most European countries, including the UK, ammunition composed of lead remains the principal type used for hunting large game animals, such as deer (family Cervidae) and wild boar (*Sus scrofa*; family Suidae), and also small game animals, including gamebirds (families Phasianidae and Tetraonidae), pigeons (family Columbidae), and rabbits and hares (family Leporidae). In the UK, it is also the principal type used to hunt wildfowl (family Anatidae), despite regulations restricting this use (Stroud et al. 2021). However, while large game animals are usually killed using bullets fired from rifles, most small game animals are killed using pellets fired from shotguns. This distinction between projectile types is important because regulatory bodies often consider regulations separately for lead in bullets and shotgun pellets. For example, the government banned the use of lead shotgun pellets in Denmark in 1996, but hunting with lead bullets remained legal, although it will be banned from April 2024 (Sonne et al. 2022). The EU's assessment of the evidence for a ban on lead ammunition through the EU REACH process (ECHA 2022a) and the UK's equivalent REACH assessment (HSE 2023a, b) have both conducted separate assessments for bullets and shotgun pellets. These assessments included evaluations of the risks to humans, wildlife and the environment of various uses, and the costs and benefits of restriction options. While EU data are available on levels of consumption by people of game shot with bullets and shotgun pellets separately, similar UK data have not been compiled. This gap has prevented the partitioning of health risks between the two ammunition types in the UK. Consequently, the benefit associated with restricting the use of lead bullets in the UK could not be quantified (HSE 2023a, b). In this paper, using an alternative approach to that used in the EU, we make the first quantitative attempt to partition dietary exposure of humans in the UK to ammunition-derived lead between the two types of projectile. We compare results from the EU and UK approaches and discuss the possible implications of relative exposure to lead from bullets and shotgun pellets for human health.

Methods

We developed a step-by-step procedure for estimating the total quantity, by mass, of lead ingested by UK game meat consumers separately for lead derived from bullets and that derived from shotgun pellets. The two main types of wild-shot game meat consumed in the UK are meat from large game animals, principally deer, killed using bullets, and meat from small game animals, principally gamebirds, killed using shotgun pellets. We were therefore able to partition ingested lead between the two ammunition types, by separately obtaining numbers of deer and small game animals killed in the UK from Aebischer (2019) and then adjusting for body weights, proportions discarded, exported, shot using non-lead ammunition, and used for food. Our procedure mostly used information from published sources, though a few steps involved previously unpublished data we collected ourselves. Full details of the data sources and logic of the procedure are described in the Supplementary Material. Tables 1 and 2 of the main text show the steps involved in the calculations. Codes for the parameters involved (e.g., SG1, SG2, D1, D2) are given in these tables and can be used to locate details and justification for the steps in the Supplementary Material. The final step was to multiply the quantity of game meat consumed by the arithmetic mean concentration of lead in both types of game meat. Ideally, we would have had sufficient information on lead concentrations in the meat of both small game and deer from samples only collected in the UK. However, although we found sufficient UK data for small game, we only found one UK study for deer meat. We therefore conducted a review of studies of lead concentration in deer meat for the whole of Europe and used a mean based upon all of the eligible studies we found. Details of the methods and criteria used for the literature review are provided in the Supplementary Material.

For comparison with the results of these calculations, we also calculated the proportions of lead from ammunition emitted into the environment from hunting using bullets and shotgun pellets, based upon estimates made by the UK REACH Agency–'the Agency' hereafter (HSE 2023a) which reported that 3 tonnes of lead bullets are used annually in the UK, compared with 1600 tonnes of lead shotgun pellets. We also calculated the proportions of lead from projectiles that strike quarry animals which is from bullets and shotgun pellets. We did this for deer by assuming that a typical bullet used to kill deer contains 9 g of lead and that 95% of bullets fired at deer strike the animal (Aebischer et al. 2014). For small game, we used an estimate of the mean number of shotgun pellets embedded in the carcasses of gamebirds killed in the UK (2.17 pellets per carcass) reported by Pain et al. (2010) and assumed that the pellets were #6 shot, each of which weighs 0.105 g. We then used our estimates of the numbers of deer and small game animals killed using lead ammunition from Tables 1 and 2 to calculate the proportion of the lead in projectiles that struck quarry animals which was from bullets.

Results

The quantities calculated using our step-by-step procedures for small game and deer are shown in Tables 1 and 2. Our results indicate that approximately 14% of the 11,339 tonnes of meat from game killed annually using lead ammunition and consumed in the UK (SG11 plus D10) is from wild-shot deer killed using bullets, with the other 86% being from

Table 1 Calculation of the annual weight of lead ingested by people in the UK from wild-shot small game animals

Parameter code	Parameter	Explanation	Estimate	LCL	UCL	Method used for uncertainty
SG1	Total bag all small game species (individuals)	Sum of species bag totals	24,038,155	21,667,421	26,478,301	PB
SG2	Total small game live weight (tonnes)	Sum of species-specific products of bag and mean live weight	23,371	20,897	25,802	PB
SG3	Total wildfowl live weight used for food (tonnes)	Sum of species-specific products of bag, proportion used for food, and mean live weight for wildfowl	1366	1083	1679	PB
SG4	Proportion of wildfowl shot with lead	Mean proportion of ducks shot using lead	0.743	0.675	0.812	PB
SG5	Total wildfowl live weight used for food & shot with lead (tonnes)	Product of SG3 and SG4	1014	788	1278	-
SG6	Total non-wildfowl live weight used for food (tonnes)	Sum of species-specific products of bag, proportion used for food, & mean live weight for non-wildfowl	20,724	18,382	23,026	PB
SG7	Proportion of non-wildfowl shot with lead	Mean proportion of pheasants shot using lead in 2022/2023	0.940	0.911	0.970	NPB
SG8	Total non-wildfowl live weight used for food & shot with lead (tonnes)	Product of SG6 and SG7	19,481	17,228	21,753	-
SG9	Total small game live weight used for food & shot with lead (tonnes)	Sum of SG5 and SG8	20,496	18,226	22,773	-
SG10	Ratio of edible meat to live weight	Ratio of mean weight of edible meat to mean live weight of pheasants	0.476	0.440	0.511	PB
SG11	Total small game meat used for food & shot with lead (tonnes)	Product of SG9 and SG10	9756	8453	11,065	-
SG12	Arithmetic mean concentration of lead in small game meat (mg/kg)	Mean Pb concentration in meat	2.321	1.216	4.275	NPB
SG13	Weight of lead ingested by people from small game meat (kg)	Product of SG12 and SG13	22.6	11.5	41.6	-

See Methods and Supplementary Material for full details of data sources and methods. 95% bootstrap lower (LCL) and upper (UCL) confidence limits are given, except for parameters for which the uncertainty was not known (shown as ND). Bootstrap methods are denoted by PB (=parametric bootstrap) and NPB (=non-parametric bootstrap). Quantities with uncertainty method marked – were derived from bootstrapped values for their constituents

small game animals killed using shotgun pellets. After multiplying by the arithmetic mean lead concentration for small game meat (2.321 mg/kg w.w., Table 1, SG12) and deer meat (3.715 mg/kg w.w., Table 2, D11), we estimated that UK consumers combined ingest approximately 28 kg of lead annually from game animals killed using lead ammunition, of which 21% is from deer killed using bullets (Table 3).

We compared the proportions of various quantities which were derived from lead bullets graphically in Fig. 1. The proportion of lead emitted into the UK environment from the use of bullets is very small (0.2%). However, the proportion by mass of lead in projectiles striking quarry from bullets (16%), the proportion of game meat consumed from animals killed using bullets (14%), and the proportion of lead in game meat consumed from animals killed using bullets (21%) were all considerably greater and are not negligible in terms of their potential impacts on human health and the environment.

Discussion

Is Partitioning of Dietary Exposure to Lead in Terms of Mass Ingested Acceptable as a Proxy for Potential Health Impacts?

The principal objective of our study is to partition, between bullets and shotgun pellets, the potential benefits

Table 2 Calculation of the annual weight of lead ingested by people in the UK from wild-shot deer meat

Parameter code	Parameter	Explanation	Estimate	LCL	UCL	Method used for uncertainty
D1	Total kill of all deer species (individuals)	Sum of species-specific kill totals	152,560	131,731	176,350	PB
D2	Total deer kill in live weight (tonnes)	Sum of species-specific products of kill total and mean live weight	9097	7616	10,876	PB
D3	Total deer kill in larder weight (tonnes)	Sum of species-specific products of kill total and mean larder weight	4537	3795	5437	PB
D4	Total larder weight of deer killed using non-lead bullets (tonnes)	Total larder weight of deer killed by FE & FES	910	ND	ND	–
D5	Total larder weight of deer killed using lead bullets (tonnes)	D3 minus D4	3627	2885	4527	–
D6	Total live weight of deer killed using lead bullets (tonnes)	D5 multiplied by D2 and divided by D3	7272	5790	9055	–
D7	Proportion of live weight of deer killed using lead bullets that is not exported	Proportion of wild-shot deer exported	0.667	ND	ND	–
D8	Total live weight of deer killed using lead bullets and not exported (tonnes)	Product of D6 and D7	4848	3860	6036	–
D9	Ratio of boned out meat to live weight	Ratio of boned out meat to live weight for Red deer	0.3265	ND	ND	–
D10	Total boned out meat from deer killed using lead bullets and not exported (tonnes)	Product of D8 and D9	1583	1260	1971	–
D11	Arithmetic mean concentration of lead in deer meat (mg/kg w.w.)	Mean Pb concentration in meat	3.715	1.232	5.738	NPB
D12	Weight of lead ingested by people from deer meat (kg)	Product of D10 and D11	5.88	1.91	9.60	–

See Methods and Supplementary Material for full details of data sources and methods. 95% bootstrap lower (LCL) and upper (UCL) confidence limits are given, except for parameters for which the uncertainty was not known (shown as ND). Bootstrap methods are denoted by PB (=parametric bootstrap) and NPB (=non-parametric bootstrap). Quantities with uncertainty method marked – were derived from bootstrapped values for their constituents

Table 3 Calculation of the annual weight of lead ingested by people in the UK from wild-shot game animals killed using lead ammunition and the proportion of this from deer killed using lead bullets.

Parameter code	Parameter	Estimate	LCL	UCL
SG13	Weight of lead ingested by people from small game meat (kg)	22.6	11.50	41.61
D12	Weight of lead ingested by people from deer meat (kg)	5.88	1.91	9.60
AG1	Weight of lead ingested by people from all game meat (kg)	28.48	16.20	47.70
AG2	Proportion of ingested lead from bullet-shot deer	0.206	0.068	0.383

See Methods and Supplementary Material for full details of data sources and methods. 95% bootstrap lower (LCL) and upper (UCL) confidence limits are given

to human health from the prevention of human dietary exposure to lead from the meat of wild-shot hunted animals. To do this, we provide estimates of the relative amounts of lead ingested by UK consumers from these two main ammunition types. However, our approach might not be valid if the ammunition types differ from each other substantially in the extent to which a given amount of ingested lead gives rise to health effects. In this section, we therefore consider those factors most likely to influence such potential differences, i.e., (a) the age distribution of consumers, (b) the size distribution of particles of lead in game meat products, and (c) the methods used to process and prepare meat.

The central nervous system is the organ system most affected by lead toxicity in humans. The developing brain of children is considered more vulnerable to the neurotoxicity of lead than the mature brain (EFSA 2010). Children are especially vulnerable to chronic lead exposure

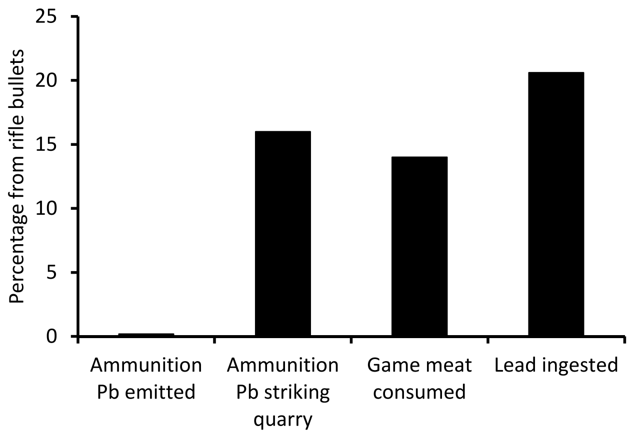

Fig. 1 Percentages of the lead ammunition emitted into the UK environment, lead striking quarry animals, quantity of game meat consumed, and quantity of lead ingested by consumers which are attributable to the use of lead bullets for hunting, rather than lead shotgun pellets

both because of this sensitivity and because they absorb a higher proportion of ingested lead than adults (Lanphear et al. 2005; EFSA 2010). Hence, if adults and children in the UK were to differ substantially in the relative amounts consumed of game meat shot using lead bullets and shotgun pellets, this might influence the accuracy of our partitioning calculations as a proxy for partitioning of health effects on the IQ of children. However, we are unaware of any data for the UK that partitions by age consumption of game shot with these ammunition types. Similarly, the Agency (HSE 2023b) did not identify relevant data for the UK. EU data suggest that there might be differences between infants, toddlers and adults in the relative consumption rates of meat from game killed using bullets and shotgun pellets in the EU (ECHA 2022a; Table 1–54), but it is not clear how precisely these apparent differences were estimated or whether UK consumption patterns are similar in relation to age. The relative amounts of game shot with bullets and shotgun pellets differ considerably between the UK and EU (ECHA 2022a; HSE 2023a; discussed further below), and we do not know if, and to what extent, this might involve differences among age groups in relative consumption patterns. We conclude that in the absence of game consumption data for the UK, there is no evidential basis for rejecting the use of mass of lead ingested as a valid proxy on this basis.

In rats, the proportion of ingested lead absorbed from metallic lead particles with sizes in the range 6–197 μm diameter increased with decreasing particle size (Barltrop and Meek 1979). We anticipate a similar relationship applies in humans, so differences in particle size distributions of lead derived from bullets and shotgun pellets in game meat are likely to influence absorption. Studies using conventional X-ray machines have shown that small metallic particles are numerous in the meat of deer killed using lead bullets (Hunt et al. 2006, 2009; Knott et al. 2010; Trinogga et al. 2019) and shotgun pellets (e.g., gamebirds, Pain et al. 2010). However, a limitation of standard X-ray imaging is the minimum particle size that can unambiguously be detected. Knott et al. (2010) found this to be 370 μm diameter in deer shot with bullets.

More sophisticated techniques suggest that far smaller lead particles are found in the meat of deer and gamebirds. Using synchrotron KES imaging, Leontowich et al. (2022) frequently detected lead particles of < 20 μm and sometimes < 10 μm in diameter in ballistic gel, which was used to simulate game animal tissue, into which bullets had been fired. Using single-particle ICP-MS mass spectroscopy, Kollander et al. (2017) reported particles of minimum estimated diameter 0.04 μm near the bullets' wound channel in the meat of roe deer (*Capreolus capreolus*) and wild boar. The authors suggested that these very small particles might form when bullet lead melted or vaporized upon impact and then solidified upon cooling. If confirmed, the presence of nanoparticles in bullet-shot game meat would have implications for the proportion of ingested lead absorbed because of their very small particle size. However, Leontowich et al. (2022) suggested that the mass spectrometry method used by Kollander et al. might have misidentified as nanoparticles lead dissolved in tissues from larger particles after impact or during sample preparation. We conclude that meat from bullet-shot large game animals certainly contains lead particles as small as 10 μm in diameter, but that it remains uncertain whether particles as small as < 0.1 μm are present.

Using X-ray microtomography, Green et al. (2022) identified lead fragments in the tissues of pheasants (*Phasianus colchicus*) killed using lead shotgun pellets in the UK. Most of the small (< 1 mm diameter) fragments identified had diameters < 300 μm, and the smallest fragment diameter measurable was 70 μm. We are not aware of mass spectrometry or synchrotron studies of lead particle size in ballistic gel or tissues of game animals killed using lead shotgun pellets. However, the lower impact velocity of shotgun pellets compared with bullets makes the formation of nanoparticles by melting, hypothesized to occur for bullets, unlikely to apply to shotgun pellets. However, comparable studies of bullets and shotgun pellets are not yet available, so we cannot draw firm conclusions about possible differences in the frequency distributions of particle size in the meat of game killed using bullets and shotgun pellets.

Differences in storage and preparation techniques of game shot with lead bullets or shotgun pellets might influence particle size and the proportion of lead dissolved and more easily absorbed. For example, the use of acidic liquids, such as vinegar, during the storage and cooking of game meat has been suggested to affect the proportion of lead absorbed (Mateo et al. 2006). However, we are not aware of data on possible differences between the two ammunition types in the frequency of use of such preparation methods by UK consumers. Another potential effect of a preparation technique is from the mincing of game meat. After excluding results from 9 samples in which whole shotgun pellets were found, Pain et al. (2023) found that the mean concentration of lead in 81 samples from three raw dog food products purchased in the UK based upon minced meat from pheasants was 34 times greater than the mean concentration in the meat of pheasants or pheasant breasts sold in the UK for human consumption, which was not minced. They suggested that a possible explanation for this large difference is that the mincing machines used to prepare the dog food might have broken some of the whole shot frequently present in pheasant carcasses into small fragments (Pain et al. 2023). If this hypothetical effect of mincing is confirmed, there may be implications for food products intended for human consumption. Most food products derived from small game animals killed using shotgun pellets, such as gamebirds, are based on whole carcasses or meat diced using a knife, whereas many meat products derived from bullet-shot large game animals are based upon minced or ground meat. More than half of the UK food products based upon UK deer meat are probably based upon minced meat, with 43% being sausages and burgers, which are certainly prepared using minced meat (Scottish Venison 2020). Studies of minced deer meat from the USA have found high concentrations of lead (e.g., Cornatzer et al. 2009; Wilson et al. 2020). If mincing of deer meat results in significant further fragmentation of large fragments of lead derived from bullets, this might result in more particles and smaller particle sizes than those reported above for unminced deer meat and therefore absorption of a greater proportion of ingested lead derived from bullets. On the other hand, a larger proportion of the fragmented lead in deer carcasses is distributed close to the wound channel than is the case for gamebirds killed using shotgun pellets, which might lead to more rifle bullet lead being removed during butchery. In the studies we examined to obtain data for calculations of the concentration of lead in deer meat (Table S6), there was a tendency to specifically exclude obviously damaged meat and that near the wound channel and to analyze marketable/consumable meat (e.g., Kollander et al. 2014; Gerofke et al. 2018).

We find that the potential may exist for differences between bullets and shotgun pellets in the extent to which a given amount of ingested lead from meat gives rise to health effects. However, the available evidence does not enable us either to quantify this or predict the direction of effects. Given current evidence it is reasonable to assume that the amount of lead consumed is the key factor influencing health risk. We therefore consider that partitioning of dietary exposure to lead in terms of mass ingested is an acceptable proxy for potential health impacts.

Factors that contribute or may contribute to the relative exposure of humans to lead from bullets and shotgun pellets are summarized in Table 4. While a small tonnage of lead bullets is used for hunting relative to lead shotgun pellets, most lead bullets hit their target while only a very small proportion of shotgun pellets do so (Fig. 1). This is the main reason why the volume of lead bullets and shotgun pellets used for hunting are not suitable comparative proxies for human exposure to dietary lead of ammunition origin.

Comparison of the Present Study with Partitioning of Human Health Risk Between Game Shot with Bullets and Shotgun Pellets in the EU REACH Process

ECHA (2022a) used data provided by the European Food Safety Authority (EFSA) to attribute dietary exposure of hunter families (children and adults) to lead from game

Table 4 Factors that contribute or may contribute to the relative exposure of humans to lead from bullets and shotgun pellets

Factor	Bullets	Shotgun Pellets
Volume used for hunting	+	+++++
Proportion used that hits target animals	+++++	+
Proportion of projectile retained as lead fragments in meat	+++++	++
Potential for butchering practices to remove the most contaminated meat	– – – –	–
Lead concentrations in marketable meat from game shot with lead ammunition	=	=
Size distribution of lead particles		
1. Presence of nanoparticles which may be readily absorbed	+?	?
2. Extent of meat sold that is minced resulting in smaller lead particles	+++?	+?
Age distribution of consumers	?	?

More + or – symbols indicate relatively increased or reduced exposure; = indicates similar exposure and ? illustrates unproven comparison. Our scoring of these potential effects is qualitative and should not be regarded as quantitative estimates of their absolute or relative magnitudes animals killed using shotgun pellets and bullets. The EFSA results were based upon recent game consumption data for the EU from food recall surveys and data on lead concentrations in food samples provided by EU countries. The dietary exposure attributions made in ECHA (2022a) showed a greater proportion of lead intake from game shot with bullets than shotgun pellets in the EU. These attributions were used to calculate relative health risks from the two ammunition types (ECHA 2022a; Table 1–54). The results were influenced by a low mean lead concentration used for the meat of game shot with shotgun pellets relative to that in game shot with bullets (0.366 mg/kg w.w. and 2.516 mg/kg w.w., respectively). In response to a subsequent specific consultation on the EFSA database (ECHA 2022b), ECHA considered that the EFSA data probably underestimated lead concentrations in small game meat. This underestimation probably led to underestimation by ECHA of the total health impacts in children and the contribution to them of lead from shotgun pellets. A review of European published literature on lead concentrations in meat from game harvested with shotgun pellets in Europe (excluding Denmark) found a weighted mean lead concentration of 2.474 mg/kg w.w. (Pain et al. 2022; similar to that found in the UK, 2.321 mg/kg w.w.; Table 1), which is similar to the value used by ECHA for meat from large game shot with bullets (2.516 ppm w.w.). These results, along with our literature review of lead concentrations in deer species in Europe (see Supplementary Material), indicate that mean lead concentrations in the EU in meat of game shot with shotgun pellets and bullets are broadly similar.

After removing the effect of the anomalously low mean lead concentration in meat from small game used in the EU REACH calculations, accurate partitioning of human health risk in the EU is likely to depend largely on rates of intake of meat killed using the two types of ammunition. In the EU process, it was calculated that the median daily consumption rates for meat from bullet-killed game, as a proportion of the total for bullet-killed and shotgun pellet-killed game combined was 0.699 for infants, 0.591 for toddlers, and 0.472 for adults (ECHA 2022a; Table 1–54). This higher overall consumption rate of meat from game killed with bullets than with shotgun pellets contrasts with our UK findings. Based upon parameter estimates D10 and SG11 from Tables 1 and 2, the equivalent proportion of UK consumption of bullet-shot game relative to that for both types of ammunition combined is given by $D10/(D10 + SG11) = 0.14$. Hence, this proportion for the UK is approximately one-quarter of that estimated for the EU, suggesting that consumption of game meat shot with bullets as a proportion of all game meat is much lower in the UK than in the EU. This is consistent with differences between the UK and EU in the use of the two types of ammunition. In the UK, it has been estimated that 3 tonnes of lead bullets are used for hunting annually, compared with 1600 tonnes of lead shotgun pellets (Table 1.17, HSE 2023a). In the EU, the equivalent annual tonnages are 134 tonnes for bullets and 14,000 tonnes for lead shotgun pellets (Table 1–10; ECHA 2022a). Hence, the proportion of annual UK lead ammunition use that is bullets is approximately one-fifth of the equivalent proportion for the EU. The difference between the UK and EU in the relative quantities of bullet-shot game meat consumed is therefore broadly consistent with the difference in the quantities of the two types of ammunition used.

We conclude that the apparently higher level of risk to human health, especially that of children, from game shot with bullets relative to shotgun pellets in the EU than in the UK is due in large part to unrepresentative information on the concentration of lead in small game meat, with the remaining difference being attributable to the greater level of hunting of large game with bullets, relative to small game with shotgun pellets, in the EU than in the UK.

Having partitioned exposure to lead from large and small game animals (i.e., those killed using bullets and shotgun pellets), ECHA (2022a) were able to model potential associated human health impacts and attribute a monetary value to them. This enables the costs and benefits associated with restricting lead shotgun pellets and bullets to take account of human health impacts separately or in combination. The preferred option, proposed as part of the EU REACH process, was a ban on the use for hunting of both lead shotgun pellets and lead bullets (ECHA 2022a).

Implications of the Present Study for Partitioning of Human Health Risk Between Game Shot with Bullets and Shotgun Pellets, Compared with that Assumed in the UK REACH Process

The UK REACH Agency estimated that there was a benefit of £51.5 million from avoided harm to human health, in monetary terms, from banning the use of lead ammunition of all types for hunting. This benefit was calculated as Present Value over a 20-year period and comprised £26.2 million from avoided harm to the IQ of children and £25.3 million from a reduction of kidney disease in adults (HSE 2023a; Table 8). It was noted that a potential benefit was also likely from reduction of cardiovascular disease in adults, but quantification of this benefit was not considered to be practical.

Throughout their risk assessment, the Agency considered whether risks could be attributed separately to the use of different types of lead ammunition. In general, annual tonnage used was considered to indicate relative risk, although it was noted that, for secondary poisoning of birds, the tonnage of bullets and shotgun pellets used is not a suitable proxy for partitioning risks (HSE 2023b; 1.4.7). The Agency did not find data on relative consumption levels by humans of game shot with shotgun pellets and bullets, but did consider the argument that humans may be exposed to considerably more lead via dietary exposure per tonne of lead bullets than per tonne of lead shotgun pellets used for hunting (Section 1.5.2.1 of HSE 2023b; our Fig. 1). All monetised human health benefits from lead ammunition restriction for hunting were assumed to relate to restricting the use of lead shotgun pellets, based on a comparison of the annual tonnages of lead shotgun pellets (~ 1600t) and lead bullets (~ 3t) estimated as used for hunting (HSE 2023a). The Agency acknowledged uncertainties associated with this approach and noted that it would consider whether apportionment of this impact is robustly feasible during the public consultation on its draft socioeconomic analysis. Our results suggest that 21% of health benefits from restricting lead ammunition for hunting would accrue from the restriction of lead bullets.

Conclusion

Our results indicate that approximately 21% of ammunition-derived lead entering the human food chain in the UK is likely to originate from bullets and 79% from shotgun pellets. This is different from the conclusion reached by the EU REACH process, which was that lead from game killed using bullets was a greater proportion of the total amount of lead ingested from game meat than that from shotgun pellets. We conclude that there were two main reasons for that difference. Firstly, the EU REACH process used a respesentative value for the mean concentration of lead in game from bullet-killed animals (broadly similar to that found in deer; D11, Table 2 and SI), but the mean concentration they used for small game meat killed using shotgun pellets is likely to have been inaccurate and was much too low. Secondly, there is considerably more hunting of large game animals using bullets relative to hunting of small game with shotguns in the EU compared with the UK.

Although the proportion of dietary exposure to lead from bullets rather than shotgun pellets is smaller in the UK than in the EU, we nonetheless estimate that, at 21%, it is not negligible. The new approach we present to partitioning human health risks from dietary exposure to lead from bullets and shotgun pellets could be used to refine both risk assessment and socioeconomic analyses for the UK and elsewhere and to provide separate monetised potential human health benefits from restrictions even when accurate data on diet are lacking.

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Data Availability Data collated and analyzed as part of this study are available in the supplementary information and are referenced.

Declarations

Competing interests *Non-financial interests*: Both authors are members of the UK REACH Scientific Expert Pool (RISEP) and the Challenge Panel on Lead in Ammunition. This research was not requested by the UK REACH Agency and the authors received no payment or other support relevant to its preparation. Consequently, any views we express are not those of HSE (the Agency for UK REACH) or its independent advisory pool on the opinion or the wider restriction process which was in train during manuscript preparation and is still incomplete at the time of writing. Deborah Pain was an unpaid Trustee of RSPB until December 2022 prior to initiation of this research; Rhys Green is an unpaid volunteer for RSPB. *Financial interests*: The authors have no relevant financial interests to disclose.

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