HUMAN EXPOSURE TO LEAD FROM AMMUNITION IN THE CIRCUMPOLAR NORTH

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ABSTRACT.—Circumpolar subsistence cultures use firearms, including shotguns and rifles, for hunting game for consumption. Lead shot is still used for waterfowl and seabird hunting in many subsistence areas (despite lead shot bans) because it is inexpensive, readily available, and more familiar than non-toxic or steel shot, which shoot differently. Here we review published literature on lead concentrations and lead isotope patterns from subsistence users in the circumpolar North, indicating that elevated lead exposure is associated with use of lead ammunition. Mechanisms of exposure include ingestion of lead dust, ammunition fragments, and shot pellets in harvested meat, and inhalation of lead dust during ammunition reloading. In Alaska, ammunition-related lead exposures have also been attributed to the use of certain indoor firing ranges, and the melting and casting of lead to make bullets. Since there is no safe lead exposure limit, especially for children, use of lead shot and bullets in subsistence cultures results in unnecessary and potentially harmful lead exposure. In order for lead ammunition to be feasibly phased out, alternatives must be affordable and readily available to subsistence hunters. Community outreach, including describing the harmful effects of even small amounts of lead, especially in children and women of child-bearing age, and training on the different shot patterns, velocities, and distances inherent in using shot and bullet materials other than lead, will also be necessary to promote acceptance of alternatives to lead ammunition. *Received 15 September 2008, accepted 3 October 2008.*

VERBRUGGE, L. A., S. G. WENZEL, J. E. BERNER, AND A. C. MATZ. 2009. Human exposure to lead from ammunition in the circumpolar north. *In* R.T. Watson, M. Fuller, M. Pokras, and W.G. Hunt (Eds.). Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans. The Peregrine Fund, Boise, Idaho, USA. DOI 10.4080/ilsa.2009.0110

Key words: Alaska, ammunition, arctic, game, human, hunters, lead, subsistence, waterfowl.

HUMANS IN THE NORTH have been exposed to lead from many of the same sources as in temperate regions. In the 20th century, the greatest exposure was inhalation of atmospherically transported lead produced from leaded gasoline. Other atmospheric sources included combustion of other fossil fuels, particularly coal, non-ferrous metal production (mining, smelting), and waste incineration (AMAP

[3] The findings and conclusions in this document are those of the author(s) and do not necessarily represent the views of the US Fish and Wildlife Service.

2004, AMAP 2002). Lead leachate from lead solder used in food cans may have poisoned the crews of *Erebus* and *Terror*, the ships of the 1850s Franklin expedition to the North Pole (Bayliss 2002). Interestingly, lead solder for canning wasn't banned in the United States until 1995 (Federal Register 60(123): 33106-9), and may still be used elsewhere. Ingestion of lead-based paint chips by children remains an issue worldwide, although in abatement with regulation of leaded paint.

With control of these lead sources, however, blood lead levels in humans have dropped over the past few decades. A phase-out of leaded gas beginning in the 1980s, for example, resulted in a substantial decline in lead levels in humans in North America (Pirkle et al. 1994) and Greenland (Hansen et al. 1991), as well as in snow from Greenland (Robinson 1981) and in the Arctic ice pack. The prevalence of blood lead levels ≥10 µg/dL dropped from over 80% before 1980 to less than 10% in the 1990s (Pirkle et al.1998).

Still, some northern populations, especially indigenous peoples dependent upon subsistence foods, continue to have elevated blood lead levels. A primary source is thought to be lead from ammunition, by ingestion of lead fragments in game shot with lead, inhalation of fumes from home production of shot or sinkers (as in rural areas in Russia; AMAP 2004), and inhalation of dust or particles during prolonged shooting. In fact, the Arctic Monitoring and Assessment Programme stated:

Lead levels in Arctic indigenous peoples have declined since the implementation of controls on lead emissions. Concentrations of lead in blood currently reported are below a level of concern, however, continued monitoring is warranted because of the potent effects of lead on neurological development in the fetus and children (AMAP 1998).

This is still valid. In addition, recent data have shown that lead shot can be a significant source of human exposure (AMAP 2003).

Lead is exceptionally dense, making it ideal for projectiles. It is also relatively soft, which allows it to be formed, even in home environments, into a variety of bullet and shot gauges. This malleability also results in fracturing of the shot and bullets. The latter can leave macro- and microscopic traces of lead on average 15 cm from bullet pathways in meat (Hunt et al. 2006) and spread over an average of 24 cm and up to 45 cm apart (Hunt et al. 2009). Therefore, even if game is carefully cleaned and damaged meat discarded, embedded and invisible fragments of lead may still contaminate the meat (Stroud and Hunt 2009, Hunt et al. 2009).

In this paper we review data on lead concentrations in people living in the circumpolar north and evaluate lead from ammunition as an important source for current lead exposure. We conclude that exposure to lead from ammunition is unnecessary and potentially harmful to Arctic indigenous populations.

REVIEW OF LEAD TOXICOLOGY

Absorption.—Lead can enter the human body through three main routes of exposure: eating, breathing, or being shot. The third route has obvious health consequences and will not be discussed further.

People can ingest lead that is present in their immediate environment, such as dust, or that is in food or water. Leachate from lead solder use in canned foods has already been discussed. Wild game that has been shot with lead ammunition can contain lead fragments, particles or dust that is consumed along with the meat. Lead can also be ingested if people handle lead products such as fishing sinkers, and then fail to wash their hands before eating food. Children often ingest lead when they mouth lead-containing toys or objects, or suck their fingers after touching lead objects or lead-containing dust or soil.

In humans, the percentage of lead that is absorbed into the bloodstream after oral ingestion is influenced by several factors, including age. Gastrointestinal absorption of water-soluble lead appears to be higher in children than in adults (ATSDR 2007). Estimates derived from dietary balance studies indicate that children (ages two weeks to eight years) absorb approximately 40–50% of ingested water-soluble lead, while non-fasting adults absorb only 3–10% of ingested water-soluble lead (ATSDR

2007). Nutritional status also affects gastrointestinal absorption of lead; fasting status increases lead absorption. The presence of food in the gastrointestinal tract lowers lead absorption, especially if calcium or phosphate is present in the meal. Children who have calcium or iron deficiencies have a higher absorption of lead from the gastrointestinal tract (ATSDR 2007).

Exposure to lead through inhalation can occur in a variety of ways. When lead is melted to make fishing sinkers, ammunition or other products, especially in a home environment, dangerous levels of lead fumes can be produced and inhaled. Lead can also be inhaled on dust particles, contaminated soils, or via occupational exposure in manufacturing and mining. When leaded gasoline is combusted, tetraalkyl lead is an inhalable byproduct.

Amounts and patterns of deposition of particulate aerosols in the respiratory tract are affected by the size of the inhaled particles, age-related factors that determine breathing patterns (e.g., nose vs. mouth breathing), airway geometry, and airstream velocity within the respiratory tract (ATSDR 2007). Absorption of deposited lead is influenced by particle size and solubility. Larger particles (>2.5 microns) that are deposited in the upper airways can be transferred by mucociliary transport into the esophagus and swallowed. Smaller particles (<1 micron) can be deposited deeper into the lungs including the alveolar region, where intimate contact with the bloodstream enhances absorption (ATSDR 2007).

Distribution and Excretion.—The excretory half-life of lead in blood is approximately 30 days for adult humans (ATSDR 2007). Lead that is retained by the body is mostly stored in bone, where it is assimilated due to its chemical similarity to calcium (AMAP 2002). Lead can be mobilized from bone and released into the bloodstream during the process of bone resorption. Mobilization of bone lead can occur during pregnancy and lactation, and after menopause due to osteoporosis (ATSDR 2007). Lead in a pregnant mother's blood is effectively transferred to the fetus, and maternal lead can also be transferred to infants during breastfeeding (ATSDR 2007).

Toxicity.—Lead poses a greater risk to children than to adults for several reasons. Lead is more toxic to children than to adults because the nervous system of children is still developing. Also, children absorb a greater percentage of the lead they are exposed to (ATSDR 2007), and children are often exposed to more lead than adults. Children play outdoors and sometimes engage in hand-to-mouth behaviors that increase their exposure potential. The crawling and mouthing behaviors of older infants and young toddlers place them at particular risk for exposure; blood lead levels (BLLs) in children typically peak at the age of two years for this reason (American Academy of Pediatrics 2005). Children are shorter than are adults; this means they breathe dust, soil, and vapors close to the ground. A child's lower body weight and higher intake rate results in a greater dose of hazardous substance per unit of body weight. If toxic exposure levels are high enough during critical growth stages, the developing body systems of children can sustain permanent damage. Children's brains are developing rapidly during the first six years of life, which is why exposure to a chemical like lead that targets the brain is most devastating at that critical time.

Lead can delay or impair brain development in children and adversely affect IQ, and impair a child's ability to learn. Lead can also cause anemia and impaired metabolism of vitamin D. The Centers for Disease Control and Prevention (1997) recognized BLLs of ≥10 µg/dL in children aged ≤6 years as levels of concern, and based on studies since then, the CDC now recognizes that 10 µg/dL does not define a lower threshold for the harmful effects of lead (Brown 2007). Multiple studies have shown that as blood lead concentrations increase, IQ decreases, for example, by 7.4 points as blood lead increased from 1 to 10 µg/dL in children up to five years old (Canfield et al. 2003), and with significantly higher rates of intellectual decrement in children with maximal BLL <7.5 µg/dL than ≥7.5 µg/dL (Lanphear et al. 2005). Thus, BLLs less than 10 µg/dL are clearly harmful, and there is growing consensus that there is no "safe" level of lead exposure. Other adverse health effects associated with relatively low BLLs in children include delayed sexual maturation, increased blood pressure, depressed renal glomerular filtration rate, and inhibition of pathways in heme synthesis (ATSDR 2007).

As BLLs rise in children, the harmful health effects of lead become more severe. A child exposed to a large amount of lead may develop anemia, kidney damage, colic, muscle weakness, and brain damage, which can ultimately kill the child (ATSDR 2007). Such symptoms of clinical lead poisoning are commonly observed in children with BLLs of 45 µg/dL or higher; children with BLLs of 70 µg/dL or higher should be hospitalized immediately for treatment (Centers for Disease Control and Prevention 2002).

Studies have reported adverse health effects in adults with blood lead levels between 25–40 µg/dL, including hypertension, subtle or sub-clinical central nervous system deficits, and adverse reproductive outcomes (Centers for Disease Control and Prevention 2002). Lead exposure is clearly related to elevated blood pressure, and may also cause negative clinical cardiovascular outcomes and impaired performance on cardiovascular function tests (Navas-Acien et al. 2007). Cardiovascular and renal effects have been seen in adults chronically exposed to lead at levels <5 µg/dL in blood, and no lower threshold has been established for any lead-cardiovascular association (Navas-Acien et al. 2007).

At high levels of lead exposure, the brain and kidney in adults or children can be severely damaged, and death can result. High levels of lead exposure may also cause miscarriage in pregnant women, and affect testicular hormones in men. Other symptoms of lead poisoning in adults include colic, anemia, and muscle weakness. Clinical symptoms of lead poisoning can occur in adults with BLLs above 40 µg/dL (ATSDR 2007).

HUMAN EXPOSURE TO LEAD IN THE ARCTIC

Research on human lead exposure in the Arctic in the last decade has linked elevated lead exposure to use of lead shot or bullets for hunting. Other lead exposures of prior importance have largely been controlled, such as lead-based paints, lead in drinking water, and lead from gasoline. Leaded gasoline was phased out from North American use in the 1980s, with subsequent declines in environmental levels, including blood lead in humans (AMAP 1998, AMAP 2003, Van Oostdam et al. 2003). The exception may be in northern Russia, where industrial contamination from mining and smelting of lead ores, and use of lead-containing gasoline, continues (AMAP 2003). However, populations in Russia who practice subsistence hunting, such as people on the Kola Peninsula, are probably also exposed to lead from ammunition (AMAP 2003, Odland et al. 1999).

Specific studies of lead exposure from lead shot began decades ago with documentation of residual (embedded or ingested) lead in waterfowl. Embedded lead shot were found in 18–45% of waterfowl, depending upon the species, tested in the USA, Canada, and Western Europe in the 1950s (Elder 1955). In Canada in the 1980s, 15% of 227 pooled breast muscle samples from waterfowl harvested with lead shot had lead concentrations >0.5 mg/kg (Canadian Wildlife Service unpublished data, cited in Scheuhammer and Norris 1995), and Frank (1986) found lead concentrations, some >100 µg/kg, in tissues of waterfowl harvested with lead shot. These fragments, confirmed by radiographs and ranging in size from dust to 1–2 mm, resulted from collision of shot with bone. In the mid-1990s, Hicklin and Barrow (2004) used fluoroscopy on live Canada Geese (*Branta canadensis*), American Black Ducks (*Anas rubripes*), Mallards (*A. platyrhynchos*) and Common Eiders (*Somateria millissima*) from eastern Canada. Twenty-five percent of 1,624 birds had embedded shot, most of which was assumed to be lead. From 15–29%, depending upon age, of over 700 Common Eiders collected in western Greenland after colliding with boats or drowning in fishing nets had embedded lead shot in them (Merkel et al. 2006). It is clear that both micro- and macroscopic lead particles remain in avian meat that has been shot with lead pellets (Scheuhammer et al. 1998) and in large mammals shot with lead-based rifle bullets (Hunt et al. 2006). Therefore, lead from ammunition is a potential public health concern for indigenous peoples (Tsuji et al. 1999) and others who depend on wild game for food.

In a study specifically designed to examine the link between lead shot use for subsistence hunting of birds and potential human exposure, Johansen et al. (2001) x-rayed 50 Thick-billed Murre (*Uria lomvia*) carcasses bought from hunters in Greenland. The birds had been harvested with lead shot, and had an average of 3.7 lead pellets per carcass (range 0–12). There was no correlation between the number of pellets and the lead concentration in meat, which ranged from 0.0074–1.63 ppm wet weight, although most lead found in the breast meat was from pellets that had gone through the meat and left fragments. The authors concluded that even after pellets were removed, lead shot fragmented to fine dust upon collision with bone, resulting in substantially greater (although variable) lead concentrations in murres shot with lead compared to those shot with steel. They estimated a potential dose of 50 µg of lead from eating one bird. An estimated 200,000 murres are harvested annually in Greenland, in addition to other seabirds and waterfowl. The authors concluded that using lead shot to hunt birds could be a significant public health concern (Johansen et al. 2001).

A variety of raptor species have been exposed to or poisoned by lead from predating or scavenging lead-shot game (Hunt et al. 2006) and waterfowl (Pattee and Hennes 1983, Elliott et al. 1992, Pain et al. 1993, Kendall et al. 1996, Miller et al. 1998, Mateo et al. 1999, Samour and Naldo 2002, Pain et al. 2009). Therefore, it is not surprising that people who consume game shot with lead can also have elevated blood lead levels. Numerous studies at both the population and individual levels have implicated and linked lead ammunition to elevated blood lead levels and clinical symptoms in northern peoples.

For example, blood lead levels were monitored in 50 male hunters in Greenland before, during, and after the bird-hunting season in order to establish the association between bird consumption and blood lead concentrations (Johansen et al. 2006). Frequency of reported bird consumption was strongly associated with measured BLLs in the hunters, and eider meals were more important than murre meals as a lead source in the blood. Mean BLLs (12.8 µg/dL) were more than eight times higher in the group reporting more than 30 bird meals per month than in the group reporting no bird consumption (1.5 µg/dL).

At the population level, the Dene/Métis and bird-hunting Inuit in Canada averaged from 3.1–5.0 µg/dL of lead in maternal blood, compared to 1.9–2.2 µg/dL among Caucasians and other Inuit (Van Oostdam et al. 2003). However, 3.4% and 2.2% of the blood samples from the Inuit and Dene/Métis women, respectively, exceeded the 10.0 µg/dL Canadian Action Level (Walker et al. 2001). In Greenland, blood lead levels in Inuit mothers averaged 3.1–5.0 µg/dL, similar to the Canadian Inuit and Dene/Métis (AMAP 2003). In Siberia, indigenous women had average blood lead levels of 2.1–3.2 µg/dL, while non-indigenous women, who presumably obtained a smaller proportion, if any, of their food from hunting, averaged 0.02–0.04 µg/dL (AMAP 2003). In Nunavik (Arctic Quebec), adult Inuit blood lead levels were elevated and were related to age, smoking and, in particular, daily consumption of waterfowl (Dewailly et al. 2001). Blood lead, adjusted for age and sex, was associated with seabird consumption in Greenland (Bjerregaard et al. 2004). In that study, Greenlanders who reported consuming sea birds several times a week had a blood lead level >50% higher than those who reported eating sea birds only a few times a month or less.

Lead shot exposure and effects have also been documented at the individual level in northern humans. For example, Madsen et al. (1988) noted that lead shot in the appendix were often seen in lower abdominal x-rays in Denmark, and those with lead in the appendix had greater blood lead concentrations. Of 132 randomly selected radiographic charts from a hospital serving six native Cree communities in Northern Ontario (1990–1995), 15% showed lead shot in the gastrointestinal system (Tsuji and Nieboer 1997). Sixty-two patients in one Newfoundland hospital had from 1–200 lead shot in their appendices (Reddy 1985), and Hillman (1967), Greensher et al. (1974), Durlach et al. (1986), and Gustavsson and Gerhardsson (2005) all documented clinical symptoms resulting from lead shot in human appendices. In the USA in 2005, Cox and Pesola (2005) published a radiograph from an Alaska Native elder with an appendix full of shot, and stated “buckshot is commonly seen in Alaskan natives.”

Using lead isotopes to identify the source of lead when blood lead is elevated combines population and individual assessments. This method was used by Tsuji et al. (2008) to definitively document lead from ammunition—both shot and bullets—as a source of lead in First Nations Cree in northern Ontario. Lead isotope signatures of southern Ontario urban dwellers were different from those of northern First Nations people, who depended upon subsistence foods. Lead from ammunition had a separate signature from that found on lichens and, significantly, isotope signatures of First Nations people overlapped with that of lead from ammunition. Levesque et al. (2003) used a similar approach to identify the source of lead in cord blood of Nunavik Inuit infants born from 1993–96. Although mobilization of maternal bone lead resulted in less definite signatures than those documented by Tsuji et al. (2008), there was still a strong suggestion that the source of elevated cord blood lead, found in approximately 7% of Inuit newborns, was lead from ammunition. There were also signature differences between Inuit infants from Nunavik in northern Quebec, and Caucasian infants from southern Quebec. In Alaska, recent lead isotope data from blood of Alaska Natives from Bethel on the Yukon-Kuskokwim Delta and Barrow on the North Slope, regions where subsistence waterfowl hunts occur, showed signatures that overlapped with those of shot (Alaska Native Tribal Health Consortium, unpubl. data).

Blood Lead Surveillance in Alaska.—Alaska regulations require laboratories and health care providers to report all blood lead test results ≥10 µg/dL to the Alaska Division of Public Health, Section of Epidemiology; however, most laboratories report all BLL results (Section of Epidemiology 2008b). The Section of Epidemiology maintains a blood lead surveillance database of all reported blood lead levels from Alaskans (>26,000 records as of August 2008), and conducts individual case follow-up activities for all elevated BLLs.

In Alaska, the majority of adults with BLLs ≥25 µg/dL were males who worked in the metal ore mining industry (State of Alaska 2008a). Across all age groups, the majority (81%) of known non-occupational elevated lead exposures involved people exposed on indoor firing ranges, followed by children who were born or adopted from abroad (10%), and people casting lead as a hobby (3.4%) (State of Alaska 2008b).

Major lead sources for children aged <6 years in the contiguous United States are lead-contaminated dust and soil and deteriorated lead-based paint (Brown 2007), but these exposure sources are not frequently encountered in Alaska. The majority of Alaska children aged <6 years with elevated BLLs obtained their lead exposures abroad (State of Alaska 2008b). Many of the other sources of non-occupational lead exposure in Alaskans reflect the hunting and fishing, outdoor lifestyle of Alaska. Lead ammunition or lead fishing sinkers are commonly implicated as the primary exposure source of elevated BLLs in Alaska.

Elevated BLLs have been attributed to use of indoor firing ranges in Alaska (Lynn et al. 2005, Verbrugge 2007). Students shooting on high school rifle teams that used the problematic indoor shooting ranges were among the persons with elevated BLLs. Inadequate ventilation systems and improper maintenance practices at indoor firing ranges were documented at several ranges with lead exposure problems. The cleaning practice of dry sweeping is particularly hazardous, and should never be performed in indoor ranges. Elevated lead exposures have also occurred among Alaskans who hand reload ammunition, and among sportsmen who melt lead to cast their own bullets (State of Alaska 2008b). In June 2001 an adult Alaskan male suffered acute lead poisoning as a result of inhaling lead dust and fumes while melting and casting lead to make fishing sinkers (State of Alaska 2001). The patient had a BLL of 133 µg/dL and exhibited symptoms of fatigue, stomach pain with gastric upset for several months, and a fever of 102ºF for 10 days. The patient was hospitalized and received chelation therapy, and his BLL subsequently declined. The State of Alaska has not yet investigated whether consumption of game shot with lead may also be causing elevated lead exposures in Alaska, although this has recently been added to the list of potential risk factors under consideration during follow-ups for elevated BLLs.

REDUCING LEAD EXPOSURE IN CIRCUMPOLAR PEOPLE

In the circumpolar north, many indigenous peoples and other rural inhabitants depend on wild game for subsistence. In Alaska and elsewhere, scientists have documented the nutritional value of traditional foods such as fish, marine and terrestrial mammals, wild birds, and plants (Egeland et al. 1998, Nobmann et al. 1992). In many rural northern communities, wage-paying jobs are limited and market food is not available or is expensive. Further, wild foods are often nutritionally superior to market foods, which have high levels of processed sugars and fats. Subsistence food gathering is essential if people are to have enough healthy food. Traditional foods represent not just a critical food source, but also an integral part of Native culture and a way of life that has existed for many generations. Risk reduction strategies for lead exposure from ammunition must account for the need for inexpensive shot that is easy to use for subsistence hunting—a niche that is still being filled by purchased and reloaded lead shot in much of the North.

Risk reduction strategies that have been suggested for reducing lead exposure from use of lead shot include culture-specific outreach (see Tsuji 1998) to lead shot users and sellers, with the goal of voluntary behavior changes; capacity-building, which trains community members in outreach regarding lead shot risks and non-lead shot shooting techniques; and regulation, both from within and outside of subsistence communities (Tsuji 1999, AMAP 2003). Some are more successful than others; for example, regulation is often most effective if it is community-generated. Enforcement from outside the community, especially with the large distances and relatively low human population densities in Arctic regions, can be inefficient on broad scales.

After Inuit from Nunavik were found to have high cord blood lead levels, lead shot bans (Dallaire et al. 2003) and public health intervention (Levesque et al. 2003) resulted in "marked" and "significant" decreases in cord blood lead concentrations, from an average of 0.20 µmol/L before the ban in 1999 to 0.12 µmol/L after the ban (Dallaire et al. 2003). In the Mushkegowuk Territory of northern Ontario, collaborative health education outreach with direct community involvement was essential to changing attitudes about the safety of lead shot and inspiring behavioral change (Tsuji et al. 1999). In Alaska, outreach to food preparers, school-age children, and hunters about the risk of lead exposure from lead shot to human and bird health, resulted in two community-generated injunctions on the use of lead shot in areas covering 83 million acres (2.4 million ha) and numerous subsistence communities on the North Slope and Yukon-Kuskokwim Delta.

Reducing lead exposure from other sources, which may not be as widespread as the use of lead ammunition, could respond well to targeted outreach and regulation. For example, as the Alaskan examples illustrate, lead should not be melted and formed into shot or sinkers in home environments. In indoor shooting ranges, ventilation systems must be built correctly and correctly maintained, dry sweeping should be prohibited, and blood lead testing for regular users such as rifle teams should be performed at the beginning and end of each shooting season.

CONCLUSION

Since bans on lead in gasoline, instituted primarily in the 1980s and 1990s, lead levels in northern hemisphere humans have generally declined. A notable exception is the blood lead levels of Arctic indigenous peoples who rely on subsistence foods. In many cases, elevated blood lead levels in the Arctic have been associated with ingestion of lead from spent ammunition, primarily shot, although lead from fragmented bullets in big game may have been overlooked as a source until recently (Hunt et al. 2006, Tsuji et al. 2008, Hunt et al. 2009, Titus et al. 2009). Other cases of harmful lead exposure have resulted indirectly from use of lead in ammunition or for fishing (indoor firing ranges, home melting and manufacture of lead sinkers, shot, or bullets, and home reloading). Because subsistence populations by definition hunt much of their food, and because this food is important economically, nutritionally, and socially (Titus et al. 2009), an inexpensive source of ammunition is required. Lead is relatively inexpensive, but use of lead in ammunition comes with risks to humans, especially children, which do not occur with non-lead substitutes. Many approaches to reducing lead exposure have been proposed or implemented. For example, human health agencies can work with ammunition manufacturers and sellers to reduce the availability of lead ammunition, facilitate the availability of inexpensive non-toxic alternatives, and offer training on the different shot patterns, velocities, and distances inherent in using materials other than lead. The most effective means of reducing lead exposure have included community-based outreach and education on the dangers of lead from ammunition to both humans and the environment. These approaches have achieved positive behavioral changes, and may result in subsistence hunters and their families choosing to use non-toxic shot and bullets for their subsistence needs.

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