ABSTRACT  Lead poisoning is a threat to birds, particularly scavenging birds of prey. With the availability of portable lead-testing kits, an increasing number of field researchers are testing wild-caught birds, in situ, for lead poisoning. We describe guidelines for evaluation of lead toxicity in wild raptors by outlining field testing of blood-lead concentrations, presenting criteria for removing a lead-poisoned bird from the wild for treatment, and suggesting strategies for effective treatment of lead intoxicated raptors. Field testing of birds is most commonly accomplished via portable electrochemical analysis of blood; visual observation of condition alone may provide insufficient evidence upon which to make a decision about lead poisoning. Our intended audience is not only the avian research community, but also rehabilitation facilities that may receive apparently uninjured birds. Best practices suggest that birds whose blood-lead levels are <40 μg/dL be released back to the wild as soon as possible after capture. The decision to release or treat birds with blood-lead levels between 40 μg/dL and 60 μg/dL should be made based on the presence of clinical signs of poisoning and relevant biological characteristics (e.g., breeding status). Finally, birds with blood-lead levels >60 μg/dL are potentially lethally poisoned and best served if removed from the wild for appropriate treatment at a licensed rehabilitation facility and later released. We present guidelines for decision-making when treating lead poisoning of wild raptors. Future work based on experimental studies will clarify the role of lead poisoning for specific species and be important to refine these guidelines to improve effectiveness.

KEY WORDS  chelation, ecotoxicology, lead toxicity, raptor, scavenger, wildlife rehabilitation.

Lead poisoning is a significant threat faced by birds. Scavenging birds are exposed to lead primarily through ingestion of spent lead ammunition, especially fragments from rifle bullets used for big game hunting or rodent shooting (Scheuhammer and Templeton 1998, Garcia-Fernandez et al. 2005, Church et al. 2006, Pain et al. 2007, Finkelstein et al. 2010). In places where lead shotgun ammunition is used for waterfowl and upland game, wounded birds carrying lead pellets have increased mortality risk from raptors and other predators. For some species, predation on wounded game birds is a common route of exposure (Helander et al. 2009). Nearly all birds of prey scavenge, including eagles, owls, hawks, falcons, and vultures; therefore, there is potential for these and other species to be poisoned by lead (T. Katzner, personal observation; Jackowski et al. 2015). Likewise, upland game birds and waterfowl ingest spent shotgun shot as grit (e.g., Keel et al. 2002, Walter and Reese 2003, Newth et al. 2013, Haig et al. 2014). Many species of waterbirds can be exposed to lead via intentionally or unintentionally discarded fishing tackle (e.g., Locke et al. 1982). Less commonly, birds may also be exposed to lead via other sources including paint, coal-fired power plant emissions, fuel, lead mining, improper disposal of lead-acid batteries, and smelting (Pacyna 1987, Thomas and Spiro 1994, Johnson et al. 2007, Pain et al. 2009, Walker et al. 2012). Records from rehabilitation organizations suggest that ≥75 species of birds have been admitted for lead toxicity (Pain et al. 2009).

Visual observation of external condition is often insufficient to make a diagnosis of lead poisoning. However, with the development of field-ready lead-testing kits (e.g., Lead-Care®; ESA Biosciences, Chelmsford, CT, USA), there is potential for immediate evaluation of lead poisoning of wild birds captured by field biologists. If, in the process of capture for research, a bird was discovered with a broken wing or leg,
most researchers would not immediately release it back to the wild. Likewise, it seems doubtful that scientists would knowingly release to the wild a lead-poisoned bird with obvious evidence of neurological or other organ impairment. However, the extent of lead poisoning as a specific clinical diagnosis may not be readily apparent through casual observation, and it can be challenging to make educated decisions about when it is appropriate to remove a bird from the wild for treatment for lead poisoning.

We describe guidelines for evaluation of lead toxicity in wild raptors, outline field testing of blood-lead levels, and present criteria for removing a lead-poisoned bird from the wild for chelation therapy. Our intended audience is not only the avian research community, but also rehabilitation facilities that may receive apparently uninjured birds from researchers. We provide detail on 4 main points: 1) the basics of lead ingestion and toxicity; 2) details on how to test wild birds for lead poisoning; 3) suggested best practices for when to remove a bird from the wild for chelation and where to bring such a bird; and 4) suggested treatment options for rehabilitation.

**Lead Ingestion by Raptors**

Lead rifle ammunition is specifically designed to fragment when it hits a target. This process facilitates transfer of kinetic energy from the projectile to the animal being shot and increases the likelihood that the impact will be fatal. As a consequence of these processes, lead fragments, some microscopic, can be found dispersed in animal tissue far from the primary path of the bullet. Lead fragments have been reported as far as 15 cm (6”; Hunt et al. 2009) and 46 cm (18”; Grund et al. 2010) from the center of the bullet’s exit hole.

Wild raptors are exposed to lead when they scavenge shot rodents or ungulates not recovered by the shooter or gut piles left by hunters (Haig et al. 2014). The ubiquity and number of ungulates harvested is widely recognized and available indirectly through hunting records (e.g., WY, USA, hunt records are available at https://wgfd.wyo.gov/Hunting/Harvest-Reports/). However, the number of rodents shot is less well-understood and estimates are only available from Harvest-Reports/). However, the number of rodents shot (Huxoll 2012). Stauber et al. (2010) reported to be 1.05 million prairie dogs (a potential mechanism of lead poisoning for raptors near water (e.g., osprey \( \text{Pandion haliaetus} \) and fish eagles \( \text{Haliaeetus spp} \), Haig et al. 2014). In rare cases, there are other mechanisms of exposure (e.g., eating lead paint; Finkelstein et al. 2012), although isotope analysis suggests that these other mechanisms are infrequent.

**Pathophysiology and Diagnosis of Lead Poisoning**

Once ingested, lead can remain in the body for days, weeks, or longer (Bates et al. 1968). In the acidic environment of the stomach, lead is worn down by the muscular action of the ventriculus, solubilized, and actively absorbed through a calcium transport mechanism (Fullmer 1991). The rate and degree of absorption depends on several factors including physical form of the lead, particle size, species-specific gastrointestinal physiology and transit time, and individual-specific nutritional status and age (Redig and Arent 2008, Pokras and Kneeland 2009). Diurnal raptors maintain a relatively low stomach acid compared with other species of birds, which likely increases the rate of absorption and may increase risk of lead intoxication (Dierenfeld 1989, Mautino 1997, Jones 2006, Redig and Arent 2008, Pokras and Kneeland 2009), months in soft tissue organs (Scheuhammer 1987, Pokras and Kneeland 2009), and years in bone (Rabinowitz 1991, Pokras and Kneeland 2009).

Lead poisoning can cause lethargy, gastrointestinal stasis, anorexia, vomiting, anemia, disturbance of cellular function, and neurologic injury potentially leading to blindness, seizures, weakness, and death (Redig et al. 1980, Franson et al. 1983, Custer et al. 1984, Pain et al. 1993). Even at low doses, lead exposure causes a number of sublethal effects such as neurological impairment, organ dysfunction, immune system disturbance, and reproductive impairment (Burger and Gochnfeld 2000). Despite the myriad effects of lead poisoning, it is important to note that not all of these consequences will necessarily be expressed in any one animal. Neurological impact, including head tilt, loss of balance, pelvic limb weakness, and loss of conscious proprioception (positional awareness) are the most widely reported visible effects (Benson et al. 1974, Redig et al. 1980, Lumeij 1985, Fisher et al. 2006). However, this same suite of symptoms can be triggered by other conditions such as head trauma, encephalitis (e.g., West Nile virus), botulism, nutritional deficiency, and other toxicities (e.g., zinc poisoning; Dierenfeld 1989, Mautino 1997, Jones 2006, Redig and Arent 2008, Gamino and Höfle 2013).

Because there is strong selection pressure on birds not to show external signs of illness and these clinical (i.e., recognizable symptoms on examination) signs associated with lead poisoning are nonspecific, diagnosis in the live bird relies on measurement of lead in blood. Background concentrations of lead in the blood of birds have been reported to be <20 \( \mu \text{g/dL} \) (<0.2 parts per million [ppm]; Pain et al. 2009, Stauber et al. 2010) although recently some authors have suggested that blood lead concentrations should be considered background only when <10 \( \mu \text{g/dL} \) (<0.1 ppm; Church et al. 2006, Cade 2007). There is general consensus that for most raptor species, blood lead concentrations ≥20 \( \mu \text{g/dL} \) (>0.2 ppm) clearly represent...
concentration measurement between 20 occurrence of the traumatic event is not known. Kramer and Redig 1997). Such birds are typically admitted to subclinical (i.e., with few obvious recognizable manifesta-
tions than did other species of birds (Carpenter et al. lead shot survived longer with elevated blood-lead concen-
trations of circulating lead can change rapidly, as present in the gastrointestinal tract at the time of diagnosis. It is therefore important for field biologists and rehabilitators to understand that 1) blood lead concentrations are dynamic; 2) a single blood test does not characterize lead exposure or degree of poisoning; and 3) the decision to treat a wild bird should be based on a thorough evaluation of all signs of exposure (see below).

Testing Wild Birds for Lead Poisoning

Reference laboratory methods for measuring lead include graphite-furnace atomic absorption spectrophotometry and inductively coupled plasma mass spectrometry (ICP-MS; Murthy et al. 1973, Ting and Janghorbani 1988). However, these methods require expensive equipment and time, and are not practical for quick assessment in the field or at a treatment facility. Inexpensive “point of care” lead analyzers developed to assess human exposure to lead have been used in a variety of wildlife settings to obtain a rapid test result. Although such lead analyzers may be less accurate than ICP-MS, they are fast, only require a small volume of blood, and come with a degree of error generally considered acceptable for clinical decision-making. The most frequently used of these analyzers rely on electrochemical anodic stripping voltammetry (LeadCare®). Within their operating ranges, these devices are correlated with ICP-MS values for samples from humans (e.g., Counter et al. 1998, McMillin and Bornhorst 2008, Sobin et al. 2011) and birds (Domenech and Langner 2009, Rodriguez-Ramos et al. 2009, Langner et al. 2015; Redig and Risebrough, unpublished data). These systems require only 50 μL of blood, providing the opportunity to safely quantify blood lead concentration in all species of raptors, regardless of body size. Disadvantages of these clinical testing units include greater among-sample variability in results than those from ICP-MS (averaging 1.0 μg/dL in human blood with lead concentrations <10 μg/dL, Sobin et al. 2011) and processing constraints to only one sample at a time. Furthermore, some of the most commonly used devices have a maximum quantifiable concentration of lead of 65 μg/dL; greater concentrations are reported as “high.” Prior to sampling birds in the field, it is important to calibrate any portable lead analyzer with laboratory measurements to define the accuracy and precision of the field test. We recommend that field test kits be calibrated with laboratory based methods whenever a new lot of test strips is opened or at the beginning of a new research project or field season.

Portable radiographic units are occasionally used in the field to check for gravidity (presence of eggs) and metal foreign bodies. Most metals appear with the same density on radiographs, and thus it is impossible to use a radiograph to distinguish between lead and other metals. Elevated blood-lead concentration combined with radiographic evidence of metal in the gastrointestinal tract is a clear indication for removing a bird from the field for decontamination. It is also critical to recognize that many individuals (especially raptors and corvids) with lead poisoning do not have metal objects present in the gastrointestinal tract at the time of diagnosis. Lead fragments can pass in the feces or be egested via pellet egestion (Pattee et al. 1981). Birds can remain poisoned long after the metal passes (Kramer and Redig 1997). Therefore, although radiographic evidence of metal in the gastrointestinal tract can occur in wild birds, blood results are necessary to further assess the animal for possible exposure to lead.

Best Practices for When to Remove a Bird From the Wild

Because of the increased accessibility and use of portable lead analyzers in the field and prevalence of lead exposure in wildlife, field scientists may encounter birds that they know, based on the field test results, have elevated blood-lead concentrations. When this situation arises, researchers have only a limited time to evaluate and determine whether the animal should be immediately returned to the wild or brought into captivity for decontamination and chelation. Furthermore, within the United States, members of the general public, including federally permitted bird banders, are allowed (under 50 C.F.R. 21) to immediately transfer an exhausted, ill, or injured bird to a federally permitted migratory-bird rehabilitator (B. Peterjohn, U.S. Geological
likely suffering from lead toxicity. Asymptomatic bird with high blood-lead concentration is when assessing toxicity, because even an apparently lead concentration and clinical signs should be considered clinical signs at all (Harmata 2011). Therefore, both blood with high blood-lead levels may exhibit no readily apparent concentration may exhibit obvious clinical signs and a bird poisoned birds encountered in the field. It is important to note that a bird with modestly elevated blood-lead concentration may exhibit obvious clinical signs and a bird with high blood-lead levels may exhibit no readily apparent clinical signs at all (Harmata 2011). Therefore, both blood lead concentration and clinical signs should be considered when assessing toxicity, because even an apparently asymptomatic bird with high blood-lead concentration is likely suffering from lead toxicity.

There are a multitude of organ system effects of lead toxicity; therefore, clinical signs can be nonspecific and may include dull mentation (e.g., slow or weak response to stimulation or handling), weakness, lack of coordination, poor body condition, or green biliverdin staining in the mouth (Table 1 and Fig. 1). Head tilting, rhythmic head twitching, nystagmus (rhythmic eye movement), and head drooping are commonly reported clinical signs in lead poisoned birds encountered in the field. It is important to note that a bird with modestly elevated blood-lead concentration may exhibit obvious clinical signs and a bird with high blood-lead levels may exhibit no readily apparent clinical signs at all (Harmata 2011). Therefore, both blood lead concentration and clinical signs should be considered when assessing toxicity, because even an apparently asymptomatic bird with high blood-lead concentration is likely suffering from lead toxicity.

Table 1. Clinical signs that can occur in birds with lead poisoning.

<table>
<thead>
<tr>
<th>Neurological</th>
<th>Gastrointestinal</th>
<th>Hematological</th>
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<tbody>
<tr>
<td>Weakness</td>
<td>Vomiting or</td>
<td>Nonregenerative anemia</td>
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<tr>
<td>Ataxia (loss of coordination)</td>
<td>regurgitation</td>
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<tr>
<td>Blindness</td>
<td>Diarrhoea</td>
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<tr>
<td>Seizures</td>
<td>Green excreta</td>
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<tr>
<td>Nystagmus (involuntary eye</td>
<td>Green staining on</td>
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<td>movement)</td>
<td>feathers</td>
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<td>Head tilt</td>
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<td>Clenched toes</td>
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<td>Drooping wings</td>
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<td>Closed eyelids</td>
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<td>Tremors</td>
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<td>Instability or unable to stand</td>
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<tr>
<td>Abnormal mentation</td>
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We describe a proposed set of best practices for evaluating potentially lead-poisoned raptors that can be used to aid decision-making (Fig. 2):

1. When blood lead concentrations are $\geq 60 \mu g/dL$ then, regardless of other symptoms, it is appropriate to transfer the bird as rapidly as possible to a licensed rehabilitator experienced with treating lead toxicity and able to further evaluate the clinical condition of the bird.
2. If the blood lead concentration is $>40 \mu g/dL$ and $<60 \mu g/dL$ and clinical signs are not present, then the most reasonable approach is to return the bird to the wild as soon as possible. If logistically feasible, properly trained field researchers should consider providing fluid administration (subcutaneous and oral) to support diuresis. Although the efficacy of a one-time fluid bolus in treating elevated blood-lead concentration is not clear, fluid diuresis is an important component of treating heavy metal intoxication and may be beneficial to a bird with subclinical lead poisoning (DeFrancisco et al. 2003).
3. If the blood lead concentration is $>40 \mu g/dL$ and $<60 \mu g/dL$ and clinical signs are present, then the bird should be transferred as rapidly as possible to a licensed rehabilitator for treatment of lead intoxication. It is possible that, in case-specific situations, removal from the wild for treatment would not be warranted, but we recommend that researchers err on the side of caution when handling birds with clinical signs of intoxication.
4. If lead concentration $<40 \mu g/dL$ and the bird otherwise appears healthy, then it should be returned to the wild as quickly as is possible.

Suggested Treatment Options for Rehabilitation Facilities

Treatment for lead poisoning has been described previously (e.g., Redig and Arent 2008). Here, we briefly review the steps that are appropriate and provide citations for those readers interested in more details. Lead poisoning may occur with or without the presence of lead visible in radiographs...
If radiographs indicate metal objects within the gastrointestinal tract, initial therapy should consist of removing ongoing exposure with, in order of most to least frequently applied, gastric lavage, emollient laxatives, carthartics, endoscopy, or proventriculotomy. Without removal of lead fragments, exposure continue, and chelation treatment is less effective. However, if circumstances dictate a delay in the implementation of any of these removal procedures, chelation therapy should be instituted immediately to reduce circulating blood levels. Prior to initiating therapy, we recommend rehabilitators repeat a measurement of blood lead to establish a pretreatment concentration.

Following decontamination or in the absence of ongoing exposure, chelation therapy is the mainstay of treatment for avian lead poisoning (DeFrancisco et al. 2003). Chelation agents that can effectively bind lead include D-penicillamine, succimer (Dimercaptosuccinic acid), British Anti-lewisite (BAL), and CaNa₂ ethylene diamine tetra acetic acid (CaEDTA). Of these, succimer and CaEDTA are the treatments of choice (Redig and Arent 2008). Prior to treating birds with chelation therapy, it is important for the veterinarian and rehabilitator to understand the possible risks that may be associated with different chelation agents and dosing protocols.

Calcium EDTA is most commonly used to treat heavy metal toxicity; it can be administered intravenously, intramuscularly, or subcutaneously, and is effective at binding lead in soft tissues. Dosing protocols vary, but CaEDTA is typically given at 35–100 mg/kg every 12 hr for 5 days. Although it has not been reported for raptors treated with this dosing protocol, calcium EDTA has the potential to be nephrotoxic (Schwartz et al. 1966). Falcons with lead intoxication treated daily at doses of 100 mg/kg for >3 weeks showed no adverse effects and had significantly reduced blood-lead concentrations (Samour and Naldo 2002). Still, because of the potential for kidney insult, it is important to maintain appropriate hydration of patients undergoing treatment, and patients on extended courses of CaEDTA should be monitored for kidney function. Five-day courses of CaEDTA can be repeated for individual patients as necessary to return blood lead levels to <0.2 ppm. Rest days are helpful between rounds for the patient to replenish divalent cations that are also chelated by the agent. Blood-lead concentration measurements should be made at the end of these rest periods because the presence of the chelation agent may interfere with results. The ultimate determination to cease treatment should be based on resolution of clinical signs and repeated measurements of blood lead concentration.

Succimer is orally administered, making it a poor choice for chelation of a vomiting bird. However, it is very effective at decreasing lead in soft tissues and believed to not be nephrotoxic. Successful treatment has used dosages of succimer in a range from 10 to 40 mg/kg, but there is limited information on an optimal duration of treatment (Hawkins et al. 2013). Succimer can be given concurrently with CaEDTA. Again, treatment duration should be based on resolution of clinical signs and repeated measurements of blood lead concentration. Birds have been treated with succimer at 30 mg/kg every 12 hr for up to 10 days without apparent side effects and with successful reduction in blood lead concentrations (Hoogesteijn et al. 2003). However, experimentally repeated administration of extremely high doses of succimer (80 mg/kg every 12 hr for 21 days) in the absence of lead intoxication resulted in regurgitation and morbidity or mortality in up to 66% of cockatiels (Nymphicus hollandicus), although the pathophysiology of this result is unknown (Denver et al. 2000). Therefore, succimer should be used at appropriate doses because the safety margin may be narrow.

Regardless of the method of chelation, supportive care including administration of fluids, benzodiazepine (e.g., diazepam) for seizure control, and treatment for concurrent disease (e.g., aspergillosis, endoparasitism, hemoparasites) is critical to successful treatment. Although chelation has been
used for decades to treat acute lead toxicity in human and veterinary medicine, treatment protocols have been based largely on observational data. Chelation therapy itself may carry risks, so it is important that rehabilitators rely on veterinarians with expertise in treating lead toxicity. Following the recommendations outlined above, side effects associated with chelation are unlikely.

CONCLUSIONS

These guidelines are suitable for treatment of wild-caught raptors regardless of whether or not they display symptoms of lead poisoning. The physiology of lead toxicity is complex and there are occasions where birds present with modest blood-lead levels and clear indications of lead toxicity or, in contrast, with high blood-lead levels and few signs of toxicity. It is thought that the relationship between an individual's condition and its blood lead concentration is determined by factors such as length of exposure, size of the original dose, and duration of exposure (e.g., Pattee et al. 2006). Furthermore, any decision to remove a bird from the wild must be weighed against the biological circumstances in the field and availability of suitable resources for treatment. Although removal from the wild of a bird without apparent symptoms may be difficult to contemplate, it is not a new idea; wild and endangered California condors (Gymnogyps californianus) are managed in exactly this way (Finkelstein et al. 2012). However, the material presented in this manuscript is for information purposes only and not intended to be a protocol for treatment of lead poisoning. Finally, researchers and rehabilitators conducting any work with raptors should always be sure to operate within the appropriate local and national permits as required where they work.

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