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Mercury and Other Metals in Feathers of Common Eider (*Somateria mollissima*) and Tufted Puffin (*Fratercula cirrhata*) from the Aleutian Chain of Alaska

Joanna Burger and

Division of Life Sciences, Rutgers University, 604 Allison Road, Piscataway, NJ 08854-8082, USA. Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Piscataway, NJ, USA. Environmental and Occupational Health Sciences Institute (EOHSI), Piscataway, NJ, USA

Michael Gochfeld

Division of Life Sciences, Rutgers University, 604 Allison Road, Piscataway, NJ 08854-8082, USA. Environmental and Occupational Health Sciences Institute (EOHSI), Piscataway, NJ, USA. Environmental and Occupational Medicine, UMDNJ-Robert Wood Johnson Medical School, Piscataway, NJ, USA

Joanna Burger: burger@biology.rutgers.edu

Abstract

We analyzed arsenic, cadmium, chromium, lead, manganese, mercury, and selenium in the feathers of common eiders (*Somateria mollissima*) and tufted puffins (*Fratercula cirrhata*) from Amchitka and Kiska islands (Aleutians). Between species, puffins had 10 times higher chromium (arithmetic mean = 1820 ppb), 7.5 times higher selenium (mean = 6600 ppb), and 3 times higher mercury (mean = 2540 ppb) than eiders. Eiders had significantly higher levels of manganese than puffins. Puffins are higher on the food chain than eiders, which is reflected in their generally higher levels of metals in their feathers. Interisland differences were generally small, and there were few significant differences as a function of the three nuclear test locations on Amchitka. The only sex-related difference was that female puffins had higher mercury than males (arithmetic mean of 3060 ppb vs. 2270 ppb). Mean levels of metals in the feathers of puffins and eiders from the Aleutians were low compared with comparable studies elsewhere, and the relatively low levels of metals do not indicate the potential for adverse behavioral or reproductive effects in the birds themselves, nor pose concern for other consumers, including subsistence hunters.

Governmental agencies, Tribal Nations, policy-makers, and the general public are concerned about the health of species and their environments, and they require indicators that assess levels of contaminants and their possible effects on the individuals themselves as well as consumers of these organisms. Levels of chemicals are elevated in marine and coastal ecosystems because of the influx from rivers, runoff, point-source pollution, and

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Correspondence to: Joanna Burger, burger@biology.rutgers.edu.

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atmospheric transport and deposition (Burger and Gochfeld 2001; Furness and Rainbow 1990). Many chemicals, such as mercury, are transported all over the world, including to relatively isolated lakes, marshes, and oceanic environments (Fitzgerald 1989; Hammerschmidt et al. 2006; Houghton et al 1992). In some studies, metal levels are higher at higher latitudes and in the northern versus the southern hemisphere (Savinov et al 2003). Marine contamination by metals and other pollutants is a source of concern, and species that forage in aquatic environments are particularly vulnerable because of the potential for rapid movement of contaminants in aquatic food chains, compared to movement in terrestrial environments, and because chemicals in estuarine and shallow marine waters can be stored in bottom sediments (including the intertidal), providing a mobilizable pool for years to come.

Marine birds are useful as bioindicators of pollution (Furness 1993; Furness and Camphuysen 1997; Gochfeld 1980; Peakall 1992; Walsh 1990) because they are exposed to a wide range of chemicals and occupy a wide range of trophic levels. Some species are at the top of the food chain, making them susceptible to bioaccumulation of pollutants (Burger and Gochfeld 2002; Lewis and Furness 1991; Nygard et al 2001). Feathers are useful indicators of metal contamination because (1) they are easy to collect noninvasively and to store for decades or longer, (2) birds sequester metals in their feathers, (3) the proportion of body burden that is in feathers is relatively constant for each metal, (4) a relatively high proportion of the body burden of mercury is stored in the feathers (Burger 1993) due to their affinity for the sulfhydryl-rich melanin pigments, and (5) there is a high correlation between levels of contaminants in the diet of seabirds and levels in their feathers (Burger 1993; Monteiro and Furness 1995). Breast feathers are the best indicator of whole-body burdens (Furness et al. 1986).

Many oceanic islands are far from the main anthropogenic sources of contamination found in temperate regions, such as urban, industrial and agricultural emissions, effluents, and runoff (Mailman 1980), yet even some polar regions have been found to contain pollutants (Metcheva et al 2006; Nygard et al 2001). Oceanic regions are extremely important to the fishing industry. The Bering Sea ecosystem, for example, provides a large percentage of the fish and shellfish for commercial sale in the United States (AFSC 2006). Dutch Harbor in the Aleutians, the port for commercial fish in the Bering Sea, had the highest tonnage of fish landings in the world in 2003 and provides 17% of Alaska's \$811 million fish landings (2.3 million metric tons of fish; NOAA 2004). Understanding contaminant levels in oceanic ecosystems and having bioindicators for these systems are very important. Moreover, in many remote areas, subsistence hunters and Native Americans use wild-caught foods. In the Aleutians, the local Aleut population eats invertebrates, shellfish, fish and birds, including eiders and puffins (Patrick 2002).

In this article we examine the concentrations of arsenic, cadmium, chromium, lead, manganese, mercury, and selenium in the feathers of common eiders (*Somateria mollissima*) and tufted puffins (*Fratercula cirrhata*) collected from breeding colonies on Amchitka and Kiska islands in the Aleutian Chain of Alaska. This suite of metals was chosen because they are the primary metals of concern for marine organisms (mercury, cadmium, lead) and because there are other comparative data for the other species (see Burger 1993).

Technically, arsenic and selenium are metalloids, but they will be included under the term “metals” in this article. We test the null hypotheses that (1) there were no interspecific differences in metal levels in feathers, (2) there were no interisland differences in metal levels in feathers, (3) there were no locality differences in feathers of adults that nested near the three underground nuclear tests on Amchitka (Long Shot 1965; Milrow 1969; Cannikin 1971), and (4) there were no gender differences in feather levels in common eiders or tufted puffins. Partly we chose these species because eiders are relatively low on the food chain, and puffins are higher on the food chain.

Materials and Analytical Methods

Study Sites and Species

Amchitka Island (Fig. 1; 51° N lat; 179° E long) is part of the Alaska Maritime National Wildlife Refuge system. It contains important ecological resources (Burger et al 2005, 2006a, 2006b; Merritt and Fuller 1977). Amchitka is the only island where the United States detonated underground tests called Long Shot (1965), Milrow (1969), and Cannikin (1971) (Fig. 2). Amchitka is unusual because of its remoteness (remote from coastal runoff with associated metals and other contaminants), depth below ground surface of some of the contamination (radionuclides), and the importance of its ecological resources and seafood productivity that could be at risk if there were significant seepage of radionuclides from Amchitka tests to the marine environment (Burger et al 2006b).

Kiska (51° N lat; 177° E long) had Japanese military occupation during the Second World War but has not been occupied since then. It contains many of the same terrestrial and benthic environments as Amchitka (Burger et al 2006b) and was selected as a reference site. The collection sites on Kiska were at least 140 km west of Amchitka. Thus, these sites were at a sufficient distance from one another that interchange of birds between the islands was very unlikely. Both islands are part of the Alaska Maritime National Wildlife Refuge, originally established in 1913 by executive order of President Taft (ATSDR 2004).

Common eiders reach adult breeding plumage at 2–4 years (Goudie et al 2000) and tufted puffin reach adult plumage at 2–3 years (Piatt and Kitaysky 2002). Tufted puffins breed from warm coastal islands off California to frozen Alaskan habitats (Piatt and Kitaysky 2002), whereas common eiders have a circumpolar breeding distribution (Goudie et al 2000). Both species are highly marine and feed on invertebrates, although puffins also eat small forage fish and squid. On Kiska and Amchitka, common eiders breed in small colonies in grass along flat coastal zones, whereas puffins breed in cracks and crevices on rocky slopes and cliffs.

Collection Protocol

Under appropriate federal and state permits, breast feathers were collected from adult common eiders and tufted puffins nesting at Amchitka and Kiska islands in the Aleutian Chain of Alaska. All birds were collected in July, during the breeding season; when both species were incubating eggs or had recently-hatched chicks. Birds were shot by Aleut hunters (both species are subsistence foods for Aleuts) for the radionuclide work, and samples were taken at this time for metals analysis. Noting the exact timing of collecting is

critical because Wayland et al (2005) found that levels of cadmium, mercury, and selenium can vary by time of the year. Breast feathers were placed in individual envelopes and labeled for later identification and were then shipped to Rutgers University for analysis.

Breast feathers were selected because they are considered to be more representative of exposure to metals than other feathers (Burger 1993; Furness et al 1986). Metals enter feathers during the 2–3 weeks it takes for them to grow, then the blood supply atrophies, and there is no further uptake of metals (Burger 1993; Thompson et al 1998). Thus, feathers are an archive of metal exposure during feather formation (Braune and Gaskin 1987). Although there is some variation in metals levels among breast feathers, by using several feathers the differences are averaged.

Adults are exposed to heavy metals and metalloids through their food and water. Once ingested, contaminants can be excreted directly or absorbed into the bloodstream. Subsequently, absorbed metals are delivered to target or storage organs or sequestered in feathers (Braune 1987; Lewis and Furness 1991) or other tissues. In some environments, feathers are susceptible to increased metal accumulation by external contamination (Goede and deBruin 1986; Rose and Parker 1982), although such external contamination might be much less in remote areas, and vigorous washing removes significant external contamination.

Kim et al. (1996) recently suggested that some pelagic seabirds (albatrosses and petrels) are capable of demethylating methylmercury in the liver and storing it as an immobilizable inorganic form; however, the mercury in feathers has been reported to be as high as 100% methylmercury (Thompson et al 1991). Heavy metals in the breast feathers represent circulating concentrations in the blood during the few weeks of feather formation, which, in turn, represents both local exposure and mobilization from internal tissues (Lewis and Furness 1991; Monteiro 1996). Both the eiders and puffins in the western Aleutians remain in the vicinity of the islands, moving offshore between October and April (Kenyon 1961).

The initial study of the marine ecosystem around Amchitka Island, by the multiuniversity Consortium for Risk Evaluation with Stakeholder Participation, was conducted to provide the Department of Energy and the state and federal resource trustees evidence regarding current radionuclide contamination at Amchitka, as well as baseline data for future biomonitoring (Powers et al 2005). Material collected as part of that study was then used for the present metal analysis.

Analytic Methods

All feathers were analyzed in the Elemental Analysis Laboratory of the Environmental and Occupational Health Sciences Institute in Piscataway, NJ. Feathers were washed three times with acetone, washed once with deionized water, air-dried, and then digested individually. A 0.05-g (dry weight) sample was digested in 3 mL ultrex ultrapure nitric acid and 2 mL deionized water in a microwave (MD 2000 CEM), using a digestion protocol of three stages of 10 min each under 50, 100, and 150 psi (3.5, 7, and 10.6 kg/cm²) at 70X power. Digested samples were subsequently diluted to 10 mL with deionized water. All laboratory equipment

and containers were washed in 10% HNO₃ solution and a deionized water rinse prior to each use (Burger et al. 2001).

Mercury was analyzed by the cold vapor technique, and the other elements were analyzed by graphite furnace–atomic absorption (Burger and Gochfeld 1991). All concentrations are expressed in nanograms per gram (ppb) on a dry weight basis using weights obtained from air-dried specimens.

Detection limit were: 0.02 ppb for cadmium, 0.08 ppb for chromium, 0.15 ppb for lead, 0.09 ppb for manganese, 0.2 ppb for mercury, and 0.7 ppb for selenium. All specimens were analyzed in batches with calibration standards, spiked specimens, and a reference material (DORM-2). Recoveries ranged from 88% to 102%. Batches with recoveries of less than 85% were reanalyzed. The coefficient of variation on replicate, spiked samples ranged up to 10%.

Kruskal–Wallis nonparametric analysis of variance was performed using the SAS PROC NPAR1WAY with the Wilcoxon option yielding a chi square statistic (SAS 1995). Both arithmetic and geometric means are given to facilitate comparisons with other studies. We accept a probability level of 0.05 as significance, but in view of sample size limitations present, all probability values below 0.10 are given to allow the reader to assess the significance for themselves.

Results

There were interspecific differences in the concentrations of metals in the feathers, except for arsenic and lead (Table 1). Puffins had significantly higher levels of chromium (10 times higher), selenium (7.5 times higher), and mercury (3 times higher) in their feathers than did common eiders. Eiders had significantly higher levels of manganese (three times higher) in their feathers than did puffins.

There were few interisland differences in metal levels in feathers from Amchitka and Kiska, and where there were differences, they were not great (Table 2). For the three test sites on Amchitka, we combined Long Shot and Cannikin because they are quite close and located on the same side of Amchitka (Bering Sea), whereas Milrow is on the Pacific Ocean side. There were no significant differences for feathers, except that manganese levels were higher in puffin feathers from near Long Shot than near Milrow (Table 3).

There were no gender-related differences in metal levels in eiders, and there was only one such difference for tufted puffins (Table 4). Female puffins had significantly higher levels of mercury in feathers than did males (geometric mean 2720 vs. 1850 ppb), which is surprising given that females can rid their bodies of heavy metals through sequestration in eggs.

The correlations among metals levels within feathers were generally weak, although there were some significant relationships (Table 5). The strongest correlation was between chromium and mercury in the feathers of both puffins and eiders. Many studies have reported a correlation between mercury and selenium for internal tissues, and in this study, they were significantly correlated only for eider feathers (Table 5). Overall, there were few

correlations for the feathers of eiders (4 of 21) and puffins (7 of 21; Table 5). Arsenic and manganese were correlated with body weight for eiders, and manganese and mercury were correlated with weight for puffins.

Discussion

To varying extents, metals can bioaccumulate to reach toxic levels that can lower survival and reproductive success in birds (Bargagli et al 1998; Burger 1993; Eisler 1987; Scheifler et al 2005). Because some pollutants undergo biomagnification up the food chain, their concentrations have often been studied in top-level predators such as raptors and fish-eating birds (Burger 2002; Burger and Gochfeld 1997, 2002, 2004; van Straalen and Ernst 1991). In this study, however, we examined mercury, lead, cadmium, and other metals in the feathers of eiders (relatively low on the food chain) and puffins (higher on the food chain). There are three key questions concerning the metals data from this study: (1) What are the causes of differences among the species? (2) What accounts for any interisland or within-Amchitka differences? (3) How does one think about the lack of gender-related differences? (4) How do these levels compare to those of birds from other areas? (5) Are the levels sufficiently high to cause adverse effects in the birds themselves or in consumers of the birds? Each of these questions is discussed next.

Interspecific Differences

Interspecific differences in metals levels in the feathers of birds could result from differences in diet (in either foods eaten, sizes of prey, or proportion of prey or other food items), absorption rates, time in the vicinity of the colony, and location of the birds at the time of molt when breast feathers were formed, as well as a possible genetic component (Kelsall and Calaprice 1972). Although both species are resident in the Aleutians, the degree that they wander from the immediate vicinity of the breeding colonies is unknown.

In this study, tufted puffins had significantly higher levels of chromium, lead, mercury, and selenium in their feathers than did common eiders, and eiders had significantly higher levels of manganese. In general, we attribute these differences to differences in diet. Common eiders eat mainly lower-trophic-level benthic invertebrates in the intertidal and subtidal regions, but sometimes they eat crustaceans and echinoderms (Goudie et al 2000). In the Pacific/Bering Sea regions, the diet of common eiders was 46% mollusks, 31% crustaceans, and 14% echinoderms (Cottam 1939). In contrast, tufted puffins feed mainly on small schooling fishes during the breeding season, although they also eat invertebrates such as squid (Piatt and Kitaysky 2002). In the Aleutians, however, diets vary by location, with squid accounting for 80% of the items in puffin diets in the western Aleutians but only 17% of diets in the eastern Aleutians (Piatt and Kitaysky 2002); fish made up 22% of diets in the eastern Aleutians. Walleye pollock, sandlance, and greenling were all important fish in the diet of puffins. Thus, to truly understand the diet of puffins, site-specific information is necessary, derived from either stomach content analysis or stable isotopic studies (Braune et al 2002). Nonetheless, it is clear that puffins normally eat a higher percent of higher-trophic-level fish and squid than do eiders, perhaps accounting for the differences.

The greatest differences between species were for chromium (10 times higher in puffins than eiders) and selenium (7.5 times higher in puffins than eiders). Mercury levels were only three times higher in puffins than eiders. These differences should reflect differences in diet for the birds foraging around Amchitka and Kiska islands, a region in which dietary data were not reported (see Piatt and Kitaysky 2002). The data that are reported, however, indicated that puffins eat more fish and higher-trophic-level invertebrates than eiders (references above), accounting for these differences.

The one unexpected result was that eiders had significantly higher levels of manganese than puffins (by three times). Further, manganese levels were significantly higher in eiders collected from the Long Shot/Cannikin area compared to those from Milrow. Manganese is a metal that is regulated internally, suggesting that eiders can sequester manganese in their feathers to rid internal tissues of manganese. The differences might also suggest that eiders can tolerate higher levels and that they were exposed to higher levels, perhaps through their invertebrate prey. Relatively few studies with feathers (or with internal tissues) examine manganese, making it difficult to compare eiders with other species. These findings suggest a need to examine manganese levels in feathers of other seabirds as a bioindicator of possible exposure and bioaccumulation. Because manganese has been used as a fuel additive and increased exposure has some human health implications (Cooper 1984), it is important to learn more about its movement through the food chain.

Interisland and Within-Amchitka Differences

Locational differences in metal levels could derive from differences in local exposure, atmospheric deposition, or foraging regimes; that is, adult eiders and puffins living on the different islands could eat different foods, of different sizes, and in different proportions. Further, exposure on Amchitka and Kiska could differ in the same foods due to differences in anthropogenic sources. Both islands were occupied by military operations in World War II. Amchitka was also occupied during the underground nuclear test shots and again during Department of Energy cleanup. Kiska Island was occupied by the Japanese during World War II. In addition to the point sources (such as military activities on both islands, nuclear testing on Amchitka), metals derive from global transport and fallout and oceanic transport. Global transport generally confers a uniform distribution within a local area, although there are regional variations attributable to precipitation regime (Simon et al 2004).

For most studies of metals in feathers, it is also important to understand both the timing and pattern of molt and where birds were at the time of the molt. Both species remain in the Aleutians all year, although they might wander offshore. We found few significant interisland differences, and, more importantly, these differences were not large, suggesting that they might have been due to small differences in diet of birds on the different islands. The only difference that was consistent for the two species was lead, which was higher on Kiska than Amchitka. The only military difference between Amchitka and Kiska is that Kiska was also occupied by the Japanese during World War II, and extensive bombing by Americans, sinking of ships, and other activities may have resulted in higher lead levels in the environment.

In a related study examining radionuclides and mercury in gulls (*Larus glaucescens*) and eiders (*Somateria mollissima*) from these same islands, we found that gull feather (*L. glaucescens*) levels were significantly higher for lead and manganese on Kiska than on Amchitka (Burger and Gochfeld 2007; Burger et al 2008). Thus, the finding of higher levels of lead on Kiska than on Amchitka was consistent for feathers of eiders, gulls, and puffins, birds of different trophic levels. This suggests that lead levels are higher in a wide range of prey of these species around Kiska than Amchitka. This was surprising to us, given that Amchitka had a much longer period of military and nuclear-related occupation.

Rocque and Winker (2004) examined levels of several metals in the livers of rock sandpipers (*Calidris ptilocnemis*) in Attu, Adak, Amlia, and the Alaskan Peninsula and found that arsenic was highest in Attu, mercury was highest in the Alaska Peninsula, and there were no differences in the other metals. For cormorant (*Phalacrocorax* spp.) livers, Attu had the highest levels of cadmium, and there were no significant differences for the other metals. Using a conversion factor from Burger (1993), mercury levels were higher in sandpipers from the Alaska Peninsula (converted, 5888 ppb) than in puffins from the Amchitka/Kiska Islands (this study, 2541 ppb). For cadmium, sandpiper levels at Attu were higher (converted, 960 ppb) than for the puffins (80 ppb) from Amchitka/Kiska. For chromium, the mean levels in sandpipers in Adak were higher (2524 ppb) than those we found for puffins (1816 ppb) at Amchitka/Kiska. For selenium, the mean levels for cormorant (4708 ppb) were also higher than for the feathers puffins (6597 ppb) at Amchitka/Kiska. There are not as much data for arsenic in feathers. However, in Franklin's gulls (*Larus pipixcan*), the ratio of feather: liver for arsenic was 1.5 for adults (Burger and Gochfeld 1996). Using this conversion, the concentration of arsenic in sandpipers (1090 ppb) was lower than for the puffins (1360 ppb) from Amchitka/Kiska. These conclusions, however, are based on two conversions: extrapolating the levels in feathers from those in liver, and converting dry weight to wet weight. Nonetheless, Rocque and Winker (2004) found that levels were generally higher in the sandpipers than the cormorants, the fish-eating species.

It is remarkable that most studies that examine metal levels in internal tissues of birds do not also measure levels in feathers (which would contribute to finer feather:tissue ratios). We suggest that scientists dealing with metals need to provide wet-dry conversions (because in drying specimens, such conversions are determined) and that there is a need for more studies that examine levels in feathers and other tissues to allow for conversions. This is particularly important because feathers are often used as convenient, noninvasive bioindicators. Further, feathers from museum collections can be used to examine temporal trends for metals not used in the preservation process (e.g., arsenic, mercury), and it is often possible to collect feathers from endangered or threatened species (whereas the collection of other tissues are prohibited to preserve dwindling populations). Alternatively, eggs can prove useful as bioindicators, particularly when birds lay large clutches or will lay replacement clutches.

Gender Differences

Most studies of metals levels in birds that use feathers as a bioindicator do not know the sex of the birds because many species, particularly seabirds, do not exhibit sexual dimorphisms.

However, in this study, we collected the birds and identified them to sex. There were no sexual difference in metals levels in the feathers of eider (even though males were significantly larger) and only one difference for puffins. Male puffins had lower mercury levels in their feathers than did females, even though there was no significant weight difference. We had expected that if there were sexual differences, males would have higher levels because females have an additional method of ridding their body of mercury; females can sequester metals, such as mercury, in their eggs (Burger 1993; Fimreite et al 1974, 1982).

Burger (1993) summarized studies of gender-related differences in metal levels in feathers and noted that for eight studies, differences were noted only for three of the eight species. In only one species were levels higher in males than females (Bonaparte's gull, *Larus philadelphia*). Since then, few studies have examined these differences. Gender did not enter as a significant variable for metal levels in feathers of albatrosses (*Diomedea immutabilis*; Burger and Gochfeld 2000d), but Gochfeld et al (1996) found that male laughing gulls (*Larus atricilla*) had higher levels of lead in feathers than did females (they examined five other metals without effect).

One difficulty with using feathers as bioindicators of internal dose is that it is often impossible to identify the sex, especially in seabirds. Even studies of metal levels in internal tissues often fail to examine gender differences because outside of the breeding season, identification by morphological examination is also often difficult. This illustrates the importance of noting gender where possible, even if the differences in metals levels by gender are not significant.

Regional Differences

It is also useful to examine metal levels in feathers of other seabirds from the Pacific region and for the same species of birds from other regions. Burger and Gochfeld (2000a) examined metals levels in the feathers of 12 species of seabirds from Midway Atoll (28° 15' N, 177° 20' W) in the northern Pacific Ocean, some 2875 km south from Amchitka and Kiska. Midway was used for communications since the early 1900 s and served as a military base during and after World War II until 1997, when it was taken over by the US Fish & Wildlife Service. Midway was thus used for military operations for longer, and more intensely, than the Aleutian Islands, suggesting that contaminant levels from local sources would be higher than those found in Amchitka birds. Species examined from Midway included terns, noddies, shearwaters, tropicbirds, and albatrosses. For all metals, the mean levels in feathers of puffins and eiders in the Aleutians were well below the species with the highest means from Midway: arsenic: mean of 136 ppb for puffin, 459 ppb for white tern *Gygis alba*; cadmium: 80 ppb for puffin, 950 ppb for gray-backed tern *Sterna lunata*; chromium: 1816 ppb for puffin, 6570 ppb for Laysan albatross (*Diomedea immutabilis*); lead: 1255 ppb for puffin, 2380 ppb for Christmas shearwater (*Puffinus nativitatis*); manganese: 1866 ppb for eider, 2050 ppb for Christmas shearwater; mercury: 2541 ppb for puffin, 19,700 ppb for Bonin petrel (*Pterodroma hypoleuca*); selenium: 6597 ppb for puffin, 10,100 ppb for Christmas shearwater (Burger and Gochfeld 2000a, d). In most of these studies, the variation was similar. Given the higher human use of Midway, compared to the

Aleutian Islands, it is not surprising the levels were higher in the feathers of birds from Midway compared to Amchitka and Kiska.

Significance of Levels

Feathers can serve as an indicator of internal contamination (Burger 1993; Goede and deBruin 1986; Furness et al 1986) and can then be used to assess whether there are potential behavioral or reproductive deficits in populations (Burger and Gochfeld 2001). Laboratory studies have been used to identify the levels of metals that result in adverse impacts on the behavior, physiology, or reproductive success of birds. In general, mercury, cadmium, and lead are of primary concern in marine environments (Thompson and Furness 1998), and each will be discussed next. Levels of metals in birds are also of interest because of potential effects on predators that might eat them (either as prey or as carrion). Both puffins and eiders are also a preferred Aleut food, and bird eggs are a delicacy during the early egg-laying and incubation period (Fish & Wildlife Service 2004; Hamrick and Smith 2003; Patrick 2002).

Mercury is the contaminant of most concern in marine ecosystems (Mailman 1980; Thompson and Furness 1998). In general, mercury levels in feathers that are associated with adverse reproductive effects in birds are 5000 ppb (Burger and Gochfeld 2000b; Eisler 1987). Concentrations of 15,000 ppb mercury are required for adverse effects in some predatory fish (Spry and Wiener 1991; Wiener and Spry 1996). Thus, the levels in the feathers of both puffins and common eiders from Amchitka and Kiska were well below the levels known to cause adverse effects in the birds themselves, or in their predators.

Lead is a second contaminant of concern in marine environments. Adverse effects in birds occur at lead levels of 4000 ppb in feathers (Burger and Gochfeld 2000c; Custer and Hoffman 1994). The levels in feathers of eiders and puffins from Amchitka and Kiska were well below this threshold level, suggesting that they are not adversely impacted.

Cadmium causes sublethal and behavioral effects at lower concentrations than lead and mercury (Eisler 1985), but feather levels known to cause adverse effects in the birds themselves have not been determined from laboratory studies. However, conversion factors developed from Burger (1993) suggest that feather levels that are associated with adverse effects would range from 100 ppb (shearwaters) to 2000 ppb (terns). Thus, the cadmium levels found in puffin and eider feathers from Amchitka and Kiska were well below the calculated effects level.

There are few controlled laboratory studies for the other metals, making it difficult to interpret the significance of these levels. However, for selenium, feather levels of 3800–26,000 ppb (depending on species) result in mortality (converted after Burger 1993), and 1800 ppb results in sublethal adverse effects (after Heinz 1996), but these conclusions are very tentative, and laboratory studies are required to establish the effects levels. The levels of selenium in feathers of puffins (6597 ppb) exceeded the 1800-ppb level and those of eiders were similar (1728 ppb), suggesting that selenium should receive more study for birds from the region.

Thus, overall, the levels of metals in feathers do not suggest any adverse effects in the birds from the Aleutians.

Conclusion

In many remote oceanic islands and arctic regions, birds are an important part of the food chain and of subsistence diets. The levels of mercury and other metals in feathers of eiders and tufted puffins were used as bioindicators of potential hazard to the birds themselves, to predators that eat them, and to humans who consume them as part of a subsistence diet. Levels of mercury and other metals were sufficiently low that they did not pose a risk to the birds themselves and to their consumers. Puffins, higher on the food chain, had much higher levels of chromium, selenium, and mercury than did eiders. There differences in levels of metals among islands were small, and probably insignificant biologically.

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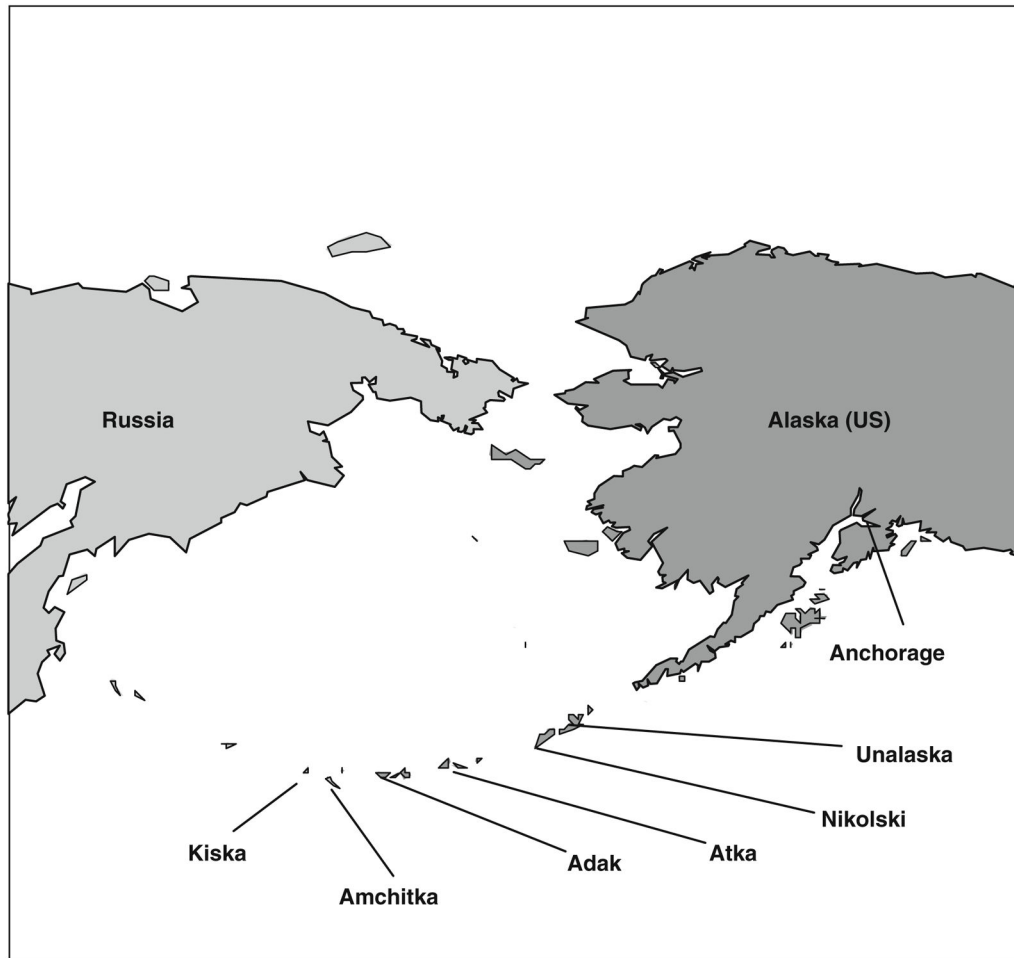


Fig. 1.
Map showing the collecting locations for eiders and puffins at Amchitka and Kiska islands in the Aleutians

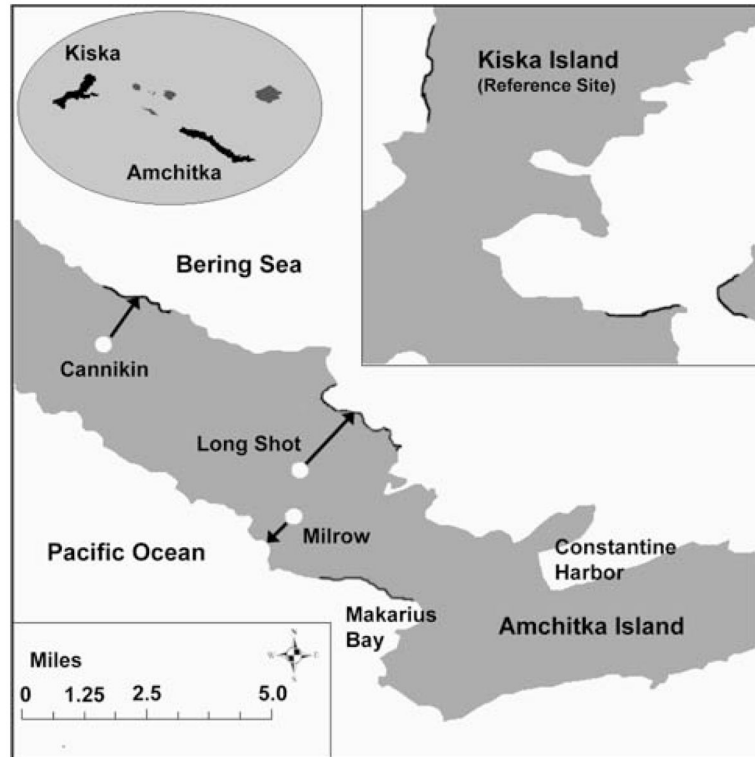


Fig. 2. Map showing the locations of the three underground nuclear test sites on Amchitka. Shading indicates areas where birds were collected

Table 1

Metal levels (ng/g = ppb, dry weight) in Common eider feathers and tufted puffin feathers collected at Amchitka and Kiska islands, Aleutians, Alaska

Feathers	Common eider (<i>n</i> = 26)	Tufted puffin (<i>n</i> = 39)	Kruskal–Wallis χ^2 (<i>p</i>)
Arsenic	138 ± 18.0 107	136 ± 25.6 15.0	1.1 (NS)
Cadmium	79.8 ± 4.0 77.0	80.3 ± 12.9 49.1	4.2 (0.04)
Chromium	172 ± 49.9 34.6	1820 ± 230 1450	42.0 (<0.0001)
Lead	992 ± 132 828	1260 ± 339 104	2.2 (NS)
Manganese	1870 ± 267 1460	622 ± 58.1 531	23.6 (<0.0001)
Mercury	840 ± 81.5 715	2540 ± 195 2120	26.9 (<0.0001)
Selenium	878 ± 88.3 731	6600 ± 344 6110	42.7 (<0.0001)

Note: For each metal, the first row provides the arithmetic mean ± standard error and the second row gives geometric means. Statistical comparison using Kruskal–Wallis nonparametric ANOVA yielding chi square statistics (*p*-values). All numbers are rounded to three significant figures

Table 2

Metal levels (ng/g = ppb dry weight) in feathers of adult common eider and adult tufted puffin collected from Amchitka and Kiska

Feathers Common eider	Amchitka <i>n</i> = 13	Kiska <i>n</i> = 13	Kruskal–Wallis χ^2 (<i>p</i>)
Arsenic	126 ± 25.3 101	151 ± 26.1 114	0.8 (NS)
Cadmium	80.9 ± 6.0 77.5	78.6 ± 5.4 76.4	0.6 (NS)
Chromium	103 ± 30.3 14.8	242 ± 92.9 81.0	1.5 (NS)
Lead	832 ± 212 653	1154 ± 151 1050	4.8 (0.03)
Manganese	2560 ± 440 1990	1177 ± 154 1070	4.8 (0.03)
Mercury	846 ± 143 659	834 ± 84.9 776	0.3 (NS)
Selenium	868 ± 132 722	888 ± 123 741	0.1 (NS)
<hr/>			
Tufted puffin	<i>n</i> = 22	<i>n</i> = 17	
Arsenic	161 ± 39.8 20.9	103 ± 27.8 9.8	0.8 (NS)
Cadmium	103 ± 20.1 66.6	51.4 ± 11.3 33.1	3.7 (0.05)
Chromium	2040 ± 342 1590	1520 ± 284 1280	0.2 (NS)
Lead	926 ± 423 29.6	1680 ± 550 525	5.7 (0.02)
Manganese	696 ± 83.4 601	527 ± 74.9 452	2.1 (NS)
Mercury	2590 ± 290 2020	2480 ± 254 2260	0.1 (NS)
Selenium	6580 ± 523 5910	6620 ± 424 6390	0.0 (NS)

Note: For each metal, the first row provides the arithmetic mean ± standard error and the second row provides geometric means. Comparison with Kruskal–Wallis nonparametric ANOVA yielding chi square statistics and *p* values. All entities are rounded to three significant figures

Table 3

Comparison of metal levels in adult tufted puffin feathers from Milrow area and Long Shot area

Feathers	Milrow (<i>n</i> = 4)	Long Shot–Cannikin (<i>n</i> = 18)	Kruskal–Wallis χ^2 (<i>p</i>)
Arsenic	131 ± 77.7 19.2	166 ± 49.1 18.8	0.05 (NS)
Cadmium	82.8 ± 54.2 37.9	107 ± 23.4 73.9	0.8 (NS)
Chromium	1780 ± 452 1610	2130 ± 432 1590	0.07 (NS)
Lead	510 ± 220 37	1080 ± 543 45.6	0.07 (NS)
Manganese	365 ± 81.2 342	786 ± 96 695	5.4 (0.02)
Mercury	3250 ± 401 3170	2450 ± 358 1780	0.8 (NS)
Selenium	5670 ± 711 5510	6780 ± 654 5970	1.1 (NS)
Weight	754 ± 41.5	806 ± 18.3	1.4 (NS)

Note: The first row provides the arithmetic mean ± standard error. The second row provides the geometric mean. Comparison by Kruskal–Wallis nonparametric one-way ANOVA yielding the chi square statistic

Table 4

Metal concentrations (ng/g = ppb on dry weight) in adult common eider and adult tufted puffin feathers by gender

Feathers Common eider	Male <i>n</i> = 6	Female <i>n</i> = 20	χ^2 (<i>p</i>)
Body weight (g)	2260 ± 85.1	1670 ± 52.6	11.4 (0.0007)
Arsenic	169 ± 46.7 139	128 ± 18.5 97.9	1.1 (NS)
Cadmium	78.8 ± 5.2 77.9	80.0 ± 4.97 76.7	0.1 (NS)
Chromium	89.9 ± 44.7 7.7	197 ± 52.9 54.3	1.1 (NS)
Lead	743 ± 138 682	1070 ± 164 877	0.9 (NS)
Manganese	1270 ± 397 1010	2040 ± 320 1630	1.5 (NS)
Mercury	782 ± 166 566	857 ± 95.5 767	0.0 (NS)
Selenium	665 ± 144 533	942 ± 104 804	1.3 (NS)
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Tufted puffin	<i>n</i> = 25	<i>n</i> = 13	
<hr/>			
Body weight (g)	819 ± 11.4	738 ± 15.1	14.0 (0.0002)
Arsenic	119 ± 34.3 5.9	164 ± 39.8 75.6	2.3 (NS)
Cadmium	68.8 ± 14.9 39.7	101 ± 25.8 69.5	1.1 (NS)
Chromium	1960 ± 336 1470	1550 ± 242 1390	0.0 (NS)
Lead	1570 ± 505 339	750 ± 252 22.1	1.1 (NS)
Manganese	694 ± 80.7 594	495 ± 68.8 430	2.0 (NS)
Mercury	2270 ± 231 1850	3060 ± 350 2230	4.0 (0.05)
Selenium	6600 ± 430 6280	6590 ± 643 5770	0.3 (NS)

Note: The first row provides the arithmetic mean ± SE and the second row provides the geometric mean. The right-hand column compares differences using Kruskal–Wallis nonparametric one-way ANOVA, yielding chi square values and *p*-values. All numbers are rounded to three significant figures

Table 5

Intermetal correlations for common eider (above the diagonal, $n = 26$) and tufted puffins (below the diagonal, $n = 39$) from Amchitka and Kiska combined

	Arsenic	Cadmium	Chromium	Lead	Manganese	Mercury	Selenium	Weight
Arsenic	*****	NS	NS	NS	NS	NS	NS	0.3 (0.03)
Cadmium	NS	*****	NS	NS	NS	NS	NS	NS
Chromium	NS	0.3 (0.008)	*****	0.3 (0.02)	NS	0.4 (0.01)	0.3 (0.05)	NS
Lead	NS	NS	NS	*****	NS	NS	NS	NS
Manganese	NS	0.3 (0.01)	NS	NS	*****	NS	NS	-0.3 (0.02)
Mercury	NS	0.2 (0.03)	0.4 (0.0005)	NS	NS	*****	0.3 (0.02)	NS
Selenium	0.3 (0.06)	NS	NS	NS	NS	NS	*****	NS
Weight	NS	NS	NS	NS	0.2 (0.07)	-0.1 (0.03)	NS	*****

Note: Kendall tau correlations (p -values); NS indicates p -values > 0.10