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Distribution of 14 Elements in Tissues and Organs of Oceanic Seabirds

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Abstract. The concentrations of 14 trace elements (Li, V, Mn, Co, Cu, Zn, Se, Rb, Sr, Ag, Cd, Cs, Pb, and Hg) were determined in tissues and organs of three species and in the liver of 11 species of seabirds. Comparatively high concentrations of Li, Co, Sr, and V were found in the femur. Cd, Se, Cu, and Mn concentrations were relatively higher in the kidney than in other tissues and organs. Rb, Cs, and Pb concentrations were rather uniform among tissues. Concentrations of essential elements such as Mn, Cu, and Co were comparable among seabird species, except high Cu concentrations in northern giant petrel. Among nonessential elements, concentrations of Cd and Hg were variable according to seabird species. Pb levels were low in all the species. High Se levels (100 µg/g dry weight) were found in the liver of black-footed albatross and grey petrel. There were significant positive correlations between Se and Cd concentrations in three species and between Se and Hg in black-footed albatross, suggesting that Se has an antagonistic action on the toxic effects of Cd and Hg. Concentrations of Li, V, Ag, and Cs were usually low (less than 1 µg/g dry weight).

Levels and flux of trace elements have been investigated in environmental media such as soil, air, and water (Nriagu and Pacyna 1988). Toxic effects and body distribution of some heavy metals have also been studied in experimental animals (Ellis and Fang 1967; Mertz 1986; Goering 1993) and wildlife (Norheim 1987; Muirhead and Furness 1988; Hansen *et al.* 1990; Honda *et al.* 1990; Wagemann and Stewart 1994). However, studies on rare trace metals are meager, particularly in wild animals.

Recently, high Ag concentrations were reported in the liver of beluga whales (Becker *et al.* 1995), which poses a concern for the possible toxic effects to wild animals. In order to understand their adverse effects in wildlife, comprehensive studies on levels and body distribution are needed.

Seabirds have been used as an indicator of heavy metal contamination in the marine environment. Accumulation of metals in oceanic seabirds has been studied increasingly in recent years (Honda *et al.* 1990; Elliott *et al.* 1992; Lock *et al.* 1992; Kim *et al.* 1996a, 1996b), due to the elevated concentrations of toxic elements such as Hg and Cd. Although the accumulation of toxic elements (Cd, Pb, and Hg) and some essential elements (Fe, Cu, and Zn) have been studied in seabirds, those of other trace elements are scarcely reported.

The objectives of the present study are to clarify the specific accumulation of trace elements in the body of seabirds and to suggest possible implications of elevated concentrations of elements to seabirds. The distribution and burdens of 14 elements (Li, V, Mn, Co, Cu, Zn, Se, Rb, Sr, Ag, Cd, Cs, Pb, and Hg) were examined in the various tissues and organs of three species of seabirds. The concentrations of 14 elements in the liver of 11 species of seabirds were also determined.

Materials and Methods

Sample Collection, Storage, and Preparation

The details of 11 species of seabirds comprising 82 individuals and their sampling locations are as follows: black-footed albatross and northern fulmar (*Fulmarus glacialis*) from the North Pacific collected in 1985; black-browed albatross (*Diomedea melanophrys*), grey-headed albatross (*Diomedea chrysostoma*), grey petrel (*Procellaria cinerea*), light-mantled sooty albatross (*Phoebetria palpebrata*), northern giant petrel (*Macronectes halli*), white-capped albatross (*Diomedea cauta*), yellow-nosed albatross (*Diomedea chlororhynchos*), royal albatross (*Diomedea epomophora*), and white-chinned petrel (*Procellaria aequinoctialis*) from the southern Indian Ocean collected in 1994. All birds were accidentally caught by fishing gear and provided by different fishing boats. All samples were stored in polyethylene bags and frozen at −20°C after collection. An individual white-chinned petrel, black-browed albatross, and grey-headed albatross were dissected. After weighing the whole animal, the brain, lung, heart, stomach, intestine, liver, pancreas, spleen, gallbladder, kidney, testis/ovary, uropygical gland, subcutaneous and abdominal fats, bone, muscle, skin, eyeball, feather, trachea, esophagus, and other organs were dissected and weighed separately. Total weight of these organs and tissues corresponded to almost 85% of whole body weight. The pectoral muscle, breast feather, and femur sample were taken for chemical analysis. The metal burdens in organs and tissues of three seabirds were calculated from the weight of organs and tissues and their metal concentrations, and the results are expressed as percentage in the organ and tissue to whole body weight (Figure 1). The liver samples

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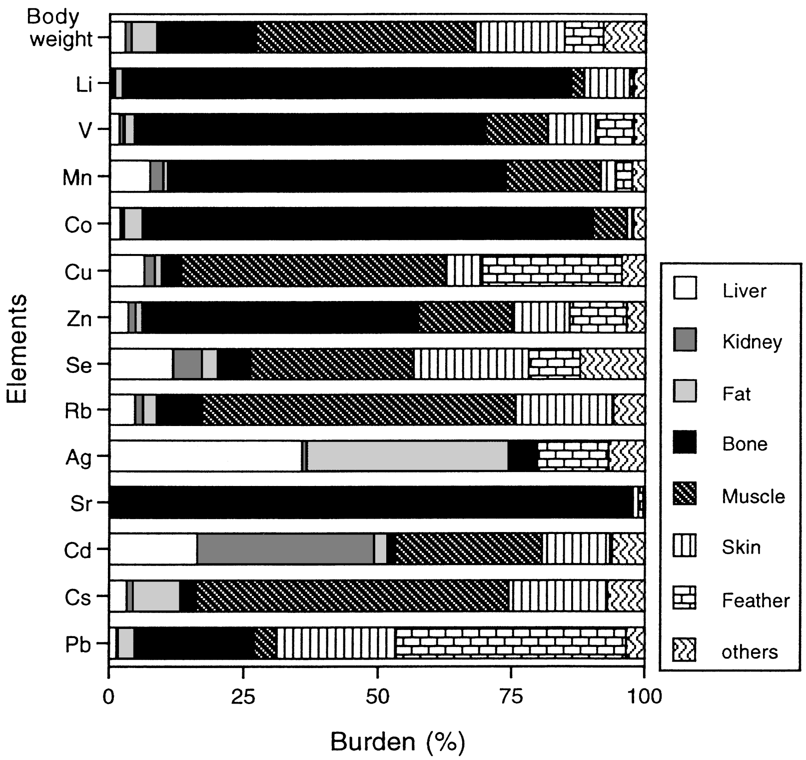

Fig. 1. Distribution of element burdens in tissues and organs of three seabirds

were collected in all the seabirds. The tissues and organs were thawed and the outer layer was removed to avoid external contamination during storage or dissection. Samples were subsequently dried in an oven at 80°C for 12 h to estimate the moisture contents. Samples were then ground to a fine powder in order to obtain a homogeneous mixture.

Element Analysis

Analysis of 13 elements (Li, V, Mn, Co, Cu, Zn, Se, Rb, Sr, Ag, Cd, Cs, and Pb) was performed by inductively coupled plasma-mass spectrometer (ICP-MS; Perkin-Elmar ELAN 5000), after microwave digestion with nitric acid in a PTFE (Teflon) vessel (Okamoto 1994). Mixed multi-element standard solution was prepared from 10 µg/g stock solution. NIST SRM 1577b bovine liver was used for the determination of reproducibility of various elements. Recoveries of determination in 11 elements except for Li and Cs, which have not certified, ranged from 91–116%. Total Hg levels were determined in the liver only by cold vapor technique using Sansou Automatic Mercury Analyzer Model HG-3000 spectraphotometer after the mineralization of samples with nitric, sulfuric, and perchloric acids (Akagi and Nishimura 1991). Analytical quality assurance was conducted using a standard reference material, NIES No. 1 (Okamoto *et al.* 1978). The Spearman rank correlation coefficient (SPSS-PC+ package) were used to determine relationships between elements in the liver of black-footed albatross, northern fulmar, black-browed albatross, and grey-headed albatross. Probability values greater than 0.05 were considered nonsignificant. Concentrations were given on dry weight basis.

Results

The concentrations of trace elements in the tissues and organs of three seabirds shown in Table 1. The highest concentrations of Sr and Cd were found in the femur and kidney, respectively. Relatively high concentrations of Li, Co, and V were also observed in the femur. Se, Cu, and Mn concentrations in the kidney were higher than in other tissues and organs. Ag concentrations were slightly higher in the liver, fat, and brain than in others, and Zn levels were elevated in the pancreas, femur, intestine, kidney, and liver. On the other hand, Rb, Cs, and Pb concentrations were rather uniform among tissues.

Figure 1 shows the distribution of trace elements in the various tissues and organs of seabirds as percentages of body burden. A relatively high burden of Cu, Se, Rb, and Cs was recorded in the muscle, and that of Pb and Cd was found in the feather and kidney, respectively. More than 50% of Li, V, Mn, Co, and Zn burdens in the seabird body was in the bone, which constituted of 18% of the body weight. Particularly, 97% of Sr burden in the body was found in the bone. Ag burdens in the liver and fat were exceed more than 35% in the whole body.

The concentrations of 14 elements in the liver of 11 species of seabirds are given in Table 2. In order to compare the variance of element concentrations in the liver of seabirds, CV% (coefficient of variability) was calculated from the mean concentration of each element (Figure 2). Except for Se and Cu, the concentrations of essential elements (Mn, Co, and Zn) were comparable among various species. Mn and Co levels in the liver were fairly constant with a value of less than 17 and 0.2 µg/g dry weight, respectively (Table 2). Zn concentrations ranged from 61 to 398 µg/g. High Zn levels (more than 300 µg/g) were recorded in black-footed albatross and black-browed albatross. Cu concentrations were consistent among species, except for northern giant petrel. In this study, two individuals of northern giant petrel exhibited 510 and 369 µg Cu/g dry weight. Se levels varied among species, and extremely high levels (more than 100 µg/g) were found in black-footed albatross and grey petrel.

Table 1. Trace element concentrations (mean, range, μg/dry g) in tissues and organs of an individual white-chinned petrel, black-browed albatross, and grey-headed albatross

	Li	V	Mn	Co	Cu	Zn	Se	Rb	Ag	Sr	Cd	Cs	Pb
Brain	0.063 (0.048–0.075)	0.043 (0.024–0.069)	1.42 (1.16–1.89)	0.026 (0.021–0.035)	9.07 (7.29–10.0)	50.6 (48.0–54.5)	14.8 (14.6–15.1)	3.61 (3.15–4.12)	0.099 (0.052–0.144)	1.28 (1.20–1.41)	0.866 (0.207–1.30)	0.017 (0.006–0.028)	0.049 (0.027–0.090)
Lung	0.302 (0.056–0.516)	0.143 (0.064–0.283)	0.93 (0.82–1.08)	0.018 (0.011–0.025)	2.55 (1.65–3.46)	62.2 (52.0–74.6)	30 (22.6–37.6)	4.99 (3.41–6.51)	0.005 (0.001–0.011)	24.5 (1.05–55.1)	5.5 (1.17–8.43)	0.025 (0.014–0.036)	0.204 (0.034–0.536)
Heart	0.174 (0.155–0.204)	0.127 (0.075–0.199)	0.991 (0.245–1.51)	0.095 (0.033–0.194)	6.67 (0.247–10.3)	51 (0.247–86.3)	13.9 (0.165–23.1)	2.4 (0.246–3.87)	0.017 (<0.001–0.048)	2.71 (0.227–5.1)	2.07 (0.218–5.74)	0.056 (0.006–0.146)	0.071 (0.020–0.165)
Stomach	0.184 (0.074–0.300)	0.106 (0.055–0.199)	1.32 (0.980–1.60)	0.037 (0.028–0.051)	6.71 (5.79–7.84)	86.6 (60.9–102)	10.7 (9.53–12.1)	2.62 (2.24–3.35)	0.007 (< 0.001–0.015)	8.09 (3.87–12.7)	3.04 (0.689–4.44)	0.021 (0.005–0.041)	0.073 (0.059–0.082)
Intestine	0.125 (0.053–0.257)	0.071 (0.033–0.135)	2.35 (1.53–3.50)	0.041 (0.020–0.083)	6.93 (4.09–9.44)	165 (127–200)	13.2 (9.35–16.6)	2.45 (0.653–3.36)	0.024 (0.011–0.034)	10 (4.03–19.6)	12.4 (2.03–25.2)	0.012 (0.005–0.024)	0.128 (0.122–0.137)
Liver	0.065 (< 0.004–0.118)	0.163 (0.057–0.276)	6.57 (4.14–10.1)	0.065 (0.037–0.095)	14.7 (11.9–17.0)	148 (110–194)	30.2 (18.3–39.2)	4.51 (3.92–5.27)	0.102 (0.052–0.132)	1.37 (0.214–2.29)	19.4 (4.12–35.5)	0.018 (0.009–0.026)	0.119 (0.017–0.303)
Pancreas	0.169 (0.071–0.290)	0.086 (0.049–0.127)	3.09 (2.20–4.13)	0.051 (0.036–0.072)	5.32 (4.82–5.63)	208 (152–262)	13.7 (11.5–17.4)	3.73 (3.36–4.42)	0.016 (< 0.001–0.042)	6.95 (2.24–13.6)	22.1 (4.57–32.9)	0.023 (0.007–0.45)	0.085 (0.062–0.120)
Spleen	0.174 (0.091–0.293)	0.13 (0.108–0.146)	1.73 (1.15–2.02)	0.027 (0.017–0.033)	4.51 (3.23–5.44)	123 (97.0–151)	25.6 (18.1–35.2)	5.54 (4.83–6.03)	0.013 (< 0.001–0.037)	5.28 (2.43–10.1)	11.1 (0.443–23.4)	0.025 (0.010–0.041)	0.095 (0.036–0.194)
Gallbladder	0.231 (0.059–0.436)	0.07 (0.031–0.133)	1.42 (0.56–2.39)	0.015 (0.009–0.021)	11.1 (7.26–16.6)	43.9 (12.5–70.7)	17.3 (11.3–25.4)	6.3 (2.86–8.54)	0.037 (0.023–0.049)	9.34 (2.40–22.7)	13.1 (0.544–23.4)	0.028 (0.012–0.060)	0.069 (0.032–0.129)
Kidney	0.198 (0.058–0.281)	0.273 (0.154–0.388)	6.71 (6.10–7.17)	0.078 (0.06–0.093)	15.1 (12.2–20.4)	157 (126–177)	45.5 (38.0–52.0)	4.91 (3.95–5.97)	0.016 (0.007–0.032)	4.73 (0.928–7.44)	106 (55.9–180)	0.023 (0.009–0.035)	0.135 (0.031–0.342)
Testis/Ovary	0.188 (0.073–0.298)	0.292 (0.077–0.635)	2.18 (2.00–2.47)	0.023 (0.010–0.035)	5.08 (4.47–6.09)	97 (85.7–106)	22.2 (13.3–33.2)	5.56 (4.07–7.23)	0.049 (< 0.001–0.130)	7.73 (2.52–10.8)	16.5 (1.36–38.9)	0.025 (< 0.0003–0.044)	0.178 (0.025–0.439)
Uro. Gland	0.069 (< 0.004–0.177)	0.063 (0.029–0.115)	0.386 (0.296–0.445)	0.019 (0.005–0.046)	3.43 (3.01–3.81)	42.6 (37.5–52.6)	17.5 (12.7–20.3)	2.64 (1.97–3.07)	0.002 (< 0.001–0.005)	2.61 (0.260–7.15)	1.44 (0.136–2.43)	0.012 (0.004–0.018)	0.194 (0.026–0.453)
Fat	0.016 (< 0.004–0.048)	0.035 (0.023–0.042)	0.132 (0.103–0.184)	0.013 (0.004–0.032)	0.833 (0.464–1.04)	11.7 (7.25–18.6)	1.85 (1.54–2.04)	0.577 (0.202–0.875)	0.112 (0.010–0.264)	0.631 (0.138–1.09)	0.651 (0.078–1.08)	0.01 (< 0.0003–0.030)	0.094 (0.025–0.164)
Femur	0.84 (0.632–0.959)	0.459 (0.324–0.554)	4.14 (3.41–4.57)	0.242 (0.117–0.347)	0.64 (0.584–0.732)	167 (146–202)	1.38 (0.449–2.64)	0.646 (0.429–1.06)	0.009 (0.002–0.014)	319 (257–389)	0.157 (0.030–0.328)	0.001 (< 0.0003–0.002)	0.148 (0.039–0.344)
Muscle	0.032 (< 0.004–0.05)	0.094 (0.052–0.148)	1.35 (1.06–1.81)	0.017 (0.009–0.027)	10.1 (7.82–12.8)	65.2 (58.2–71.2)	6.86 (6.54–7.04)	5.06 (3.73–5.82)	0.002 (< 0.001–0.005)	0.4 (0.320–0.482)	2.7 (0.618–3.98)	0.027 (0.015–0.037)	0.037 (0.014–0.080)
Skin	0.091 (0.02–0.128)	0.071 (0.035–0.101)	0.253 (0.143–0.397)	0.009 (0.005–0.013)	1.34 (1.13–1.64)	41.5 (25.9–61.5)	4.97 (4.51–5.27)	1.67 (1.04–2.04)	0.002 (< 0.001–0.005)	2.5 (0.467–3.75)	1.83 (0.223–4.06)	0.009 (0.005–0.014)	0.193 (0.056–0.443)
Eyeball	0.164 (0.089–0.217)	0.112 (0.091–0.128)	0.805 (0.644–1.06)	0.019 (0.016–0.023)	2.45 (1.83–3.25)	100 (69.5–132)	32.9 (32.0–33.9)	3.07 (2.58–3.85)	0.001 (< 0.001–0.003)	18.6 (10.7–24.0)	1.55 (0.558–2.57)	0.015 (0.006–0.023)	0.053 (0.022–0.105)
Breast feather	0.013 (< 0.004–0.020)	0.106 (0.069–0.158)	0.365 (0.078–0.937)	0.005 (0.003–0.006)	10.4 (9.29–11.2)	71.7 (42.9–115)	4.06 (2.42–5.11)	0.035 (0.028–0.044)	0.011 (0.004–0.017)	6.62 (6.11–7.23)	0.07 (0.025–0.152)	<0.0003	0.426 (0.343–0.587)
Trachea	0.157 (0.062–0.245)	0.133 (0.077–0.187)	0.466 (0.343–0.659)	0.036 (0.017–0.057)	2.59 (1.53–4.08)	46 (36.7–51.3)	9.28 (7.41–10.6)	2.21 (1.49–2.85)	0.011 (< 0.001–0.033)	9.97 (3.60–15.9)	1.92 (0.566–2.79)	0.021 (0.006–0.044)	0.184 (0.046–0.445)
Esophagus	0.206 (0.053–0.392)	0.118 (0.053–0.197)	0.473 (0.372–0.530)	0.013 (0.010–0.019)	3.61 (2.02–5.67)	51 (38.7–57.8)	9.71 (8.80–11.1)	2.5 (1.31–3.80)	0.005 (< 0.001–0.013)	7.68 (2.50–13.8)	2.12 (0.474–3.79)	0.015 (0.009–0.024)	0.352 (0.063–0.807)

Table 2. Mean and range concentrations (μg/g dry weight) of 14 elements in the liver of seabirds

Species	No.		Li	V	Mn	Co	Cu	Zn	Se	Rb	Ag	Sr	Cd	Cs	Pb	Hg
Royal albatross (*Diomedea epomophora*)	3	Mean	0.14	0.174	7.25	0.063	26.5	119	16.7	4.33	0.621	3.07	8.05	0.014	0.071	27.4
		Max.	0.158	0.194	8.07	0.074	50.3	149	18.5	4.83	1.07	4.73	21.1	0.025	0.085	35.6
		Min.	0.121	0.153	6.24	0.055	18.1	105	14.8	3.99	0.362	2.22	4.9	0.009	0.063	19.7
Black-footed albatross (*Diomedea nigripes*)	18	Mean	0.086	0.41	9.12	0.073	18	226	107	6.06	0.154	2.70	70.6	0.022	0.122	22.7
		Max.	0.212	1.895	12.8	0.16	25.9	398	311	9.83	0.644	7.83	125	0.049	0.402	723
		Min.	0.022	0.156	6.47	0.035	13	150	39	3.95	0.026	0.822	41.8	0.007	0.056	30.7
Black-browed albatross (*Diomedea melanophrys*)	9	Mean	0.089	0.149	10.2	0.077	18.1	186	40	6.45	0.105	0.86	15.6	0.022	0.034	31.1
		Max.	0.193	0.349	16.7	0.136	24.6	344	78.1	11.8	0.339	2.51	46.8	0.042	0.065	138
		Min.	0.046	0.082	6.69	0.035	12.7	125	24.6	3.48	0.047	0.341	3.2	0.013	0.019	13.6
White-capped albatross (*Diomedea cauta*)	3	Mean	0.058	0.121	5.33	0.048	12.8	109	41.4	4.45	0.253	0.897	16.1	0.029	0.065	33.4
		Max.	0.144	0.248	11.4	0.08	38.7	165	56.4	7.32	0.475	1.61	8.3	0.039	0.059	71.7
		Min.	0.069	0.13	7.8	0.045	11.9	115	30.6	4.38	0.19	1.21	3.17	0.011	0.023	41.6
Yellow-nosed albatross (*Diomedea chlororhynchos*)	4	Mean	0.089	0.149	10.2	0.077	18.1	186	40	6.45	0.105	0.86	15.6	0.022	0.034	31.1
		Max.	0.063	0.271	8.45	0.063	14.3	120	61.6	10.2	0.056	1.15	20.3	0.079	0.085	18.8
		Min.	0.025	0.058	4.53	0.044	9.88	75.7	26	5.28	0.021	0.157	5.09	0.029	0.025	6.22
Grey-headed albatross (*Diomedea chrysostoma*)	10	Mean	0.08	0.287	8.06	0.074	19.9	158	54.1	6.88	0.355	0.828	45.1	0.016	0.046	57.4
		Max.	0.129	0.704	13.2	0.118	28.3	296	114	8.78	4.73	2.13	171	0.031	0.227	118
		Min.	0.03	0.162	4.33	0.039	13.1	27.5	23.9	5.87	0.088	0.125	6.93	0.011	0.016	22.8
Light-mantled sooty albatross (*Phoebetria palpebrata*)	4	Mean	0.071	0.149	5.86	0.061	19	146	71.5	6.72	0.265	1.06	23	0.016	0.038	81.1
		Max.	0.106	0.171	7.53	0.068	29.9	161	94.9	8.02	0.684	2.52	33.6	0.02	0.056	216
		Min.	0.047	0.134	4.97	0.051	13.5	120	47.9	5.79	0.062	0.572	19.5	0.014	0.017	39.8
Northern giant petrel (*Macronectes halli*)	6	Mean	0.062	0.176	9.33	0.078	64	157	69.1	7.94	0.613	0.988	19.9	0.014	0.051	33.8
		Max.	0.133	0.219	12.2	0.097	510	204	154	9.84	7.78	2.51	58.9	0.034	0.088	203
		Min.	0.018	0.15	7.88	0.068	17.3	103	35.6	4.45	0.054	0.197	2.84	0.005	0.032	3.16
Northern fulmar (*Fulmarus glacialis*)	17	Mean	0.059	0.116	9.23	0.052	13.6	108	29.8	4.96	0.042	1.90	16.2	0.016	0.086	2.13
		Max.	0.087	0.21	14.1	0.08	17.6	153	56.7	7.21	0.226	5.70	36	0.036	0.162	43.5
		Min.	0.024	0.055	4.79	0.018	8.59	61	12.2	3.54	0.013	1.04	6.06	0.008	0.043	1.85
Grey petrel (*Procellaria cinerea*)	5	Mean	0.082	0.119	7.64	0.074	17.6	154	90.2	6.05	0.522	1.39	43.9	0.023	0.057	69.1
		Max.	0.168	0.173	8.91	0.107	20.2	210	194	7.25	1.32	2.16	96	0.038	0.077	279
		Min.	0.054	0.078	5.52	0.05	14.5	111	49	4.80	0.183	0.885	23.9	0.01	0.024	16.2
White-chinned petrel (*Procellaria aequinoctialis*)	3	Mean	0.058	0.121	5.33	0.048	12.8	109	41.4	4.45	0.253	0.897	16.1	0.029	0.065	33.4
		Max.	0.147	0.169	6.83	0.053	13.8	117	85.4	5.72	0.391	3.42	16.7	0.039	0.102	47.1
		Min.	0.026	0.065	4.62	0.046	11.3	102	28	3.85	0.12	0.189	15.2	0.024	0.048	28

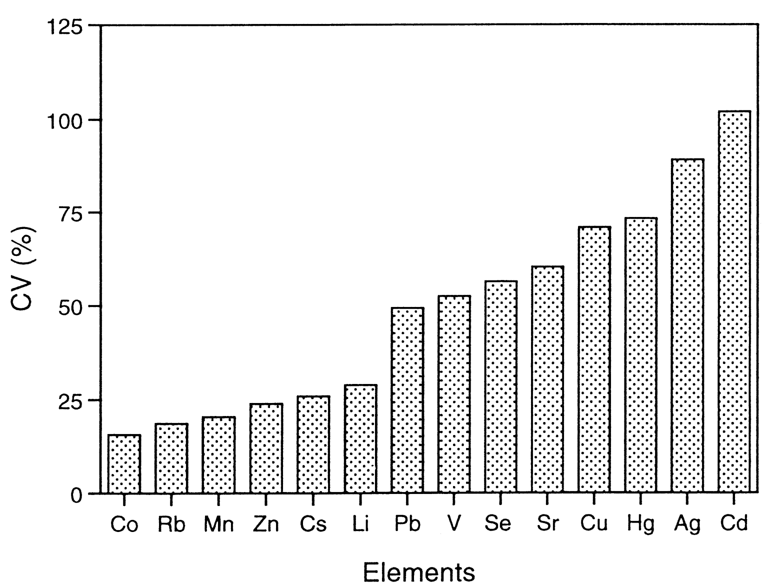

Fig. 2. Coefficient variance (%) of mean concentrations of elements in the liver of 11 seabird species

The CV for Cd was the largest among elements examined (Figure 2), and high Cd levels were observed in black-footed albatross, grey-headed albatross, and grey petrel (mean 70.6, 45.1, and 43.9 μg/g dry weight, respectively) (Table 2). Hg levels varied considerably from 16.2 μg/g in northern fulmar to 279 μg/g in black-footed albatross. Pb levels were low, less than 0.5 μg/g dry weight in the liver of our 11 seabird species.

Li, Rb, and Cs concentrations ranged from 0.022–0.212, 3.48–11.8, and 0.005–0.079 µg/g dry weight, respectively (Table 2). Sr concentrations were variable (ranged from 0.125 to 7.83 µg/g dry weight) and V ranged from 0.065 to 0.704 µg/g dry weight. Ag concentrations were also variable, but generally low in all species. Among seabird species examined, the highest Ag level (7.78 µg/g dry weight) was found in northern giant petrel.

Table 3 shows the relationships between elements in the liver of four seabird species, for which sample sizes were high enough for statistical treatments. Numerous significant correlations between elements were found. For essential elements, Mn concentrations correlated positively with those of Co, Cu, and Zn. Between essential and nonessential elements, Zn exhibited significant correlation with Cd in black-footed albatross and northern fulmar. Positive correlations were found between Se and Cd in the liver of black-footed albatross, northern fulmar, and grey-headed albatross; and between Se and Hg in black-footed albatross, which exhibited the highest Hg levels. For other elements, V showed significant correlations with Ag and Cd. Positive correlations were also found between Ag and Se in northern fulmar and grey-headed albatross.

Discussion

Distribution of trace element concentrations and burdens was element specific in tissues and organs of seabirds. Li, Co, and Sr exhibited more than 80% of their burdens in the skeleton (Figure 1). Li and Sr have similar metabolism process with Ca in the body (Nielson 1986a). Due to the high concentrations, more than 30% of total Cd burdens were found in the kidney, which constituted only 1.2% of the body weight.

In the present study, Pb burdens in the feather were rather higher than those in other tissues. Bird feathers diminish Hg burdens in the soft tissue by the molting process (Honda *et al.* 1986; Braune and Gaskin 1987). Therefore, bird feathers were used as bioindicators of Hg exposure though the diet. However, Pb in feathers would be from direct atmospheric contamination onto feather surface rather than the food chain through excretion into growing feathers.

Many correlations between metal concentrations were found in livers of seabirds. Some of these correlations may be due to chance. The variation of liver lipid content among bird species will tend to generate positive correlations between metal concentrations, although the burden of abdominal and subcutaneous fat in all seabird samples was always less than 5% of total body weight. Therefore, in the present study, correlations found in more than two species and correlations for toxic elements that exhibited high concentrations were the main focus. For essential elements, Mn, Co, and Zn concentrations appeared to be closely regulated in the body of seabirds. Concentrations of these elements in organs and tissues were in the range of other seabird species reported (Honda *et al.* 1990). Several positive correlations among Mn, Co, Cu, and Zn concentrations were found in the liver of black-footed albatross, northern fulmar, black-browed albatross, and grey-headed albatross (Table 3), possibly relating to hemoglobin synthesis and metallothionein (Morris 1986). Although few data are available concerning the Co concentration in birds (Blomqvist *et al.* 1987), liver Co levels are generally low in comparison with other essential elements. Normally, hepatic Zn levels in seabirds are less than 200 µg/g on dry weight basis (Ohlendorf *et al.* 1985) and 50 µg/g on wet weight basis (Honda *et al.* 1990). High Zn levels (more than 300 µg/g) in the present study were recorded in black-footed albatross and black-browed albatross. Hutton (1981) also noted high Zn concentrations (ranging from 61 to 497 µg/g dry weight) in the great skua (*Stercorarius stua*). It has been reported that higher Zn concentrations in tissues are generally associated with higher Cd levels in several marine bird species (Norheim 1987; Muirhead and Furness 1988; Honda *et al.* 1990; Elliot *et al.* 1992). In this study, significant positive correlations were found between Zn and Cd in the liver of black-footed albatross and northern fulmar (Table 3). In ringed turtle doves exposed to dietary Cd, the accumulation of Cd in the liver and kidney was correlated with both Zn and MT levels (Scheuhammer and Templeton 1990). Although liver MT levels were not measured in the present study, higher hepatic Zn levels are likely to be associated with MT induction by chronic Cd accumulation.

Relatively higher CV% were found in Cu and Se concentrations than that of other essential elements (Figure 2), due to high concentrations in some of seabird species. In case of Cu, two individuals of northern giant petrel exhibited 510 and 369 µg Cu/g dry weight in their lives. High Cu concentrations in the muscle of three species of petrel were also reported by Anderlini *et al.* (1972). High Cu levels have been noted in the liver of some waterfowls without any sign of toxic effects (Clausen and Wolstrup 1978; Kim *et al.* 1996a). It is noteworthy that the two individuals of northern giant petrel with the highest Cu levels also exhibited highest Ag levels. Nielsen (1986a) noted that Cu levels in the liver was increased with dietary Ag increased, suggesting that these two elements may have synergistic effects in the liver of some birds.

Se is known to have an antagonistic action on the toxic effects of Hg and Cd (Magos and Webb 1980; Norheim 1987). In the present study, positive correlations were found between Se and Cd, and between Se and Hg in the liver of several seabirds. An analogous relationship between these elements has not been clearly demonstrated in marine birds. Kim *et al.* (1996c) reported a clear relationship between hepatic Hg and Se concentrations in some marine birds such as black-footed albatross, brown booby, grey petrel, and northern giant petrel, but not found in other seabird species. Furness and Hutton (1979) found the significant correlations between Cd and Se levels in the kidney of great skua, and suggested the detoxification of some heavy metals by a binding process requiring Se. The present study may also support the specific accumulation and detoxification of toxic elements in seabirds.

The dietary habit of birds would be an important factor to explain the variation of Cd and Hg levels among seabirds, although the variations may also be responsible for other factors such as age, sex, collection date, and geographical location. Birds that feed mainly on squid tend to accumulate high Cd levels, whereas those that feed mainly on squid and fish have high Hg levels (Muirhead and Furness 1988; Honda *et al.* 1990). In this study, black-footed albatross, which feeds largely on fish in their diet (Ogi 1986), had higher Hg levels than other birds feeding mainly on krill and occasionally on fish.

Recent studies have elucidated a negative correlation between organic Hg and total Hg concentrations in the liver, muscle, and kidney of several seabird species (Thompson and Furness 1989; Kim *et al.* 1996b). Kim *et al.* (1996b) reported

Table 3. Spearmann correlation coefficients for interelement concentrations with statistically significance in the liver of four seabird species (A, black-footed albatross and northern fulmar; B, black-browed albatross and grey-headed albatross)

A														Black-footed albatross
Element	Li	V	Mn	Co	Cu	Zn	Se	Rb	Sr	Ag	Cd	Cs	Pb	Hg
Li		0.466*		0.543*					0.911***					
V				0.782***	0.536*				0.506*	0.831***	0.470*			
Mn		0.598**		0.609**	0.461*	0.747***					0.539*			
Co			0.606**		0.728***	0.769***		0.566*	0.530*	0.819***	0.616**		0.534*	
Cu			0.678**			0.653**		0.730***		0.613**	0.583**		0.549*	
Zn			0.540*		0.525*		0.595**	0.495*		0.521*	0.647**			
Se						0.587*					0.758***			0.919***
Rb														
Sr														
Ag							0.544*				0.627*		0.515*	
Cd						0.746***	0.631**			0.526*			0.588**	0.630**
Cs														
Pb														
Hg														
Northern fulmar														

(B)														Black-browed albatross
Element	Li	V	Mn	Co	Cu	Zn	Sc	Rb	Sr	Ag	Cd	Cs	Pb	Hg
Li														
V											0.750*			
Mn						0.850**		0.767*		0.800*			0.700^{-*}	0.717*
Co	0.783*		0.717*		0.733*			0.700*		0.683*				
Cu			0.750*	0.733*		0.767*		0.700*						
Zn													0.683^{-*}	
Se		0.929**										0.833^{-**}	0.767^{-*}	
Rb							0.762^{-*}			0.733*			0.783^{-*}	0.700*
Sr	0.700*			0.700*										
Ag		0.767*					0.905**	0.817^{-**}					0.700^{-*}	0.833**
Cd							0.833*	0.783^{-*}					0.867^{-**}	
Cs														
Pb														
Hg					0.683*									
Grey-headed albatross														

Statistical context based on calculation at 95% confidence internal (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$)
Negative correlations were expressed as $^{-*}$, $^{-**}$, and $^{-***}$

that more than 90% of total Hg in the livers of black-footed albatross was inorganic Hg, in spite of the existence of high proportion of organic Hg in dietary organisms. The variations of Hg levels found in the present study could also be explained partly by prey items, life span, and molting pattern, as well as demethylation capacity of seabirds as documented by earlier studies (Thompson and Furness 1989; Honda *et al.* 1990; Kim *et al.* 1996b).

Normal background levels of Pb in adult bird species living in uncontaminated areas are 2–5 µg/g dry weight in the bone, 1–10 µg/g in the kidney, and 0.5–5.0 µg/g in the liver (Connors *et al.* 1975; Kendall and Scanlon 1981; Custer *et al.* 1984). Pb levels in the livers of seabirds examined in the present study tended to be lower (less than 0.5 µg/g) than in these previous reports.

Little is known about the behavior of Li, Rb, and Cs in the body of seabirds as well as other animals. It can be postulated, in analogy to the behavior of Na and K, that most Li in foods may be absorbable into body (Nielsen 1986a). Interest in the biology of Rb and Cs has been increasing due to their close physicochemical properties to K and their significant levels in tissues. Rb and Cs may have the ability to act as nutritional substitutes for K (Nielsen 1986a). Rb concentrations in seabirds were high compared to other minor trace elements.

In the present study, V concentrations ranged from 0.06 to 0.7 µg/g dry weight in the liver of seabirds. In dunlin, the highest record in hepatic tissue was 0.04 µg/g wet weight (Blomqvist *et al.* 1987). Low concentrations of V have been reported in a wide range of animals (Nielsen 1986b).

Sr concentrations in the livers of 11 seabird species examined ranged from 0.1 to 7.8 µg/g dry weight. In general, biological distribution and behavior of Sr are similar to those of Ca (Nielsen 1986a). The major sites of retention of both elements are the skeleton. Sr is incorporated mainly in the mineral phase of bones (Nielsen 1986a). In black-footed albatross and grey-headed albatross significant positive correlations between Sr and Li and between Sr and Co were found (Table 3), however, the mechanism of their interaction is unknown.

The available data on the levels of Ag in seabirds is scarce. Ag has been known to interact metabolically with Se and to alleviate Se toxicity (Nielsen 1986a). Ag has been shown to accentuate or induce vitamin E– and Se-type deficiency signs in chicks, rats, turkeys, pigs, and ducklings (Nielsen 1986a). Although the reason for the positive correlation found between Ag and Se in northern fulmar and grey-headed albatross is unclear, the antagonistic action of Ag to Se accumulation might be considered.

Reports on the body distribution and monitoring data of some elements such as Li, V, Rb, Sr, Ag and Cs in seabirds examined in this study were rather scarce. The present study provides basic information on multi-element accumulation in seabirds, which may help to understand the behavior and toxicity of various elements in marine seabirds.

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