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Environmental Toxicology and Chemistry, Vol. 22, No. 10, pp. 2482–2491, 2003
Printed in the USA
0730-7268/03 $12.00 + .00

ENANTIOMER-SPECIFIC BIOMAGNIFICATION OF α-HEXACHLOROCYCLOHEXANE AND SELECTED CHIRAL CHLORDANE-RELATED COMPOUNDS WITHIN AN ARCTIC MARINE FOOD WEB

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(*Received* 30 *September* 2002; *Accepted* 25 *February* 2003)

Abstract—Concentrations of achiral and chiral organochlorine contaminants (OCs), including hexachlorocyclohexane isomers (HCH), chlordane congeners (*cis*- and *trans*-chlordane, *cis*- and *trans*-nonachlor, MC5, MC7, and U82), and related metabolites (oxychlordane [OXY] and heptachlor *exo*-epoxide [HEPX]), were quantified in seawater (100 L; $n = 6$) and biota from the coastal Beaufort–Chukchi Seas food web near Barrow (AK, USA). The biota included zooplankton (*Calanus* spp.; $n = 5$), fish species such as arctic cod (*Boreogadus saida*; $n = 10$), arctic char (*Salvelinus alpinus*; $n = 3$), and marine mammals including bowhead whales (*Balaena mysticetus*; liver: $n = 23$; blubber: $n = 40$), beluga whales (*Delphinapterus leucas*; blubber: $n = 20$), ringed seals (*Phoca hispida*; blubber: $n = 20$), and bearded seals (*Erignathus barbatus*; blubber: $n = 7$). The food web magnification factors (FWMFs) for HCHs and chlordane compounds ranged from 0.5 (γ-HCH) to 6.5 (HEPX) and were expected based on known recalcitrance and biotransformation of OCs. The enantiomer fractions (EFs) of all chiral OCs were near racemic (EF = 0.50) in seawater, zooplankton, and all fish analyzed. In contrast, the EFs for most OCs analyzed were nonracemic (EF ≠ 0.50) in the marine mammals blubber (range: 0.09–0.79) because of enantiomer-specific biotransformation and (or) accumulation. However, EF values were not significantly correlated with isotopically determined trophic level. The EFs for all chiral OCs (except α-HCH) in bowhead whale liver closely approximated the values in zooplankton, suggesting that the accumulation of chiral OCs from prey into this cetacean is not enantiomer specific. However, the modification of EFs from bowhead liver to blubber suggests that this species has the ability to enantioselectively biotransform and accumulate several chiral OC compounds.

Keywords—Bioaccumulation Cetaceans Enantiomer fractions Organochlorines Pinnipeds

INTRODUCTION

The Arctic has become contaminated by various anthropogenic compounds, such as persistent organochlorines (OCs), released into the environment and subsequently transported and deposited to remote, polar regions via biological, atmospheric, and oceanic processes [1]. Because of recalcitrance and hydrophobicity, OCs accumulate directly from water into lower-trophic-level organisms and may biomagnify with increasing trophic position because of dietary exposure [2]. This is particularly evident in the arctic marine environment, where the biomagnification of OCs is enhanced by high lipid content and efficient energy transfer within food webs and longevity of higher-trophic-level mammalian predators [3].

The accumulation and possible biotransformation and/or elimination of OCs by lower-trophic-level biota will affect the concentration in higher-trophic-level predators. As a result, it is necessary to quantify the biomagnification of OCs to address the exposure and risk to human and wildlife populations [3]. As stable nitrogen-15 (^{15}N) isotopes are enriched relative to ^{14}N via dietary uptake, the quantification of stable N isotope signatures ($\delta^{15}N$) provides a continuous variable for the characterization of relative trophic position and the transfer of OCs within complex food webs [3–6].

Several OC contaminants are chiral and exist as two structurally distinct, mirror images called enantiomers because of a lack of axial symmetry (such as α-hexachlorocyclohexane [α-HCH]) or contain at least one center of asymmetry (e.g., chlordane-related compounds) [7]. Enantiomers have identical physical properties and are designated as either (+) or (−), corresponding to their ability to rotate a plane of polarized light, and are released into the environment as a racemic (1:1) mixture as a result of nonenantioselective chemical synthesis [7]. However, chiral compounds may exhibit enantiomer-specific biological and toxicological characteristics [8–11]. Thus, the quantification of enantiomer fractions (EFs) [12] of chiral compounds can be used to assess the potential stereoselectivity of biotransformation pathways and enantiomer-specific biological activity, as these processes may affect the relative accumulation of chiral OCs in biota.

Previous studies have investigated the enantiomer-specific distribution of OCs in Arctic and sub-Arctic air and seawater [13–16], low-trophic-level biota [17,18], avian biota [19], and marine mammals [9,18,20–22]. However, limited information exists on the influence of stereochemistry on the biomagnification of chiral OCs within marine food webs [21,22]. This study addresses the enantiomer-specific accumulation of chiral OCs (α-HCH and several chlordane components and metabolites) in selected biota in an isotopically characterized food web from arctic Alaska and investigates the utility of EFs to elucidate biotransformation pathways and/or exposure among marine biota.

METHODOLOGY

Field sampling techniques

Biological samples (listed later) and seawater were collected from Barrow (71°17′N, 156°45′W) and Point Lay (AK,

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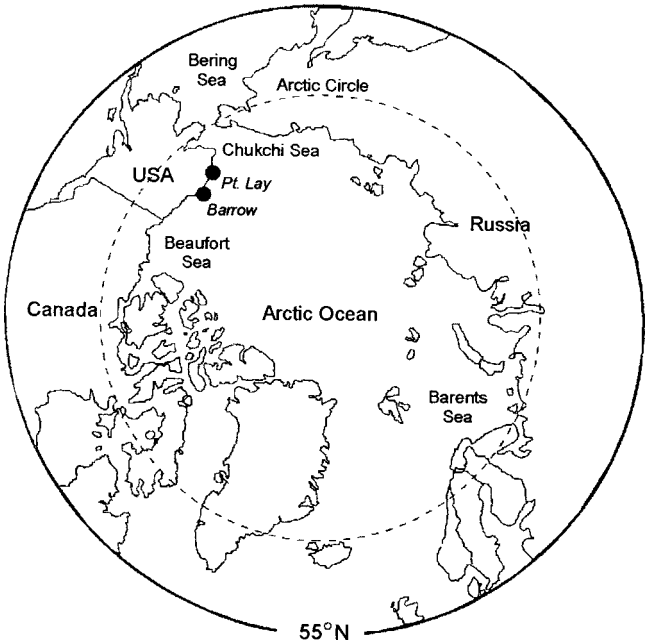

Fig. 1. Location of sampling sites (●) at Point Lay (beluga only) and Barrow (AK, USA; all other biota, water samples), 1998–2001.

USA) (69°43′N, 163°00′W) from 1998 to 2001 (Fig. 1). Selected chemical components of filtered water samples (100 L volume per sample) were sequestered using solid-phase extraction (XAD-2 resin column) with an automated in situ sampler (Infiltrex II system, Axys Environmental Systems, Sidney, BC, Canada) deployed at a depth of 15 m [23]. The suspended particulate matter in the water column was removed using glass-microfiber filters prefired at 450°C to remove potential OC contamination. Dissolved OC analytes collected on the XAD-2 resin were stored at 2°C until time of analysis.

Zooplankton samples (*Calanus* spp.) were collected using an acetone-rinsed 100-μm plankton tow (1 m^2) and were stored in precleaned glass jars [23]. Whole arctic cod (*Boreogadus saida*) and arctic char (*Salvelinus alpinus*) were obtained from Native Alaskan (Inuit) subsistence fishers. Muscle and blubber samples from ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) were collected from Inuit subsistence harvests in Barrow through the North Slope Borough Department of Wildlife Management (DWM) and Alaska Department of Fish and Game (ADFG). Blubber and muscle samples from beluga whales (*Delphinapterus leucas*) from Point Lay, and bowhead whales (*Balaena mysticetus*, including liver samples) from Barrow were obtained from Inuit subsistence whalers with the permission of the Alaskan Eskimo Whaling Commission. Field sampling techniques of mammalian tissues have been previously described [24].

Personnel from DWM and ADFG recorded the life history information (sex, length, weight) for all specimens obtained in this study. Samples were transported to the National Water Research Institute (Environment Canada, Burlington, ON) under U.S. Export and Canadian Import permits in accordance with the Convention on International Trade in Endangered Species (US694250 and CA-CW-IM-0053-00, respectively) and via prevision of the U.S. Marine Mammal Protection Act (782-1399; http://www.nmfs.noaa.gov/prot_res/laws/MMPA/MMPA.html). All samples were homogenized and stored at −20°C in precleaned glass containers.

OC extraction

Sample extraction was performed using previously established methodology [23,24]. Briefly, water samples (XAD-2 resin) were extracted under clean-room laboratory conditions (positive pressure, carbon, and HEPA™ filters, Anaheim, CA, USA) with field and laboratory blanks extracted concurrently. The XAD-2 resin columns were transferred and eluted with methanol and then dichloromethane (DCM). The combined eluate was shaken with 3% NaCl solution, and the lower, organic (DCM) layer was separated. The DCM extracts were fortified in 2,2,4-trimethylpentane (isooctane) and concentrated.

Zooplankton (~10–20 g, wet wt), whole-fish homogenates (5–10 g wet wt), and marine mammal liver (10 g wet wt) and blubber (1–2 g wet wt) were homogenized with Na_2SO_4 and spiked with two polychlorinated biphenyl (PCB) internal standards (PCB-30 and PCB-204) to monitor the efficiency of the extraction protocol. Zooplankton, fish, and bowhead liver samples were extracted with DCM using Soxhlet extraction for 16 h and subsequently concentrated. Blubber samples were extracted with DCM by using a Polytron® homogenizer (Brinkmann, Westbury, NY, USA). Lipids and other bio-organic materials in each sample were removed using gel permeation chromatography, and the lipid percentage was determined gravimetrically.

Analytes in all water and biotic samples were separated on 8 g of 100%-activated silica gel into two fractions: 100% hexane (fraction 1) and 50% hexane:50% dichloromethane (by volume; fraction 2). Endrin ketone and 1,3-dibromobenzene were added as laboratory spiking surrogates to determine fractionation performance. Samples were transferred to isooctane and concentrated to 100 μl. The hexachlorobiphenyl PCB-166 was added an external performance standard.

Achiral and chiral OC analysis

The quantification of HCH isomers and chlordane-related components in arctic seawater and biota were determined using a Hewlett-Packard (HP; Agilent, Mississauga, ON, Canada) 5890 gas chromatograph (GC) with a ^{63}Ni-electron capture detector [23]. Confirmation was accomplished using a HP6890 GC-5973 mass-selective detector (GC-MSD) with electron-capture–negative-ion mode [23]. Detailed methods of analysis of other OCs in water and marine biota from this region have been previously reported [23–25].

The methodology employed for the quantification of enantiomer profiles of chiral OCs was derived from previously established techniques [17,26]. In brief, enantiomer analysis for all OCs was completed using multidimensional GC-MSD on a HP6890/5973 operating in electron-capture–negative-ion mode. A Gerstal (Mülheim an der Ruhr, Germany) DCS2 heart-cut valve, in combination with a liquid nitrogen cold trap, allowed for the application of MDGC. Separation of α-HCH and chlordane-related compounds (*cis*- and *trans*-chlordane, oxychlordane [OXY], heptachlor *exo*-epoxide [HEPX], MC5, MC7, and U82) was performed using an achiral HP-1 column (30 m × 0.25 mm i.d. × 0.25 μm d.f.). Target analytes were subsequently heart-cut onto the chiral BGB-172 column (30 m × 0.25 mm i.d. × 0.18 μm d.f.; BGB Analytik, Adiswil, Switzerland) for enantiomer separation. Thermal conditions and other instrumental parameters are further discussed in Wong et al. [26].

Enantiomeric fractions (EFs) for the chiral PCBs and OCs were calculated as follows [12]:

$$EF = \frac{ER}{1 + ER} = \frac{1}{1 + \frac{1}{ER}} \quad (1)$$

The enantiomeric ratios (ERs) were quantified as ER = (+)/(−) concentration ratios when enantiomer elution order was known from enantiomer-enriched standards (α-HCH, OXY, HEPX, and *cis*- and *trans*-chlordane from Ehrenstorfer, Augsburg, Germany) and as the areas of the first eluting to the second-eluting enantiomers for MC5, MC7, and U82. The nomenclature and structure of these minor compounds of technical chlordane has been summarized elsewhere [17,27,28].

Stable isotope analysis

The trophic status of selected biota from the local arctic marine food web at Barrow was previously described using stable nitrogen isotope ratios ($^{15}N/^{14}N$; $\delta^{15}N$) [29]. In brief, $\delta^{15}N$ values in pooled zooplankton and individual muscle tissue of fish and marine mammals were analyzed using a Micromass Optima continuous-flow isotope-ratio mass-selective detector (Micromass, Manchester, UK) directly coupled to a Carlo Erba NA1500 elemental analyzer (Carlo Erba, Milan, Italy). Isotopically determined trophic levels (TL) were calculated using the relationship developed by Fisk et al. [3]:

$$TL = 2.0 + (\delta^{15}N_{consumer} - \delta^{15}N_{\textit{Calanus}})/3.8 \quad (2)$$

where $\delta^{15}N_{consumer}$ is the $\delta^{15}N$ signature in the specified organism, $\delta^{15}N_{\textit{Calanus}}$ is the mean (±1 standard error), $\delta^{15}N$ is the value for *Calanus* spp. (9.8‰ ± 0.2‰), and 3.8 is the trophic enrichment factor for $\delta^{15}N$ in an arctic marine food web [30]. It was assumed that the *Calanus* copepods collected in this study were primary herbivores and occupied a secondary trophic position (TL = 2.0).

Analytical quality assurance

Recovery of PCB surrogate standards was considered acceptable if greater than 70% for both PCB-30 and PCB-204 and concentrations were corrected for average recovery of the internal standards. Detection limits were approximately 0.02 ng/g for all OC analytes. Sample quantification was performed using a series of multiple external standards that were analyzed after every 10 samples. Quality assurance protocol for OC analysis included the use of two standard reference materials (SRM1588 cod liver oil and SRM1945 whale blubber homogenate) from the National Institute of Standards and Technology (Gaithersburg, MD, USA). Analyte concentrations were within 10 to 15% of the certified values. Standard reference materials (SRM 1588 and 1945) and racemic standards were analyzed concurrently during chiral analysis to monitor enantiomer separation efficiency and elution order of the target analytes [26].

Data analysis and OC trophic transfer calculations

Statistical analyses were performed using Systat®, Version 8.0 (SPSS, Chicago, IL, USA). All hypotheses tested were two tailed, and the maximum probability of a type I error rate (α) was established at 0.05. Initial analyses found that OC concentrations were significantly correlated with lipid content ($p < 0.05$ for all comparisons; data not shown). As a result, statistical comparisons of OC concentrations and relative distribution among species were performed using lipid-normalized concentrations to reduce the effect of interspecies variation of lipid content on analyte concentration [31].

Lipid-normalized OC concentrations were $\log_{10}$ transformed prior to statistical analysis to reduce the heterogeneity of variance and/or nonnormality of the raw data. Interspecies comparisons of lipid-normalized OC concentrations were evaluated by a model I one-way analysis of variance (ANOVA) with the Tukey's honestly significant difference test. The influence of gender, age (if available) or length cohort (for bowhead whales) [32], and all first-order interactions on the achiral concentrations in each species were determined using a general linear model (GLM). A separate GLM investigated the effect of OC concentration, gender, and age (or length cohort) and all first-order interactions on the EFs of chiral OCs. Further analysis of those variables deemed statistically significant via type III sum of squares was investigated using model I first-order linear regression or ANOVA. In addition, comparison of EFs to values from a racemic standard (EF = 0.50) was performed via the *Z* test.

The transfer of OCs through the entire food web was determined by calculating a food web magnification factor (FWMF) based on the relationship between TL and lipid-normalized OC concentration data [3]. The FWMF value was quantified from the slope of the model I first-order linear relationship among lipid-normalized, $\log_{10}$-transformed OC concentration and trophic level (summarized in [3]). A second method was employed to investigate the trophic-level-corrected, biomagnification factors (BMFs) of OCs between species:

$$BMF = (OC_{predator}/OC_{prey})/(TL_{predator}/TL_{prey}) \quad (3)$$

where $OC_{predator}$ and OC_{prey} represent the lipid-normalized concentrations of a specific OC in the predator and prey species [3]. The BMF were not calculated for bearded seals, as the dietary contribution of epibenthic biota in this species was not available, and the magnification of OCs from only pelagic fishes (arctic cod and arctic char) would bias these results.

In addition, BMFs were normalized to the ubiquitous and recalcitrant PCB-153 ($BMF_{PCB\text{-}153}$). Those OCs with FWMF and BMF values found to be statistically greater than unity (via *Z* test) were considered to accumulate from prey to predator (for BMFs) and within the selected food web (for FWMF). A $BMF_{PCB\text{-}153}$ less than unity indicates that the compound is biotransformed and/or eliminated to a greater extent than PCB-153, whereas a $BMF_{PC\text{-}153}$ approximately 1 or greater suggests a slow rate of biotransformation relative to PCB-153 and/or product formation [33]. Enantiomer-specific BMF values were compared using the Student's *t* test.

RESULTS AND DISCUSSION

Achiral concentrations

Achiral concentrations in seawater and selected biota from the southern Beaufort–Chukchi Seas region are reported in Table 1. The α-, β-, and γ- isomers of HCH were quantified in all matrices. While most of the major components of technical chlordane were found in seawater and biota, the selected minor CHLOR compounds, MC5, MC7, and U82 [34], were quantifiable only in arctic cod and higher-trophic-level biota. The chiral octa-Cl-substituted chlordane congeners, MC5, MC7, and U82, are present as minor components of the technical mixture (6.1% for MC5 and 2.2% for U82 and MC7) [34]. However, all three isomers have been quantified in higher-trophic biota at significantly greater concentrations compared to other isomers that predominate technical CHLOR [22,27,35].

Table 1. Mean (±1 standard error) trophic level (TL), lipid content, and concentrations and food web magnification factors (FWMFs) of selected persistent organochlorine contaminants (OCs) in seawater (ng/L) and biota (ng/g lipid wt) from arctic Alaska (USA) (1998–2001). Chemical abbreviations are defined in Table 2

Variable Sample type	FWMF[a] (r^2)	Water, filtered	*Calanus*,[b] whole	Bowhead Whale Liver	Bowhead Whale Blubber	Char[c] whole	Cod[d] whole	Beluga blubber	BS[e] blubber	RS[f] blubber
Trophic level[g]		—	2.0 ± 0.1	2.9 ± 0.1		3.1 ± 0.1	3.3 ± 0.1	3.8 ± 0.2	3.8 ± 0.1	4.1 ± 0.2
n[h]		6	5	23	40	3	10	20	7	20
Lipid %		—	27.3 ± 0.9	10.4 ± 0.2	75.8 ± 1.6	4.5 ± 2.5	3.7 ± 0.4	84.8 ± 1.8	79.5 ± 3.9	83.6 ± 3.6
PCB-153[i]	6.68 (0.64)	0.003 ± 0.001	2.6 ± 0.4	4.5 ± 0.6	17.3 ± 3.1	8.3 ± 1.0	11 ± 0.8	220 ± 25	53.4 ± 4.8	84.1 ± 10
α-HCH	1.75 (0.23)	1.419 ± 0.351	10.5 ± 6.2	94.0 ± 6.1	150 ± 23	30.2 ± 2.5	28.6 ± 9.3	82.0 ± 34	42.4 ± 9.8	42.3 ± 9.8
β-HCH	2.92 (0.62)	0.070 ± 0.013	3.3 ± 1.2	34.1 ± 3.4	75.5 ± 12	5.6 ± 2.1	6.4 ± 7.6	117 ± 12	17.2 ± 2.9	17.2 ± 2.9
γ-HCH	0.51 (0.10)	0.615 ± 0.117	5.7 ± 1.8	12.6 ± 1.6	38.1 ± 11	9.3 ± 0.6	6.6 ± 3.1	26.9 ± 2.2	1.5 ± 0.4	1.5 ± 0.4
ΣHCH	3.25 (0.52)	2.110 ± 0.460	18.6 ± 6.2	144 ± 6.7	267 ± 28	48.8 ± 2.3	45.7 ± 7.1	224 ± 44	64.1 ± 11	64.4 ± 11
cis-Nonachlor	2.65 (0.26)	NQ[j]	1.9 ± 0.6	4.6 ± 0.6	21.8 ± 2.3	8.6 ± 1.1	7.8 ± 1.2	106 ± 44	2.9 ± 0.4	19.8 ± 3.6
trans-Nonachlor	5.02 (0.57)	0.004 ± 0.002	5.6 ± 2.3	18.2 ± 2.0	44.7 ± 3.1	24.5 ± 1.2	23.0 ± 2.2	400 ± 52	75.9 ± 4.8	97.7 ± 22
cis-Chlordane	0.72 (0.54)	0.002 ± 0.001	1.8 ± 0.9	15.2 ± 1.6	20.2 ± 5.4	8.3 ± 1.0	8.2 ± 2.9	75 ± 40	21.4 ± 1.2	38.2 ± 11
trans-Chlordane	1.55 (0.09)	ND[k]	1.7 ± 0.6	12.1 ± 1.3	20.5 ± 6.2	4.0 ± 0.2	3.0 ± 1.2	8.9 ± 1.3	3.2 ± 1.0	10.4 ± 3.2
OXY	5.62 (0.79)	ND	3.4 ± 2.1	7.6 ± 1.6	151 ± 16	7.1 ± 0.4	7.3 ± 1.7	287 ± 39	66.1 ± 7.6	158 ± 33
HEPX	6.46 (0.63)	0.004 ± 0.001	2.3 ± 1.1	24.2 ± 3.1	57.6 ± 8.2	9.6 ± 0.5	12 ± 1.8	328 ± 30	64.8 ± 7.0	163 ± 35
MC5	—	NQ	0.7 ± 0.1	NQ	16.0 ± 3.8	NQ	5.9 ± 1.7	13 ± 0.8	16.0 ± 3.4	38.5 ± 5.1
MC7	—	ND	ND	NQ	0.7 ± 0.2	ND	NQ	40.2 ± 5.0	19.2 ± 5.6	8.1 ± 1.9
U82	—	ND	NQ	4.3 ± 2.2	14.1 ± 0.9	NQ	4.2 ± 1.4	73.1 ± 8.0	60.4 ± 12	42.2 ± 14
ΣCHLOR	4.90 (0.55)	0.010 ± 0.004	18.6 ± 2.6	81.8 ± 7.8	325 ± 12	51.4 ± 3.5	70.7 ± 11	1,420 ± 130	294 ± 20	588 ± 49

[a] Bowhead whale blubber OC concentrations were used in determining FWMFs.
[b] Calanoid copepods (zooplankton).
[c] Arctic char (*S. alpinus*).
[d] Arctic cod (*B. saida*).
[e] BS = bearded seals (*E. barbatus*).
[f] RS = ringed seals (*P. hispida*).
[g] Trophic level from Hoekstra et al. [29].
[h] n = number of samples analyzed.
[i] PCB-153 data from Hoekstra et al. [25].
[j] NQ = not quantified (signal/noise <5).
[k] ND = not detected (signal/noise <3).

Table 2. Enantiomer-specific biomagnification factors (BMFs) on a lipid-weight basis for selected chiral persistent organochlorine contaminants (OCs) in Alaskan (USA) arctic marine biota. Enantiomer-specific $BMF_{PCB\text{-}153}$ values that are statistically different are italicized (Student's *t* test, $p < 0.05$)

	BMFs[a]				BMFs relative to PCB-153 ($BMV_{PCB\text{-}153}$)[b]			
OC analyte	*Calanus* to fish	*Calanus* to bowhead	Fish to beluga	Fish to ringed seal	*Calanus* to fish	*Calanus* to bowhead	Fish to beluga	Fish to ringed seal
PCB-153[c]	2.8	14.7	20.2	10.4	1.0	1.0	1.0	1.0
(±)-α-HCH[d]	1.75	9.85	2.35	1.12	0.63	0.67	0.17	0.11
(+)-α-HCH	1.94	16.1	3.00	1.30	0.96	*1.09*	*0.15*	0.12
(−)-α-HCH	1.59	4.56	1.68	0.94	0.57	*0.31*	*0.08*	0.09
(±)-*cis*-Chlordane	2.88	7.74	7.91	3.59	1.03	*0.53*	0.39	0.35
(+)-*cis*-Chlordane	2.91	1.45	1.63	4.59	1.04	*0.10*	*0.08*	*0.44*
(−)-*cis*-Chlordane	2.85	13.5	13.8	2.65	1.01	*0.92*	*0.68*	*0.25*
(±)-*trans*-Chlordane	1.31	8.32	2.11	2.29	0.46	0.57	0.11	0.22
(+)-*trans*-Chlordane	1.43	12.1	2.58	1.83	0.51	*0.82*	*0.13*	*0.17*
(−)-*trans*-Chlordane	1.19	4.80	1.60	2.79	0.43	*0.32*	*0.08*	*0.27*
(±)-OXY[e]	1.33	30.4	39.6	17.1	0.47	2.07	1.66	1.64
(+)-OXY	1.35	35.2	48.4	20.7	0.48	*2.39*	*2.40*	*2.00*
(−)-OXY	1.30	25.5	17.5	13.2	0.46	*1.73*	*0.87*	*1.27*
(±)-HEPX[f]	2.93	17.2	25.6	11.8	1.05	1.17	1.27	1.13
(+)-HEPX	2.97	21.3	31.6	9.41	1.06	*1.44*	*1.56*	*0.95*
(−)-HEPX	2.90	13.0	18.9	14.4	1.03	*0.88*	*0.93*	*1.38*
(±)-MC5	—	—	1.87	5.11	—	—	0.09	0.49
MC5-E1	—	—	2.84	7.46	—	—	*0.14*	*0.72*
MC5-E2	—	—	0.82	2.56	—	—	*0.04*	*0.24*
(±)-U82	—	—	14.6	7.80	—	—	0.72	0.75
U82-E1	—	—	15.2	10.1	—	—	0.75	*0.98*
U82-E2	—	—	14.1	5.46	—	—	0.70	*0.53*

[a] Trophic corrected BMF values.
[b] $BMF_{PCB\text{-}153}$ calculated by BMF of specific OC divided by BMF for PCB-153 within a specific predator–prey interaction.
[c] Polychlorinated biphenyl (PCB)-153 data from Hoekstra et al. [25].
[d] α-HCH = α-hexachlorocyclohexane.
[e] OXY = oxychlordane.
[f] HEPX = heptachlor *exo*-epoxide.

The lipid-adjusted concentrations for these selected OCs were not significantly influenced by age (or length cohorts for bowhead whales) or gender in all biota collected in this study. As a result, concentration data were combined for each species with no separation for sex or age for all subsequent comparisons. While it is generally understood that the accumulation of persistent lipophilic contaminants is age and/or gender dependent in marine mammals [36], the biases associated with the collection of marine mammals due to hunting preferences (e.g., smaller [younger] animals collected, migration behavior of the targeted species, time of year, and so on) may influence these results.

Concentrations of ΣHCH, ΣCHLOR, and their respective components increased from seawater to zooplankton to fish and various marine biota from the coastal Beaufort–Chukchi Seas areas and were similar to other studies from the Alaskan and western Canadian Arctic [37–39]. In general, OC concentrations quantified in this study were lower than those previously reported in the eastern Canadian and European Arctic [3,4,22,40]. Results are consistent with the geographical trends observed for these compounds in the Arctic [23,41,42] attributed to differences in regional heterogeneity of contaminants [25].

The FWMFs of HCH isomers and CHLOR-related compounds ranged from 0.72 to 6.46 (Table 1). These FWMF values for HCHs and CHLORs, including racemic α-HCH and chiral CHLOR components, were similar to previously reported values in arctic biota [3,4] and are expected on the basis of known OC recalcitrance, partition-based physical chemistry, metabolism, and metabolite formation [3,21,43]. The FWMFs for MC5, MC7, and U82 were not calculated, as these compounds were not detectable in lower-trophic biota. It has been previously documented that U82 and MC5 were the most abundant octa-Cl-substituted chlordane congeners in high-trophic-level mammals, such as ringed seals, polar bears, and humans [22,27]. The stepwise accumulation of these compounds into higher-trophic predators in this study, as described by the racemic BMFs (Table 2), is consistent with the relative accumulation of U82, MC5, and MC7 (highest to lowest) in mammalian systems [27]. The chlordane congeners U82 and MC5 are believed to be more recalcitrant in biota compared to other chlordane compounds, such as *cis*- and *trans*-chlordane, and MC7 because of *exo-endo-exo* Cl-substitution on the C1, C2, and C3 positions [28].

Enantiomeric profile of chiral OCs

The mean EFs in seawater were approximately racemic (EF = 0.50) for all chiral OCs (Fig. 2) and not correlated with concentration (model I, first-order linear regression, $p = 0.783$). The results of chiral analysis of α-HCH, heptachlor *exo*-epoxide (HEPX), and *cis*- and *trans*-chlordane in filtered seawater reported in this study were similar to previous measurements of chiral OCs in surface waters (dissolved phase) from the Bering–Chukchi–Beaufort Seas [44]. All zooplankton samples were racemic for all quantifiable chiral OCs and were not significantly different from seawater (ANOVA, $p > 0.05$), suggesting that the bioaccumulation of OCs is not stereospecific. In addition, the enantiomer profiles of chiral OCs in arctic cod and arctic char were racemic and not statistically different from each other or from seawater and zooplankton (ANOVA, $p > 0.05$ for all comparisons). As a result, the EFs for arctic

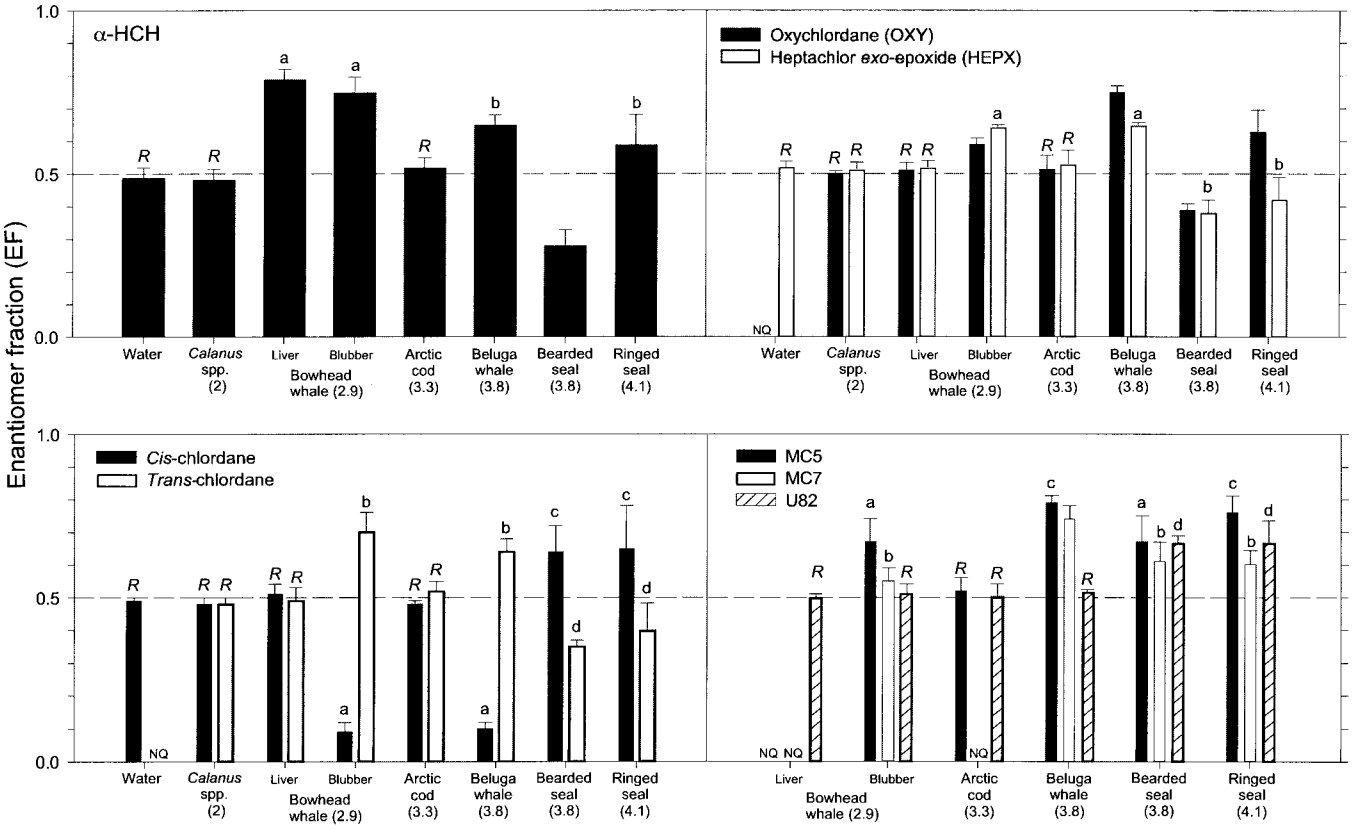

Fig. 2. Enantiomer fractions (EF; mean ± 1 standard deviation) of the (+)-enantiomer (or E1) of α-hexachlorocyclohexane (HCH) and chlordane-related compounds in seawater and biota from Barrow (AK, USA). Isotopically derived trophic levels are indicated in parentheses. EF values from pinnipeds and cetaceans derived from blubber samples (unless indicated otherwise). Arctic cod and zooplankton samples derived from whole tissues. R indicates EFs not significantly different from the racemic standard (Z test, $p > 0.05$). EFs that are designated with the same letter (a, b, c, d) are not statistically different (analysis of variance, Tukey's honestly significant difference, $p < 0.05$). MC5, MC7, and U82 were not quantifiable (NQ; signal/noise < 5) in all water and zooplankton samples.

char were omitted from Figure 2 to reduce the complexity of the graph.

The EF values in arctic cod were not influenced by age, gender, and fork length (GLM, type III sums of squares, $p > 0.15$ for all interactions). Size and age data were not available for arctic char, which were subsequently omitted from this statistical analysis. The ERs of several chiral OCs (α-HCH, *cis*- and *trans*-chlordane, HEPX, OXY, U81, U82, MC5, MC6, and MC7) in cod (*Gadus morhua*) and herring (*Clupea harengus*) from the Barents and Baltic Seas [17,18] were nonracemic and influenced by specimen gender and/or age. However, the collection of younger specimens in this study (otolith age: 0–2 years) limits statistical comparison. Our data are consistent with other investigations in which chiral OCs in arctic cod were near racemic and similar to potential prey [21,22]; implying that accumulation of α-HCH and chlordane components and possible metabolite formation (OXY and HEPX) in these fish species is not enantioselective.

In general, the EFs of chiral chlordane components and α-HCH were nonracemic in the marine mammal tissues analyzed in this study, suggesting that cytochrome P450 (CYP)–mediated metabolism as well as other processes that influence bioaccumulation are enantioselective. The stereochemical selectivity of enzymes is well documented [45], including CYP-dependent monooxygenase activity [46] and CYP1A and epoxide hydrolase isozymes [47,48]. However, highly selective, non-CYP mediated processes also influence the stereochemically specific bioactivity of chiral molecules [11,49,50]. As a result, the term ''biotransformation'' in this manuscript refers to all possible processes related to CYP-mediated metabolism, receptor-mediated disposition, and other unidentified mechanisms responsible for enantiomer-specific accumulation of chiral OCs in biota.

The EFs for all chiral OCs (except α-HCH) in bowhead whale liver closely approximated the values in zooplankton (Fig. 2), suggesting that the accumulation of chiral OCs from prey into this cetacean is not enantiomer specific. The accumulation of several chiral PCBs in bowhead whale blubber was enantiomer specific relative to liver and zooplankton [51], suggesting that processes governing the absorption of OCs from prey are controlled by partition-based processes [2,52] and are unlikely to be stereospecific. However, the modification of EFs from liver to blubber were significant ($p < 0.032$ for all comparisons, except for α-HCH and U82 with $p > 0.05$) and suggests that bowhead whales have the ability to enantioselectively biotransform several chiral OC compounds. The modification of the EF value for α-HCH in bowhead whale liver relative to zooplankton may reflect a more rapid biotransformation of the (−)-enantiomer, enantiomer-specific deposition, and remobilization from lipid reservoirs [11] or other compartments and/or other unidentified factors that influence OC accumulation in this cetacean. The EFs for U82 were near racemic in both bowhead liver and blubber and not statistically

different ($p < 0.03$), suggesting that bioaccumulation of this compound by this cetacean was not enantiomer specific.

The EFs of the chiral OCs quantified in all marine mammals were not significantly influenced by age or gender and OC concentration (GLM, $p > 0.10$ for all comparisons). However, interspecies differences in the enantiomeric profile of α-HCH and some chlordane-related compounds were observed (Fig. 2). The mean EFs (±1 standard deviation) of α-HCH in water, zooplankton, arctic cod, and arctic char from the Beaufort–Chukchi Seas region were essentially racemic (0.49 ± 0.03, 0.46 ± 0.07, 0.52 ± 0.03, and 0.50 ± 0.05, respectively), suggesting some enantioselective biotransformation of (−)-α-HCH by ringed seals (0.59 ± 0.09) and the cetaceans (beluga whale: 0.65 ± 0.03; bowhead whale blubber: 0.76 ± 0.03; liver: 0.79 ± 0.03). The enrichment of (+)-α-HCH relative to the (−)-enantiomer was quantified in the blubber of harbor (*P. vitulina*) and grey (*P. grypus*) seals [53], other ringed seal populations [20,21], and small cetaceans [54].

In contrast to other marine mammals, the enantiomer-specific distribution of α-HCH in bearded seals (EF: 0.28 ± 0.05) was dominated by (−)-α-HCH. While this may be attributed to species-specific biotransformation of α-HCH enantiomers, the exposure to the (−)-enantiomer via dietary intake may influence the EF of α-HCH in bearded seals. In general, the diet of bearded seals consists of benthic invertebrates and epibenthic fish [55], whereas the feeding strategies of the other marine mammals sampled in this study are more oriented toward the pelagic marine environment [56–58]. Harner et al. [13] found that abundance of (−)-α-HCH dramatically increased with water column depth within the eastern Arctic Ocean, presumably because of enantiomer-specific microbial degradation of the (+)-enantiomer [13], suggesting that benthos from this region would be enriched with (−)-α-HCH. However, benthos may also constitute a significant dietary contribution to the beluga whale [56], which preferentially accumulated the (+)-enantiomer of this OC (Fig. 2). As the EFs of α-HCH in this cetacean were significantly different from bearded seals, that possibility of species-specific accumulation of α-HCH enantiomers cannot be ignored.

The mean EFs for *cis*- and *trans*-chlordane found in the pinniped and cetacean blubber samples were significantly different than in potential prey items such as zooplankton (0.48 ± 0.02 and 0.48 ± 0.02), arctic cod (0.47 ± 0.01 and 0.53 ± 0.03), and arctic char (0.50 ± 0.01 and 0.52 ± 0.02), suggesting enantioselective biotransformation and accumulation ($p < 0.01$ for all comparisons). The EFs of *cis*- and *trans*-chlordane quantified in the blubber of both pinnipeds (ringed seal: 0.62 ± 0.16, 0.42 ± 0.08; bearded seals: 0.64 ± 0.08, 0.35 ± 0.02, for *cis*- and *trans*-chlordane, respectively) were similar to previous studies of seals [18,20,22]. However, the enantiomeric profiles observed in cetacean (beluga and bowhead whale) blubber for *cis*-chlordane (beluga whale: 0.10 ± 0.02; bowhead whale: 0.09 ± 0.03) and *trans*-chlordane (beluga: 0.64 ± 0.04; bowhead: 0.70 ± 0.06), respectively, was dominated by the opposite enantiomer. The relatively lower EFs of *cis*-chlordane in cetaceans are likely due to the biotransformation of (+)-enantiomer, whereas (−)-*cis*-chlordane is eliminated in pinnipeds (Table 2). The opposite scenario is evident for *trans*-chlordane.

The enantiomeric profiles of the octachlordanes MC5, MC7, and U82 were similar among cetaceans and pinniped blubber samples. The first-eluting enantiomers (E1) of MC5 and MC7 were more abundant than the second enantiomer in all marine mammal blubber samples analyzed (bowhead whale: MC5: 0.67 ± 0.07, MC7: 0.55 ± 0.04; beluga whale: MC5: 0.79 ± 0.02, MC7: 0.74 ± 0.04; bearded seal: MC5: 0.67 ± 0.08, MC7: 0.61 ± 0.06; ringed seal: MC5: 0.76 ± 0.05, MC7: 0.58 ± 0.06), whereas U82 was near racemic in beluga (0.52 ± 0.01) and bowhead whale (0.51 ± 0.03) blubber but dominated by E1 in pinnipeds (ringed seals: 0.65 ± 0.07; bearded seals: 0.65 ± 0.02). The nonracemic values of MC5, MC7, and U82 are consistent with the enantiomeric distribution in ringed seals from the Baltic Sea [18]. To our knowledge, this is the first time that EFs for chlordane-related compounds have been reported in any cetacean. These interspecies differences may be due to dietary exposure, metabolic capacity, and/or other stereoselective processes that influence OC accumulation.

The enantiomer-specific enrichment of OXY, an environmentally persistent metabolite of *cis*- and *trans*-chlordane [59], in ringed seal (EF: 0.63 ± 0.07), beluga whale (0.75 ± 0.02), and bowhead whale blubber (0.59 ± 0.02) relative to the near racemic values in potential prey (zooplankton: 0.51 ± 0.01; arctic cod: 0.52 ± 0.04; arctic char: 0.52 ± 0.05) is consistent with past observations in ringed seals [20,22], polar bears [22], and seabirds [19] from the Canadian Arctic. As with α-HCH, the EF of OXY in bearded seals was significantly different (EF: 0.39 ± 0.02) from the ringed seals analyzed in this study, suggesting that the stereoselective metabolism of technical chlordane components and/or dietary exposure is different among pinnipeds.

The racemic (or near racemic) enantiomer profile of OXY in poikilotherms (invertebrates and fish) is an interesting observation. It is generally regarded that OXY is not produced abiotically in the environment but rather is formed via biotransformation of technical chlordane compounds by homeotherms and excreted into the environment. The near racemic values in zooplankton and fish analyzed in this study imply that enantioselective degradation of (+)-OXY, likely mediated by microbial activity, has occurred in this region.

The enantiomers of HEPX were near racemic in all lower-trophic biota (zooplankton: 0.52 ± 0.02; arctic cod: 0.53 ± 0.04; arctic char: 0.52 ± 0.02). However, the nonracemic EFs of HEPX in the blubber of cetaceans (bowhead whales: 0.64 ± 0.01; beluga whales: 0.65 ± 0.01) and pinnipeds (ringed seals: 0.42 ± 0.07; bearded seals: 0.38 ± 0.04) suggests that enantiomer-specific biotransformation of heptachlor and/or accumulation of HEPX has occurred in both groups. While the EFs of HEPX in seals are similar to previously published values in other pinniped species and populations [18,20,22], the relative enrichment of the opposite enantiomer, (+)-HEPX, in cetacean blubber indicates that the biotransformation and/or accumulation of HEPX is uniquely different among these groups of marine mammals.

Enantiomer-specific biomagnification

The EFs for all chiral OCs were not significantly correlated with trophic level (first-order linear regression; $p > 0.15$ for all comparisons). In addition, the enantiomer-specific FWMFs determined for each chiral OC were not significantly different from values found for racemic concentrations ($p > 0.25$ for all comparisons; data not shown) because only higher-trophic-level biota had EFs significantly different from EF = 0.50. However, the stepwise biomagnification of contaminants from prey to predators (BMFs) and BMFs relative to the recalcitrant PCB congener PCB-153 ($BMF_{PCB\text{-}153}$) of several chiral OC con-

centrations were enantiomer specific (Table 2). Biomagnification factors for MC7 were not calculated because concentrations in lower-trophic-level biota (zooplankton and fish) were below detection limits.

The enantiomer-specific BMFs for the chiral OCs selected in this study ranged from 0.82 for the second-eluting enantiomer (E2) of MC5 to 48.4 for (+)-OXY (Table 2). The enantiomer-specific $BMF_{PCB\text{-}153}$ values ranged from 0.04 for MC5-E2 to 2.40 for (+)-OXY. The normalization of BMF values to PCB-153 not only reduces the variances associated with concentrations among individuals but also provides insight into the relative accumulation of OCs, as PCB-153 is highly resistant to metabolism in most biota [60] and approximates the maximum achievable BMFs for chemicals (excluding metabolites) with similar octanol–water partition coefficients [33].

The $BMF_{PCB\text{-}153}$ from zooplankton to fish for the enantiomers of the chiral OCs ranged from 0.43 ([−]-*trans*-chlordane) to approximately 1.0 (for both HEPX enantiomers), indicating that the accumulation and/or formation (in case of HEPX) were less than or equal to PCB-153 accumulation. However, the relative biomagnification of all chiral OCs was not enantiomer specific ($p > 0.35$ for all comparisons). Moisey et al. [21] determined that the BMFs from *C. hyperboreus* to arctic cod were the same for both α-HCH enantiomers [21]. While the enantioselective elimination of some OCs by fish has been documented [61], such data suggest that the accumulation of chiral OCs in these arctic fish species is not enantiomer specific.

The $BMF_{PCB\text{-}153}$ values for chiral OCs in cetaceans and pinnipeds were both class and enantiomer specific, providing additional evidence for stereoselective accumulation and biotransformation (Table 2). While the relative accumulation of both α-HCH enantiomers was essentially the same in ringed seals ($p = 0.072$), (−)-α-HCH was preferentially eliminated in both cetaceans analyzed in this study ($p < 0.01$ for both comparisons). This was particularly evident in the bowhead whales, where the biotransformation and/or rate of accumulation for (+)-α-HCH is similar to PCB-153 ($BMF_{PCB\text{-}153} = 1.09$).

In general, the biomagnification of *cis*- and *trans*-chlordane enantiomers in cetaceans and ringed seals was less than PCB-153 (all $BMF_{PCB\text{-}153} < 1$). However, the biotransformation and/or elimination of *cis*- and *trans*-chlordane was enantiomer specific and unique in cetaceans and pinnipeds. The $BMF_{PCB\text{-}153}$ values of (+)-*cis*- and (−)-*trans*-chlordane were significantly lower (~2–9 times) in cetaceans compared to the opposite enantiomer ($p < 0.001$ for all comparisons), whereas in ringed seals the inverse was true, as (−)-*cis* and (+)-*trans*-chlordane were preferentially eliminated.

The greater biomagnification factors (relative to PCB-153) of U82 compared to MC5 in beluga whales (0.72 vs 0.09) and ringed seals (0.75 vs 0.49) are consistent with previous reports of chlordane accumulation [27]. The MC5 may be more susceptible to biotransformation than U82 because of an unsubstituted C5 atom; however, this has not been investigated. In addition, the dechlorination of *trans*-nonachlor into *trans*-chlordane is rate limited in mammals [59]. The U82 has the same Cl configuration as *trans*-nonachlor (but without Cl substitution at C7 [34]) and may explain the slow biotransformation from the marine mammals analyzed in this study. The relative accumulation of MC5-E1 was significantly greater in both species compared to the second-eluting enantiomer ($p < 0.001$ for both comparisons) and is similar to past measurements in ringed seals [22]. While the accumulation of U82 enantiomers in the beluga whales analyzed were not statistically different, the preferential elimination of U82-E2 and/or accumulation of U82-E1 in ringed seals (relative to PCB-153) was observed.

The persistent CHLOR metabolite, OXY, accumulated in marine mammals ($BMF_{PCB\text{-}153} \sim 2$) via dietary consumption and biotransformation of chlordane components. However, the formation of (+)-OXY was greater relative to the (−)-enantiomer in the cetaceans and ringed seals analyzed in this study ($p < 0.001$ for all comparisons). While the stereoselective and stereospecific epoxidization of *trans*-chlordane enantiomers has been demonstrated in the laboratory [62], the relationship between the EFs of OXY formed from enantiomer-specific biotransformation and/or accumulation of *cis*- and *trans*-chlordane from diet has not been elucidated. The enrichment of (+)-OXY in cetaceans and ringed seals may be due to the enantiomer-specific biotransformation of the (+)-enantiomers of *cis*- and *trans*-chlordane. However, the elimination of (−)-*trans*-chlordane by the bowhead and beluga whales and (−)-*cis*-chlordane by ringed seals further complicates this interpretation. These results are similar to those observed in ringed seals [20,22] and may be due to incomplete conversion of *cis*- and *trans*-chlordane to OXY within species, enantiomer-specific accumulation of (+)-OXY from prey, preferential elimination of (−)-OXY, and/or other factors not identified by this study.

The rate of accumulation from dietary exposure and/or formation of HEPX was similar to PCB-153 in all marine mammals studied ($BMF_{PCB\text{-}153} \sim 1$). However, the accumulation of HEPX was species and enantiomer specific. The (+)-enantiomer of HEPX was preferentially accumulated in cetaceans to a greater extent than PCB-153, whereas (+)-HEPX was slightly depleted in ringed seal blubber. These data are consistent with previous EFs and $BMF_{PCB\text{-}153}$ reported for this pinniped [20,22] and further illustrates the importance of chiral analysis for understanding the enantiomer-specific biological activities of chiral OCs and the stereoselectivity of metabolism and other processes that may influence contaminant accumulation in biota.

Acknowledgement—The Cooperative Institute for Arctic Research (University of Alaska–Fairbanks, Fairbanks, AK, USA) provided financial support for this project. The authors are very grateful for the provision of samples by Inuit hunters. Benny Akootckok, C.D.N. Brower, H. Brower Jr., L.A. Dehn, J.C. George, C. Rosa, G. Sheffield, R. Suydam, V. Woshner, and many others assisted with sample collection. The help of L. Dehn (UAF) and M. Gosho (NOAA, Seattle, WA, USA) in acquiring the necessary permits and sample transport was indispensable. Analytical standards of MC5, MC7, and U82 were generously provided by M. Oehme, Z. Zencak, and colleagues from the University of Basel (Basel, Germany). C. Teixeira (Environment Canada, Burlington, ON) prepared the XAD-2 resin and performed subsequent extractions. This project would not have been possible without the support of the Department of Wildlife Management, including T. Albert, C.D.N. Brower, D. Norton, L. Dela Rosa, A. Brower, D. Vinas, and C. Willetto.

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