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Cephalopods as a vector for the transfer of cadmium to top marine predators in the north-east Atlantic Ocean

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Abstract

Three hundred and fifty individuals of 12 species of cephalopods which differed in their feeding habitats were sampled from the French Atlantic coast to the sub-Arctic region (Bay of Biscay, English Channel, west Irish coast and Faroe Islands) and analysed for their cadmium contents. Comparison of the Cd levels of the cephalopods showed that those from the sub-Arctic area contained very high Cd concentrations compared to those from lower latitudes such as along the French Atlantic coast. High Cd levels in cephalopods from the sub-Arctic zone correspond closely to the reported high Cd concentrations in the tissues of top vertebrate predators from the same area. Comparison of the weekly Cd intakes for the Faroe Island pilot whales with the 'Provisional Tolerable Weekly Intake' for humans recommended by the World Health Organisation, showed that top vertebrate predators are often subjected to Cd doses far in excess of those recommended for humans. Our limited survey results suggest that cephalopods constitute an important source of Cd for cephalopod predators, and that this bioaccumulation effect is most evident at high latitudes.

Keywords: Cephalopods; Heavy metals; Cadmium; Transfer; Top predators; Dose; Seabirds; Marine mammals

1. Introduction

Cadmium, like other heavy metals, is well known to accumulate in a great number of marine invertebrates, especially bivalve and gastropod molluscs (Bryan, 1984), however, concentrations of cadmium and other metals in cephalopods, one of the essential links in marine trophic chains (Amaratunga, 1983; Rodhouse, 1989; Rodhouse and White, 1995), have rarely been documented. Previous studies have been mostly concerned with essential elements (Ghiretti-Magaldi et al., 1958; Rocca, 1969; Nardi et al., 1971; Martin and Flegal, 1975; Schipp and Hevert, 1978; Miramand and Guary, 1980; Smith et al., 1984; Finger and Smith, 1987; Miramand

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and Bentley, 1992; Bustamante et al., 1998), and reports of levels of toxic metals such as cadmium are relatively few (Renzoni et al., 1973; Martin and Flegal, 1975; Ueda et al., 1979; Miramand and Guary, 1980; Smith et al., 1984; Finger and Smith, 1987; Miramand and Bentley, 1992; Yamada et al., 1997; Bustamante et al., 1998). The studies addressing cadmium levels in cephalopods have shown varied results with high values often present in tissues (Miramand and Guary, 1980; Smith et al., 1984; Finger and Smith, 1987; Miramand and Bentley, 1992) and the very high concentrations in certain cases are remarkable (Martin and Flegal, 1975; Bustamante et al., 1998). Furthermore, all of these studies have highlighted the ability of cephalopods to concentrate cadmium in the digestive gland, even in unpolluted areas like the Kerguelen Islands (Bustamante et al., 1998).

In this paper, we examine the hypothesis that cephalopods from the North Atlantic Ocean are a significant source of cadmium to their predators which in some areas exhibit high levels of this metal in their liver and kidney. This hypothesis was first proposed by Honda and Tatsukawa (1983) for striped dolphins from Japan and by Muirhead and Furness (1988) to explain very high cadmium concentrations in the tissue of squid-eating seabirds from Gough Island. Indeed, a large number of top predators regularly include cephalopods in their diets, or at least ingest them opportunistically. Cephalopods are eaten by many oceanic animals, such as marine mammals (Clarke, 1996; Klages, 1996), seabirds (Croxall and Prince, 1996) and fish (Smale, 1996). Over 80% of Odontocete species and two species of baleen whales regularly include cephalopods in their diets (Clarke, 1996). In 28 Odontocetes, cephalopods comprise the main food with the Ziphiidae and Physeteridae being the principal consumers. Nevertheless, cephalopods are an important part of the diets of all the other Odontocete species: Monodontidae (e.g. narwhal), Phocaenidae (e.g. harbour porpoise), Delphinidae (e.g. common dolphin, pilot whale), Stenidae (e.g. striped dolphin). Among the various cephalopod groups, the Ommastrephidae are the most common cephalopod family consumed by Odontocetes in oceanic waters, and the family Loliginidae is the main squid group consumed in neritic waters (Clarke, 1996). For 31 of the 33 existing species of pinnipeds, it is either known or suspected that cephalopods are a primary food source in their diets (Klages, 1996). Although data are few, the Ommastrephidae, Loliginidae, Onychoteuthidae, Gonatidae and Octopodidae are the most common cephalopod families recorded in the diet of seals. Likewise, a great number of seabirds, such as penguins, procellariforms, pelecaniforms and alcids, are known to feed on cephalopods, mainly squid (Croxall and Prince, 1996). Numerous seabird species prey upon cephalopods which are as important as fish or crustaceans for some albatrosses and petrel species (Croxall and Prince, 1996). Penguins, auks and terns also eat significant quantities of squid during certain seasons. Among the cephalopods, squid are generally the most common prey for seabirds, and the Ommastrephidae, Onychoteuthidae, Histioteuthidae and Gonatidae families probably provide the greatest contributions (Croxall and Prince, 1996).

To estimate the intake of cadmium for cephalopod consumers, cadmium concentrations in cephalopods originating from French, Irish and Faroe Island waters were determined and compared. Then, the weekly intake of cadmium in predators due to ingestion of cephalopods was estimated and compared with the ‘Provisional Tolerable Weekly Intake’ (PTWI) recommended for humans by the WHO (1989).

2. Materials and methods

2.1. Sampling and sample preparation

A large sampling of several species of cephalopods, caught by trawl between 1992 and 1997 in waters of the Bay of Biscay, English Channel, the Atlantic Irish coast and Faroe Islands, have been used in the analysis. Samples were immediately frozen on board in individual plastic bags. In addition, three squids from the Kerguelen Islands were collected in a single stomach of a grey-headed albatross caught by long-lined fisheries. Each individual was weighed and measured (mantle length, total length), and the sex determined. The origin, number of individuals and body weight for each species of cephalopods are given in Table 1. Whenever it was possible, the digestive gland was totally removed from the dissected individuals and treated separately from the remains of the animals. Cadmium concentrations in the whole animals were calculated from concentrations in the remains and in the digestive gland.

2.2. Analytical procedure

Tissue samples were dried for several days at 80°C to a constant weight. Two aliquots of approx. 300 mg of each homogenised dry sample were digested with 4 ml of 65% HNO_3 and 1 ml of 70% $HClO_4$ during 24 h at 80°C. After evaporation, the residues were dissolved in N nitric acid. Blanks were carried through the procedure in the same way as the sample. Cadmium was determined by flame atomic absorption spectrophotometry (AAS) for the digestive gland and by graphite furnace AAS for the remaining tissues using a Varian spectrophotometer Vectra 250 Plus with deuterium background correction. Reference materials, dogfish liver DOLT-2 (NRCC) and MA-A-2 fish-flesh standard (IAEA), were treated and analysed in the same way. Our results for the standard reference materials were in good agreement with certified values. The detection limits for cadmium were 0.05 $\mu g/g$ by flame AAS and 0.003 $\mu g/g$ by flameless AAS.

2.3. Statistical analysis

The hypothesis of normal distribution was tested using the Anderson–Darling test provided in MINITAB for Windows. All the data were normalised by appropriate transformation and null hypotheses were tested by ANOVA followed by Tuckey test. Null hypotheses were rejected at the 95% significance level ($P < 0.05$). Genus *Loligo* (*Loligo vulgaris* and *L. forbesi*) and Ommastrephidae family (*Illex coindetii* and *Todarodes sagittatus*) were used for differences between sites. Differences between families were performed for the Bay of Biscay (Loliginidae, Ommastrephidae, Sepiidae and Octopodidae), the Faroe Islands (Loliginidae, Ommastrephidae and Octopodidae) and the Irish shelf (Loliginidae and Ommastrephidae). Finally, differences between ecological niche were tested with combined data for benthic (Sepiidae and Octopodidae) and pelagic (Loliginidae and Ommastrephidae) cephalopods of all sites.

3. Results

Our sampling included most of the species commonly encountered in French nearshore waters and some other cephalopods from the Irish coast and Faroe Islands. The study analysed both males and females over a large range of size and weight. Cadmium concentrations ($\mu g/g$ wet wt.) in these whole cephalopods are reported in Table 1 along with other values for these cephalopods from the English Channel reported in the literature. In our analysis, the octopus *Eledone cirrhosa* from the Faroe Island shelf exhibited the highest cadmium concentrations, 9.06 ± 3.38 $\mu g/g$ wet wt., while the lowest concentrations were encountered in the Loliginidae squid, *Alloteuthis subulata*, *Loligo forbesi* and *L. vulgaris*, from French and Irish waters with values of approx. 0.10 $\mu g/g$ wet wt. Indeed, statistical analysis showed significant variability in tissue concentrations between species in a same area and between different areas for the same species. Because of the disparity of our data, the difference between areas were only tested for the genus *Loligo* ($F = 27.44$, d.f. = 74, $P < 0.001$) and the Ommastrephidae family ($F = 51.48$, d.f. = 48, $P < 0.001$) which are common to most of the areas (Table 1). The Tuckey test showed no significant differences ($P > 0.05$) between the Bay of Biscay, English Channel and Irish shelf for the genus *Loligo*. Significant differences between species by areas were found in Irish ($F = 22.87$, d.f. = 18, $P < 0.001$), Faroese ($F = 56.75$, d.f. = 41, $P < 0.001$) and French ($F = 22.66$, d.f. = 117, $P < 0.001$) coasts. The Tuckey test showed no significant differences ($P > 0.05$) between Sepiidae and Ommastrephidae from the Bay of Biscay.

Moreover, whatever the origin of the cephalopods was, an ANOVA test showed sig-

Table 1
Compilation of cadmium concentrations (μg/g wet wt.) and cadmium content (μg) in whole cephalopods from different geographical locations in the north-east Atlantic Ocean

Origin and species	Sample size	Fresh weight (g)	Water content (%)	Cd concentration (μg/g wet wt.)	Weekly dose (g/kg)	μg Cd per individual	Reference
Faroe Islands							
Loliginidae							
Loligo forbesi	21	123 ± 61	78 ± 1	0.46 ± 0.30	16.3	57 ± 46	This study
Ommastrephidae							
Todarodes sagittatus	17	221 ± 125	75 ± 2	3.46 ± 1.49	2.0	765 ± 544	This study
Octopodidae							
Eledone cirrhosa	4	448 ± 85	81 ± 1	9.06 ± 3.38	0.8	4059 ± 1699	This study
West Irish shelf							
Loliginidae							
Loligo forbesi	18	91 ± 37	78 ± 1	0.11 ± 0.03	63.6	10 ± 5	This study
Ommastrephidae							
Todarodes sagittatus	5	2692 ± 460	76 ± 3	8.41 ± 5.99	0.8	22 640 ± 16 583	This study
Octopodidae							
Benthoctopus ergasticus	1	1512	87	3.65	1.9	5519	This study
Opisthoteuthidae							
Opisthoteuthis agassizii	1	1206	94	0.70	10.0	844	This study
English Channel							
Loliginidae							
Alloteuthis subulata		–	78	0.31	–	–	Bryan (1976)
Alloteuthis subulata	56	3.5 ± 2.0	78 ± 3	0.37 ± 0.17	18.9	1 ± 1	This study
Loligo forbesi	9	1195 ± 585	78 ± 1	0.10 ± 0.04	70.0	120 ± 76	This study
Loligo vulgaris	8	56 ± 49	75 ± 1	0.10 ± 0.03	70.0	6 ± 5	This study
Octopodidae							
Eledone cirrhosa	15	494 ± 108	78	1.19 ± 0.24	5.9	588 ± 175	Miramand and Bentley (1992)
Sepiidae							
Sepia officinalis	15	518 ± 74	76	0.33 ± 0.01	21.2	171 ± 25	Miramand and Bentley (1992)
Bay of Biscay							
Loliginidae							
Alloteuthis subulata	92	8.4 ± 1.1	78 ± 2	0.10 ± 0.02	70.0	0.8 ± 0.2	This study
Loligo vulgaris	21	118 ± 73	78 ± 3	0.14 ± 0.06	46.7	17 ± 12	This study
Ommastrephidae							
Illex coïndetii	22	165 ± 191	79 ± 2	0.29 ± 0.09	25.0	48 ± 30	This study
Todarodes sagittatus	5	93 ± 113	83 ± 4	0.21 ± 0.02	33.3	20 ± 24	This study
Octopodidae							
Eledone cirrhosa	6	214 ± 146	81 ± 1	0.49 ± 0.10	14.3	105 ± 75	This study
Octopus vulgaris	13	1486 ± 581	82 ± 1	0.54 ± 0.24	13.0	802 ± 475	This study
Sepiidae							
Sepia elegans	14	28 ± 11	75 ± 2	0.90 ± 0.43	7.8	25 ± 16	This study
Sepia officinalis	22	112 ± 85	77 ± 1	0.20 ± 0.06	28.0	22 ± 18	This study
Sepia orbignyana	15	57 ± 24	76 ± 2	0.41 ± 0.28	17.9	23 ± 19	This study

The weekly dose is the cephalopod weight ingested necessary to reach the WHO 'Provisional Tolerable Weekly Intake' limit for humans of 7 μg Cd/kg/week. In most all cases values are mean ± 1 S.D.

nificant differences between benthic and pelagic individuals ($F = 9.85$, d.f. = 192, $P = 0.002$). Cadmium concentrations in the benthic cuttlefish *Sepia elegans* and the octopuses *E. cirrhosa* and *Octopus vulgaris* from the Bay of Biscay were five to nine times higher than those found in the squid *A. subulata* and *L. vulgaris* (Table 1). Likewise, the octopus *E. cirrhosa* from the Faroe Islands exhibited cadmium concentrations 18 times higher than the same species from the Bay of Biscay (Table 1).

According to the World Health Organisation, the limit of cadmium intake is 1 μg/kg/day for humans, i.e. 7 μg/kg/week. The minimum weight of cephalopods necessary to reach these limits has been calculated for each species (in g/kg) and is called 'weekly dose' (Table 1). For the Ommastrephidae squid *Todarodes sagittatus* from Irish waters and the octopus *E. cirrhosa* from the Faroe Islands, the weekly dose was reached with less than 1 g of cephalopod. The total cadmium content in cephalopods was calculated using means of fresh weight and cadmium concentrations (Table 1). Cadmium contents of cephalopods were very high with more than 22 mg of cadmium for a single *T. sagittatus* from Irish waters and more than 4 mg of cadmium for an *E. cirrhosa* from the Faroe Islands (Table 1).

4. Discussion

Cadmium concentrations show high variability in North Atlantic cephalopods with respect to the families, geographical origin and feeding habits (benthic or pelagic). For example, in cephalopods from the Bay of Biscay, the lowest concentrations are encountered in Loliginidae while the highest are found in Octopodidae and Sepiidae (Table 1). These differences may be diet-related: benthic cephalopods (octopuses and cuttlefish) feed mainly on bottom invertebrates [mostly crustaceans, bivalves and polychetes (Boyle, 1990; McQuaid, 1994)] while neritic and pelagic cephalopods (mostly squid) prey mainly on fish and other cephalopods (Rocha et al., 1993; Pierce et al., 1994; Collins and Pierce, 1996). In the same area, fish exhibit lower cadmium concentrations than benthic invertebrates (Cossa and Lassus, 1988), thus diets of the benthic cephalopods should be more rich in cadmium than those based on fish.

In addition, cephalopods show large differences in cadmium concentrations depending upon their origin. For example, the Ommastrephidae squid *Todarodes sagittatus* from the Faroe Islands contained very high cadmium concentrations (approx. 3.5 μg/g wet wt.) while the cadmium levels in the same species of similar sizes from the Bay of Biscay were 17 times lower (Table 1). The same species from Irish waters exhibited very high values (i.e. 8.4 μg/g wet wt., Table 1) perhaps because they are very large individuals. Likewise, cadmium concentrations in the octopus *Eledone cirrhosa* were very different depending on their origin; the lowest levels were encountered in individuals coming from the Bay of Biscay (0.5 μg/g wet wt.) with more elevated concentrations noted in individuals from the English Channel (1.2 μg/g wet wt.) and Faroe Islands (9.1 μg/g wet wt.) (Table 1). Furthermore, with respect to the large differences in cadmium concentrations in cephalopods, species from the sub-Arctic area contained very high cadmium concentrations (Table 1). According to the data in Table 1, the sub-polar area appears to be the region where there is a cadmium enrichment in the food web. If this is true, top predators from polar and sub-polar areas which ingest cephalopods should exhibit high cadmium concentrations in their tissues, particularly in the liver and kidney which are target organs for this metal. Such spatial differences in temperate areas are confirmed when concentrations in the tissues of marine mammals (Wagemann et al., 1990) and seabirds (Schneider et al., 1985; Muirhead and Furness, 1988) are considered. For example, the beluga whale *Delphinapterus leucas* exhibits cadmium concentrations in kidney ranging from 10 to 22 μg/g wet wt. (Wagemann et al., 1990, 1996) in Arctic areas whereas in the same species from the Saint Lawrence estuary, cadmium concentrations in this tissue are approx. 1.5 μg/g wet wt. (Wagemann et al., 1990). Likewise, cadmium concentrations in the liver of the harbour porpoise *Phocoena phocoena* from the Atlantic waters vary from less than 0.07 to 0.5 μg/g wet wt. (Law et al., 1992), whereas some individuals from Greenland have levels as high as 11.9 μg/g in the liver and 72.5 μg/g wet wt. in the kidney (Paludan-Müller et al., 1993).

In older individuals of these species from the Arctic and sub-Arctic areas (e.g. pilot whales, beluga, narwhal), the cadmium concentrations in kidney are close to or higher than critical values established for humans (Hansen et al., 1990; Caurant et al., 1994; Wagemann et al., 1996). A recent study has shown that high cadmium concentrations in the beluga whale and walrus from the Canadian Arctic are in all probability natural (Outridge et al., 1997). Values as high as 500–900 μg/g wet wt. have been measured in some pilot whales from the Faroe Islands (Caurant, 1994). The critical values are approx. 200 μg/g wet wt. in the renal cortex (Lauwerys, 1990). Such cadmium concentrations could lead to severe toxic effects which are nevertheless difficult to show in wild animals. Despite such high concentrations, there is no evidence of a decrease of whale populations in these areas, an observation which suggests physiological adaptations in cadmium metabolism. Indeed, over time, consumers of cephalopods have been subjected to high doses of cadmium, and they probably evolved to withstand cadmium toxicity using efficient detoxification processes, like metallothioneins.

If we consider all existing data on cadmium concentrations in cephalopods, the range of these concentrations varies over one to two orders of magnitude between the lowest levels found in the French waters and the highest in the Faroe Islands (Table 1). Nevertheless, regardless of the origin of the cephalopods, we propose that cephalopods constitute an important source of cadmium for many oceanic top predators in the North Atlantic area. We have estimated the weight of cephalopods necessary to reach the 'Provisional Tolerable Weekly Dose' determined by the World Health Organisation for humans which is relatively low (1 μg cadmium/kg human/day). The maximum weight estimated is approx. 70 g of cephalopod per kilogram of predator with Loliginidae squids from French waters, and the minimum is approx. 1 g/kg for several species of the sub-Polar area [Table 1; *Benthoctopus thielei* and *Graneledone* sp. from Kerguelen Islands (Bustamante et al., 1998)]. For purposes of comparison, the lowest fish weight necessary to reach the equivalent of the PWTI is approx. 70 g fish/kg/week with the Arctic Cod (few data concerning cadmium concentrations in whole fish from high Atlantic Ocean are available, most of them concern muscle or liver levels, see for example Macdonald and Sprague, 1988), but this weight would range from 250 to 3500 g of fish/kg/week for most of the fish species from the French Atlantic coast (Table 2). Hence, consumption of cephalopods results in a high exposure of cadmium to marine predators and could explain the high cadmium concentrations found in their target organs. In the case of pilot whales whose diets have been well-studied (Desportes, 1985; Desportes and Mouritsen, 1993; Gannon et al., 1997a,b), there is strong evidence for a large cadmium contribution from cephalopods to total cadmium intake in this species. For example, very high values of cadmium have been recorded in the liver (63 μg/g wet wt.) and kidney (78 μg/g wet wt.) of pilot whales from the Faroe Islands (Caurant et al., 1994). Caurant et al. (1994) made their estimates of total intake of cadmium from diet studies of pilot whales from the Faroe Islands which found a mean of 18.3 cephalopods per stomach with exceptional numbers as high as 380 cephalopod remains in one stomach (Desportes, 1985; Desportes and Mouritsen, 1993). Our estimates of total cadmium content using the cadmium concentrations found in the squid *Todarodes sagittatus*, the most common prey in the diet of Faroe Island pilot whales (Desportes and Mouritsen, 1993), are approx. 765 μg of cadmium per cephalopod (Table 1). We have calculated a minimum weekly intake of 98 mg of cadmium per week, and a maximum intake was estimated to be approx. 2035 mg of cadmium per week. With a mean weight for pilot whales of 690 kg, the total weekly intake ranges from 142 to 2949 μg/kg/week. This is much higher than values calculated by Caurant and Amiard-Triquet (1995) using another squid prey species, *Loligo forbesi*; their estimates ranged from 25.2 to 516.6 μg/kg/week. All these dosages are much higher

Table 2
Cadmium concentrations in whole fish from different locations in the North Atlantic and the Arctic Oceans

Origin and species	Sample size	Cd concentration (μg/g wet wt.)	Weekly dose (g/kg)	Reference
North American Arctic				
Arctic cod (*Boreogadus saida*)	50	0.10 (0.05–0.19)	70 (37–133)	Macdonald and Sprague (1988)
English Channel				
Pout whiting (*Trisopterus luscus*)		0.004–0.011	636–1750	Miramand (unpublished data)
Sand goby (*Potamoschistus minutus*)	10	0.013 ± 0.008 (0.004–0.028)	538 (250–1750)	Miramand et al. (1997)
Flounder (*Platichtys flesus*)	40	0.005 ± 0.002	1400	Miramand et al., 1998 (in press)
Bass (*Dicentrarchus labrax*)	20	0.006 ± 0.002	1167	Miramand et al., 1998 (in press)
French Atlantic coast				
Sand goby (*Potamoschistus minutus*)	–	0.002	3500	Amiard-Triquet et al. (1983)
Flounder (*Platichtys flesus*)		0.003	2333	Amiard-Triquet et al. (1983)
Dragonet (*Calionymus lyra*)	–	0.009	778	Amiard-Triquet et al. (1983)
Whiting (*Merlangius merlangius*)	–	0.005	1400	Amiard-Triquet et al. (1983)
Pollack (*Pollachius pollachius*)	–	0.008	875	Amiard-Triquet et al. (1983)

The weekly dose is the fish weight ingested necessary to reach the WHO 'Provisional Tolerable Weekly Intake' limit for humans of 7 μg Cd/kg/week. All values were converted from dry wt. to wet wt. concentrations, assuming a wet/dry wt. ratio of 4.0.

than intake reported by Nogawa (1984) as limits beyond which metabolic disorders appear in human beings. This author has shown in Japanese people exposed to cadmium through rice consumption that an increase of metabolic disorders was evident for a weekly intake of 1.41–2.03 mg of cadmium for people older than 50 years. For a mean weight of 70 kg, the weekly intake for humans ranges from 20 to 29 μg/kg/week.

Cephalopods should also play an important role in the transfer of cadmium to seabirds, particularly in the Southern Ocean where a large number of seabird species feed on cephalopods. Indeed, the highest cadmium concentrations in seabirds seem to be related to cephalopod consumption in this area (Muirhead and Furness, 1988). Nevertheless, the only available data concerning cadmium concentrations in cephalopods from the Southern Ocean showed high concentrations in two octopus species from Kerguelen Islands (Bustamante et al., 1998). In this area, they are common food items of black-browed albatrosses during the chick-rearing period (Y. Cherel and H. Weimerskirch, unpublished data) and they have been found in the diet of gentoo penguins (Bost, 1991). Thus, through cephalopod consumption these seabirds could achieve high levels of cadmium in their tissues (Bustamante et al., 1998). Instantaneous intake of cadmium has been estimated for one grey-headed albatross from Kerguelen Islands whose stomach contained the three *Todarodes* sp. (undetermined species between *Todarodes filippovae* or *T. angolensis*). For this albatross weighing 4.8 kg, the stomach contained 0.95 kg of squid and fish which corresponds approx. to the daily food requirement (van Franeker, 1992). The corresponding quantity of cadmium in the stomach contents would be 7653 μg. This value corresponds to a weekly dose of 11.2 mg of Cd/kg of body/week which is approx. 500 times more than the weekly tolerable intake for humans reported by Nogawa (1984). In one feeding, this grey-headed albatross had ingested the equivalent of the Provisional Tolerable Weekly Intake of cadmium for humans for more than 4 years.

Cadmium levels in top vertebrate predators can be very high in sub-polar areas remote from industrial sites (e.g. Faroe Islands, Gough Island, Kerguelen Islands) whereas in the shelf waters of industrialised countries (e.g. French Atlantic coast), vertebrate predators regularly exhibit cadmium concentrations lower than those in similar species from sub-polar areas (Honda et al., 1983; Wagemann et al., 1990; Law et al., 1992; Leonzio et al., 1992; Cardellicchio, 1995; Mackey et al., 1995). This apparent high natural accumulation of cadmium in marine mammals and seabirds can thus be explained by the contribution obtained from consuming cephalopods. The wide variation of cadmium concentrations in cephalopods as a function of their geographical origin and ecological behaviour may explain why top predators bioaccumulate cadmium to relatively high levels in sub-polar areas remote from any industrial area. Although in our study we have measured cadmium levels in five families of cephalopods including 12 different species from the North Atlantic Ocean, we still lack information about most of the important cephalopod families eaten by whales, pinnipeds and seabirds (i.e. Cranchidae, Gonatidae, Histioteuthidae, Onychoteuthidae, Octopoteuthidae). Future works focused on these families should shed further light on the phenomenon of cadmium transfer to top predators in marine food chains.

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