Available online at www.sciencedirect.com
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The Science of the Total Environment 313 (2003) 25–39
the Science of the Total Environment
An International Journal for Scientific Research into the Environment and its Relationship with Man
www.elsevier.com/locate/scitotenv

Distribution of trace elements in the tissues of benthic and pelagic fish from the Kerguelen Islands

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Received 17 June 2002; accepted 12 April 2003

Abstract

New information on the concentrations of Cd, Cu, Hg and Zn in the liver, kidney and muscles of eight marine benthic and pelagic sub-Antarctic fish species are presented to determine the importance of these metals in the marine systems of the Kerguelen Islands. Compared to the reported metal concentrations in other Antarctic fish species, the present results are globally within the same range of concentrations, although Cd displayed a very high interspecific variability in liver and kidney. Indeed, the highest Cd concentrations in liver, ranging from 10.0 to 52.1 $\mu g\ g^{-1}$ dry wt. but also the lowest Cd concentrations in muscles ($<0.030\ \mu g\ g^{-1}$ dry wt.) have been displayed by the pelagic Myctophidae *Gymnoscopelus piabilis*. Metal concentrations differences might be related to diet and feeding habits of benthic and pelagic fish species. However, Cd and Hg concentrations in the edible muscle are lower than the French limit values ($\leqslant 0.155\ \mu g$ Cd g^{-1} dry wt. and $\leqslant 1.51\ \mu g$ Hg g^{-1} dry wt.) for these toxic metals as well as for edible and non-commercially interesting fish species. Results for Cd in fish tissues are consistent with the hypothesis of Cd-enrichment in the polar food webs typically explained by essential elements depletion. In fact, Zn concentrations in fish from the Kerguelen Islands are comparable to those of other areas but low Cu concentrations in fish livers, ranging from 0.9 to 24.7 $\mu g\ g^{-1}$ dry wt., might indicate low availability of this essential element in these sub-Antarctic waters.

Keywords: Antarctic; Heavy metals; Cd-enrichment; Myctophidae

1. Introduction

Heavy metal concentrations in the organisms from the Austral Ocean have been globally poorly investigated. However, all the studies report high toxic metal concentrations, especially for Cd and Hg, in comparison with those from northern temperate waters. Such metals enrichment have been reported for polar areas (Petri and Zauke, 1993; AMAP, 1998; Sanchez-Hernandez, 2000) but in the Antarctic and sub-Antarctic food webs, it remains unclear even if the extreme environmental conditions (e.g. temperature, seasonal alternation, essential elements availability) might play a key role on the processes of uptake, storage and elimination of the metals by organisms. Moreover,

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0048-9697/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0048-9697(03)00265-1

local environmental factors such as volcanism or upwellings could increase metal concentrations in the marine environment.

Specifically, in the Kerguelen Islands environment, high concentrations of Cd have been found to occur in two species of benthic octopuses (Bustamante et al., 1998). Generally, cephalopods are known to strongly accumulate Cd in their digestive gland but the concentrations reported for the Kerguelen octopuses were particularly high. Such high Cd levels have also been reported for some Antarctic zooplankton species as a likely result of very low essential elements availability to these organisms (Rainbow, 1989; Petri and Zauke, 1993). The Cd-enrichment in the zooplankton cannot be fully considered as the direct result of anthropogenic contamination owing to the very low levels reported for other zooplankton species living in the same waters (see the data compiled by Sanchez-Hernandez (2000)).

Several studies report metal concentrations in the tissues of 13 fish species of various Antarctic areas (Honda et al., 1983; Lenihan et al., 1990; Capelli et al., 1991; Szefer et al., 1993; Miganti et al., 1994, 1995; Bargagli et al., 1996, 1998a,b; de Moreno et al., 1997; Marquez et al., 1998). However, no data for the fish from the Kerguelen Islands are available to date. This sub-Antarctic Archipelago is of a great ecological interest since millions of seabirds and numerous marine mammals breed there every year (Guinet et al., 1996). Furthermore, as in many sub-Antarctic areas, commercial fisheries developed at the end of the 1960s, targeting fish of the families Nototheniidae and Channichthyidae (Duhamel and Hureau, 1981). Thus, baseline information on heavy metal concentrations in the tissue of fish are needed in order to evaluate the fish quality for human consumption as well as for piscivorous predators.

For these reasons, selected heavy metals have been analysed in the liver, kidney and muscles of several fish species, including benthic (neritic) and pelagic (oceanic) ones. Thus, 35 specimens representing eight different species from the Kerguelen Island waters have been individually analysed for each Cd, Cu, Hg and Zn contents. Metal concentrations and tissue distribution, are compared between species from different Antarctic areas, and influence of the diet of benthic and pelagic species on the accumulation are discussed.

2. Materials and methods

2.1. Sampling and sample preparation

Pelagic fish were collected on cruises of the RV 'La Curieuse' during austral summer. Myctophidae and Gempylidae were caught in the eastern part of the peri-insular shelf in February 1998, using a IYGPT trawl (International Young Gadoid Pelagic Trawl, opening 12×7 m^2) with 10 mm mesh size in the cone.

Benthic fish were captured either by net fishing overnight in the Morbihan Bay (*Notothenia rossii* and *Paranotothenia magellanica*) or by commercial trawling on the Kerguelen shelf (*Channichthys rhinoceratus*, *Champsocephalus gunnari* and *Lepidonotothen squamifrons*) (Table 1).

The fish were separated by species and stored on board at -20 °C in plastic bags prior to analysis. Subsequently, the length, weight and sex of fish were determined. Moreover, otoliths of Myctophidae species were taken out to ensure identification of the species. Then, specimens were dissected and liver, kidney and muscle tissues were treated separately. The remainders of each dissected individual were also analysed individually in view of determining the percentage distribution of the metals. Characteristics of the samples (i.e. family, species, length, weight and sex) are shown in Table 1.

2.2. Analytical procedure

Separated tissue samples were dried to a constant weight for several days at 60 °C and then homogenised. Whenever possible, two aliquots of approximately 300 mg of each homogenised dry sample were digested with 5 ml of 65% HNO_3 and 0.3 ml of 70% $HClO_4$ at 80 °C for 24 h. The residues obtained after evaporation of the acids were dissolved in 0.3 N nitric acid. Cd, Cu and Zn were assayed using flame and graphite furnace atomic absorption spectrophotometer Varian 250 Plus with deuterium background correction.

Table 1
Characteristics of the fish samples, together with the water content in the tissues and organs allowing conversion of dry wt. to wet wt. metal concentrations

Family / Species	Localisation	Sample size	Length (mm)	Fresh weight (g)	Sex	Water content (%) Liver	Kidney	Muscle
Pelagic fish								
Gempylidae								
Paradiplospinus gracilis	Oceanic zone	1	370	67	♂	55	78	71
Myctophidae								
Gymnoscopelus nicholsi	Oceanic zone	4	144±15	31±8	4 ♀	42±6	45±11	62±2
G. piabilis	Oceanic zone	5	151±11	37±6	5 ♀	56±8	48±15	76±3
Benthic fish								
Channichthyidae								
Champsocephalus gunnari	Kerguelen shelf	5	314±13	202±34	1 ♂, 4 ♀	73±2	73±5	76±2
Channichthys rhinoceratus	Kerguelen shelf	5	344±52	435±150	2 ♂, 3 ♀	75±4	83±2	81±3
Nototheniidae								
Paranothothenia magellanica	Morbihan Bay	5	157±8	92±17	2 ♂, 3 ♀	77±2	81±2	78±0
Notothenia rossii	Morbihan Bay	5	237±41	300±135	2 ♂, 3 ♀	73±4	81±1	80±1
Lepidonotothen squamifrons	Kerguelen shelf	5	284±29	279±90	3 ♂, 2 ♀	71±8	78±4	76±2

For Hg, aliquots ranging from 10 to 50 mg of dried material have been analysed directly in a advanced mercury analyser spectrophotometer, Altec AMA 254. Hg determination involved evaporation of Hg by progressive heating until 800 °C under oxygen atmosphere for 3 min and subsequent amalgamation on a Au-net. Afterwards, the net was heated to liberate the collected mercury and subsequently measured by UV atomic absorption spectrophotometry. However, Hg analysis were not performed in the liver and kidney of the pelagic fish nor for *Lepidonotothen squamifrons*.

Quality assurance was assessed using dogfish liver DOLT-2 (NRCC) and dogfish muscle DORM-2 (NRCC) as reference materials. These standards were treated and analysed under the same conditions as the fish samples, and recoveries of the metals ranged from 92 to 105%. Detection lifmits, calculated as 3 S.D. of the mean of eight blanks, were 0.004 for Cd, 0.5 for Cu, 3 for Zn and 0.005 for Hg ($\mu g\, g^{-1}$ dry wt.). All metal concentrations in fish tissues are also reported in $\mu g\, g^{-1}$ dry wt. Water contents allowing recalculations of the metal concentrations from dry wt. to wet wt. are given in Table 1.

2.3. Statistical procedures

Statistically analysis of results used commercially available packages. As concentration of some elements did not follow a normal distribution, non-parametric analysis using Kruskall–Wallis test for multiple comparisons and Mann–Whitney *U*-test were performed in the MINITAB 13.1 for WINDOWS. A statistically significant difference was considered to exist whenever the probability is lower than $P \leqslant 0.05$.

3. Results

Results on heavy metal concentrations in the tissues of fish from the Kerguelen Islands are compiled in Tables 2–4 for liver, kidney and muscle, respectively.

In liver, metal concentrations exhibited a large variability among species. For Hg, concentrations differ in two orders of magnitude, i.e. between 0.042 and 1.51 $\mu g\, g^{-1}$ dry wt. The Myctophidae *Gymnoscopelus piabilis* and the Notothenidae *Lepidonotothen squamifrons* showed significantly higher Cd and Zn concentrations in liver. For Cu

Table 2
Mean ± S.D. and range of the metal concentrations (μg g^{-1} dry wt.) in the liver of benthic and pelagic fish from the Kerguelen Island waters

<table>
<tr><th>Metal</th><th></th><th>Species</th><th>N</th><th>Mean ± S.D.</th><th>Range</th><th colspan="3">Group</th></tr>
<tr><th></th><th></th><th></th><th></th><th></th><th></th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>Cd</td><td>Pelagic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paradiplospinus gracilis</td><td>1</td><td>–</td><td>0.94</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Gymnoscopelus nicholsi</td><td>4</td><td>4.23 ± 0.34</td><td>3.90–4.66</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>G. piabilis</td><td>5</td><td>28.5 ± 16.9</td><td>10.0–52.1</td><td></td><td></td><td>|</td></tr>
<tr><td></td><td>Benthic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Notothenia rossii</td><td>5</td><td>2.82 ± 1.60</td><td>0.82–4.26</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paranothothenia magellanica</td><td>5</td><td>4.15 ± 2.19</td><td>2.03–7.35</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Channichthys rhinoceratus</td><td>5</td><td>4.37 ± 2.00</td><td>2.73–6.78</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Champsocephalus gunnari</td><td>5</td><td>5.52 ± 4.48</td><td>1.04–10.6</td><td>|</td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Lepidonotothen squamifrons</td><td>5</td><td>10.8 ± 4.59</td><td>5.42–15.4</td><td></td><td>|</td><td>|</td></tr>
<tr><td>Cu</td><td>Pelagic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paradiplospinus gracilis</td><td>1</td><td>–</td><td>14.1</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Gymnoscopelus nicholsi</td><td>4</td><td>5.8 ± 1.3</td><td>5.1–7.5</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>G. piabilis</td><td>5</td><td>10.2 ± 3.5</td><td>6.3–14.8</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td>Benthic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Notothenia rossii</td><td>5</td><td>4.8 ± 1.6</td><td>3.2–7.3</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paranothothenia magellanica</td><td>5</td><td>16.8 ± 4.5</td><td>13.7–24.7</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Channichthys rhinoceratus</td><td>5</td><td>4.0 ± 1.2</td><td>3.2–6.1</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Champsocephalus gunnari</td><td>5</td><td>3.1 ± 2.5</td><td>0.9–7.1</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Lepidonotothen squamifrons</td><td>5</td><td>3.8 ± 1.1</td><td>2.5–5.6</td><td>|</td><td></td><td></td></tr>
<tr><td>Hg</td><td>Pelagic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paradiplospinus gracilis</td><td>1</td><td>NA</td><td>–</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Gymnoscopelus nicholsi</td><td>4</td><td>NA</td><td>–</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>G. piabilis</td><td>5</td><td>NA</td><td>–</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Benthic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Notothenia rossii</td><td>5</td><td>0.513 ± 0.208</td><td>0.219–0.743</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Paranothothenia magellanica</td><td>5</td><td>0.370 ± 0.114</td><td>0.245–0.524</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Channichthys rhinoceratus</td><td>5</td><td>0.686 ± 0.510</td><td>0.160–1.51</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Champsocephalus gunnari</td><td>5</td><td>0.047 ± 0.006</td><td>0.042–0.055</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Lepidonotothen squamifrons</td><td>5</td><td>0.078 ± 0.032</td><td>0.052–0.133</td><td>|</td><td></td><td></td></tr>
<tr><td>Zn</td><td>Pelagic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Paradiplospinus gracilis</td><td>1</td><td>–</td><td>112</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Gymnoscopelus nicholsi</td><td>4</td><td>92.9 ± 18.2</td><td>70.8–113</td><td>|</td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>G. piabilis</td><td>5</td><td>142 ± 30.6</td><td>108–184</td><td></td><td></td><td>|</td></tr>
<tr><td></td><td>Benthic</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Notothenia rossii</td><td>5</td><td>99.0 ± 18.9</td><td>75.6–119</td><td></td><td>|</td><td></td></tr>
<tr><td></td><td></td><td>Paranothothenia magellanica</td><td>5</td><td>143 ± 16.2</td><td>123–165</td><td></td><td></td><td>|</td></tr>
<tr><td></td><td></td><td>Channichthys rhinoceratus</td><td>5</td><td>70.4 ± 13.8</td><td>61.4–93.0</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Champsocephalus gunnari</td><td>5</td><td>62.7 ± 32.0</td><td>28.8–100</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Lepidonotothen squamifrons</td><td>5</td><td>110 ± 32.3</td><td>63.5–149</td><td></td><td>|</td><td>|</td></tr>
</table>

N, independent samples. NA, not analysed. Bars (|) indicates groups identified by non-parametric tests.

Table 3
Mean ± S.D. and range of the metal concentrations (μg g^{-1} dry wt.) in the kidney of benthic and pelagic fish from the Kerguelen Island waters

Metal		Species	*N*	Mean ± S.D.	Range	Group				
						1	2	3	4	5
Cd	Pelagic									
		Paradiplospinus gracilis	1	–	1.69					
		Gymnoscopelus nicholsi	4	2.66 ± 1.03	2.07–4.19			|		
		G. piabilis	5	15.7 ± 8.10	5.92–28.5					|
	Benthic									
		Notothenia rossii	5	0.13 ± 0.09	0.04–0.27	|				
		Paranothothenia magellanica	5	0.28 ± 0.20	0.10–0.59	|	|			
		Channichthys rhinoceratus	5	0.31 ± 0.10	0.20–0.43		|			
		Champsocephalus gunnari	4	2.57 ± 0.78	1.58–3.31			|		
		Lepidonotothen squamifrons	5	4.28 ± 1.42	1.99–5.89				|	
Cu	Pelagic									
		Paradiplospinus gracilis	1	–	7.2					
		Gymnoscopelus nicholsi	4	4.8 ± 1.3	3.5–6.4	|	|			
		G. piabilis	5	10.7 ± 5.4	6.1–19.5			|		
	Benthic									
		Notothenia rossii	5	3.7 ± 0.7	3.0–4.9	|				
		Paranothothenia magellanica	5	4.4 ± 0.8	3.7–5.7		|			
		Channichthys rhinoceratus	5	3.2 ± 0.7	2.1–3.8	|				
		Champsocephalus gunnari	4	2.2 ± 0.7	1.2–2.7	|				
		Lepidonotothen squamifrons	5	4.0 ± 1.0	2.9–4.8	|				
Hg	Pelagic									
		Paradiplospinus gracilis	1	NA	–					
		Gymnoscopelus nicholsi	4	NA	–					
		G. piabilis	5	NA	–					
	Benthic									
		Lepidonotothen squamifrons	5	NA	–					
		Notothenia rossii	5	0.470 ± 0.252	0.134–0.721			|		
		Paranothothenia magellanica	5	0.102 ± 0.010	0.092–0.119		|			
		Channichthys rhinoceratus	5	0.533 ± 0.327	0.172–1.05			|		
		Champsocephalus gunnari	4	0.030 ± 0.006	0.024–0.038	|				
Zn	Pelagic									
		Paradiplospinus gracilis	1	–	110					
		Gymnoscopelus nicholsi	4	86.2 ± 6.8	77.4–93.5	|	|			
		G. piabilis	5	113 ± 23.1	86.1–146		|	|		
	Benthic									
		Notothenia rossii	5	84.1 ± 8.8	70.5–92.3	|				
		Paranothothenia magellanica	5	138 ± 15.9	122–161			|		
		Channichthys rhinoceratus	5	143 ± 38.3	102–202			|		
		Champsocephalus gunnari	4	85.7 ± 15.2	69.4–106	|	|			
		Lepidonotothen squamifrons	5	181 ± 66.4	113–264			|		

N, independent samples. NA, not analysed. Bars (|) indicates groups identified by non-parametric tests.

Table 4
Mean ± S.D. and range of the metal concentrations ($\mu g\ g^{-1}$ dry wt.) in the muscle of benthic and pelagic fish from the Kerguelen Island waters

Metal		Species	Mean ± S.D.	Range	*N*	Group			
						1	2	3	4
Cd	Pelagic								
		Paradiplospinus gracilis	–	0.006	1				
		Gymnoscopelus nicholsi	0.010 ± 0.008	0.004–0.021	4	|			
		G. piabilis	0.016 ± 0.009	0.006–0.029	5	|			
	Benthic								
		Notothenia rossii	0.049 ± 0.011	0.034–0.064	5		|		
		Paranothothenia magellanica	0.035 ± 0.021	0.014–0.063	5	|	|		
		Channichthys rhinoceratus	0.051 ± 0.025	0.024–0.090	5		|		
		Champsocephalus gunnari	0.086 ± 0.052	0.034–0.155	5		|		
		Lepidonotothen squamifrons	0.053 ± 0.026	0.026–0.085	5		|		
Cu	Pelagic								
		Paradiplospinus gracilis	–	0.4	1				
		Gymnoscopelus nicholsi	2.5 ± 0.7	1.9–3.4	4			|	
		G. piabilis	1.2 ± 0.4	0.8–1.7	5		|		
	Benthic								
		Notothenia rossii	0.7 ± 0.1	0.6–0.9	5	|	|		
		Paranothothenia magellanica	0.9 ± 0.0	0.9–1.0	5		|		
		Channichthys rhinoceratus	0.5 ± 0.2	0.2–0.8	5	|			
		Champsocephalus gunnari	0.6 ± 0.1	0.4–0.8	5	|			
		Lepidonotothen squamifrons	1.0 ± 0.3	0.7–1.4	5		|		
Hg	Pelagic								
		Paradiplospinus gracilis	–	0.251	1				
		Gymnoscopelus nicholsi	0.205 ± 0.126	0.157–0.297	4		|	|	
		G. piabilis	0.310 ± 0.126	0.177–0.475	5			|	
	Benthic								
		Notothenia rossii	0.255 ± 0.059	0.192–0.344	5			|	
		Paranothothenia magellanica	0.140 ± 0.037	0.097–0.191	5		|		
		Channichthys rhinoceratus	1.19 ± 0.367	0.606–1.51	5				|
		Champsocephalus gunnari	0.044 ± 0.012	0.034–0.065	5	|			
		Lepidonotothen squamifrons	0.126 ± 0.033	0.094–0.180	5		|		
Zn	Pelagic								
		Paradiplospinus gracilis	–	10.0	1				
		Gymnoscopelus nicholsi	9.2 ± 4.0	6.6–15.0	4	|			
		G. piabilis	9.9 ± 1.2	8.4–11.3	5	|			
	Benthic								
		Notothenia rossii	19.6 ± 1.1	18.6–21.0	5		|		
		Paranothothenia magellanica	22.0 ± 1.6	20.2–23.7	5			|	
		Channichthys rhinoceratus	33.2 ± 7.4	23.6–40.7	5				|
		Champsocephalus gunnari	29.1 ± 1.9	27.1–31.1	5				|
		Lepidonotothen squamifrons	19.9 ± 2.6	16.7–22.9	5		|	|	

N, independent samples. Bars (\|) indicates groups identified by non-parametric tests.

and Zn, *Paranothothenia magellanica* also exhibited the highest concentrations. Among the three organs considered, liver displays the highest Cd and Cu concentrations. Compared to muscle, hepatic Cd concentrations are 2–4 orders of magnitude higher whereas Cu concentrations are only 2–10 times higher (Table 2).

Despite the heterogeneity of metal concentrations in liver, no clear segregation between pelagic and benthic fish could be done. This was also the case for kidney. Compared to muscle, kidney shows elevated concentrations of Cd and Cu. Among the three tissues, kidney had the highest Zn but the lowest Hg concentrations. As in liver, the Myctophidae *G. piabilis* and the Notothenidae *L. squamifrons* exhibited significantly higher renal Cd concentrations compared to the other fish species. Renal Cu concentrations were significantly elevated only for *G. piabilis* (Table 3).

Compared to the results for liver and kidney, Cd, Cu and Zn concentrations appeared to be low in fish muscles although the important variability among species is remarkable (Table 4). Muscular Cd and Zn concentrations were generally lower in pelagic fish than in benthic ones. Similarly, mean Hg concentrations varied on three orders of magnitude in the muscle (from 0.044 to 1.19 $\mu g\,g^{-1}$ dry wt.) in both benthic and pelagic fish. Nevertheless, the Channichthydae *Channichthys rhinoceratus* exhibited clearly the highest Hg concentrations (Table 4).

Complete dissection of fish allowed to calculate the distribution of metals between liver, kidney (representing less than 5% and than 1% of the whole body mass, respectively) and the remaining tissue including muscle. The percentage of each metal contained in these compartments is shown in Table 5.

Cd and Cu concentrations displayed the same distribution pattern in the tissues of benthic and pelagic fish: liver > kidney > muscle. Despite several orders of magnitude between Cd concentrations in muscle and liver, the latter generally contained less than 50% of the total body burden of metal. Thus, most of this Cd was muscular except for the Channichthydae *C. rhinoceratus* (87% of Cd located in liver; Table 5). Owing to the small differences between muscle and liver Cu concentrations and to the respective proportions of these tissues in the fresh weight of fish, less than 20% of the metal was stored in the hepatic compartment (Table 5).

Zn concentrations showed the following sequence: kidney > liver > muscle but the two first organs contained less than 15% of the total body burden of Zn.

Although no clear differences of concentrations between the three tissues appears, the muscular parts of fish contained up to 90% of the total body burden of Hg due to its significance (Table 5).

4. Discussion

4.1. Levels of trace metals

Despite the past and present human fishing pressure on some of the Austral Ocean areas and their major role in the ecosystems (Guinet et al., 1996; Chérel et al., 2000), data on metal levels in the fish still lacks. Such assessment is particularly true for the sub-Antarctic zone while Antarctic Ocean is more documented. Thus, this study represents the first investigation concerning the distribution of trace elements in the tissue of eight fish species from the sub-Antarctic Kerguelen Islands. A recent review of trace element contamination around Antarctica (Sanchez-Hernandez, 2000) allows to compare the present results with those of several fish species from the Antarctic Ocean.

Overall, the present results about metal concentrations in the tissues of benthic and pelagic fish from the Kerguelen Islands waters fall within the range for the other fish species from the Antarctic Ocean (data compiled in Tables 6–8). Reported data for fish liver (Table 6) range from 0.86 to 21.6 μg Cd g^{-1}, from 3.3 to 92 μg Cu g^{-1}, from 0.02 to 0.82 μg Hg g^{-1} and from 87.7 to 106 μg Zn g^{-1} (values are expressed in dry wt. after conversion from wet wt. for some data using a 4.0 correction factor). Generally, the heavy metal levels in fish liver from the Kerguelen Islands tended to be slightly higher than those reported in the current literature (Table 6), except for Hg which is closely in the same concentration range.

Concerning kidney, data for Antarctic fish are rarely reported (Table 7). They range from 0.17

Table 5
Distribution of the metals in benthic and pelagic fish from the Kerguelen Islands waters

Metal	Habitat	Species	*N*	Liver	Kidney	Muscular parts and remainders
Cd	Pelagic	*Paradiplospinus gracilis*	1	11.7	1.5	86.8
		Gymnoscopelus nicholsi	4	36.1±13.1	4.0±1.7	59.9±13.9
		G. piabilis	5	47.8±15.4	5.7±2.5	46.5±17.6
	Benthic	*Champsocephalus gunnari*	5	13.8±12.0	0.6±0.6	85.6±12.3
		Channichthys rhinoceratus	5	87.1±7.5	0.6±0.4	12.4±7.2
		Paranothothenia magellanica	5	21.3±5.2	0.6±0.3	78.1±5.7
		Notothenia rossii	5	41.2±14.2	0.5±0.3	58.3±15.0
		Lepidonotothen squamifrons	5	28.7±11.2	2.1±1.1	69.2±12.7
Cu	Pelagic	*Paradiplospinus gracilis*	1	19.6	0.7	79.7
		Gymnoscopelus nicholsi	4	6.2±2.5	1.0±0.6	92.4±5.7
		G. piabilis	5	11.3±3.0	2.3±0.8	86.5±3.3
	Benthic	*Champsocephalus gunnari*	5	5.1±5.0	0.3±0.3	94.5±5.3
		Channichthys rhinoceratus	5	7.5±1.1	0.5±0.2	92.0±0.9
		Paranothothenia magellanica	5	10.9±2.7	1.1±0.1	87.9±3.9
		Notothenia rossii	5	6.8±2.8	1.4±0.3	91.8±2.6
		Lepidonotothen squamifrons	5	6.5±5.2	0.9±0.1	92.6±8.8
Hg	Benthic	*Champsocephalus gunnari*	5	2.8±0.8	0.1±0.1	97.1±1.8
		Channichthys rhinoceratus	5	4.3±1.6	0.4±0.3	95.4±1.2
		Paranothothenia magellanica	5	5.6±3.0	0.6±0.3	93.8±4.2
		Notothenia rossii	5	7.1±2.6	1.7±0.6	91.2±2.9
		Lepidonotothen squamifrons	5	1.5±1.0	N.D.	98.5±1.5
Zn	Pelagic	*Paradiplospinus gracilis*	1	8.9	0.6	81.5
		Gymnoscopelus nicholsi	4	10.7±2.0	1.9±0.9	87.3±3.9
		G. piabilis	5	2.3±5.2	1.9±0.3	95.9±5.2
	Benthic	*Champsocephalus gunnari*	5	2.0±1.1	0.2±0.2	97.8±1.4
		Channichthys rhinoceratus	5	3.1±0.8	0.7±0.7	96.3±1.7
		Paranothothenia magellanica	5	3.7±0.5	1.4±0.2	95.0±1.3
		Notothenia rossii	5	6.0±1.6	1.4±0.4	92.6±2.1
		Lepidonotothen squamifrons	5	4.7±2.7	1.2±0.2	94.1±5.0

Mean%±S.D. referred to the fresh weight of organs and tissues. ND, not determined.

to 10.1 μg Cd g^{-1}, and from 0.09 to 2.60 μg Hg g^{-1} (dry wt.) while the only values reported for Cu and Zn concern two benthic species, i.e. *Notothenia coriiceps* (Marquez et al., 1998) and *Trematomus bernacchii* (Bargagli et al., 1998b). Despite such few data, it also appears that several fish species from the Kerguelen Islands show higher heavy metal concentrations in the kidney compared to other Antarctic fish species. More fish muscle values from the Antarctic Ocean are available (Table 7). Thus, our results are closely within the same range of the reported data: from 0.01 to 1.0 μg Cd g^{-1}, from 0.2 to 2.5 μg Cu g^{-1}, from 0.01 to 1.79 μg Hg g^{-1} and from 2.0 to 125 μg Zn g^{-1} (values are expressed in dry wt. after conversion from wet wt. for some data using a 5.0 correction factor). Considering the French limit value for human consumption of toxic metals, i.e. 0.5 μg g^{-1} for Cd and 2.5 μg g^{-1} for Hg (CSHPF, 1995), metal concentrations in fish

Table 6
Metal concentrations in the liver of fish from the Antarctic Ocean

Species	Sample area	*N*	Cd	Cu	Hg	Zn	Basis	Reference
Chaenocephalus aceratus	Antarctic peninsula	4	1.01–1.25	3.3–5.4	–	87.7–106.0	dry wt.	Szefer et al. (1993)
Chionodraco hamatus	Terra Nova Bay	20	1.02–14.53	–	–	–	dry wt.	Bargagli et al. (1996)
Chionodraco hamatus	Terra Nova Bay	18	–	–	0.02–0.44	–	dry wt.	Bargagli et al. (1998a,b)
Chionodraco hamatus	Terra Nova Bay	16	0.99±0.97	0.85±0.70	–	18.70±5.13	dry wt.	Santovito et al. (2000)
Cryodraco antarcticus	Terra Nova Bay	6	0.86–4.25	–	–	–	dry wt.	Bargagli et al. (1996)
Notothenia coriiceps (male)	South Shetland Islands	9	–	2.46±0.84	–	29.55±8.64	wet wt.	Marquez et al. (1998)
Notothenia coriiceps (female)	South Shetland Islands	10	–	1.58±0.38	–	23.62±2.20	wet wt.	Marquez et al. (1998)
Pagothenia borchgrevinski	Syowa Station	18	0.30–2.46	0.92–5.88	0.005–0.026	22.4–34.2	wet wt.	Honda et al. (1983)
Trematomus bernacchii	Terra Nova Bay	18	3.36–21.60	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus bernacchii	Terra Nova Bay	11	–	–	0.10–0.82	–	dry wt.	Bargagli et al. (1998a,b)
Trematomus bernacchii	Terra Nova Bay	15	7.30±5.61	5.19±3.03	–	44.35±24.72	dry wt.	Santovito et al. (2000)
Trematomus hansoni	Terra Nova Bay	18	5.09–16.42	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus hansoni	Terra Nova Bay	18	–	–	0.08–0.69	–	dry wt.	Bargagli et al. (1998a,b)
Trematomus newnesi	Terra Nova Bay	8	0.98–5.75	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus newnesi	Terra Nova Bay	7	–	–	0.09–0.28	–	dry wt.	Bargagli et al. (1998a,b)
Trematomus sp.	Winter Quarters Bay	–	5.0–21.0	5.0–23	–	110–140	wet wt.	Lenihan et al. (1990)
Trematomus sp.	Cinder cones	–	12±4	14±2	–	127±25	wet wt.	Lenihan et al. (1990)

Values represent the ranges or Mean±S.D., expressed as $\mu g\ g^{-1}$ dry wt. or wet wt.

Table 7
Metal concentrations in the kidney of fish from the Antarctic Ocean

Species	Sample area	*N*	Cd	Cu	Hg	Zn	Basis	Reference
Chionodraco hamatus	Terra Nova Bay	20	0.26–0.87	–	–	–	dry wt.	Bargagli et al. (1996)
Chionodraco hamatus	Terra Nova Bay	20	–	–	0.10–0.85	–	dry wt.	Bargagli et al. (1998a)
Cryodraco antarcticus	Terra Nova Bay	6	0.18–0.62	–	–	–	dry wt.	Bargagli et al. (1996)
Notothenia coriiceps (male)	South Shetland Islands	10	–	1.56 ± 0.43	–	23.30 ± 6.63	wet wt.	Marquez et al. (1998)
Notothenia coriiceps (female)	South Shetland Islands	10	–	1.72 ± 0.56	–	23.69 ± 10.16	wet wt.	Marquez et al. (1998)
Pagothenia bernacchii	Terra Nova Bay	16	–	–	0.227–2.50	–	dry wt.	Capelli et al. (1991)
Trematomus bernacchii	Terra Nova Bay	18	2.05–10.11	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus bernacchii	Terra Nova Bay	10	–	–	0.32–2.60	–	dry wt.	Bargagli et al. (1998a)
Trematomus bernacchii	Terra Nova Bay	27	1.8–3.0	5.1–5.7	0.47–0.83	110–116	dry wt.	Bargagli et al. (1998b)
Trematomus hansoni	Terra Nova Bay	18	1.60–3.29	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus hansoni	Terra Nova Bay	13	–	–	0.10–1.75	–	dry wt.	Bargagli et al. (1998a)
Trematomus newnesi	Terra Nova Bay	8	0.17–3.91	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus newnesi	Terra Nova Bay	8	–	–	0.09–0.82	–	dry wt.	Bargagli et al. (1998a)

Values represent the ranges or mean expressed as $\mu g\ g^{-1}$ dry wt. or wet wt.

Table 8
Metal concentrations in the muscle of fish from the Antarctic Ocean

Species	Sample area	*N*	Cd	Cu	Hg	Zn	Basis	Reference
Chionodraco hamatus	Terra Nova Bay	20	0.01–0.03	–	–	–	dry wt.	Bargagli et al. (1996)
Chionodraco hamatus	Terra Nova Bay	7	–	–	0.01–0.92	–	dry wt.	Bargagli et al. (1998a)
Chionodraco hamatus	Terra Nova Bay	10	0.97 ± 0.47	0.70 ± 0.67	–	6.27 ± 3.73	dry wt.	Santovito et al. (2000)
Chaenocephalus aceratus	Antarctic peninsula	3	0.05–0.13	1.0–2.0	–	28.6–35.5	dry wt.	Szefer et al. (1993)
Cryodraco antarcticus	Terra Nova Bay	6	0.01–0.06	–	–	–	dry wt.	Bargagli et al. (1996)
Notothenia coriiceps (male)	South Shetland Islands	10	–	1.00 ± 0.34	–	4.77 ± 1.08	wet wt.	Marquez et al. (1998)
Notothenia coriiceps (male)	South Orkney Islands	11	< 0.05	0.04–0.50	0.01–0.10	1.00–6.70	wet wt.	de Moreno et al. (1997)
Notothenia coriiceps (female)	South Shetland Islands	10	–	4.79 ± 0.81	–	1.01 ± 0.62	wet wt.	Marquez et al. (1998)
Notothenia coriiceps (female)	South Orkney Islands	17	< 0.05	0.05–0.40	0.01–0.09	2.00–5.40	wet wt.	de Moreno et al. (1997)
Notothenia gibberifrons	Antarctica	3	0.02–0.04	0.71–0.98	–	20.7–24.2	dry wt.	Szefer et al. (1993)
Pagothenia borchgrevinski	Syowa Station	22	0.01–0.04	0.17–1.39	0.002–0.009	4.27–8.15	wet wt.	Honda et al. (1983)
Pagothenia bernacchii	Terra Nova Bay	18	–	–	0.230–0.990	–	dry wt.	Miganti et al. (1994)
Trematomus bernacchii	Terra Nova Bay	18	0.01–0.08	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus bernacchii	Terra Nova Bay	12	–	–	0.17–1.79	–	dry wt.	Bargagli et al. (1998a)
Trematomus bernacchii	Terra Nova Bay	27	0.03–0.05	1.9–2.5	0.49–0.74	22.8–23.6	dry wt.	Bargagli et al. (1998b)
Trematomus bernacchii	Terra Nova Bay	10	0.74 ± 0.48	0.32 ± 0.23	–	2.88 ± 1.89	dry wt.	Santovito et al. (2000)
Trematomus hansoni	Terra Nova Bay	18	0.01–0.05	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus hansoni	Terra Nova Bay	15	–	–	0.11–1.08	–	dry wt.	Bargagli et al. (1998a)
Trematomus newnesi	Terra Nova Bay	8	0.02–0.05	–	–	–	dry wt.	Bargagli et al. (1996)
Trematomus newnesi	Terra Nova Bay	7	–	–	0.09–0.82	–	dry wt.	Bargagli et al. (1998a)
Trematomus sp.	Winter Quarters Bay	–	0.1–0.2	0.1–0.3	–	0.4–25	wet wt.	Lenihan et al. (1990)
Trematomus sp.	Cinder cones	–	0.2	0.9 ± 0.8	–	41 ± 13	wet wt.	Lenihan et al. (1990)

Values represent the ranges or mean expressed as $\mu g\ g^{-1}$ dry wt. or wet wt.

muscles appear to be low, as well for the commercially fished species like *C. rhinoceratus*, *C. gunnari* and *N. rossii*, than for the other species presented here.

Heavy metals investigations in fish mainly consider concentrations in muscle and/or in liver, in detriment of gills or kidney as well. Furthermore, little information concerning metal distribution has been reported especially for the Antarctic fish. For this reason, comparison with fish outside the Austral Ocean was necessary and revealed that metal distribution in the tissues of Austral Ocean fish is very similar to that of fish from the temperate waters (Miramand et al., 1991).

4.2. Interference on routes of metal uptake

The very low Cd concentrations in the muscle of most of the fish species investigated (including Myctophidae) suppose effective processes of Cd sequestration in liver and kidney and demonstrate that dietary uptake of Cd is likely to be the most important route of assumption in Kerguelen Islands fish. Enrichment of cadmium in liver and kidney with respect to muscles is particularly evident for zooplankton-eating fish, such as Myctophidae (Hulley, 1990). Thus, these species from the Kerguelen Islands displayed the highest Cd concentrations in liver and kidney, i.e. from 10.0 to 52.1 $\mu g\ g^{-1}$ dry wt. in *G. piabilis* compared to 0.86–21.6 $\mu g\ g^{-1}$ dry wt. in the liver of the species from other areas (Table 6). The diet of *Gymnoscopelus* consists of crustaceans plankton including euphausiids and euphausiid larvae, hyperiids and mysids (Hulley, 1990). Some of these planktonic species from the Austral Ocean (e.g. euphausiids) exhibit relatively high levels of Cd for crustaceans, with values ranging from 0.15 to 3.4 $\mu g\ g^{-1}$ dry wt. in the krill *Euphausia superba* (Rainbow, 1989; Petri and Zauke, 1993). However, some other planktonic species could reach extremely high levels of Cd like the hyperiid amphipod *Themisto gaudichaudii*, which concentrate the metal from 8.0 to 118 $\mu g\ g^{-1}$ dry wt. (Hennig et al., 1985; Rainbow, 1989). Similarly to those reported results, *T. gaudichaudii* show very high Cd concentrations ranging from 21.2 to 81.7 $\mu g\ g^{-1}$ dry wt. in the Kerguelen Island waters (Bustamante, unpublished data). Thus, the high Cd levels recorded in the kidney and liver of *G. piabilis* would be a direct result of a Cd-rich diet. On the contrary, fish species having the lowest Cd concentrations in their tissues, e.g. *N. rossii* or *P. magellanica*, are benthic feeders, and include algae, polychaetes, crustaceans, gastropods and fish in their diet (Gon and Heemstra, 1990). However, the *Trematomus* fish which are typical benthic feeders of the Antarctic Ocean, exhibit relatively high values reaching 21.6 and 10.1 μg Cd g^{-1} in their liver and kidney, respectively (Tables 6 and 7). This difference can be due to a substantial heterogeneity of age. Thus, these benthic species, as *N. rossii* and *P. magellanica* used in our study were juveniles (<4 years old) while *Trematomus* were supposed to be adults after length measurements as suggested by Gon and Heemstra (1990).

4.3. Interference on the origin of the metals

Elevated Cd concentrations in the biota from the Austral Ocean were surprisingly high for this area remote from human activities. However, except in some localised spots, anthropogenic Cd contamination does not occur in the Austral Ocean, suggesting that the high concentrations found in the examined marine species are essentially due to natural conditions. Thus, the elevated concentrations of this toxic element in both benthic and pelagic invertebrates seem to correspond to Cd-abnormalities in polar waters as inferred for crustaceans and molluscs (Petri and Zauke, 1993; Bargagli et al., 1996; de Moreno et al., 1997; Ritterhoff and Zauke, 1997; Bustamante et al., 1998; Sanchez-Hernandez, 2000). Indeed, the low Cd concentrations in fish muscle indicate low artificial contamination but the elevated Cd concentrations in both liver and kidney highlight exposure of the fish to the metal. Thus, the high Cd levels in liver and kidney of several Antarctic fish species is a matter of concern.

As it occurs for the Arctic fish (Macdonald and Sprague, 1988; Hellou et al., 1992; Zauke et al., 1999), bioaccumulation of Cd in the fish from the

Austral Ocean is difficult to explain since the Cd concentrations in the sea water from polar regions are low. Nevertheless, the occurrence of upwelling of deep waters in the Kerguelen region (Plancke, 1977) should bring an enrichment of Cd in the surface waters. The increase of Cd bioavailability in the Kerguelen Island waters by upwelled deep waters might be at the origin of an increase of Cd concentrations in the marine biota on a local scale, as discussed for benthic octopus from this area (Bustamante et al., 1998). On the other hand, Bucciarelli et al. (2001) found an iron enrichment of the coastal waters of the Kerguelen Islands and explained it in terms of direct inputs of terrestrial material, as a consequence of riverine discharge, soil leaching by rainwater and aeolian input by strong winds, but also by inputs from the sediments due to resuspension and effluxes from the sediment at the water interface. However, our results for Cd but also for Cu, Hg and Zn in the tissue of Kerguelen Islands fish do not show an enrichment following the same processes as Fe. Indeed, Cd concentrations in both liver and kidney of fish caught in close coastal waters (i.e. *N. rossii* and *P. magellanica*) are the lowest among the eight studied species. Similarly to fish, metal concentrations in crustaceans also distinguish the coastal samples from the continental-shelf ones. For example, the hyperiid amphipod *T. gaudichaudii* display Cd concentrations from 21.2 to 27.3 $\mu g\ g^{-1}$ dry wt. in the coastal waters (Morbihan Gulf) while 68.2–80.7 μg Cd g^{-1} dry wt. were found in the individuals from the shelf waters (Bustamante unpublished data). These new findings point out the necessity to investigate carefully the metal concentrations, particularly for Cd, in the waters surrounding Kerguelen Islands, to determine the sources to biota in this area.

Cd-enrichment in marine animals from the Austral Ocean was also proposed to occur for organisms suffering essential elements deficiency, which have evolved very efficient mechanisms of elemental uptake (Petri and Zauke, 1993). However, these mechanisms are probably non specific to the essential metal and so, Cd might be absorbed by the same pathways than elements like Cu or Zn. Zn deficiency is not evident in the Kerguelen Island waters as its concentrations in fish tissues from this area are of the same order than concentrations reported for fish from various areas (Hellou et al., 1992; Roméo et al., 1999; Zauke et al., 1999). Similarly to fish, Zn concentrations found in the digestive gland of octopus from the Kerguelen Islands are of the same order compared to other cephalopod species (Bustamante et al., 1998). As for Cd, Zn could also be carried by upwelled waters, becoming more available in this area than in open Ocean where upwellings do not occur. Contrarily to Zn, low concentrations of Cu in the liver of fish from the Kerguelen Islands might be due to a low availability of this element. Indeed, Cu concentrations appear to be under close physiological regulation in most species (Thompson, 1990). In the same way, low Cu concentrations were also found in octopus from Kerguelen Islands compared to data reported for other cephalopods.

5. Conclusion

The present work provides new information on the distribution of heavy metals in fish from the Kerguelen Islands. Considering the muscle, concentrations of Cd and Hg in both benthic and pelagic species are below the values fixed as a limit by the CSHPF (1995). On the other hand, liver and kidney display very high Cd consequently to high exposure through diet, but very low hepatic Cu concentrations. This is in accordance with the hypothesis of Cd-enrichment related to Cu deficiency. In this context, studies on the detoxification and storage processes of Cd in the liver and kidney of Kerguelen Islands fish should be thoroughly carried out.

Acknowledgments

We thank Guy Duhamel and the crew of the RV ‘La Curieuse’ for their help in the collection of the fish specimens. This work was financially supported by the ‘Conseils Généraux des Deux-Sévres et de la Charente Maritime’, and by the Institut Français pour la Recherche et la Technol-

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