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Interspecific and geographical variations of trace element concentrations in Pectinidae from European waters

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Abstract

Cd, Cu and Zn were analysed in the organs and tissues of the three scallop species from the Bay of Biscay, the variegated *Chlamys varia* L., the queen scallop *Aequipecten opercularis* L. and the common scallop *Pecten maximus* L. for interspecific comparisons. In *P. maximus* the greatest concentrations of Cd and Cu were found in the digestive gland, whereas the two other species showed similar levels of Cd between digestive gland and kidneys and higher renal Cu concentrations. However, the digestive gland of all Pectinidae species contained from 75% to 93% and 52% to 74% of the total body burdens of Cd and Cu, respectively. Whatever the species, kidneys displayed the highest Zn concentrations, which therefore contained from 53% to 97% of the total body burden of this metal. Also using reported results, ratios between the concentrations in the digestive gland and that in the kidneys discriminated two groups of Pectinidae: (1) the *Pecten* group (*P. maximus*, *P. jacobeus* and *Adamussium colbecki*) with a Cd ratio $\geqslant 4$, a Cu ratio $\geqslant 1$ and a Zn ratio $>20\times10^{-3}$; (2) the *Chlamys* group with a Cd ratio $\leqslant 1$, a Cu ratio $\leqslant 1$ and a Zn ratio $\leqslant 6\times10^{-3}$. However, no differences in the detoxification processes in the digestive gland were found between groups in this study. 72–80% of the total Cd was found to be soluble, probably bound to metalloproteins such as metallothioneins, while Cu and Zn were mainly found associated to the insoluble fraction of the digestive gland cells whatever the species. Queen scallops from the Faroe Islands were also considered to examine variations of the metal concentrations due to the geographical origin. In this northern area, queen scallops displayed Cd concentrations 2, 4 and 6 times higher in kidneys, muscle and digestive gland, respectively, compared to those from the Bay of Biscay. Consequently, the Cd concentrations in the whole soft parts of the queen scallops were more than 6 times higher in the Faroe Islands than in the Bay of Biscay. In contrast to Cd, both Cu and Zn concentrations in the whole soft parts were 2 times lower in the Faroe Islands, suggesting lower bioavailability of these essential elements.
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1. Introduction

Among seashells, numerous scallop species represent an important target to commercial fisheries. Many of them are actually cultured for direct commercial production or to provide juveniles for reintroduction

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programs in areas over-exploited. On the French Atlantic coasts and in the English Channel, scallops are relatively common, largely distributed and belong to three species: the variegated scallop *Chlamys varia* on rocky substrata, the queen scallop *Aequipecten opercularis* and the common scallop *Pecten maximus* on sandy bottoms. In France, these three species are captured during winter time and mobilises around one thousand fishing boats with various duration. The total of the catch varies greatly form one year to another, ranging from 6000 tons to 25 000 tons per year (Quéro and Vayne, 1998). The three species are also captured for leisure activities, directly on the shore or by snorkelling. Scallops represent therefore an elevated economic values in fishing areas.

Bivalves are classically chosen for studies on trace element bioaccumulation (Bryan, 1976). They are poorly capable to regulate ion concentrations in internal fluids and they are highly tolerant, metal ions being sequestered in excess of metabolic requirement (George, 1980). Therefore, bivalves often display high accumulation levels without apparent toxic effect. Among bivalves, scallops have shown a particular ability to concentrate high levels of pollutants such as trace elements, even in areas remote from direct anthropogenic contamination like the Antarctic (Mauri et al., 1990; Berkman and Nigro, 1992; Viarengo et al., 1993) or the Arctic Oceans (Stepnowski and Skwarzec, 2000). Therefore, scallops are generally considered as valuable bioindicators to monitor marine pollution (Bryan, 1973; Bustamante et al., 2002a). However, large interspecific variations seem to occur when compared trace element concentrations between different scallop species (Mauri et al., 1990; Viarengo et al., 1993). Such variations are not well characterised since only a single species is usually studied at the same place. Furthermore, geographical variations for a single scallop species have been rarely considered, different species from various latitudes being generally compared.

In this study, Cd, Cu and Zn, were analysed in the organs and tissues of the three common scallop species living along the Atlantic coast of France. Those metals were determined by flame and graphite atomic absorption spectrophotometry in the variegated scallop *C. varia*, in the queen scallop *A. opercularis* and in the common scallop *P. maximus*, from the Charente-Maritime coasts, Bay of Biscay, France, in an attempt to determine the interspecific variations in the metal bioaccumulation. Furthermore, specimens of *A. opercularis*, a widely distributed species in the Northeastern Atlantic from Morocco to the north of Norway, were collected off the Faroe Islands for comparison. Elemental concentrations, tissular and subcellular distributions, and interspecific and geographical differences were therefore examined.

2. Material and methods

2.1. Sampling and sample preparation

In February 1996, 41 variegated scallops (*Chlamys varia*, Linné, 1758) were collected by hand in the infralittoral zone in the coast of Charente-Maritime (Bay of Biscay, France). After 48 h depuration in clean sea water to eliminate faecal and pseudo-faecal material, scallops were pooled by size classes.

The queen and common scallops (*Aequipecten opercularis*, Linné, 1758 and *Pecten maximus*, Linné, 1758, respectively) have been opportunistically collected by bottom trawl along the Charente-Maritime coasts between February and May 1997. Individuals ($n = 11$ for each species) were separated in individual plastic bags and frozen on board.

Queen scallops *A. opercularis* from the Faroe Islands have also been collected opportunistically by bottom trawl in August 1996 and frozen on board as described above ($n = 31$).

For each scallop, adductor muscle, gonad, gills, kidneys, and digestive gland were separated from the rest of the soft part. The remaining tissues including the mantle, the foot, the intestine and the heart, were also analysed in order to calculate the whole trace element contained of the soft parts.

2.2. Subcellular fractionation

The partitioning of trace elements between soluble and insoluble subcellular fractions of the digestive gland was investigated in the three scallop species. Thus, 40 *C. varia*, 23 *P. maximus*, and 10 *A. opercularis* were devoted to subcellular investigations. Four pools were made with the digestive glands removed from the soft parts of *C. varia* and *P. Maximus* freshly dissected. In the case of *A. opercularis*, digestive glands were removed on board to be deep frozen in liquid nitrogen and consequently were treated individually.

Both pooled and individual digestive glands were subsequently homogenised in a Dounce potter on ice with 10 volumes of a 0.02 M TRIS–HCl buffer in 0.25 M sucrose with 1 mM PMSF (phenylmethylsulfonylfluoride, as protease inhibitor) and 5 mM DTT (dithiothreitol, as reducing agent), at pH 8.6 (Bustamante et al., 2002b). The homogenates were centrifuged at 100 000*G* for 1 h at 4 °C in a Beckman LE-70 ultracentrifuge. Particle-free supernatants (cytosols) were separated from the pellet. Aliquots of the homogenates, cytosols and pellets were analysed for trace elements.

2.3. Trace element analyses

Tissue samples were dried for several days at 80 °C to constant weight. Whenever possible, two aliquots of

Table 1
Comparison of trace elements concentrations (μg g^{-1} dwt) of dogfish liver DOLT-2 (NRCC), and dogfish muscle (NRCC) determined in the present study with certified values

Metals	DOLT-2 (n = 5)		DORM-2 (n = 5)	
	Certified values	Present study	Certified values	Present study
Cd	20.8 ± 0.5	19.7 ± 0.6	0.043 ± 0.008	0.042 ± 0.014
Cu	25.8 ± 1.1	24.9 ± 1.2	2.34 ± 0.16	2.30 ± 0.22
Zn	85.8 ± 2.5	84.5 ± 2.8	25.6 ± 2.3	26.3 ± 1.8

approximately 300 mg of each homogenised dry sample were digested with 4 ml of 65% ultrapure HNO_3 and 0.3 ml of ultrapure 70% $HClO_4$ at 80 °C until the solution was clear. Then acids were evaporated and residues were dissolved in 0.3 N ultrapure nitric acid.

Cadmium, copper and zinc were determined by flame and graphite furnace atomic absorption spectrophotometry with a Varian spectrophotometer Vectra 250 Plus, with Deuterium background correction. Certified reference materials, dogfish liver DOLT-2 (NRCC) and dogfish muscle DORM-2 (NRCC), were treated and analysed in the same way as the samples. The results for standard reference materials were in good agreement with certified values (Table 1). The detection limits calculated for 0.3 g of dry tissue were (μg g^{-1} dwt): 0.005 (Cd), 0.5 (Cu), and 3 (Zn). Metal concentrations in tissues are given relatively to the dry weight (μg g^{-1} dwt) while the distribution percentages were calculated for wet weight.

2.4. Data analyses

Comparison of metal concentrations between species were tested by one-way ANOVA (after log transformation of data when necessary) followed by the Tukey's multiple comparison test in the MINITAB 13.1 software. Changes in metal distribution among scallop tissues were tested for significance by the G procedure (adapted from the log-likelihood ratio test) for $2 \times k$ contingency tables (Zar, 1996). The significance level for statistical analyses was always set at $\alpha = 0.05$.

3. Results

Concentrations of Cd, Cu and Zn in the tissues of three scallop species from the Bay of Biscay and one species from the Faroe Islands are presented in Table 2. Concentrations in the whole soft parts were calculated using the concentrations determined in each compartments. The body distribution of the trace elements of the scallops is presented in Table 3.

Table 2
Mean ± SD of Cd, Cu, and Zn concentrations (μg g^{-1} dwt) in the organs and tissues of three scallop species from the Bay of Biscay and the Faroe Islands

Element species	Location	Digestive gland	Kidneys	Gonad	Gills	Muscle	Remaining tissues	Whole soft parts
Cd								
Aequipecten opercularis	Bay of Biscay	27.5 ± 4.24	21.1 ± 3.15	3.99 ± 3.17	7.41 ± 0.03	0.70 ± 0.24	4.74 ± 2.13	5.70 ± 1.21
Aequipecten opercularis	Faroe Islands	123 ± 14	159 ± 80	3.54 ± 0.89	8.46 ± 3.38	0.49 ± 0.09	10.5 ± 2.84	38.7 ± 11.1
Chlamys varia	Bay of Biscay	40.0 ± 4.43	38.8 ± 11.1	2.11 ± 0.27	4.12 ± 0.39	0.54 ± 0.08	2.06 ± 0.32	7.69 ± 0.77
Pecten maximus	Bay of Biscay	264 ± 33	70.6 ± 12.6	5.28 ± 5.44	4.68 ± 2.26	2.01 ± 1.07	3.58 ± 0.60	29.7 ± 12.0
Cu								
Aequipecten opercularis	Bay of Biscay	43.6 ± 19.5	507 ± 144	8.1 ± 0.6	7.1 ± 0.7	1.7 ± 0.9	4.5 ± 0.8	15.0 ± 4.6
Aequipecten opercularis	Faroe Islands	14.0 ± 0.8	106 ± 49	6.5 ± 0.7	4.7 ± 0.2	1.0 ± 0.1	2.5 ± 0.1	7.6 ± 2.3
Chlamys varia	Bay of Biscay	88.1 ± 13.8	142 ± 20	29.6 ± 6.0	8.1 ± 0.8	1.8 ± 0.2	5.5 ± 0.4	19.2 ± 1.7
Pecten maximus	Bay of Biscay	40.7 ± 7.8	13.5 ± 2.0	19.7 ± 16.1	5.3 ± 2.4	1.2 ± 0.3	3.4 ± 0.3	6.5 ± 1.6
Zn								
Aequipecten opercularis	Bay of Biscay	198 ± 47	31 053 ± 8147	195 ± 16	384 ± 74	79 ± 17	200 ± 35	437 ± 159
Aequipecten opercularis	Faroe Islands	77 ± 14	6632 ± 3664	120 ± 15	96 ± 7	39 ± 4	105 ± 32	193 ± 106
Chlamys varia	Bay of Biscay	149 ± 27	24 107 ± 3465	239 ± 45	232 ± 99	101 ± 13	181 ± 61	781 ± 120
Pecten maximus	Bay of Biscay	804 ± 92	7278 ± 3041	254 ± 105	143 ± 4	64 ± 7	87 ± 6	235 ± 110

Table 3
Body distribution of Cd, Cu, and Zn (% of the wet weight) in the organs and tissues of three scallop species from the Bay of Biscay and the Faroe Islands

Species	Location	Digestive gland	Kidneys	Gonad	Gills	Muscle	Remaining tissues
Cd							
Aequipecten opercularis	Bay of Biscay	75 ± 8	4 ± 3	5 ± 2	3 ± 1	8 ± 3	12 ± 2
Aequipecten opercularis	Faroe Islands	90 ± 3	5 ± 3	1 ± 0	1 ± 0	<1	3 ± 1
Chlamys varia	Bay of Biscay	80 ± 3	8 ± 2	<1	2 ± 0	4 ± 1	5 ± 1
Pecten maximus	Bay of Biscay	93 ± 1	2 ± 1	<1	<1	3 ± 1	1 ± 0
Cu							
Aequipecten opercularis	Bay of Biscay	52 ± 9	37 ± 6	5 ± 3	1 ± 1	8 ± 5	3 ± 1
Aequipecten opercularis	Faroe Islands	61 ± 4	18 ± 10	7 ± 3	4 ± 1	5 ± 2	5 ± 2
Chlamys varia	Bay of Biscay	74 ± 7	12 ± 3	2 ± 0	1 ± 0	5 ± 10	6 ± 1
Pecten maximus	Bay of Biscay	70 ± 6	2 ± 2	11 ± 8	3 ± 3	11 ± 3	3 ± 1
Zn							
Aequipecten opercularis	Bay of Biscay	1 ± 1	97 ± 1	1 ± 0	1 ± 0	<1	1 ± 0
Aequipecten opercularis	Faroe Islands	17 ± 6	53 ± 18	6 ± 4	5 ± 2	9 ± 4	9 ± 5
Chlamys varia	Bay of Biscay	5 ± 1	72 ± 4	1 ± 0	2 ± 1	14 ± 3	7 ± 2
Pecten maximus	Bay of Biscay	14 ± 11	81 ± 14	3 ± 1	1 ± 0	1 ± 1	1 ± 0

3.1. Cadmium

Among tissues, the digestive gland and the kidneys displayed the highest Cd concentrations for all species and in both areas. Interestingly, the Cd values measured in the different species were in the same range of concentrations in both organs with the exception of *P. maximus*. In this species, Cd concentrations in this species were around 4 times higher in the digestive gland than in the kidneys, i.e. $264 \pm 33\,\mu g\,g^{-1}$ dwt vs $70.6 \pm 12.6\,\mu g\,g^{-1}$ dwt, respectively (Table 2). The digestive gland contained most of the total body burden of Cd in all species, probably because of the significance in weight of this organ (Table 3). For Cd, a G-test did not indicate any significant ($p > 0.05$) difference among metal body distribution between species and areas.

Among the scallops from the Bay of Biscay, *P. maximus* showed a strong accumulation of Cd in its tissues, especially in kidneys, muscle and digestive gland compared to the other species. Thus, these tissues displayed Cd concentrations 2, 4, and 6 times higher, respectively, than those measured in *C. varia* and in *A. opercularis* (Table 2). Consequently, the whole soft parts of *P. maximus* contained Cd concentrations more than 4 times higher than in the other two scallop species (Table 2).

When compared Faroe Islands and Bay of Biscay, Cd concentrations in *A. opercularis* were in the same range in the gonad, gills, and muscles for both geographic areas ($F = 2.31$ $p = 0.140$). Nevertheless, *A. opercularis* from the Faroe Islands displayed more than 4 times Cd concentrations in the digestive gland and 7 times higher in the kidneys than in queen scallops from the Bay of Biscay (Table 2). Consequently, the digestive gland of *A. opercularis* from the Faroe Island contained even higher percentage to the total body burdens of Cd, i.e. 90% vs 75% (Table 3). Whichever the origin was, in the digestive gland of the three species more than 70% of the total Cd was found in the particle-free supernatants (Table 4).

3.2. Copper

Similarly to Cd, the digestive gland and the kidneys displayed the highest Cu concentrations for all species and in both areas. However, this metal displayed large

Table 4
Proportion of Cd, Cu, and Zn in the cytosol of the digestive gland cells (% of the wet weight) of three scallop species from the Bay of Biscay and the Faroe Islands

Species	Location	*N*	Cd	Cu	Zn
Pecten maximus	Bay of Biscay	23	72 ± 5	43 ± 4	38 ± 7
Chlamys varia	Bay of Biscay	40	78 ± 5	25 ± 8	41 ± 3
Aequipecten opercularis	Faroe Islands	10	80 ± 7	35 ± 16	50 ± 11

N: number of individuals.

variations according to the species and to the origin of the scallop.

In the scallops from the Bay of Biscay, Cu clearly showed the highest concentrations in kidneys except for *P. maximus*, whose concentrations were 3 times higher in the digestive gland (Table 2). Specifically in this species, the gonad exhibited relatively elevated Cu concentrations ($19.7 \pm 16.1\,\mu g\,g^{-1}$ dwt), which were in the same order of magnitude than in kidneys ($13.5 \pm 2.0\,\mu g\,g^{-1}$ dwt). Despite such variations in the Cu concentrations, the digestive gland of the different scallop species contained most of the whole body burden of Cu (Table 3). Therefore, tissue distribution of Cu did not varied significantly (G-test, $p > 0.05$) between all the different scallop species.

Considering the whole soft parts, scallops from the Faroe Islands showed Cu concentrations 2 times lower than those from the Bay of Biscay (Table 2). Globally, the concentrations of Cu in the gonad, gills, muscle and remaining tissues were slightly lower in scallop from the Faroe Islands. This difference was even more important for the digestive gland and kidneys (Table 2). However, the digestive gland of the scallops from the Faroe Islands also contained most of the whole body burden of Cu, i.e. $61 \pm 4\%$ (Table 3).

Whichever the origin was, in the digestive gland most of the Cu was found associated to the pellet of centrifugation, only 25–43% of the total Cu being soluble (Table 4).

3.3. Zinc

In scallops, kidneys displayed the highest Zn concentrations for all species and in both areas (Table 2). These concentrations were several thousand of μg (i.e. exceeding $30\,000\,\mu g\,Zn\,g^{-1}$ in *A. opercularis* from the Bay of Biscay).

In the Bay of Biscay, the concentrations of Zn were 7 times higher in *A. opercularis* than in *P. maximus* but not significantly different from *C. varia*. In contrast, *P. maximus* exhibited Zn concentrations in the digestive gland which were 4 times higher than in *C. varia* and *A. opercularis*. Despite such differences in the tissue concentrations, kidneys of the different scallop species contained from 72% to 91% of the whole body burden of Zn (Table 3). Moreover, a G-test did not indicate any significant ($p > 0.05$) difference among metal body distribution between these species.

In the Faroe Islands, *A. opercularis* exhibited lower Zn concentrations in all their tissues than in the Bay of Biscay (Table 2). This was particularly obvious for the kidneys which concentrations were 7 times lower compared to *A. opercularis* from the Bay of Biscay while such a difference was only a 2- or 3-fold for the other tissues. Consequently, *A. opercularis* from the Faroe Islands only exhibited 53% of the whole body burden of Zn in their kidneys (Table 3).

Despite interspecific and geographical differences in the concentrations, the proportion of soluble Zn within the digestive gland cells poorly varied, i.e. from 38% to 50% in the different scallop species (Table 4).

4. Discussion

4.1. Interspecific comparisons

Among bivalves, scallops accumulate trace elements at often high concentrations, depending on the metal and the tissue. The kidney and the digestive gland have a major importance in the bioaccumulation of Cd, Cu and Zn in Pectinidae. These organs exhibited high metal concentrations and contained most of the total body burden of these trace elements (Tables 2 and 3). The other tissues seems to have a minor importance in the storage of Cd, Cu and Zn although they might have a major role in uptake and transfer of trace elements. However, one of the goals of the present study was to provide background levels against which to perform interspecific comparison within the Pectinidae family. Results from this study allowed to discriminate two groups of scallops: on the one hand *C. varia* and *A. opercularis* (formerly called *Chlamys opercularis*) and on the other side *P. maximus*. These two groups are revealed by the ratio between the concentrations of trace elements in the digestive gland and that in kidneys: (1) the *Pecten* group (*P. maximus*) with a Cd ratio $\geqslant 4$, a Cu ratio $\geqslant 1$ and a Zn ratio $>20 \times 10^{-3}$ and, (2) the *Chlamys* group (*C. varia* and *A. opercularis*) with a Cd ratio $\leqslant 1$, a Cu ratio $\leqslant 1$ and a Zn ratio $\leqslant 6 \times 10^{-3}$. Even though metal concentrations have been studied in various scallop species, little data from the current literature allowed to make such calculations, mainly because of the lack of values in kidneys. Table 5 reports Cd, Cu and Zn concentrations in the digestive gland and kidneys of different scallops species from various locations. Although the variation of the concentrations of Cd, Cu and Zn in both tissues is very large, the ratio of the concentrations between the digestive gland and the kidneys were consistent with our results. Thus, *P. maximus* from the English Channel and *P. jacobeus* from the Mediterranean showed ratios around 4 for Cd, $>20 \times 10^{-3}$ for Zn, and respectively 3 and 1 for Cu. These calculated ratio were even higher for the Antarctic scallop *A. colbecki* (i.e. 12 for Cd, 3 for Cu and 377×10^{-3} for Zn) suggesting a metabolism of metals close to the one of the *Pecten* group. In contrast, taking into account the moisture of the tissues, a ratio around 1 for Cd suggests that *Placopecten magellanicus* is closer to the *Chlamys* group.

The bioaccumulation of trace elements in the digestive gland and kidneys might be related to the detoxification

Table 5
Mean ± SD of Cd, Cu, and Zn concentrations ($\mu g\,g^{-1}$ dwt) in different scallop species from various locations

Species	Location	*N*	Cd	Cu	Zn	Reference
Digestive gland						
Amussium balloti	Australia	10	111[a]	–	–	Francesconi et al. (1993)
Adamussium colbecki	Antarctic	30	142 ± 57	12.6 ± 3.3	74.9 ± 25.4	Mauri et al. (1990)
Adamussium colbecki	Antarctic	6	26.51 ± 6.09[a]	3.52 ± 0.49[a]	17.42 ± 2.91[a]	Viarengo et al. (1993)
Aequipecten opercularis	Northeast Atlantic	31	123 ± 14	14.0 ± 0.8	77 ± 14	Present study
Aequipecten opercularis	English Channel	11	27	36.7 ± 11.4	132 ± 26	Bryan (1973)
Aequipecten opercularis	Bay of Biscay	11	27.5 ± 4.24	43.6 ± 19.5	198 ± 47	Present study
Chlamys varia	Bay of Biscay	41	40.0 ± 4.43	88.1 ± 13.8	149 ± 27	Present study
Pecten jacobeus	Mediterranean Sea	30	41.0 ± 18.2	16.6 ± 6.6	124 ± 55	Mauri et al. (1990)
Pecten jacobeus	Mediterranean Sea	6	7.19 ± 1.23[a]	3.13 ± 0.55[a]	28.63 ± 3.29[a]	Viarengo et al. (1993)
Pecten maximus	English Channel	11	321	57.9 ± 27.4	407 ± 123	Bryan (1973)
Pecten maximus	Bay of Biscay	11	264 ± 33	40.7 ± 7.8	804 ± 92	Present study
Placopecten magellanicus	Northwest Atlantic	6	94.68 ± 8.42[a]	–	–	Uthe and Chou (1987)
Kidney						
Adamussium colbecki	Antarctic	30	11.6 ± 3.3	4.0 ± 1.7	199 ± 89	Mauri et al. (1990)
Aequipecten opercularis	Northeast Atlantic	31	159 ± 80	106 ± 49	6632 ± 3664	Present study
Aequipecten opercularis	English Channel	11	41	1285 ± 591	40 800 ± 7290	Bryan (1973)
Aequipecten opercularis	Bay of Biscay	11	21.1 ± 3.15	507 ± 144	31 053 ± 8147	Present study
Chlamys varia	Bay of Biscay	41	38.8 ± 11.1	142 ± 20	24 107 ± 3465	Present study
Pecten jacobeus	Mediterranean Sea	30	10.7 ± 4.0	17.5 ± 10.9	2790 ± 1340	Mauri et al. (1990)
Pecten maximus	English Channel	11	79	20.8 ± 10.3	19 300 ± 4800	Bryan (1973)
Pecten maximus	Bay of Biscay	11	70.6 ± 12.7	13.5 ± 2.0	7278 ± 3041	Present study
Placopecten magellanicus	Northwest Atlantic	6	62.61 ± 25.33[a]	–	–	Uthe and Chou (1987)

N: sample size.
[a] Values expressed relatively to wet weight.

processes of metals. The reasons of high concentrations of trace elements in the tissues of Pectinidae are typically attributed to the binding to cytosolic proteins in the digestive gland and to precipitation on granules in kidneys (George et al., 1980; Ballan-Dufrançais et al., 1985; Stone et al., 1986; Fowler and Gould, 1988; Mauri et al., 1990; Viarengo et al., 1993). Globally, information on the subcellular distribution of metals in Pectinidae is scarce. The cytosolic proteins of the digestive gland cells of the three scallop species seem to have a minor importance in the binding of Cu and Zn. These two metals were generally found in large proportions into the insoluble fraction, which represent the metals trapped within the organites, associated to membranes or to granules. This might be due to their numerous biochemical functions that imply they are involved in the structure of several proteins. In contrast to Cu and Zn, from 72% to 80% of the total Cd was found in the cytosolic fraction of the digestive gland cells of the three scallop species. With the exception of the Antarctic scallop *A. colbecki*, for which only 30% of the total Cd was soluble (Viarengo et al., 1993), 60–99% of the Cd was found in the soluble fraction of the digestive gland of Pectinidae from field or after experimental exposure to this metal (Evtushenko et al., 1986, 1990, Stone et al., 1986; Lukyanova and Evtushenko, 1989). This strongly suggests the occurrence of mechanisms of accumulation and detoxification of Cd involving proteins such as metallothioneins (Evtushenko et al., 1986, 1990; Stone et al., 1986; Viarengo et al., 1993; Bustamante, 1998). Similar detoxification strategies for Cd, Cu and Zn in the digestive gland of the *Chlamys* and the *Pecten* groups suggest that differences between the two groups are related to detoxification and excretion processes in the kidneys. Indeed, metal-rich granules from the kidney of *P. maximus* are considered as excretory concretions which can be eliminated in urine (George et al., 1980). Higher excretion rates in the *Pecten* group compared to the *Chlamys* one might lead to overall lower Cd, Cu and Zn concentrations in this organ. However, further studies in the *Chlamys* group are needed to support this hypothesis.

4.2. Geographical comparisons

Scallops of different species within the same area and scallops of the same species from different latitudes showed elevated variations in their ability to concentrate trace elements (Table 5). Such variations are due to interspecific diversity but also to geographic conditions. Accumulation of high metal concentrations, particularly Cd, even in unpolluted areas might be related to different bioavailability of the elements, to different feeding habits, as well as to physiological features. As regards to the concentrations found in the gills, seawater appears to be an important source of metals for scallops. However, trace element concentrations in the soft tissues and primarily in the digestive gland might substantially be influenced by the metal content of their food. Indeed, scallops are filter feeders using different types of food such as phytoplankton, detritus and resuspended matter which are major components of the variation in food quality in the field through variation in their carbon and nitrogen contents (Grant and Cranford, 1991; Alber and Valiela, 1996). It would therefore be of particular interest to characterise the food composition and its metal concentrations of the different scallops.

As reported for other marine invertebrates (Cubadda et al., 2001), the use of scallops as biomonitors on large geographical scales, i.e. between 44 and 46 °N for the Bay of Biscay, and 61 and 63 °N for the Faroe Islands, might be envisaged with caution. In this investigation, the higher Cd concentrations found in *A. opercularis* from the Faroe Islands compared to those from the Bay of Biscay highlighted that the contents of one or more metals in marine organisms can be increased by specific geochemical or hydrodynamic conditions. In the Faroe Islands, enrichment of metals due to industrial contamination does not exist. Consequently, the high Cd concentrations in the tissues of *A. opercularis* might be considered as natural in this subpolar area. Reported Cd enrichment throughout the Arctic remained globally unclear. Several authors have proposed that a phenomenon of Cd abnormality occurs in polar and subpolar areas, leading to very high Cd concentrations in marine biota (Petri and Zauke, 1993; Bargagli et al., 1996; Bustamante et al., 1998a; Zauke et al., 1999). Several results suggest that such an abnormality has also to be considered in the Faroe Islands (Caurant et al., 1994; Bustamante et al., 1998b, 2004). Indeed, similarly to polar regions, soluble trace element concentrations in seawater appear to be relatively low around this area (Mart and Nürnberg, 1984). Despite that, very high Cd concentrations have also been found in several cephalopod species caught around the archipelago, i.e. from 2.1 $\mu g\,g^{-1}$ dwt in the Loliginid squid *Loligo forbesi*, to 46.8 $\mu g\,g^{-1}$ dwt in the octopus *Eledone cirrhosa* (Bustamante, 1998; Bustamante et al., 1998b). Moreover, coastal invertebrates such as dog-whelks and limpets also displayed elevated Cd concentrations, i.e. 140 $\mu g\,g^{-1}$ dwt and 50 $\mu g\,g^{-1}$ dwt, respectively (Dam, 2000). Therefore, the high Cd concentrations in the tissues of *A. opercularis* might reflect a global enrichment by this metal in the Faroe Islands biota. Nevertheless, the reasons of such an enrichment remain to be determined.

In contrast, Cu and Zn appeared to be concentrated in much lower extent in the scallops from the Faroe Islands compared to those from the Bay of Biscay and from the English Channel (Bryan, 1973). Lower concentrations of these essential elements could be due to low bioavailability of these two metal in the Faroe Island waters. High Cd concentrations associated with low Cu and Zn values are typically attributed to the substitution of Cd ions for essential metals under deficient conditions (Petri and Zauke, 1993; Bustamante et al., 1998a). This possibly occurred in *A. opercularis* from the Faroe Islands. Indeed, the digestive gland showed a high Cd/Cu ratio (i.e. 8.8) compared to the Bay of Biscay (i.e. 0.6). In the Faroe scallops, this high ratio was due to both elevated Cd concentrations and to low Cu concentrations. Cu concentrations in the digestive gland were lower than concentrations found in the temperate scallop species but in the same range than the concentrations reported for the Antarctic scallop *A. colbecki* (Table 5). Large amounts of Cu are essential to marine mollusks, for which Cd and Cu are known to interfere on the same type of metalloproteins (i.e. metallothioneins) in the digestive gland. A competition or a substitution between the two elements may have occurred in the Faroe scallops.

5. Conclusion

The three different species examined in this study accumulated high trace element concentrations in their tissues, particularly in the digestive gland and in the kidney. The accumulation of Cd was even higher in the subpolar Faroe area. In contrast to Cd, lower Cu and Zn concentrations suggests a poor bioavailability of these essential elements in this area. Regardless of the species and the origin, Cd appeared to be associated to cytosolic proteins involved in detoxification functions. The presence of Cu and Zn on organites and membranes might be due to their essentiality.

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References

Alber, M., Valiela, I., 1996. Utilization of microbial organic aggregates by bay scallops, *Argopecten irradians* (Lamarck). J. Exp. Mar. Biol. Ecol. 195, 71–89.

Ballan-Dufrançais, C., Jeantet, A.Y., Feghali, C., Halpern, S., 1985. Physiological features of heavy metal storage in bivalve digestive cells and amoebocytes: EPMA and factor analysis of correspondences. Bio. Cell. 53, 283–292.

Bargagli, R., Nelli, L., Ancora, S., Focardi, S., 1996. Elevated cadmium accumulation in marine organisms from Terra Nova Bay (Antarctica). Polar Biol. 16, 513–520.

Berkman, P.A., Nigro, M., 1992. Trace metal concentrations in scallops around Antartica: extending the Mussel Watch Programme to the Southern Ocean. Mar. Pollut. Bull. 24 (6), 322–323.

Bryan, G.W., 1973. The occurrence and seasonal variation of trace metals in the scallops *Pecten maximus* (L.) and *Chlamys opercularis* (L.). J. Mar. Biol. Assoc. U.K. 53, 145–166.

Bryan, G.W., 1976. Some aspects of heavy metal tolerance in aquatic organisms. In: Lockwood, A.P.M. (Ed.), Effects of Pollutants on Aquatic Organisms. Academic Press, London, pp. 7–34.

Bustamante, P., 1998. Etude des processus de bioaccumulation et de détoxication d'éléments traces (métaux lourds et terres rares) chez les mollusques céphalopodes et bivalves pectinidés. Implication de leur biodisponibilité pour le transfert vers les prédateurs. PhD thesis, University of La Rochelle, France.

Bustamante, P., Chérel, Y., Caurant, F., Miramand, P., 1998a. Cadmium, copper and zinc in octopuses from Kerguelen Islands, Southern Indian Ocean. Polar Biol. 19, 264–271.

Bustamante, P., Caurant, F., Fowler, S.W., Miramand, P., 1998b. Cephalopods as a vector for the transfer of cadmium to top marine predators in the north-east Atlantic Ocean. Sci. Total Environ. 220, 71–80.

Bustamante, P., Germain, P., Leclerc, G., Miramand, P., 2002a. Concentration and distribution of ^{210}Po in the tissues of the scallop *Chlamys varia* and the mussel *Mytilus edulis* from the coasts of Charente-Maritime (France). Mar. Pollut. Bull. 44 (10), 997–1002.

Bustamante, P., Cosson, R.P., Gallien, I., Caurant, F., Miramand, P., 2002b. Cadmium detoxification processes in the digestive gland of cephalopods in relation to accumulated cadmium concentrations. Mar. Environ. Res. 53, 227–241.

Bustamante, P., Morales, F., Mikkelsen, B., Dam, M., Caurant, F., 2004. Individual and population significance of trace elements bioaccumulation in the grey seal *Halichoerus grypus* from the Faroe Islands. Mar. Ecol. Prog. Ser. 267, 291–301.

Caurant, F., Amiard, J.C., Amiard-Triquet, C., Sauriau, P.G., 1994. Ecological and biological factors controlling the concentrations of trace elements (As, Cd, Cu, Hg, Se, Zn) in delphinids *Globicephala melas* from the North Atlantic Ocean. Mar. Ecol. Prog. Ser. 103, 207–219.

Cubadda, F., Conti, M.E., Campanella, L., 2001. Size-dependent concentrations of trace metals in four Mediterranean gastropods. Chemosphere 45, 561–569.

Dam, M., 2000. Integrated ecological monitoring in the coastal zone; Environmental Pollutants. The Food and Environmental Agency of the Faroe Islands, Report no. 2, 97 p.

Evtushenko, Z.S., Belcheva, N.N., Lukyanova, O.N., 1986. Cadmium accumulation in organs of the scallop *Mizuhopecten yessoensis*. II. Subcellular distribution of metals and metal-binding proteins. Comp. Biochem. Physiol. 83C, 377–383.

Evtushenko, Z.S., Lukyanova, O.N., Belcheva, N.N., 1990. Cadmium bioaccumulation in organs of the scallop *Mizuhopecten yessoensis*. Mar. Biol. 104, 247–250.

Fowler, B.A., Gould, E., 1988. Ultrastructural and biochemical studies of intracellular metal-binding patterns in kidney tubule cells of the scallop *Placopecten magellanicus* following prolonged exposure to cadmium or copper. Mar. Biol. 97, 207–216.

Francesconi, K.A., Moore, E.J., Joll, L.M., 1993. Cadmium in the saucer scallop, *Amussium balloti*, from western Australian waters: concentrations in adductor muscle and redistribution following frozen storage. Aust. J. Mar. Fresh. Res. 44, 787–797.

George, S.G., 1980. Correlation of metal accumulation in mussels with the mechanisms of uptake, metabolism and detoxification: biochemical and ultrastructural studies. Thalassia jugoslav. 16, 347–365.

George, S.G., Pirie, B.J.S., Coombs, T.L., 1980. Isolation and elemental analysis of metal-rich granules from the kidney of the scallop, *Pecten maximus* (L.). J. Exp. Mar. Biol. Ecol. 42, 143–156.

Grant, J., Cranford, P.J., 1991. Carbon and nitrogen scope for growth as a function of diet in the sea scallop *Placopecten magellanicus*. J. Mar. Biol. Assoc. U.K. 71, 437–450.

Lukyanova, O.N., Evtushenko, Z.S., 1989. Binding of zinc and cadmium with cytoplasmic proteins in the Yezo scallop at the increased concentrations of zinc in water. Sov. J. Mar. Biol. 15, 306–311.

Mart, L., Nürnberg, H.W., 1984. Trace metal levels in the eastern Arctic Ocean. Sci. Total Environ. 39, 1–14.

Mauri, M., Orlando, E., Nigro, M., Regoli, F., 1990. Heavy metals in the Antarctic scallop *Adamussium colbecki*. Mar. Ecol. Prog. Ser. 67, 27–33.

Petri, G., Zauke, G.P., 1993. Trace metal in the crustaceans in the Antarctic Ocean. Ambio 22, 529–536.

Quéro, J.C., Vayne, J.J., 1998. Les fruits de mer et plantes marines des pêches françaises. Delachaux & Nestlé, Lausanne—Paris, 256 p.

Stepnowski, P., Skwarzec, B., 2000. A comparison of ^{210}Po accumulation in molluscs from the southern Baltic, the coast of Spitsbergen and Sasek Wielki Lake in Poland. J. Environ. Radioact. 49, 201–208.

Stone, H.C., Wilson, S.B., Overnell, J., 1986. Cadmium binding components of scallop (*Pecten maximus*) digestive gland. Partial purification and characterisation. Comp. Biochem. Physiol. 85C, 259–268.

Uthe, J.F., Chou, C.L., 1987. Cadmium in sea scallop (*Placopecten magellanicus*) tissues from clean and contaminated areas. Can. J. Fish. Aquat. Sci. 44, 91–98.

Viarengo, A., Canesi, L., Mazzucotelli, A., Ponzano, E., 1993. Cu, Zn and Cd content in different tissues of the Antarctic scallop *Adamussium colbecki*: role of the metallothionein in heavy metal homeostasis and detoxification. Mar. Ecol. Progr. Ser. 95, 163–168.

Zar, JH., 1996. Biostatistical Analysis, third ed. Prentice-Hall, Upper Saddle River, NJ.

Zauke, G.P., Savinov, V.M., Ritterhoff, J., Savinova, T., 1999. Heavy metals in fish from the Barents Sea (summer 1994). Sci. Total Environ. 227, 161–173.