

Variation of heavy metal concentrations (Ag, Cd, Co, Cu, Fe, Pb, V, and Zn) during the life cycle of the common cuttlefish *Sepia officinalis*

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Abstract

The developmental changes in the concentration of 8 essential and non-essential heavy metals (Ag, Cd, Cu, Co, Fe, Pb, V, Zn) in the tissues (digestive gland, cuttlebone and whole animal) of the common cuttlefish *Sepia officinalis* collected in the bay of the river Seine were monitored from the end of the embryogenesis until the adult reproductive stage. Compared to embryos, juveniles after hatching displayed much higher concentrations of Ag, Cu, Fe and Zn, suggesting an efficient incorporation from seawater. Conversely, the amounts of Cd, Pb and V in hatchlings remained constant suggesting that these metals are barely bioavailable for juveniles. Once the juveniles start to feed, the digestive gland appears to play a major role in the storage of all metals. After only one month of benthic life, the digestive gland already contains up to 90% of the total metal body burden, indicating that it plays a major role in the storage and presumed detoxification of the selected metals. Metal concentrations in the digestive gland increase in a logarithmic fashion with age during the entire life of cuttlefish, except for Ag, which decreases as soon as cuttlefish migrate to open sea. This strongly suggests that (1) Ag is excreted from the digestive gland in relation to presumably lower exposure in less contaminated environments compared to coastal waters and (2) the digestive gland of cephalopods could be a very good indicator of Ag contamination in the marine environment.

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1. Introduction

As with other cephalopods, the cuttlefish *Sepia officinalis* has a very short life cycle during which migrations related to growth and reproduction take place. In

the English Channel and the Atlantic inshore areas, the reproductive season after which these organisms die, occurs between April and August of their second year of life, when they are aged between 14 and 18 months (Boucaud-Camou et al., 1991; Legoff and Daguzan, 1991). Only some male individuals that do not attain their sexual maturity during this period can survive for another year. Therefore, the life of a cuttlefish never exceeds 2 years in these areas (Richard, 1971). During this period, the growth rate of cuttlefish is very high.

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Their weight can even be multiplied by a factor of 2000, cuttlefish weighs 0.25 g after hatching and more than 600 g at sexual maturity (Richard, 1971; Pascual, 1978; Forsythe et al., 1994). This exceptional growth rate can be explained in terms of their active metabolism owing to their carnivorous diet (Mangold, 1989).

Despite such a short life cycle, the strong capability of cuttlefish to concentrate a large number of metals in their tissues has been previously shown, as well as the major role of the digestive gland in the bioaccumulation processes (e.g. Declair et al., 1978; Miramand and Bentley, 1992; Bustamante et al., 1998, 2002a). This capability seems to be shared by many other species of cephalopods, including Octopodidae, Teuthoidae and Nautilidae (Rocca, 1969; Nardi et al., 1971; Schipp and Hevert, 1978; Miramand and Guary, 1980; Smith et al., 1984; Finger and Smith, 1987; Bustamante, 1998; Bustamante et al., 1998, 2000). More recently, radio-tracer experimental studies have shown the relative importance of the various transfer pathways (water, food, sediments) in the bioaccumulation of 4 heavy metals (Ag, Cd, Co, Zn) in juvenile and adult cuttlefish (Bustamante et al., 2002b, 2004), confirming the storage nature of the digestive gland regardless of the uptake pathway.

However, little is known about the temporal changes in metal concentrations and burdens during embryogenesis and growth of *S. officinalis*. The aim of this study was therefore to investigate the variation of the concentrations of 8 essential and non-essential (Ag, Cd, Cu, Co, Fe, V, Pb, Zn) heavy metals during the growth of the cuttlefish from embryogenesis to the reproductive stage. Eggs, hatched juveniles, juveniles during their 2 first months of benthic life, immature individuals and mature adults returning to the coast to mate were analysed. Thus, both the physiological changes and the migrations have been considered. The former occur during the life cycle of cuttlefish and may modify the bioaccumulation processes of metals, whereas during the migrations the animals move from coastal areas (with metallic inputs of anthropogenic origin) to the open sea (presumably less polluted than the coast) hence potentially modifying the metal concentrations in their tissues. In this work, special attention has been paid to the digestive gland owing to its major role in the metabolism of metals. To this end, the study area chosen is particularly interesting since direct arrivals of metallic contaminants, especially Ag (RNO, 2001) and Cd (Chiffolleau et al., 1994, 1996; Miramand et al., 2001) are discharged by the Seine River. Furthermore, the bay of the Seine constitutes a spawning and nursery area for the common cuttlefish that is subjected to fishery activities of important eco-

nomic impact in the region (Boucaud-Camou, 1988; Boucaud-Camou and Boismery, 1991).

2. Materials and methods

2.1. Biological material

2.1.1. Animals from the field

Between July 1989 and July 1991, 153 cuttlefish were collected on 6 dates in the bay of the Seine off the harbour of Ouistreham (Normandy, France; 49° 20' N and 0° 15' E). The age of the animals was estimated according to the previous works of Medhioub (1986) and Boucaud-Camou et al. (1991) using the model of seasonal growth established by Pauly and Gaschütz (1979). According to their mantle length (ML), the animals were pooled into estimated age classes for heavy metal analysis as follows:

- about 1 week old: 3 pools of 25 individuals (mean ML = 10 ± 1 mm);
- about 2 weeks old: 4 pools of 8 individuals (mean ML = 18 ± 3 mm);
- about 1 month old: 3 pools of 4 individuals (mean ML = 33 ± 4 mm);
- about 2 months old: 4 pools of 4 individuals (mean ML = 59 ± 6 mm);
- about 12 months old (immature cuttlefish): 3 pools of 5 individuals (mean ML = 133 ± 19 mm);
- about 18 months old (mature cuttlefish): 3 pools of 1 individual (mean ML = 215 ± 5 mm).

The cuttlefish specimens were immediately frozen on board and stored at -20 °C. After a short frozen period (<1 month), each individual was dissected in the laboratory: the digestive gland and cuttlebone were removed from the remaining tissues and pooled to allow metal analyses in minute organs and tissues. Our sampling of cuttlefish is assumed to represent a single cohort, at least for the individuals of the first year.

2.1.2. Eggs reared in the laboratory

Eggs collected in the same area and the same period as the cuttlefish were incubated at the laboratory in aquaria with an open circulation system. 4 pools of 25 eggs were dissected and embryos, yolk and eggshells were separated for analysis. The embryos collected from the eggs were about to hatch and were completely formed but still attached to the yolk sack, which was not completely resorbed. The rest of the eggs were

Table 1

Comparison of elemental concentrations ($\mu\text{g g}^{-1}$ dwt) of Orchard-Leaves standard, SRM 1571 (National Bureau of Standards), copepods homogenate, MA-A-1 and fish flesh homogenate, MA-A-2 (International Agency of Atomic Energy) obtained in the present study with certified values

Standard	Ag	Cd	Co	Cu	Fe	Pb	V	Zn
Orchard-Leaves								
Present study	–	0.10±0.05	0.17±0.04	10±1	272±14	38±2	0.5±0.1	22±6
Certified values	–	0.11±0.02	(0.2)	12±1	300±20	45±3	(0.6)	25±3
MA-A-1								
Present study	0.2±0.1	0.73±0.06	0.12±0.02	6.9±0.4	61±4	2.0±0.5	–	161±1
Certified values	0.33±0.06	0.75±0.03	0.12±0.01	7.6±0.2	60±2	2.1±0.3	–	158±2
MA-A-2								
Present study	0.12±0.01	0.07±0.01	0.09±0.04	3.4±0.7	65±5	0.43±0.14	–	35±4
Certified values	0.10±0.01	0.066±0.004	0.08±0.01	4.0±0.1	54±1	0.58±0.07	–	33±1

(): recommended values.

maintained in aquaria until hatching, and the subsequent 25 juveniles hatching (ML=10±1 mm) were dissected as previously described.

2.2. Sample preparation and analytical procedure

All the samples were dried at 60 °C for several days to constant weight and then reduced to powder using a porcelain mortar and pestle. Aliquots ranging from 10 to 300 mg of the homogenised samples were digested with 4 ml of 14N Ultrapur HNO₃ and 1 ml of 22N Ultrapur HClO₄ at 100 °C on a hot plate for 3 days. After evaporation of the acids, the residues were resuspended in 5 ml 0.3 N HNO₃. Ag, Cd, Co, Cu, Pb and V were analysed by Zeeman graphite furnace atomic absorption spectrophotometry and Fe and Zn by flame atomic absorption spectrophotometry. Heavy metal concentrations in whole individuals were calculated for reconstructed individuals from analysis of the remaining tissues, cuttlebone and di-

gestive gland. However, the high Ca content in the cuttlebone hindered Co measurements in this organ, so that calculations were impossible for whole juveniles and adults.

Quality control was ensured by assaying heavy metal analyses in blanks and reference materials. Thus, Orchard-Leaves (National Bureau of Standards) and MA-A-1, MA-A-2, respectively, copepods and fish flesh standard (IAEA) were treated and analysed in the same way as the samples. Our results for the standard reference materials were in good agreement with the certified values (Table 1). The detection limits were ($\mu\text{g g}^{-1}$ dwt): 0.004 (Cd), 0.02 (Ag), 0.1 (Co, Pb), 0.5 (Cu, V, and Zn) and 2.5 (Fe). Results are also expressed in micrograms per gram of the dry tissue weight ($\mu\text{g g}^{-1}$ dwt).

2.3. Statistical analysis

Comparison of the metal concentrations between eggshell and embryos/yolk was assessed using *t*-test

Table 2

Heavy metal concentrations (Mean±SD; $\mu\text{g g}^{-1}$ dwt) in whole *Sepia officinalis* sampled in the bay of the Seine at different stages of its life cycle

Life stage	Mantle length	Estimated age	<i>n</i>	Ag	Cd	Co	Cu	Fe	Pb	V	Zn
Eggs	Eggshell	–	4 (25)	0.07±0.01	0.59±0.13	1.75±0.26	14±2	398±64	1.38±0.35	3.43±0.59	69±2
	Embryos	–	4 (25)	0.16±0.04	0.76±0.17	0.25±0.05	31±1	14±8	<0.10	<0.10	68±3
	Yolk	–	1 (25)	0.22	0.40	NM	19	11	<0.10	<0.10	50
Hatchlings	ML=10 mm	0 days	1 (25)	1.80	0.50	NM	60	80	<0.10	<0.10	100
Juveniles	ML=10±1 mm	7 days	3 (25)	1.82±0.35	0.44±0.14	NM	63±2	107±16	<0.10	<0.10	100±3
	ML=18±3 mm	15 days	4 (8)	2.40±0.63	1.32±0.15	NM	77±6	196±51	<0.10	<0.10	119±5
	ML=33±4 mm	1 month	3 (4)	1.42±0.20	1.25±0.31	NM	73±3	38±8	<0.10	<0.10	113±4
	ML=59±6 mm	2 months	4 (4)	3.04±0.29	0.71±0.09	NM	67±4	23±6	<0.10	0.6±0.14	113±3
Immature adults	ML=133±19 mm	12 months	3 (5)	1.82±0.49	2.03±0.07	NM	104±3	41±9	0.65±0.05	0.47±0.15	145±7
Mature adults	ML=215±5 mm	18 months	3 (1)	0.60±0.10	1.10±0.10	NM	70±1	30±5	0.20±0.10	0.50±0.20	156±6

n: number of pool analysed. (): number of individuals in each pool. ML: mantle length; NM: not measured.

Table 3

Heavy metal concentrations (Mean±SD; $\mu\text{g g}^{-1}$ dwt) in the digestive gland of *Sepia officinalis* sampled in the bay of the Seine at different stage of its life cycle

Mantle length (mm)	Age (estimation)	n	Ag	Cd	Co	Cu	Fe	Pb	V	Zn
Juveniles										
10±1	7 days	3 (25)	10±1	2.0±0.1	0.3±0.1	175±5	90±10	<0.1	0.3±0.2	240±5
18±3	15 days	4 (8)	18±7	11±1	1.3±0.3	400±10	160±10	<0.1	0.8±0.1	400±10
33±4	1 month	3 (4)	14±1	15±3	2.6±0.5	450±10	210±10	0.5±0.2	1.6±0.4	500±10
59±6	2 months	4 (4)	35±7	7.5±0.2	3.5±0.5	450±20	110±10	0.5±0.2	2.5±0.7	400±10
Immature										
133±19	12 months	3 (5)	19±7	22±2	6.8±0.9	760±80	340±30	2.4±0.5	2.9±0.1	770±40
Mature adults										
215±5	18 months	3 (1)	13±2	25±5	10±2	600±10	390±10	2.2±0.5	3.3±0.1	1400±500

n: number of pool analysed. (): number of individuals in each pool. ML: mantle length.

comparisons of means. Differences between metal concentrations at the different ages were tested using the non-parametric Kruskal–Wallis test. Regressions between the concentrations measured in the cuttlefish digestive gland and mantle length were tested using regression procedures for linear and non-linear fitted models. Accumulation of metals in the cuttlefish was described by linear and logarithmic fitted models, with the exception of Ag in the digestive gland, which was described by a two-order linear component model. Statistical analyses were performed using XLStat Pro 7.0. The level of significance was always set at $\alpha=0.05$.

3. Results

3.1. Metal concentrations and distribution among compartments

The heavy metal concentrations in eggs, embryos, juveniles of different sizes, immature and mature *S. officinalis* are given in Table 2.

At the end of embryo development, the eggs were dissected into eggshell, yolk and embryo. Heavy metal concentrations were similar in both yolk and

embryo, except for Cd and Cu. However, when metal concentrations of these internal compartments were compared with the external one (i.e. the eggshell), the results appear to differ. For Co, Fe, Pb, and V, the concentrations in the eggshell were significantly ($P_{t\text{-test}} < 0.0001$ for the 4 metals) higher than in the yolk and embryo whereas they were significantly lower for Ag ($P_{t\text{-test}} = 0.015$) and Cu ($P_{t\text{-test}} < 0.0001$).

Overall, metal concentrations in the embryos extracted from the eggs were generally lower (Ag, Cu, Fe, and Zn) or within the same range (Cd, Pb and V) as those in hatchlings. These concentrations were between 2 and 4 times lower than those measured in mature individuals. During the whole life cycle of cuttlefish, metal concentrations showed significant variations (H -value ranges from 15.32 to 17.34, and $P_{\text{Kruskal-Wallis}}$ -value ranges from 0.004 to 0.009). Overall, the highest metal concentrations correspond to those of the essential metals Cu, Fe and Zn (between 30 and 200 $\mu\text{g g}^{-1}$ dwt) and the lowest to non-essential metals (between 0.13 and 2.4 $\mu\text{g g}^{-1}$ dwt).

The dissection of cuttlefish from 7 days old to 2 years old showed that the digestive gland had about one order of magnitude higher metal concentrations compared to the whole animal (Table 3). Consequently,

Table 4

Percentage distribution (Mean±SD; %) of heavy metals in the digestive gland of *Sepia officinalis* sampled in the bay of the Seine at different stage of its life cycle

Life stage	Mantle length (mm)	Estimated age	n	Proportion of whole wt. (%)	Ag	Cd	Cu	Fe	Pb	V	Zn
Juveniles											
	ML=10±1	7 days	3 (25)	10±2	55±7	49±4	29±6	9±3	<10	18±10	20±3
	ML=18±3	15 days	4 (8)	8±1	61±8	72±2	43±2	7±2	<10	17±5	28±1
	ML=33±4	1 month	3 (4)	7±1	76±3	88±5	48±1	48±5	<10	49±18	34±2
	ML=59±6	2 months	4 (4)	8±1	93±1	82±5	57±4	46±3	28±2	38±19	34±1
Immature adults	ML=133±19	12 months	3 (5)	8±1	80±9	87±6	59±6	68±10	30±7	54±20	43±1
Mature adults	ML=215±5	18 months	3 (1)	3±1	54±16	75±5	42±8	48±5	31±14	20±15	40±2

n: number of pool analysed. (): number of individuals in each pool.

Table 5

Heavy metal concentrations (Mean±SD; $\mu\text{g g}^{-1}$ dwt) in the cuttlebone of *Sepia officinalis* sampled in the bay of the Seine at different stage of its life cycle

Mantle length (mm)	Age (estimation)	n	Ag	Cd	Cu	Fe	Pb	V	Zn
Hatching		1 (25)	0.03±0.10	0.08±0.02	38±6	21±2	0.6±0.3	<0.5	30±2
Juveniles									
10±1	7 days	3 (25)	0.73±0.14	0.10±0.02	25±6	28±3	<0.1	<0.5	75±5
18±3	15 days	4 (8)	0.65±0.24	0.13±0.02	14±4	25±1	<0.1	<0.5	75±5
33±4	1 month	3 (4)	0.10±0.02	0.06±0.01	12±8	28±1	<0.1	<0.5	75±5
59±6	2 months	4 (4)	0.10±0.02	0.08±0.01	9±1	23±3	<0.1	<0.5	80±5
Immature									
133±19	12 months	3 (5)	0.08±0.02	0.22±0.09	8±2	15±3	0.9±0.1	<0.5	116±7
Mature adults									
215±5	18 months	3 (1)	0.08±0.02	0.03±0.01	5±1	25±2	0.3±0.2	<0.5	150±20

n: number of pool analysed. (): number of individuals in each pool.

this organ generally contained a great proportion of the whole-body burden of the metals (Table 4). In contrast, the cuttlebone displayed very low non-essential metal concentrations (Table 5). In this organ, Pb and V concentrations remained close to the detection limit throughout the whole life cycle, and Ag and Cd concentrations were one order of magnitude lower than those measured in the whole animal. Therefore, the cuttlebone only contained a small fraction of the total non-essential metal load (Table 6). Finally, the concentrations of the essential metals measured in the cuttlebone were similar (Fe and Zn) or lower (Cu) than those found in the whole organisms (Table 5).

3.2. Variation of metal concentrations and burdens with age

Immediately after hatching, the concentrations of Cu, Fe, and Zn strongly increased in cuttlefish (Table 2). Indeed, the very young cuttlefish displayed concentration values of 1.5 to 2 (Cu and Zn) and 6 (Fe)

times higher than those found in the embryos taken from the eggs immediately before hatching. However, in terms of the whole-body concentrations, Cu and Zn increased significantly with age in a logarithmic fashion ($R=0.408$, $df=18$, $P<0.05$ and $R=0.865$, $df=18$, $P<0.0001$, respectively) whereas Fe tended to decrease significantly ($R=0.657$, $df=18$, $P<0.001$). Among toxic elements, Ag was the only metal showing a significant tendency to decrease with age ($R=0.558$, $df=18$, $P<0.01$) whereas Cd, Pb and V tended to increase (Table 2). However, such variations in the whole-body animals are likely to be due to the variations in the storage organs such as the digestive gland. These tissue-specific variations are actually masked by natural dilution by non-storage organs. Therefore, the tissues dissected at all stages of the life cycle, i.e. the digestive gland and the cuttlebone, were considered to investigate metal variations with age (Figs. 1 and 2, respectively).

Regardless of the essential or non-essential role of the metals, their concentrations in the digestive gland

Table 6

Percentage distribution (Mean±SD; %) of heavy metals in the cuttlebone of *Sepia officinalis* sampled in the bay of the Seine at different stage of its life cycle

Mantle length (mm)	Estimated age	n	Proportion of whole wt. (%)	Ag	Cd	Cu	Fe	Pb	V	Zn
Hatching		1 (25)	13±8	4.0±0.1	1.3±0.4	14±7	24±16	14±3	<10	8±4
Juveniles										
10±1	7 days	3 (25)	8±1	3.1±0.6	1.9±0.4	3.2±0.9	1.6±1.2	<10	<10	5.7±0.6
18±3	15 days	4 (8)	8±1	2.8±1.6	0.8±0.1	1.7±0.3	1.2±0.3	<10	<10	5.5±0.6
33±4	1 month	3 (4)	8±1	0.9±0.6	0.5±0.3	1.8±1.2	6.7±1.5	<10	<10	7.3±1.2
59±6	2 months	4 (4)	8±1	0.4±0.3	1.6±0.2	1.5±0.6	13±3.8	<10	<10	10±1.4
Immature										
133±19	12 months	3 (5)	14±1	0.7±0.4	1.5±0.6	1.0±0.3	5.4±1.6	<10	<10	11±1.0
Mature adults										
215±5	18 months	3 (1)	20±2	2.2±0.1	0.7±0.1	1.3±1.0	16±4.0	<10	<10	19±4.0

n: number of pool analysed. (): number of individuals in each pool.

showed significant variations throughout the life of cuttlefish (Table 3). The amounts of metals contained in the digestive gland relative to the whole-body burden

also show remarkable changes during the life cycle (Table 4). With the exception of Ag, all metal concentrations and burdens in the digestive gland increased

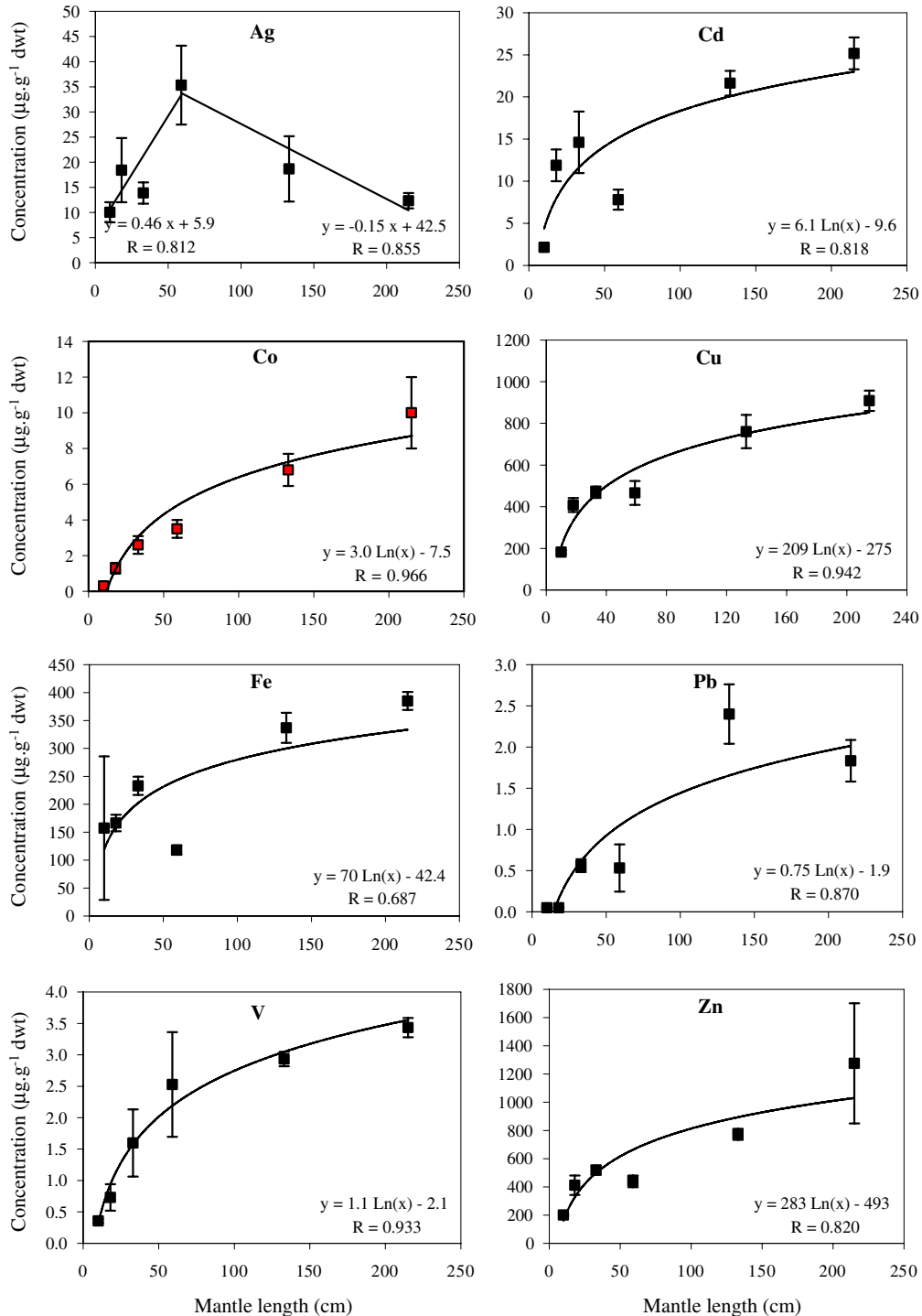


Fig. 1. Variations of metal concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ dwt) in the digestive gland of *Sepia officinalis* in relation to the mantle length.

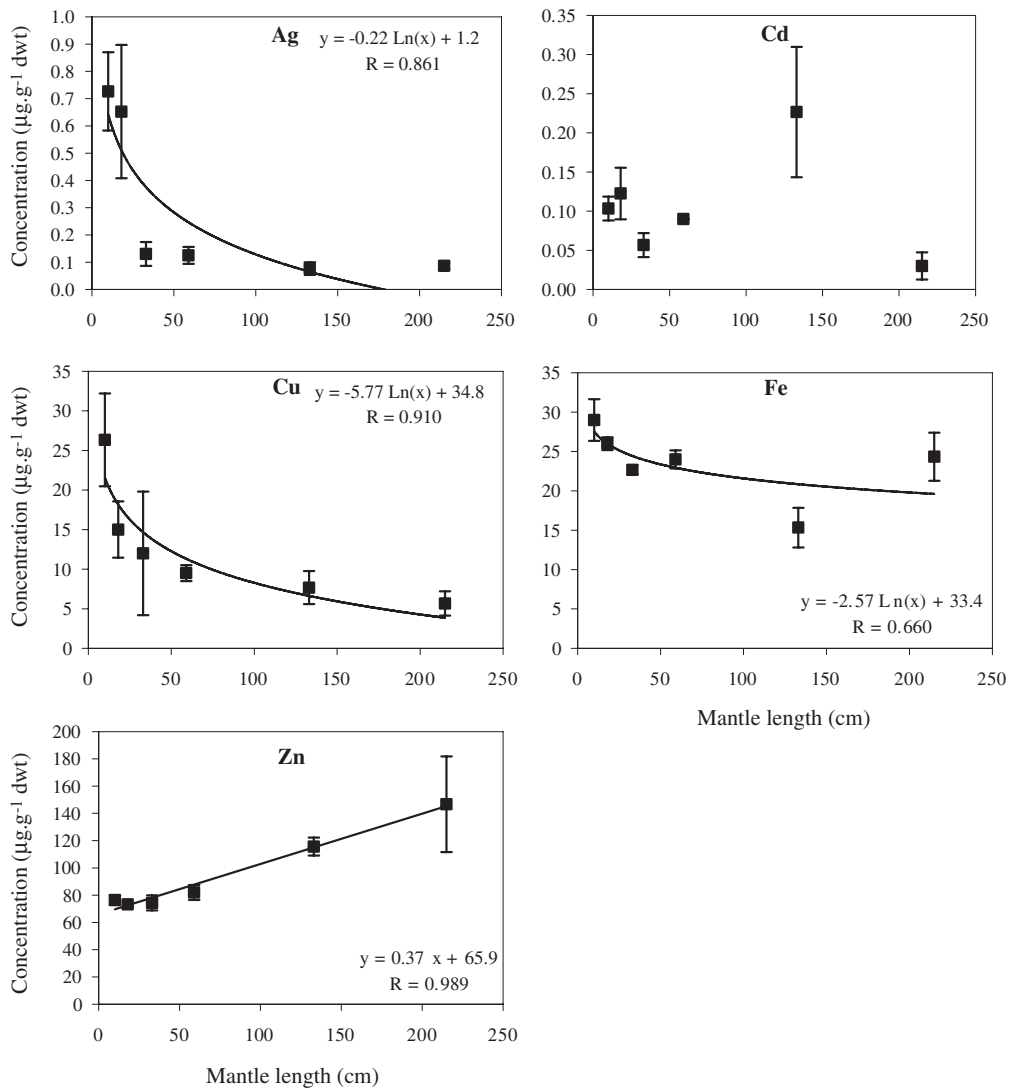


Fig. 2. Variations of metal concentrations ($\mu\text{g g}^{-1}$ dwt) in the cuttlebone of *Sepia officinalis* in relation to the mantle length.

significantly with age following a logarithmic fashion (Figs. 1 and 3). Ag concentrations increased linearly ($R=0.812$, $df=13$, $P<0.001$) until the age of 2 months (ML=59 mm), then decreased linearly ($R=0.855$, $df=9$, $P<0.001$) when cuttlefish migrate to open ocean waters.

In the cuttlebone, the concentrations of Ag, Cu and Fe decreased with age following a logarithmic fashion ($R=0.861$, $df=18$, $P<0.001$; $R=0.910$, $df=18$, $P<0.001$; $R=0.660$, $df=18$, $P<0.005$, respectively) whereas Zn displayed a linear accumulation ($R=0.989$, $df=18$, $P<0.001$) (Fig. 2). The other metals either varied randomly (i.e. Cd) or were below the detection limit (i.e. Pb and V).

Fig. 3 shows the variation of metal burdens in relation to the mantle length (age) of the cuttlefish. Both

essential and non-essential element burdens clearly increased throughout the life cycle of the cuttlefish, with the exception of Ag whose burdens decreased in mature individuals.

4. Discussion

4.1. Metal bioaccumulation in eggs and hatchlings

At the end of embryonic development, the embryos showed very low metal concentrations compared to older cuttlefish (Table 2). Such concentrations are close or even identical to those measured in the vitellus of the newly spawned eggs, suggesting that the vitellus contains a sufficient amount of essential metals (Cu, Fe, and

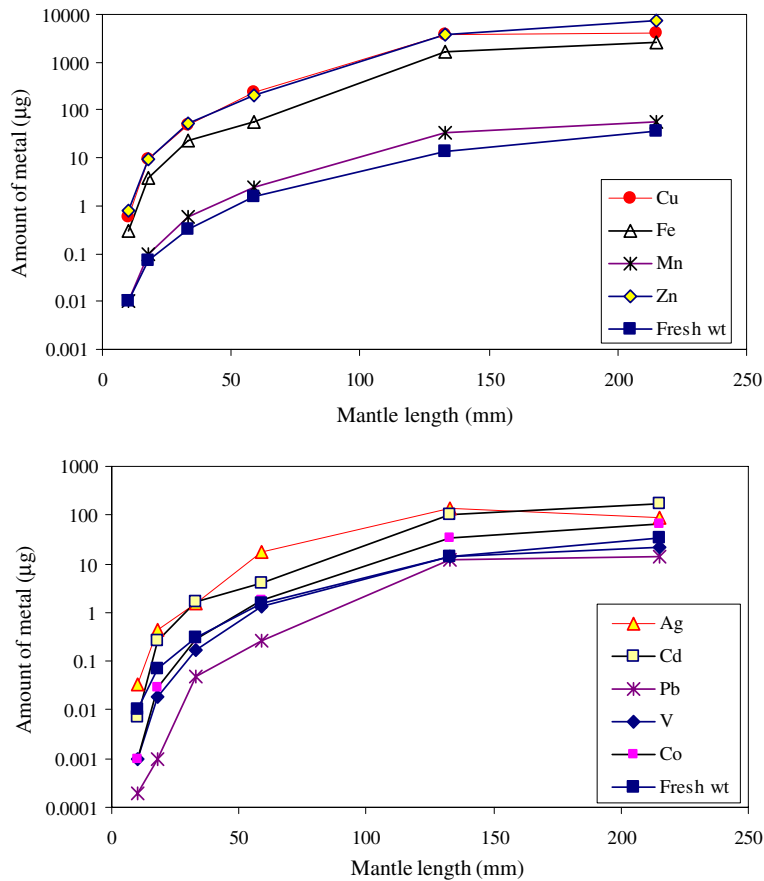


Fig. 3. Amounts of metal (μg) contained in the digestive gland of *Sepia officinalis* in relation to the mantle length during the life cycle in the bay of Seine.

Zn) needed for the development of the embryos. Previous studies with radio-labelled metals have demonstrated that ^{65}Zn , ^{109}Cd and ^{57}Co were mainly retained on the eggshell (96% after 11 days exposure), acting as a protective barrier limiting/hindering the incorporation of waterborne metals. However, the thickness of the eggshell changes during embryonic development. When spawned, its thickness is of the order of 1 mm, (Lemaire, 1971) and is composed of albumin and other proteins, that harden when coming into contact with seawater. Then, it becomes thinner during embryonic development, being almost transparent at the moment of hatching (Wolf et al., 1985). Very low concentrations of Pb and V in the embryos also suggest a specific limitation of their incorporation into the eggs, but this issue should be addressed specifically in the future.

Immediately after hatching, the rapid increase of Cu, Fe and Zn concentrations in cuttlefish tissues (Table 2) suggests that the hatchlings are highly dependent on the essential metals to fulfil their metabolic demands. It therefore follows that the metals are rap-

idly taken up once they are in contact with seawater. At this stage, the accumulation only occurs through the dissolved pathway by branchial absorption and tegumental adsorption, the hatchlings still living only on their vitellary reserves for a week (Mangold and Bidder, 1989). A high ^{65}Zn accumulation rate has been experimentally shown for juveniles exposed to radio-labelled seawater (Bustamante et al., 2002b). Like the essential elements, Ag concentrations are 10 times higher in hatchlings than in the embryos (Table 2), showing a very rapid bioaccumulation of the metal. Similarly to ^{65}Zn , exposure of hatchlings to $^{110\text{m}}\text{Ag}$ via seawater leads to high concentration factors (i.e. 320) after a period of only 36 h (Bustamante et al., 2004). Therefore, the dissolved pathway appears to be a very important route for essential elements and Ag, whereas this route appears rather limited for Cd (Bustamante et al., 2002b), Pb and V (Miramand et al., 1980, 1981) whose concentrations remained very low. Further investigations on the uptake of V and Pb are specifically needed to assess this hypothesis.

4.2. Metal bioaccumulation during growth

After a week of benthic life, the hatchlings use up their vitellary reserves and therefore need to eat. Once they start to feed, cuttlefish grow rapidly (data not shown) but at the same time, they are exposed to a new source of metals. Despite dietary intakes, the concentrations of most of the metals in the whole organisms did not vary significantly and only a few metals showed a significant increase of the concentrations in the whole cuttlefish (i.e. Cd, Fe, Table 2). This could be due either to 1) control of essential element concentrations through homeostatic regulation, or to 2) dilution of non-essential accumulated metals related to very fast somatic growth. With the exception of Fe, the essential metals seem to be well regulated and Cu and Zn showed remarkably homogenous concentrations throughout life (Table 2). Among the non-essential elements, the Ag concentration is also slightly influenced by dietary supplies. Concentrations of Pb and V in the whole cuttlefish remain very low and are only above the detection limit after 1 or 2 months of benthic life, respectively. Therefore, as far as the whole animal is concerned, cuttlefish bioaccumulate these 2 metals poorly.

Because of the metal dilution with somatic growth, it was necessary to consider the tissues separately and particularly the digestive gland as a storage organ of metals. With the first feeding, the immature digestive gland of the juveniles starts to develop to be fully functional at the age of one month (Yim and Boucaud-Camou, 1980). Food intake provokes the beginning of the digestive processes, i.e. secretion of enzymes, absorption of nutrients, and excretion of digestive residues. In a few weeks, the digestive gland takes a dark colour due to the development of digestive cells called “Boules” cells (e.g. Boucaud-Camou, 1973; Boucaud-Camou and Boucher-Rodoni, 1983; Boucher-Rodoni et al., 1987). The development of the digestive gland in the retention process of metals is very important and is reflected by the increased fraction of the whole-body burdens of all metals in this organ (Table 4). This process is particularly significant in the case of Fe, for which the metal content stored in the digestive gland rises, respectively, from 6% to about 50% before and after digestive gland development. After only two months of benthic life, the digestive gland contains between 30% (Pb) and 90% (Ag) of the total amount of metals (Table 4). These contents are identical to those previously measured in adult cuttlefish collected in the same area (Miramand and Bentley, 1992).

Thus, the digestive gland plays a major role in the metabolism of all metals in cuttlefish, and especially Cd

(Fig. 1). Indeed, during the period of development of the digestive gland (i.e. the first month of benthic life), Cd concentrations are increased 9 times compared to a factor 2 for the remaining metals. During this period, the digestive gland weight increased 30 times and the Cd amounts in this organ were multiplied by 230, i.e. 3 to 5 times higher than for the other metals (Fig. 3). The digestive gland plays a primary role in the accumulation of Cd in cuttlefish, as also reported after both field and experimental studies (Miramand and Bentley, 1992; Bustamante, 1998; Bustamante et al., 2002b). Such a role of the digestive gland can be related both to the very efficient detoxification processes of the metal occurring in this organ (Bustamante et al., 2002a) and to the very high Cd assimilation efficiency (viz. 62% for juvenile cuttlefish). Both processes lead to a strong retention of the metal in the digestive gland, whose biological half-life ($T_{b1/2}$) exceeds 8 months in juveniles (Bustamante et al., 2002b).

4.3. Influence of age

The process of bioaccumulation of all metals except Ag appears to be age-dependent in the digestive gland (Fig. 1). Indeed, the digestive gland weight is increased by 3500 between hatching and sexual maturity whereas its metal content is increased between 6000 and 9000 for the essential metals (Cu, Fe, Zn), more than 20,000 for Cd and V and about 70,000 for Co (Fig. 3). After 2 years of life the digestive gland therefore contains between 15 and 90 μg of Ag, Co, Pb and V, 165 μg of Cd and between 3 and 7 mg of Cu, Fe and Zn (Fig. 3). Therefore, the digestive gland bioaccumulates large concentrations of the metals. From the start of cuttlefish benthic life, the digestive gland shows 5 to 6 times higher Ag and Cd concentrations than those measured in the whole organisms (Tables 2 and 3) and already accounts for 50% to 90% of the total amount of these two metals (Table 4).

Because of its storage capacities, all the metal concentrations increased according to a logarithmic pattern in the digestive gland. Ag is the only exception to this pattern (Fig. 1) and its concentrations seem to be strongly influenced by the migration behaviour of the cephalopods. Indeed, after a few months in coastal areas, juveniles migrate to deeper ocean waters and return to coastal areas to mate only the following year (Richard, 1971). The migration to less polluted areas is likely to provoke a decrease in metal concentrations when they have a relatively rapid turnover. In cuttlefish, Ag has short biological half-life either following exposure from seawater or from food (less than 2 weeks), as a

consequence of its high elimination rates (Bustamante et al., 2004). Our results are probably due to the equilibrium established between episodes of contamination (when the animals live near the coast) and decontamination (when the animals live in the open sea). Therefore, both the high bioaccumulation of Ag and its weak retention in the digestive gland of cephalopods will allow these molluscs to be used to monitor Ag concentrations in the marine environment.

Decontamination is actually much slower in the case of other metals such as Cd or Co for which the biological half-lives measured in adults after incorporation of Cd or Co by the food pathway is much higher than the lifetime of cuttlefish (Bustamante et al., 2002b, 2004). Owing to this, it is very likely that after the beginning of the migration to the open sea, the Ag content of digestive gland in adults is strongly decontaminated but very little in terms of Co and Cd. Since the main incorporation mechanism of V into the marine organisms seems to be the food pathway (Miramand et al., 1981, Miramand and Fowler, 1998), the behaviour of V is similar to Cd and Co and is strongly retained by cuttlefish. Thus, it would be very interesting to confirm experimentally such a hypothesis.

In contrast to the digestive gland, the concentrations measured in the cuttlebone of juveniles are very low, with most of the metals showing concentrations close to those observed in juveniles just after hatching (Tables 2 and 5). The shell in cuttlefish is internal, therefore not exposed to metal adsorption phenomena by direct contact with seawater, unlike other molluscs, especially mussels (Van Weers, 1973; Fowler and Benayoun, 1976; Ünlü and Fowler, 1976; Miramand et al., 1980). As discussed above, despite the significant penetration of metals into the tissues, internal transfer of metals to the cuttlebone appear to be very slow and somatic growth of this organ leads to an overall dilution of most metals. The only exception was Zn whose concentrations significantly increase with age, whereas the other analysed elements tended to decrease (Fig. 2). Consequently, the metal content contained in the cuttlebone corresponds in fact either to their ponderable importance (Cu, Pb and Fe) or is clearly lower (Ag, Cd, V and Zn) (Table 6). This observation is in good agreement with the experimental radiotracer results obtained for Ag, Cd and Zn (Bustamante et al., 2002b, 2004).

4.4. Influence of sexual maturation

In two-year old individuals (sexually mature), Ag, Cd, Cu and Pb concentrations are lower than those in one-year old animals (immature) compared to those of

Fe, V, and Zn (Table 2). This could be due to physiological changes related to sexual maturation as well as to the growth of the gonads. Overall, these organs exhibit low metal levels in cephalopods (Miramand and Bentley, 1992) and help dilute non-essential metal (Ag, Cd and Pb) concentrations in the whole animals. This is clearly exemplified by the fact that, with the exception of Zn, metal concentrations in the digestive gland do not significantly differ between mature and immature individuals (Table 3). High levels of Zn in the genital tract of male and female *S. officinalis* (190 ± 22 and $123 \pm 3 \mu\text{g g}^{-1}$ dw, respectively) have been reported (Miramand and Bentley, 1992), which would explain why Zn concentrations still increased after sexual maturation. This 1.5-fold increase observed in the whole animals is in all likelihood due to a Zn accumulation in the digestive gland. This value represents a very significant concentration in the mature individuals and is 3 and 2 times higher than that measured in juveniles and in immature individuals, respectively (Table 3). During this period, the cuttlebone also showed a higher Zn concentration than that measured in juveniles and in one-year old immature individuals. This observation could have been the consequence of an increased flow of Zn in the haemolymph of cuttlefish during this period of sexual maturity. This metal could therefore be partially accumulated by the cuttlebone. In the animals collected at the end of their sexual maturity the amounts of Zn associated with the cuttlebone (expressed as total percentage of Zn contained in the whole organism) were therefore almost 2 times higher compared to the contents calculated in juveniles and in one-year old immatures. Interestingly, this phenomenon seems to be limited to Zn. The concentrations of the remaining 7 metals measured in the cuttlebone and the percentages they represent did not vary during this period (Tables 5 and 6).

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