The effect of body size on metal accumulations in the bivalve

*Laternula elliptica*

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Abstract: Variations of metal concentrations with body size were investigated in kidney, digestive gland and gill of the Antarctic clam, *Laternula elliptica*, collected from a near-shore habitat at King George Island. Positive relationships for metal concentrations with body size were common among the three organs for most of the metals, while an inverse relationship was found only in the digestive gland for Cu, Zn and Mn. In the gill, concentrations of eight out of the ten metals increased linearly with body size, whilst in the kidney concentrations of Cd, Zn, Pb, Co and Ni were best fitted by quadratic regression curves, viz. increasing continuously until reaching a peak at around an 80 mm shell length. This may reflect specific regulatory activities for the extremely high accumulation of these metals in the kidney, particularly Cd (28–354 µg g⁻¹ tissue dry weight). The overall prevalence of positive relationships indicate net accumulation of these metals throughout life, which may be at least in part associated with the slow growth and long life span of this cold-water bivalve species. The study demonstrates distinct body size-metal concentration relationships in the three organs of *L. elliptica*, and suggests they may be useful as biomonitors for assessing changes in metal concentrations in Antarctic waters.

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Key words: Antarctic clam, body size, heavy metals, King George Island, *Laternula elliptica*

Introduction

Antarctica is still the most pristine environment in the world, but some local inshore areas are potentially subject to contamination by pollutants arising from station operations, such as waste disposal, oil spills, and emissions from the burning of fossil fuels and of waste (see for review Boutron & Wolff 1989, Suttie & Wolff 1993). This is especially the case for King George Island where eight countries have been operating stations for many years. A recent study undertaken to assess impacts of human activities at a station on this island reported that lichens and topsoil at sites close to the station contained highly elevated levels of Pb and some other metals with a dramatic decrease away from the station (Hong et al. 1999). The elevation of Pb levels was attributed to combustion of leaded gasoline at the station. Hong et al. (1999) also reported that topsoil at the station was contaminated with Cr and Mo as well as Pb, ascribing this to the use of spray paint. Signs of metal contamination due to the local human activities were also found in the marine environment. Lead concentrations were found to be much higher in the inshore water close to the station with a dramatic decrease offshore (Lee et al. 1990). Regular and effective monitoring using appropriate biomonitor species is therefore required to assess anthropogenic metal pollution and to facilitate early detection of possible unforeseen negative effects in the near-shore marine environment.

Mussels and oysters have been used world-wide as biomonitors for pollution in temperate coastal waters under the design of ‘Mussel Watch’ programme (Farrington et al. 1983, Goldberg et al. 1983, Lauenstein et al. 1990), but these bivalve species are absent from the Antarctic waters. Instead, the two Antarctic bivalves, the Antarctic clam *Laternula elliptica* (King and Broderip) and the Antarctic scallop *Adamussium colbecki* (Smith) have been recognized as potential sentinel organisms for environmental monitoring by virtue of their wide distribution, large body size, and high population density (Mauri et al. 1990, Berkman & Nigro 1992, SCAR 1996). Recently baseline metal concentrations were determined in the principal body organs of *L. elliptica* collected from a near-shore site at King George Island, and *L. elliptica* was shown to have a strong metal-accumulating tendency (Ahn et al. 1996). These results strongly support the idea that this species can be used as a suitable biomonitor for the presence of heavy metals in Antarctic waters.

The aim of the present study is to develop the use of *L. elliptica* as a metal pollution biomonitor in Antarctic waters. An understanding of the relationship between body size and metal concentration is an essential prerequisite to the use of a specific biomonitor species. In this study, relationships between metal concentrations and body size were investigated in the three non-reproductive body parts (kidney, digestive gland and gill) of *L. elliptica*, which were reported to have a strong metal accumulation tendency in the previous study (Ahn et al. 1996). The suitability of each body part as a biomonitor of metal pollution is also discussed.
mixed with sand and gravel (KORDI 2000). Marian Cove is a typical fjord-like Antarctic embayment, characterized by a U-shaped deep basin, within Maxwell Bay. Surface water freezes in winter and melts in summer, but a variable cover of drifting ice occurs during most of the year. Seawater temperature varies seasonally from the maximum c. 1.7°C in February to the minimum c. -1.7°C in August, and salinity from 32.7 to 35.1% (Kim 1996, Kang et al. 1997, KORDI 1999). It has been reported that massive land runoff from the surrounding ice fields occurs every summer, influencing sedimentary processes and physicochemical properties of the near-shore seawater (Chang et al. 1990, Ahn 1994, Yoo et al. 1999). Further details of the hydrographical features and other environmental condition of this area have been well described elsewhere (Chang et al. 1990, Ahn 1997, Kang et al. 1997, Ahn et al. 2000).

Sample preparation for analysis

After sampling, L. elliptica were held in a flow-through culture tank (Ahn & Shun 1998) for two days at the ambient temperature (c. 1°C) and allowed to expel habitat sediment inside the mantle cavity before being dissected as in Ahn et al. (2000). Various sizes of individual were selected for the determination of the effect of size on metal concentrations. The excised body parts were freeze-dried for about 48 h at the station. Freeze-dried tissue weight was determined to the nearest 1 mg. Shell length (SL, the longest shell dimension) of each individual was determined to the nearest 0.1 mm with Vernier callipers.

Analytical procedures

Freeze-dried tissue samples were ground and homogenized before analysis. Due to the small size of the kidney, two or four kidney samples from clams with similar shell sizes (mostly the clams less than 70 mm in SL) were pooled to obtain the minimum amount (> 0.1 g) of samples necessary for metal analysis. For digestion, about 0.2 to 0.3 g of each tissue sample (c. 0.1 g for the kidney) was placed in a 30-ml Teflon tube and oxidized with 6 ml concentrated nitric acid (Suprapur®.

Table 1. Analytical results of metal concentrations (µg g⁻¹ dry weight) in the standard reference materials of oyster (SRM 1566a, NIST, USA) and mussel (CRM 278, IRMM-BCR, Belgium) tissues. Values are means ± standard deviations. Values in parenthesis are not certified.

<table>
<thead>
<tr>
<th>Element</th>
<th>Certified</th>
<th>Measured (n = 11)</th>
<th>%Recovery</th>
<th>Certified</th>
<th>Measured (n = 11)</th>
<th>%Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>4.15 ± 0.38</td>
<td>4.35 ± 0.27</td>
<td>105</td>
<td>0.34 ± 0.02</td>
<td>0.31 ± 0.02</td>
<td>91.7</td>
</tr>
<tr>
<td>Zn</td>
<td>830 ± 57</td>
<td>813 ± 21</td>
<td>98.0</td>
<td>76 ± 2</td>
<td>70.6 ± 2</td>
<td>92.8</td>
</tr>
<tr>
<td>Cu</td>
<td>66.3 ± 4.3</td>
<td>62.4 ± 1.75</td>
<td>94.1</td>
<td>9.6 ± 0.16</td>
<td>8.74 ± 0.30</td>
<td>91.0</td>
</tr>
<tr>
<td>Pb</td>
<td>0.371 ± 0.014</td>
<td>0.334 ± 0.012</td>
<td>90.1</td>
<td>1.910 ± 0.04</td>
<td>1.72 ± 0.13</td>
<td>89.9</td>
</tr>
<tr>
<td>Cr</td>
<td>1.43 ± 0.46</td>
<td>1.29 ± 0.17</td>
<td>90.2</td>
<td>0.8 ± 0.08</td>
<td>1.10 ± 0.23</td>
<td>137</td>
</tr>
<tr>
<td>Mn</td>
<td>12.3 ± 1.5</td>
<td>11.5 ± 0.85</td>
<td>93.3</td>
<td>7.3 ± 0.2</td>
<td>7.12 ± 0.36</td>
<td>97.7</td>
</tr>
<tr>
<td>Fe</td>
<td>539 ± 15</td>
<td>490 ± 29</td>
<td>90.9</td>
<td>133 ± 4</td>
<td>119 ± 7</td>
<td>89.2</td>
</tr>
<tr>
<td>As</td>
<td>14 ± 1.2</td>
<td>13.6 ± 0.74</td>
<td>97.0</td>
<td>5.9 ± 0.2</td>
<td>5.57 ± 0.44</td>
<td>94.3</td>
</tr>
<tr>
<td>Co</td>
<td>0.57 ± 0.11</td>
<td>0.45 ± 0.065</td>
<td>78.6</td>
<td>(0.34)</td>
<td>(0.32 ± 0.023)</td>
<td>94.5</td>
</tr>
<tr>
<td>Ni</td>
<td>2.25 ± 0.44</td>
<td>2.66 ± 0.43</td>
<td>118</td>
<td>(1.0)</td>
<td>0.93 ± 0.15</td>
<td>93.2</td>
</tr>
</tbody>
</table>
Merk) at room temperature for two hours. For complete digestion each Teflon tube was tightly screw-capped and heated in a multi-block heater (c. 100°C) for about six hours. The sample was then cooled to room temperature and dried to remove excess acid at c. 100°C with the cap open. The residue was dissolved in 20 ml of 1% nitric acid in the heated multi-block for about an hour, and then cooled to room temperature. After centrifuging, the supernatant was taken and diluted as appropriate (up to 1:20) with 1% nitric acid for measurement.

Metal concentrations were determined by inductively coupled plasma (ICP)-atomic emission spectrometry (AES) (JOBIN YVON, JY 38 Ultrace) for Mn, Cu, Zn, Fe, As and ICP-mass spectrometry (MS) (VG Elemental, PQ I1 Plus) for Cd, Pb, Cr, Co and Ni. The accuracy of the analytical method used for the clam tissues was tested using the standard reference materials for oyster (SRM 1566a, National Institute of Standards and Technology, NIST, USA) and mussel tissues (CRM 278, Institute for Reference Materials and Measurements, Community Bureau of Reference, IRMM-BCR, Belgium). Analytical results for the reference materials are shown in Table I.

Data handling and statistical analysis

Weight-specific concentration in a specific organ of each individual clam was related to its shell length, and the regression lines were fitted by the least squares method. Differences between metal concentrations in the three organs were tested using analysis of covariance (ANCOVA) (Sokal & Rohlf 1981). All the data were analysed using a statistical program MINITAB12 (MINITAB Inc).

Results

A total of 33 clams were analysed, and these ranged from 52.5 to 97.7 mm (mean = 72.1, s = 12.9) in SL and 1.25 to 8.60 g (mean = 3.81, s = 1.98) in total soft tissue dry weight (TDW). The total soft TDW, however, was calculated by combining the weights of the freeze-dried body parts of each clam, and is likely to be underestimated due to small losses of tissue fractions during dissection. Dry weights of total soft tissues, gill and kidney are plotted against SL in Fig. 2. Regression analysis showed that the dry weight of total soft tissues, gill and kidney was proportional to the square of SL. There were no significant differences among the regression slopes (a combined regression slope, b = 2.14). Dry weight of the gill of *L. elliptica* ranged from 0.09 to 1.01 g with a mean of 0.41 g, constituting about 11% of total TDW. Dry weight of the kidney ranged from 0.01 to 0.22 g with a mean of 0.09 g, representing c. 2% of total soft tissues. Since the digestive gland is fused with the gonadal part and incompletely separable, its relation to body size was not determined in this study. It has, however, been reported that the gland constituted approximately 14–21% of

<table>
<thead>
<tr>
<th>Organ</th>
<th>Cd</th>
<th>Zn</th>
<th>Cu</th>
<th>Pb</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Co</th>
<th>Ni</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kidney</td>
<td>28-354</td>
<td>400-6850</td>
<td>7.5-46</td>
<td>10.5-116</td>
<td>0.82-3.27</td>
<td>96-418</td>
<td>1570-12270</td>
<td>2.44-13.7</td>
<td>2.66-15.8</td>
<td>18.1-52.5</td>
</tr>
<tr>
<td>(174)</td>
<td>(4155)</td>
<td>(21)</td>
<td>(87.8)</td>
<td>(2.13)</td>
<td>(260)</td>
<td>(6210)</td>
<td>(9.9)</td>
<td>(12.1)</td>
<td>(33)</td>
<td></td>
</tr>
<tr>
<td>Digestive gland</td>
<td>12.6-28.1</td>
<td>96-136</td>
<td>50-112</td>
<td>1.96-5.11</td>
<td>1.02-2.94</td>
<td>3.92-14.1</td>
<td>670-2390</td>
<td>0.93-3.61</td>
<td>0.64-2.87</td>
<td>30.2-120</td>
</tr>
<tr>
<td>(18.7)</td>
<td>(118)</td>
<td>(75)</td>
<td>(3.53)</td>
<td>(1.65)</td>
<td>(7.48)</td>
<td>(1450)</td>
<td>(1.90)</td>
<td>(1.74)</td>
<td>(64)</td>
<td></td>
</tr>
<tr>
<td>Gill</td>
<td>0.88-5.35</td>
<td>93-187</td>
<td>5.8-11</td>
<td>0.343-1.95</td>
<td>0.45-2.27</td>
<td>5.3-34.6</td>
<td>440-2610</td>
<td>0.48-3.55</td>
<td>0.70-2.30</td>
<td>17.7-92.8</td>
</tr>
<tr>
<td>(2.75)</td>
<td>(124)</td>
<td>(8.2)</td>
<td>(0.87)</td>
<td>(1.23)</td>
<td>(14.5)</td>
<td>(1260)</td>
<td>(1.49)</td>
<td>(1.27)</td>
<td>(45)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. The relations of shell length (SL, mm) to total soft tissue dry weight (TDW, mg), gill tissue dry weight (mg) and kidney dry weight (mg) of *Laternula elliptica* collected from Marian Cove, King George Island; regression line A, LogY = -0.312 + 2.08 LogX (n = 33, SEb = 0.22, r² = 0.74, F = 88.07, P < 0.001); regression line B, LogY = -1.73 + 2.31 LogX (n = 33, SEb = 0.30, r² = 0.65, F = 57.71, P < 0.001); regression line C, LogY = -1.87 + 2.04 LogX (n = 30, SEb = 0.46, r = 0.41, F = 19.28, P < 0.001), where X, Y, Y, and Y, represent SL, total soft TDW, gill TDW and kidney TDW of a individual clam, respectively.

Table II. Ranges of element concentrations (µg g⁻¹ tissue dry weight) in the three organs of *Laternula elliptica* over a range of shell lengths from 52.5 to 97.7 mm. Figures in the parenthesis are the estimated concentrations for a standard *L. elliptica* of 75-mm shell length, which were calculated from the regression equations in Table III. Concentrations of all the metals except Cu and As were significantly higher (P < 0.001, analysis of covariance), by one or two orders of magnitude, in the kidney than in the other two organs. The Cu and As concentrations were significantly higher (P < 0.001) in the digestive gland than in the other organs, whereas Cr was relatively evenly distributed among the three organs.
Metal concentrations were highly variable among the three organs (Table II). In particular, concentrations of Mn, Fe, Zn, Cd, Pb, Ni and Co were significantly higher ($P < 0.001$, ANCOVA), by one or two orders of magnitude, in the kidney than in the other two organs. On the other hand, Cu and As concentrations were significantly higher ($P < 0.001$) in the digestive gland than in the other organs, whereas Cr was relatively evenly distributed among the three organs. Within each organ, metal concentrations varied significantly between individuals and mostly were related to body size.

There were positive relationships of metal concentrations with the body size for most of the metals, whilst an inverse relationship was found only in the digestive gland for Cu, Zn and Mn (Table III). In particular, in the gill, concentrations of all the metals except Pb and Zn increased linearly with body size, and none of the metals showed a negative relationship. The regression coefficients were somewhat variable among the three organs for a specific metal. In the gill, the regression coefficient ($b$) varied from 0.51 to 2.14. The concentrations of Cd, Mn, Ni, and Fe were approximately proportional to shell length ($b = 1.0$), while the concentrations of Co, As, and Cr were related to the square of shell length ($b = 2.0$). The Cu concentration was related to 0.5 power of SL. On the other hand, Pb and Zn varied independently of body size.

For the digestive glands, As, Co, Cr, Fe, Ni and Pb also showed positive relationships with the regression coefficients ranging from 0.82 to 1.94. On the other hand, Cu, Zn and Mn varied inversely with size. The concentrations of Cr, Fe and Pb were directly proportional to shell length ($b = 1.0$), and the concentrations of Co and Ni were proportional to the square of shell length ($b = 2.0$). Cadmium concentration changed little with size. As for the kidney, concentrations of As and Mn varied proportionally with shell length with the regression coefficient values of 1.32 and 1.55, respectively (Table III). However, concentrations of Cd, Zn, Pb, Co and Ni were best fitted on quadratic regression curves.
Discussion

Use of particular body organs as biomonitors for metal pollution

The use of a particular tissue or an organ in bivalves can provide some advantages over using their whole tissues. Certain organs in molluscs, such as the digestive gland (hepatopancreas) and kidney, concentrate metals more than other organs, and the analysis of these organs can provide a solution to problems of detection limits (Segar 1971, Bryan et al. 1977, Scholz 1980, Köhler & Riisgård 1982, Nolan & Duke 1983, Viarengo et al. 1987, Cossa 1989, Nott et al. 1993). Non-reproductive tissues, such as foot and gill should be more suitable than others whose metal concentration are to a greater extent affected by the reproductive cycle (Martinic et al. 1987, Cossa 1989, Odzak et al. 1994). Other advantages of the use of particular tissues in bivalves over using the whole soft tissues were well reviewed by Cossa (1989) and Odzak et al. (1994).

*Laterula elliptica* is large (≈ 110 mm in SL, Ahn 1994) with its wet flesh weighing up to 80 g (personal observations). Therefore, it may be cumbersome and time-consuming to process its whole tissues for metal analysis. Previous work (Ahn et al. 1996) demonstrated that concentrations of most of the metals were highest in the kidney, followed by digestive gland, gill, gonad and muscle (mostly siphon). Concentrations of most of the metals were higher, by one or two orders of magnitudes, in the kidney than in any other tissues (Ahn et al. 1996, table 3). Their concentrations in the digestive gland and the gill were much lower than in the kidney, but they were significantly higher than in the rest of the tissues. The metal concentrations in the digestive gland and the gill also well represented the average metal levels for the whole tissues (Ahn et al. 1996, table 6). On the other hand, the concentrations of most metals in the muscle tissues and the gonad were found to be far below the values averaged for the whole tissue. Besides, muscle tissues constitute the largest fraction (≈ 50%) of the whole tissue mass (Ahn et al. 1996, table 4, Ahn et al. 2000, table 1). It would, therefore, be very time-consuming and also not very effective to detect variability in tissue metal concentrations between individuals if whole tissues were used. For this, the three non-reproductive organs, kidney, digestive glands, and gill were selected.

Relationships between metal concentrations and body size in the different organs of *L. elliptica*

Element concentration per individual clam is commonly related to tissue weight, being expressed as a power function of tissue dry weight (Boyden 1974, 1977). However, some authors recognized the great variability of soft body weight as a limitation of this approach, and instead have related tissue metal concentrations to a less variable parameter, e.g. shell weight (Fisher 1983) or shell length (Cain & Luoma 1990). In the case of *L. elliptica*, a preliminary study showed that tissue metal concentrations in *L. elliptica* correlated better with shell length than with tissue dry weight. This seems to be attributable in part to weight loss associated with spawning, as observed in many other bivalves. Spawning of *L. elliptica* in this region occurs from December to the end of February (Urban & Mercuri 1998, Ahn et al. 2000), and the smallest animal size with mature eggs was about 39 mm SL (Kordi 1998). In the present study sampling was conducted in mid-January, and therefore all the clams analysed were expected to have partially or fully spawned, and significantly reduced their tissue weight. Shell length, on the other hand, does not change with spawning, and is also a better indicator of clam age than tissue weight.

There have been few studies on the metal concentration and body size relationship for a specific organ or tissue in natural bivalve populations. Various mollusc species show that whole body concentrations commonly decrease with increasing body size, so the higher metal concentrations in the smaller individuals cause a negative slope in the metal concentration–body size relationship (Boyden 1974, 1977, Cossa et al. 1979, 1980, Ramelow 1985, Mouniery et al. 1998, Leung & Furness 1999). Some short-term bioaccumulation experiments suggest this is likely to be the result of higher rates of metal uptake in smaller individuals than in larger ones (see for review Cossa 1989). In *L. elliptica*, however, the inverse relationship between weight-specific metal concentration and body size was found only in the digestive gland for Cu, Zn and Mn, and positive relationships were prevalent.

Positive relationships between metal concentrations in whole body tissues and body size have been reported occasionally from a variety of bivalves and gastropods (Boyden 1974, 1977, Cossa 1989, Odzak et al. 1994). It is likely that when tissues grow more quickly than the metal can be absorbed, there will be a reduction in metal concentrations in soft tissue. Since in nearly all species, smaller (younger) individuals grow faster than the older ones, dilution of metal concentrations by tissue growth should have a greater effect in smaller individuals than in larger ones, causing a positive slope in the metal concentration–body size relationship (Strong & Luoma 1981).

On the other hand, positive relationships observed in some mollusc species have been explained in terms of extremely slow rates of elimination of a metal from the body of an organism with non-regulatory uptake (Langston & Zhou 1987a, 1987b). This suggests that the net accumulation of the metals may occur throughout the life of the organisms and that higher concentrations in the larger (older) individuals reflect previous longer-term exposures (Boyden 1977). Antarctic marine organisms are known to grow very slowly compared with related species in temperate waters. For a same-sized individual, therefore, Antarctic species may be several times older than related species in temperate waters, and thus probably accumulate metal for a longer period of time. *Laterula elliptica* is reported to reach the shell length of c. 100 mm in over 20 years (Breay & Mackensen 1997). This growth rate is lower than those of related temperate species of a similar ecological niche, such as the soft clam *Mya arenaria* L. (Ralph...
Thus the positive relationships of metal concentration with body size in the three organs of *L. elliptica* may be at least in part related to their very low growth rate coupled with the long life span. Likewise, the greatest accumulation of Cd found in the oldest individuals of the mussel *Mytilus californianus* Conrad, was interpreted as an irreversible accumulation of metal in the oldest specimens and related to their very low rate of growth (see for review Cossa 1989).

The negative relationship found in the digestive gland for Cu, Zn and Mn is probably related to higher feeding activity observed in the smaller-sized *L. elliptica* (Ahn 1993). This would indicate that these metals are associated with food or other particulate matter in the seawater and taken up via filter-feeding. In particular, this appears to be the case for copper. Copper concentrations were significantly higher (*P* < 0.001, ANCOVA) in the digestive gland (50–112 μg g⁻¹ TDW) than in the kidney (7.5–46 μg g⁻¹ TDW) or in the gill (5.8–11 μg g⁻¹ TDW), strongly supporting the interpretation that Cu is taken up mainly via feeding. A similar trend was also reported for Cu-exposed mussels. Viarengo *et al.* (1993) reported that Cu concentration in mussels increased more rapidly in the digestive gland when copper was associated with particulate matter, whilst when present as a solute in seawater, it was mainly accumulated in the gill.

The concentrations of Cd, Zn, Pb, Ni, and Co in the kidney peaked at around 80-mm SL, which may indicate specific regulatory activities at high concentration (Table II). The Cd concentrations in the kidney of *L. elliptica* are comparable to those reported from the kidneys or the digestive glands of other bivalves exposed to unnaturally high Cd concentrations in experimental media (Scholz 1980, Köhler & Riisgård 1982, Nolan & Duke, 1983, Langston & Zhou 1987a, Viarengo *et al.* 1987). A similar pattern of accumulation was also reported for the kidney of the gastropod *Littorina littorea* (Linne) exposed to a high concentration of Cd (Langston & Zhou 1987a). During the 39-day period exposed to 400 μg Cd 1⁻¹, accumulation of Cd in the kidney of *L. littorea* declined after 30 days of increase (up to the level of 557 μg g⁻¹ TDW), while in other tissues it continued to increase during the whole period of exposure, notably in the gill. Langston & Zhou (1987a) suggested that this resulted from the saturation of binding sites in the kidney after a prolonged period of exposure period together with subsequent offloading and transfer of Cd to other tissues.

However, kinetics of metal accumulation/excretion in cold-water organisms like *L. elliptica* with slow growth and long life-spans may be different from those of temperate molluscs exposed to unnaturally high concentrations of metals in short-term experiments. *Elevation of cadmium* is reportedly a unique feature of the Antarctic marine herbivorous organisms (Honda *et al.* 1987, Mauri *et al.* 1990, Berkman & Nigro 1992, Ahn *et al.* 1996, Bargagli *et al.* 1996, De Moreno *et al.* 1997) living in the naturally Cd-rich waters. The Cd levels in the Southern Ocean are several times higher than in any other oceans, accounted for by the upwelling of nutrient-enriched deep water to the surface (Orren & Monteiro 1985, Honda *et al.* 1987, Fowler 1990). Future studies are, therefore, needed to elucidate the processes of metal accumulation and excretion in the kidney of *L. elliptica*.

Alternatively, this may be associated with change in feeding rate with body size/age, because in the Antarctic, Cd accumulated in herbivores like *L. elliptica* is likely to be taken up primarily from food particles. Feeding strategies of *L. elliptica*, however, are largely unknown, although a previous experimental study revealed that the smaller *L. elliptica* have a higher feeding rate than the larger ones (Ahn 1993). In a future study, feeding processes in relation to Cd uptake need to be investigated along with the life cycle of this bivalve species.

**Suitability of the individual organs as a biomonitor of changes in metal concentration in the environment**

Distinct body size–metal concentration relationships in the three organs suggest the utility of these organs as biomonitors for assessing changes in the environment. In particular, in the gill, concentrations of eight out of the ten metals increased linearly with body size, indicating that the gill may be the most suitable biomonitor for changes in metal levels (solute) in the surrounding seawater. Metal concentrations in the gills of other mollusc species have already been shown to increase proportionally to the concentrations in the experimental media or the environment (Scholz 1980, Nolan & Duke 1983, Langston & Zhou 1987a, Roesijadi & Klerks 1989, Roesijadi & Unger 1993, Odzak *et al.* 1994). In addition, the TDW of the gill of *L. elliptica* was also shown to be directly proportional to the shell length (Fig. 2), suggesting its value as a good estimator for body size. For Cu and other metals associated with food and particulate matter the digestive gland would serve as a better biomonitor. The kidney of *L. elliptica* which strongly accumulates most of the metals could also serve as a useful biomonitor when concentrations of the metals in other organs are under detection limit.

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