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Uptake and depuration of cesium in the green mussel *Perna viridis*

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Abstract The accumulation and depuration of Cs in the green mussels (*Perna viridis*) commonly found in the subtropical and tropical waters were studied under the laboratory conditions using radiotracer techniques. Following an initial rapid sorption onto the mussel's tissues, uptake of Cs exhibited linear patterns over a short exposure time (8 h) at different ambient Cs concentrations. The concentration factor was independent of ambient Cs concentration. The calculated uptake rate and initial sorption constant of Cs were directly proportional to the ambient Cs concentration. The calculated uptake rate constant from the dissolved phase in the mussels was as low as 0.026 l g^{-1} d^{-1}. Uptake rates of Cs in the mussels were inversely related to the ambient salinity. Uptake increased about twofold when the salinity was reduced from 33 to 15 ppt. The effect of salinity on Cs uptake was primarily due to the change in ambient K^+ concentration. The uptake rate decreased in a power function with increasing tissue dry weight of the mussels, although the initial sorption was not related to the mussel's body size. The efflux rate constant of Cs in the mussels was 0.15 to 0.18 d^{-1}, and was the highest recorded to date among different metals in marine bivalves. The efflux rate constant also decreased in a power function with increasing tissue dry weight of mussels. A simple kinetic model predicted that the bioconcentration factor of Cs in the green mussels was 145, which was higher than measurements taken in their temperate counterparts. The bioconcentration factor also decreased in a power function with increasing tissue dry weight of mussels.

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Introduction

Development of nuclear facilities, including nuclear power stations, fuel reprocessing plants and waste disposal installations, has resulted in the release of many radionuclides into aquatic environments. Many of these radionuclides are of considerable environmental concern because of their long half-lives, mobility in the environment and their direct interaction with aquatic organisms, including potential transfer to the top trophic levels. Among the many radionuclides, ^{134}Cs (half-life of 2.1 years) and ^{137}Cs (half-life of 30.2 years) are the fission products which may be present in the low level aqueous radioactive wastes discharged from nuclear facilities. Understanding the biological fate and transport of these radionuclides in aquatic environments is essential for sound risk assessment on human health.

The bioaccumulation of many radionuclides (including ^{134}Cs and ^{137}Cs) in aquatic organisms has been examined in many previous studies (e.g. Bryan 1963; Nolan and Dahlgaard 1991; Hutchins et al. 1996a, b, 1998). In an earlier study, Bryan (1963) investigated the accumulation of radiocesium in representative marine invertebrates. Bioaccumulation of Cs was consistently found to be slow, and was potentially mediated by

the ambient K^+ concentration (due to their chemical similarity). Many studies have exposed the aquatic organisms to Cs for a long period of time, and a bioconcentration factor was calculated based on the assumption that an equilibrium between the organisms and ambient Cs has been reached. With this experimental approach, the uptake (exposure) pathway of radionuclides cannot be clearly quantified. Relatively few studies have employed the kinetic approach, which has received increasing attention in recent years (Luoma and Fisher 1997; Reinfelder et al. 1998), to study the accumulation of radionuclides in aquatic organisms. Furthermore, studies designed to examine specifically the accumulation of radionuclides in subtropical and tropical organisms are rare. Recent evidence suggested that the concentration factors of radionuclides in fish from subtropical and tropical regions were much lower than those predicted from temperate species, and thus radiological dose assessment models based on temperate fish may give overestimates of dose when applied to subtropical and tropical fish (Twining et al. 1996).

Although considerable interest has been generated regarding the bioaccumulation of radionuclides in aquatic food chains, factors affecting the bioaccumulation of these radionuclides are not well understood (Rowan and Rasmussen 1993). Models that describe the transfer of radionuclides in aquatic food chains must also rely on rigorous and realistic measurements of the kinetic parameters governing radionuclide bioaccumulation (e.g. Le Fur et al. 1991; Garnier-Laplace et al. 1998). Rowan and Rasmussen (1993) indicated that the bioaccumulation of ^{137}Cs by fish was a negative function of the ambient K^+ concentration and suspended sediment concentrations, but a positive function of ambient temperature. Furthermore, Cs concentration in piscivorous fish was greater than its concentration in planktivores and benthivores, implying the possibility of biomagnification (Forseth et al. 1991). The bioconcentration factor of Cs in seabirds was also higher than the bioconcentration factors in invertebrates and seaweeds, although there is a considerable variation of bioconcentration factors even within each taxonomic group (Fisher et al. 1999).

We have recently modeled the tissue distribution of Cs in green mussels by stable Cs analysis (Yu et al. 2000), and found that the bioconcentration factors in the different tissues were low (in the range of 8 to 22). Notwithstanding, the factors affecting Cs bioaccumulation in green mussels remain largely unknown. In the present study, we examined the kinetics of uptake and depuration of Cs from the dissolved phase in green mussels (*Perna viridis*) commonly found in tropical and subtropical waters, including areas near the nuclear power station in Guangdong, China. Our objectives were to examine Cs accumulation and depuration in green mussels under various physico-chemical and biological conditions. A kinetic model was then applied to predict the bioconcentration factor of Cs in the mussels using the kinetic parameters determined in this study.

Materials and methods

Green mussels (*Perna viridis*) of 3.0 to 4.0 cm shell length were collected from Lantau Island, Hong Kong, during July and August, 1999. The mussels were cleaned of fouling organisms on the shells, and acclimated in the laboratory for 1 to 2 weeks prior to experiments. Unless otherwise stated for specific experiments, the seawater temperature and salinity used in the experiments were 25 °C and 28 ppt, respectively. During the acclimation period, the mussels were continuously fed with the diatom *Thalassiosira pseudonana* (Clone 3H) at a rate of about 2% of their tissue dry weight a day.

Cs uptake from the dissolved phase

Uptake of Cs in the mussels from the dissolved phase was followed using radiocesium (^{137}Cs) as the radiotracer. Radioisotope ^{137}Cs (as CsCl, in 0.1 *N* HCl) was obtained from New England Nuclear. A kinetic approach was used to determine the rate of Cs uptake in the mussels as described in Wang and Dei (1999). Radioactive additions were 6.3 kBq l^{-1} (corresponding to 0.04 n*M*). Under most circumstances (except measuring Cs uptake at different ambient Cs concentrations), the uptake of Cs was measured at a Cs concentration of 6 n*M* (by the addition of stable Cs). Radioisotope and stable Cs were equilibrated for 12 h before the uptake measurements. In general, mussels were individually placed in 400 ml 0.2 μm filtered seawater containing both the radiotracer (^{137}Cs) and stable Cs (as CsCl). There were five replicates for each experimental treatment. At time intervals (2, 4, 6, 8 h), mussels were removed from the radioactive medium, rinsed with nonradioactive water, and their radioactivity counted nondestructively by a NaI gamma detector. Following the radioactivity measurements, mussels were returned to the radioactive beakers. Our preliminary experiments demonstrated that a significant amount of Cs was absorbed onto the tissues when the mussels were in direct contact with Cs (see "Results"), thus it was necessary to perform kinetic measurements of Cs uptake at different time intervals. The uptake rate was calculated from the slope of the regression of Cs concentration against time of exposure. By the end of the experiments, mussels were dissected and the tissue dry weights were measured by drying at 80 °C overnight.

Cs uptake at different ambient concentrations

The uptake of Cs was determined at different ambient Cs concentrations: 6, 30, 120 and 600 n*M* (added as stable Cs). The lowest concentration was about three times higher than the typical background concentration (2.2 n*M*) in coastal waters (Bruland 1983).

Cs uptake at different salinities

Mussels (collected from 28 ppt water) were acclimated to different salinities (15, 22, 28 and 33 ppt) for a period of 2 weeks prior to the kinetic measurements. During the acclimation period, mussels were fed with the diatom foods. The seawater was renewed every 2 d. For the lowest salinity treatment (15 ppt), mussels were first acclimated to 22 ppt for 4 d, followed by acclimation at 15 ppt for another 10 d. The range of salinity (15 to 33 ppt) covered the typical salinity range in Hong Kong coastal waters in different seasons. Low-salinity seawater was prepared by diluting the seawater with Nanopure distilled water.

Cs uptake at different K^+ concentrations

Cs uptake was measured at different ambient K^+ concentrations over an 8 h exposure period using artificial seawater (Blust et al. 1992). The artificial seawater contained: 320 m*M* NaCl, 22.5 m*M*

$NaSO_4$, 8.0 m*M* $CaCl_2$, 1.87 m*M* $NaHCO_3$, 42.4 m*M* $MgCl_2$ and 0.34 m*M* H_3BO_3. The salinity of the seawater was maintained at 28 ppt. The experimental K^+ concentrations were 3.91, 5.74, 7.30 and 8.60 m*M*, corresponding to K^+ concentrations found in seawater at 15, 22, 28 and 33 ppt salinity, respectively. Nanopure distilled water was used to prepare the seawater medium and the pH was maintained at 7.8. The seawater was aerated for 4 h and then filtered through 0.2 μm polycarbonate membranes before additions of radiocesium and stable Cs.

Cs uptake at different temperatures

Mussels were acclimated at 18 and 25 °C for 1 week prior to uptake experiments at these two temperatures. The uptake of Cs was measured over an 8 h exposure period, as described above.

Cs uptake in mussels of different body sizes

The uptake of Cs in mussels of different body sizes (1 to 9 cm, 0.05 to 1.5 g dry tissue weight) was measured over an 8 h exposure period, as described above.

Cs depuration in green mussels

Two groups of mussels (ten individuals in each group) were exposed to ^{137}Cs in the dissolved phase for 12 h and 7 d, respectively. Mussels were placed in 1.5 liters of 0.2 μm filtered seawater (28 ppt and 25 °C) during the exposure period. Radioisotope addition was 123 and 12.3 kBq l^{-1} for 12 h and 7 d exposure, respectively. Each day, mussels were removed and fed with nonradioactive diatoms for 4 h, and then returned to radioactive water. The water was changed every 2 to 3 d for the 7 d exposure experiment. Following radioactive uptake, mussels were placed individually in a 240 ml plastic beaker held in an enclosed recirculating seawater aquarium, as described in Wang et al. (1995). The depuration of ^{137}Cs from the mussel body was then followed for 15 d. During the depuration period, mussels were continuously fed with the nonradioactive diatoms. The seawater was renewed every 4 d to prevent the buildup of radioisotope in the water and, thus, the recycling of Cs into the mussel tissues. On Days 0, 12 and 15, two mussels were removed and dissected. The radioactivity in different tissues (soft tissues, digestive gland and shell) was then measured.

In addition, the effect of body size on Cs efflux was also determined. Different sizes of mussels (11 individuals) were radiolabeled with Cs for 1 d, after which the mussels were placed in depuration beakers, as described above. The depuration of Cs in mussels of different sizes was then followed for 14 d.

Gamma radioactivity measurements

The gamma radioactivity of the mussels was measured by a Wallac 1480 NaI(Tl) gamma detector or a Canberra NaI(Tl) gamma detector. All measurements were calibrated to appropriate standards. The gamma emission of ^{137}Cs was determined at 665 keV. Counting times were adjusted to yield a propagated counting error $< 5\%$.

Kinetic modeling of Cs bioconcentration in the mussels

The uptake of Cs by the mussels from the dissolved phase can be modeled by the following first order equation:

$$dC/dt = k_u C_w - k_e C \quad , \tag{1}$$

where C is the Cs concentration in the mussels at time t, k_u is the Cs uptake rate constant from the dissolved phase, C_w is the Cs concentration in the dissolved phase and k_e is the Cs efflux rate constant. Yu et al. (2000) demonstrated that a steady state of Cs bioaccumulation in the green mussels was reached within 20 d of exposure. Thus, under steady state conditions, Cs concentration (C_{ss}) can be calculated as:

$$C_{ss} = k_u C_w / k_e \quad . \tag{2}$$

The bioconcentration factor (BCF) of Cs can simply be calculated as:

$$BCF = k_u / k_e \quad . \tag{3}$$

Results

Cs uptake at different ambient Cs concentrations

In general, Cs bioconcentration factor, calculated as the ratio of Cs concentration in the mussels to Cs concentration in the dissolved phase, exhibited a linear pattern between 2 and 8 h of exposure (Fig. 1). There was, however, significant Cs uptake within the first 2 h of exposure, presumably due to the rapid sorption onto the mussel's tissues. The amount of Cs associated with the shells was consistently $< 2\%$ of the Cs in the whole individual mussel throughout the 8 h uptake period. Thus, we considered the uptake of Cs measured for the whole individual mussel representative of uptake by the tissues.

Because Cs accumulation in the mussels was linear over 2 to 8 h of exposure, it was possible to calculate the uptake rate of Cs from the kinetic measurements. We regressed the calculated Cs concentration in mussels against time of exposure (2 to 8 h) at each Cs concentration. The slope of the linear regression represented the uptake rate, and the y-intercept of the regression represented the initial sorption onto the mussel's tissues. There was a log-log linear relationship between the uptake rate and the dissolved Cs concentration, and between the initial sorption and the dissolved Cs concentration (Fig. 2). The coefficient describing the log-log linear relationship was close to 1, indicating that

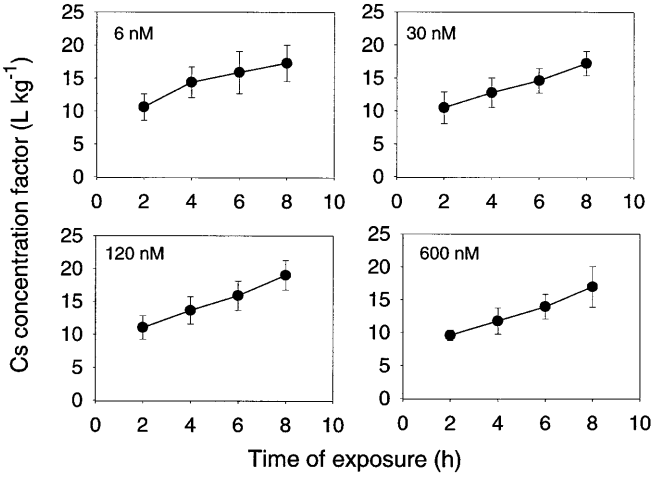

Fig. 1 *Perna viridis*. The concentration factor of Cs in the mussels over time at different ambient Cs concentrations. Mean ± SD ($n = 5$). Concentration factor was calculated as the ratio of Cs concentration in the mussels and Cs concentration in the dissolved phase

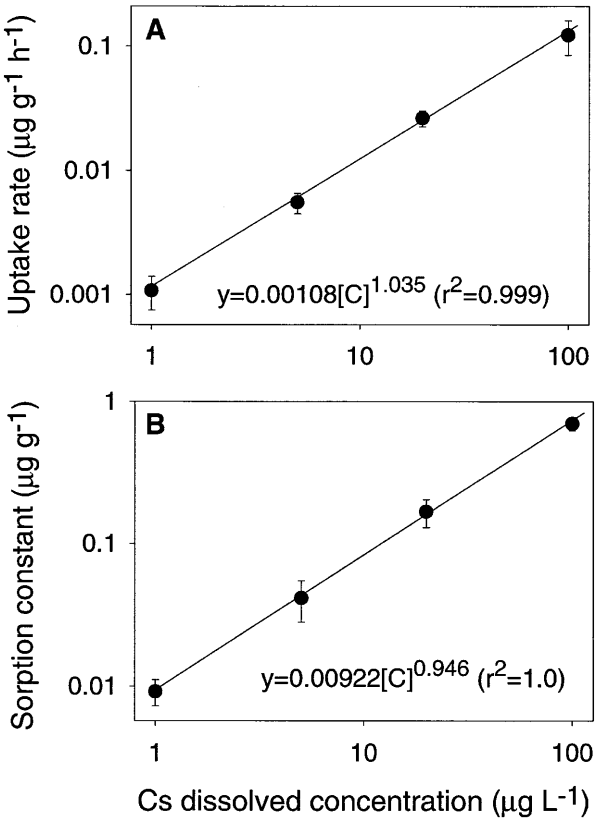

Fig. 2 *Perna viridis*. The calculated uptake rate (**A**) and the initial sorption constant (**B**) of Cs in the mussels as a function of Cs concentrations in the dissolved phase. Mean ± SD ($n = 5$)

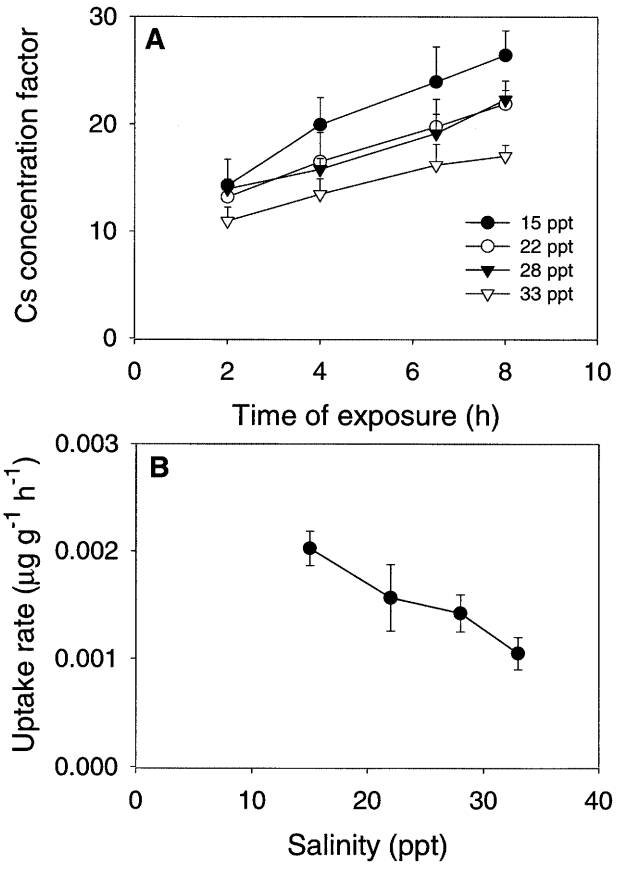

Fig. 3 *Perna viridis*. **A** The concentration factor of Cs in the mussels over time at different ambient salinities; **B** the calculated uptake rate of Cs in the mussels as a function of salinity. Mean ± SD ($n = 5$)

the uptake rate and initial sorption were directly proportional to the ambient Cs concentration. Thus, the calculated dissolved uptake rate constant was 0.026 l g^{-1} d^{-1}.

Cs uptake at different salinities

A linear pattern of Cs uptake over time was also observed at different salinities (Fig. 3). The calculated Cs concentration factor increased with a decrease in salinity. For example, Cs concentration factor in mussels after 8 h of exposure was 1.55 times higher at 15 ppt than at 33 ppt. Cs concentration factors were, however, comparable between 22 and 28 ppt. There was a linear relationship between the Cs uptake rate (which was calculated from the slope of the linear regression between Cs concentration in mussels and time of exposure) and the salinity, suggesting that the salinity significantly affected Cs uptake in the mussels ($P < 0.05$, one-way ANOVA). The ratio of Cs uptake rate was 1.93:1.49:1.36:1.00 at salinity 15:22:28:33 ppt.

Cs uptake at different K^+ concentrations

Cs uptake at different K^+ concentrations (but at 28 ppt) exhibited a linear pattern over time of exposure (Fig. 4). A lower K^+ concentration resulted in a higher Cs concentration factor in the mussels within the 8 h exposure period. The calculated uptake rates of Cs in the mussels were also significantly related to the ambient K^+ concentration ($P < 0.05$, one-way ANOVA). Ratio of Cs uptake rate was 1.99:1.46:1.34:1.00 at K^+ concentrations of 3.91:5.74:7.30:8.60 m*M*.

Cs uptake at different temperatures

Only two temperatures were examined in this study (Fig. 5). Cs concentration factor in mussels increased linearly with time of exposure, and appeared to be higher at 25 °C than at 18 °C. The calculated uptake rate constant of Cs was 1.35 times higher at 25 °C than at 18 °C, but the difference between these two treatments was not statistically significant ($P > 0.05$).

Cs uptake in mussels of different body sizes

A linear pattern of Cs uptake over the 8 h exposure period was also evident for mussels of different sizes (data not shown). The calculated uptake rate constants of Cs exhibited a log-log relationship with the dry weight

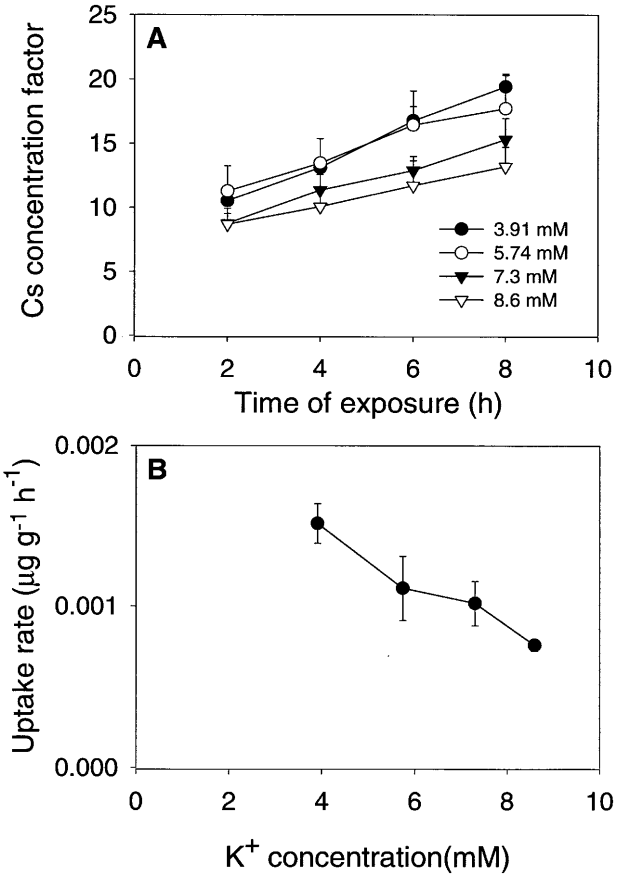

Fig. 4 *Perna viridis*. **A** The concentration factor of Cs in the mussels over time at different ambient K^+ concentrations; **B** the calculated uptake rate of Cs in the mussels as a function of K^+ concentrations. Mean ± SD ($n = 5$)

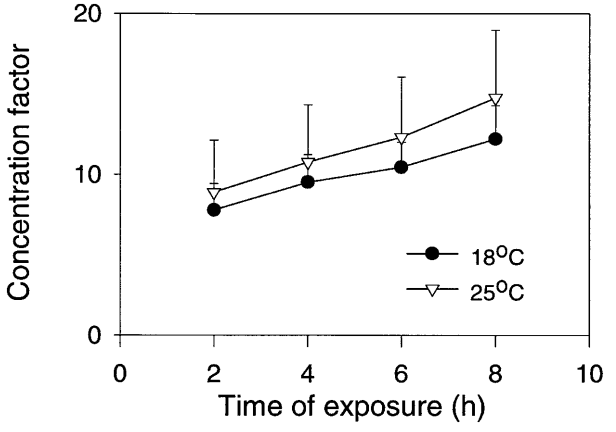

Fig. 5 *Perna viridis*. The concentration factor of Cs in the mussels over time at two different temperatures. Mean + SD ($n = 5$)

of mussel tissues ($P < 0.01$, Fig. 6). The power coefficient of the relationship was −0.464. The initial sorption constant, however, did not show any relationship with the tissue dry weight and was relatively constant for mussels of different sizes.

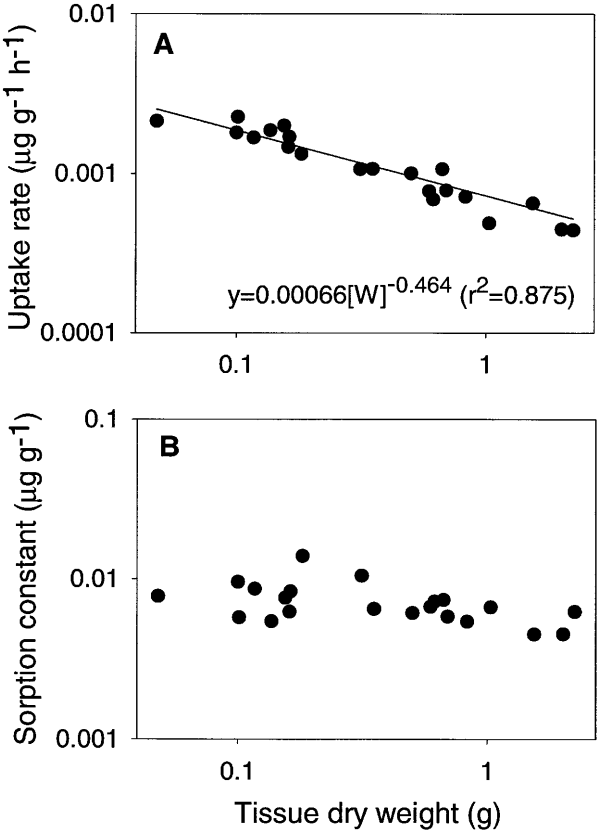

Fig. 6 *Perna viridis*. The calculated uptake rate (**A**) and the initial sorption constant (**B**) of Cs in the mussels as a function of mussel's tissue dry weight. Each data point represents one individual mussel ($n = 21$)

Cs depuration in green mussels

There was an initial rapid loss of Cs from the tissues within the first 2 d of depuration, followed by a second slower loss between 2 and 15 d (Fig. 7). Over 73 and 61% of Cs was lost from the mussels within the first 2 d following 12 h and 7 d of radiolabeling, respectively. The experiment was terminated on Day 15 because only a small percentage of Cs (4 to 5%) was retained in the mussels. The efflux rate constant was calculated from the slope of the linear regression between the ln percent retained in the mussels and the time of exposure (between 3 and 15 d). The calculated efflux rate constants were 0.178 and 0.156 d^{-1} for 7 d and 12 h exposure, respectively (Table 1). There was no statistically significant difference in the efflux rate constant between the two treatments (12 h and 7 d of exposure).

The distribution of Cs in different body compartments of the mussels (soft tissue, digestive gland and shell) throughout the depuration period is shown in Fig. 8. The shell generally contained negligible amounts of Cs throughout the depuration period. Most of the Cs was distributed in the soft tissues (> 70%), with the remaining contained mostly in the digestive glands. The fraction of Cs in the digestive glands decreased with time

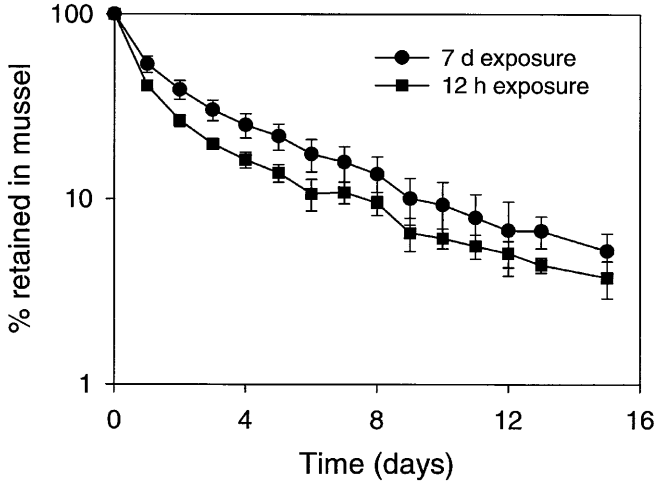

Fig. 7 *Perna viridis*. Retention of Cs in the whole mussel in nonradioactive water following 12 h or 7 d exposure to Cs in the dissolved phase. Mean ± SD ($n = 6$ to 8)

Table 1 *Perna viridis*. Compartmental analysis of Cs depuration in the mussels following 12 h and 7 d exposure to Cs in the dissolved phase (k_e efflux rate constant; $tb_{1/2}$ biological half-life). Data are mean ± SD, n = 6–7

Exposure, compartment	Percent in compartment	k_e (d^{-1})	$tb_{1/2}$ (d)	r^2
12 h				
0–2 d	71.4 ± 5.1	0.498 ± 0.043	1.05 ± 0.06	0.961
3–19 d	28.6 ± 5.1	0.156 ± 0.020	4.52 ± 0.59	0.960
7 d				
0–2 d	47.3 ± 11.2	0.295 ± 0.069	1.49 ± 0.19	0.964
3–19 d	52.6 ± 11.2	0.178 ± 0.050	4.15 ± 0.91	0.987

of depuration, whereas the fraction of Cs in the soft tissues increased with time of depuration. There was no evidence to suggest that the duration of Cs exposure affected Cs distribution in different mussel tissues.

For mussels of different sizes (0.05 to 0.86 g tissue dry weight), similar patterns of depuration were observed throughout the 14 d depuration period (data not shown). The calculated efflux rate constant (calculated from the slower compartment, 3 to 15 d) ranged between 0.127 and 0.188 d^{-1}. There was a significant power relationship between the efflux rate constant and tissue dry weight (Fig. 9), suggesting that larger mussels tended to have a lower efflux rate constant. The percentage of Cs partitioned into the second exchanging compartment, however, did not correlate with the tissue dry weight of the mussels (data not shown).

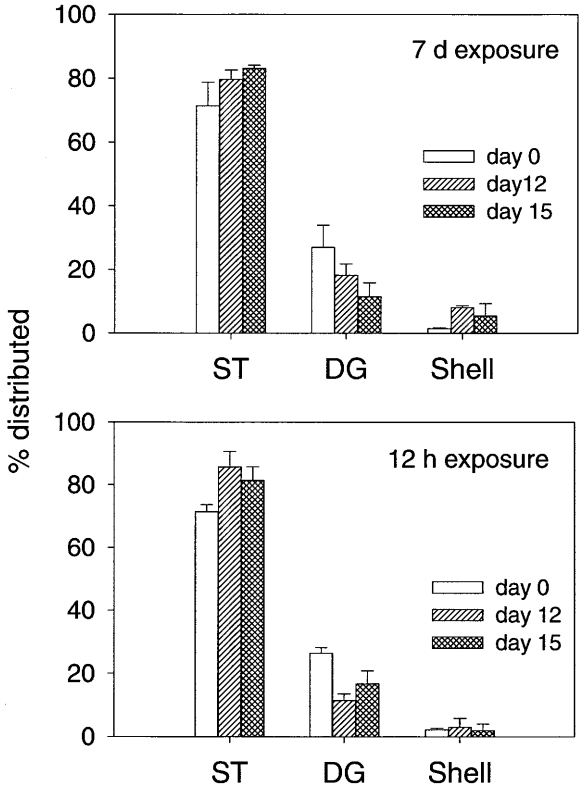

Fig. 8 *Perna viridis*. Distribution of Cs in different parts of mussels at different periods of depuration. Mussels were exposed to Cs in the dissolved phase for 7 d or 12 h before depuration. Mean ± SD ($n = 2$ to 3) (*DG* digestive gland; *ST* soft tissue without DG)

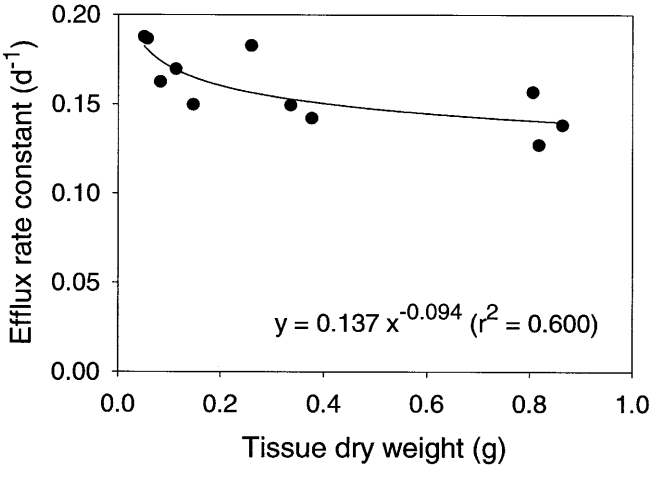

Fig. 9 *Perna viridis*. The efflux rate constant of Cs in the mussels in relation to tissue dry weight. Each data point represents one individual mussel

Kinetic modeling of Cs bioconcentration in mussels

With a known uptake rate constant from the dissolved phase and the efflux rate constant, it is possible to calculate a bioconcentration factor of Cs under steady state conditions using Eq. 3. Thus, for the mussel size of 3 to 4 cm (typically used in our experiments, k_u of 0.026 l g^{-1} d^{-1} and k_e of 0.178 d^{-1}), we calculated that the likely BCF is 145 (l kg^{-1}). However, because k_u and k_e are both directly dependent on body size, the calcu-

lated BCF as a function of tissue dry weight (W, in g) can be described by the following equation:

$$\mathrm{BCF} = 115[W]^{-0.370} \quad . \tag{4}$$

Discussion

In this study, there was an initial rapid sorption of Cs onto the mussel's tissues within the first 2 h of exposure, after which Cs uptake was linear over time. The initial sorption constant conformed with the Freundlich adsorption isotherm, suggesting that the Cs sorption was a passive process. In previous studies, a linear pattern of metal uptake over time has been documented in several marine bivalves within a short exposure period (e.g. Bjerregaard et al. 1985; Nolan and Dahlgaard 1991; Wang and Dei 1999). Accumulation of Cs in different body parts of mussels can also approximately be described by a linear function of time within the initial exposure period (Bryan 1963; Yu et al. 2000). Because there was a disproportional uptake of Cs when the mussels were in direct contact with Cs (presumably due to the initial sorption), measurements of Cs influx rate into the mussels can be considerably overestimated if only one exposure duration is considered. The initial surface sorption must be properly considered when the animals are exposed to radionuclides. Under such circumstances, it is necessary to perform kinetic measurements of Cs uptake in the mussels.

Accurate measurement of the uptake rate constant of Cs is critical for the delineation of the exposure pathway of this radionuclide in the mussels. By calibrating the initial surface sorption, the calculated Cs uptake rate constant ($0.026\ \mathrm{l\ g^{-1}\ d^{-1}}$) in green mussels was much lower than the uptake rate constant of other trace elements in bivalves, including the green mussel (Wang et al. 1996; Lee et al. 1998; Wang and Dei 1999; Chong and Wang in preparation). For example, among several trace elements studied so far in marine bivalves [^{241}Am, Ag, Cd, Co, Cr(III), Cr(IV), Se and Zn], the uptake rate constant is generally lowest for the oxyanionic metals such as selenite [Se(IV)], which may be mainly taken up by passive diffusion or by anionic channels (Simkiss and Taylor 1995; Wang and Dei 1999). The uptake rate constants of Se(IV) in the common mussel *Mytilus edulis* and the black mussel *Septifer virgatus* were 0.035 and $0.031\ \mathrm{l\ g^{-1}\ d^{-1}}$, respectively (Wang et al. 1996; Wang and Dei 1999). A plausible explanation for the low Cs uptake rate may be competitive inhibition by the overwhelmingly high concentration of K^+ in the seawater (mM level) (Bryan 1963).

Our study indicated that Cs uptake was considerably affected by ambient salinity, consistent with many previous observations on the effects of salinity on metal uptake (Wright 1995; Wang et al. 1996; Wang and Dei 1999). Influx rate of Cs increased about twofold when the salinity was decreased from 33 to 15 ppt. In *Mytilus edulis*, uptake rates of metals were increased 1.5 to 1.6 times when the salinity was reduced from 33 to 15 ppt (Wang et al. 1996). Various mechanisms have been proposed for the underlying salinity effects, including changes in metal speciation and physiological conditions of the mussels such as the pumping rate, or changes in cell volume and permeability (Wright 1995). Our study, however, demonstrated that variability of Cs uptake at different salinities was primarily due to a change in ambient K^+ concentration. The degree to which Cs uptake was affected by salinity was similar to that predicted based on a change in ambient K^+ concentration alone. Thus, higher Cs uptake at lower salinity was attributable to a decrease in K^+ concentration in the ambient water. The pumping rates of the mussels were maintained relatively constant at these salinity ranges following 2 weeks of acclimation (Chong and Wang in preparation). Cs speciation in seawater, which is dominated by free Cs ions, is unlikely to be affected by the change in salinity.

Biological factors, such as body size, could also be important in affecting Cs uptake in mussels. Body size has been recognized as an important biological factor in controlling metal accumulation in marine bivalves (Nolan and Dahlgaard 1991; Wang and Fisher 1997; Lee et al. 1998; Wang and Dei 1999; Chong and Wang in preparation). However, there appear to be variations in the power coefficient describing the relationship between metal uptake and body size, in regard to different metal species, different bivalves and, presumably, under different ecological conditions (Boyden 1974, 1977). For example, the power coefficients of the Se and Cr uptake rates in the mussel *Septifer virgatus* were −0.317 and −0.344, whereas the power coefficients of Cd and Zn were found to be much greater (−0.437 to −0.537, Wang and Dei 1999). Wang and Dei (1999) postulated that the allometry of gill surface area may be responsible for the observed allometric uptake of Cr(VI) and Se(IV), which may be transported by simple diffusion or anionic channel. For Class B or borderline metals such as Cd and Zn, which require binding with specific protein ligands for internalization, the power coefficient may not be simply controlled by the allometric change in gill surface area. The power coefficient for Cs (−0.464) was comparable to the allometric coefficient of the mussel's pumping rate (−0.443, Chong and Wang in preparation), suggesting that the pumping activity of mussels may have controlled Cs uptake in mussels of different sizes.

The measured efflux rate constant of Cs in the mussels was much higher than the efflux rate of any other metals in marine bivalves studied so far. In general, it has been observed that the efflux rates of metals in marine bivalves were relatively constant and, generally, $< 0.03\ \mathrm{d^{-1}}$ (e.g. Fisher et al. 1996; Wang et al. 1996; Lee et al. 1998). Hutchins et al. (1998) reported that the depuration of ^{137}Cs from the shells of *Macoma balthica* was slow ($0.03\ \mathrm{d^{-1}}$). Efflux rate constants of ^{137}Cs in the sea star *Asterias forbesi* and the bristle star *Ophiothrix fragilis* were also slow ($< 0.03\ \mathrm{d^{-1}}$). The much higher efflux rate of Cs determined in the present study (0.15 to

0.18 d^{-1}) presumably indicated that mussels metabolized Cs in a way similar to K^+. Previous studies in the mussel *Mytilus edulis* and the clam *Macoma balthica* demonstrated that body size in general did not influence the efflux rate of trace metals, except Cd (Wang and Fisher 1997; Lee et al. 1998). Hutchins et al. (1996a, b) indicated that the depuration of ^{137}Cs in the sea star *A. forbesi* and the bristle star *O. fragilis* was independent of the ambient temperature. Elimination of Cs in fishes was, however, found to be related to temperature (Rowan and Rasmussen 1995). Recent evidence indicated that the depuration of Cs in fish can be extremely slow; the biological half-life of Cs can be as long as 8 to 22 years (Jonsson et al. 1999).

Because most Cs was found in the soft tissues of mussels, the efflux rate constant determined for whole individual mussel represented the efflux from the tissues. In this study, we did not find any difference in efflux rate constant and Cs distribution in different body compartments of the mussels exposed for 12 h and 7 d. Consequently, 12 h exposure should be sufficient for the determination of the Cs efflux rate constant. Because very little Cs was retained in the mussels following 15 d depuration, our results did not indicate a third compartment of loss from the mussels, in contrast to many other metals in mussels (e.g. Wang et al. 1996). Previous studies on Cs depuration in marine bivalves generally indicated a two-compartmental or three-compartmental loss (Cranmore and Harrison 1975; Dahlgaard 1981; Clifton et al. 1983). Dahlgaard (1981) showed that the depuration of Cs in the mussel *Mytilus edulis* was so rapid that the excretion could only be followed for a few weeks. Cranmore and Harrison (1975) found that the Cs depuration rate constant (slower compartment of loss) in the oyster *Crassostrea gigas* was 0.01 d^{-1}, and in the mussel *M. edulis* the loss rate constant was 0.02 to 0.09 d^{-1} (Dahlgaard 1981; Clifton et al. (1983). These values were obtained by depurating the bivalves for about 1 year, and it is unknown whether a change in bivalve's body size may affect the depuration rate constant.

The Cs bioconcentration factor in green mussels, predicted by the simple kinetic model, was comparatively higher than the previous experimental measurements in marine bivalves from temperate or polar regions (Bryan 1963; Cranmore and Harrison 1975; Fisher et al. 1999). For example, the bioconcentration factor measured for the mussel *Mytilus edulis* was in the range of 7 to 14 (Bryan 1963), and among clams was 3 to 5 (Harrison 1972; Hutchins et al. 1998). Fisher et al. (1999) reviewed the bioconcentration factors of radionuclides in diverse marine organisms from polar regions. Bioconcentration factors measured in bivalves were 63 ± 42, compared to 30 for temperate species, as reported by the IAEA (1985). In our study, the bioconcentration factor predicted by the kinetic model was 145 (for a mussel size of 3 to 4 cm), and was inversely related to the body size of the mussels. It may be speculated that the higher Cs bioconcentration factor observed in green mussels, compared with other bivalves from temperate regions, could be due to the higher temperature which may result in an increase in Cs uptake. In this study, we did not test the temperature-dependence of Cs efflux in the mussels, but it is noted that temperature had no major influence on the efflux of Cs in echinoderms (Hutchins et al. 1996a, b). An alternative explanation for the discrepancy in the bioconcentration factor is that values measured using equilibrium approaches may have underestimated the bioaccumulation of Cs because of the reduction in the animal's pumping activity associated with long-term starvation stress. For example, bioconcentration factors as low as 8 to 22 were found for green mussels exposed to Cs over 1 to 2 months at a Cs concentration of 37 μM (Yu et al. 2000). In addition, both environmental conditions (e.g. temperature, salinity) and biological conditions (e.g. body size) can considerably influence Cs bioconcentration factors due to their direct effects on uptake and efflux. Consequently, bioconcentration factors are unlikely to be a constant for mussels under different physico-chemical and biological conditions.

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