Comparative Uptake and Elimination of Radiocobalt in Organic Complexed and Ionic Forms by Mussel, Mytilisepta virgatus

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(Received May 2, 1979; Revised version received July 31, 1979)

Organic complexed cobalt/Marine bivalve/Uptake and elimination

The uptake and elimination of radiocobalt in organic complexed and ionic forms by mussel, Mytilisepta virgatus were studied under laboratory conditions. The $^{57}$Co-trisglycinato complex and $^{60}$Co in CoCl$_2$ were used as tracers for organic complexed and ionic cobalt, respectively. The physico-chemical characteristics of both the radiocobalt in rearing waters were also investigated. Most of the cobalt, not only ionic but also organic complexed are of quite soluble form in seawater. The dominant species in ionic $^{60}$Co was cationic, while that in $^{57}$Co-trisglycinato complex was almost neutral. Neither $^{57}$Co-trisglycinato complex nor ionic $^{60}$Co in seawater was adsorbed on Amberlite XAD-2 resin, however, ionic $^{60}$Co was adsorbed slightly on activated carbon and much more adsorption was observed for $^{57}$Co-trisglycinato complex.

The rates of uptake, the turnover rates and the concentration factors for $^{57}$Co-trisglycinato complex in both the soft parts and the shell of mussel were smaller than those in ionic $^{60}$Co from the analysis based on an exponential model. In the uptake experiments, the exchanged cobalt in the soft parts of mussel could be calculated to be 0.26% for $^{57}$Co-trisglycinato complex and 1.93% for ionic $^{60}$Co at the equilibrium state, respectively. The whole-body elimination curves of both the radiocobalt at least consisted of the initial short component and the following long one. The elimination of $^{57}$Co-trisglycinato complex was larger than that of ionic $^{60}$Co. Mass balance calculations at the conclusion of the uptake experiments showed a remarkable difference in the distribution between the radiocobalt in $^{57}$Co-trisglycinato complex and ionic $^{60}$Co in the systems.

INTRODUCTION

Radiocobalt such as $^{57}$Co, $^{58}$Co and $^{60}$Co are among the most interesting radionuclides occurred in power reactor effluent which are mainly discharged into the marine environment, because of relatively high concentration by some species of marine organisms$^{1-2}$. The physico-chemical states of radionuclides in seawater are of funda-
mental importance to the distribution and the uptake and elimination processes by aquatic organisms. Some informations on the physico-chemical forms of cobalt in seawater have been obtained\(^6\)-\(^8\), however, there are few reports on the occurrence of organic cobalt in seawater except for cyanocobalamin, Vitamin B\(_{12}\). Recently, Sugimura et al.\(^9\) demonstrated that most of the cobalt in surface seawater existed in the organic forms such as aromatic structures including cyanocobalamin using adsorption technique onto Amberlite XAD-2 resin.

Regarding the biological availability of radiocobalt in marine organisms, Ericson\(^10\) and Lowman et al.\(^11\) reported that there were some differences in the uptake by some marine algae or in the turnover by clams between ionic and organic cobalt in cyanocobalamin. Kimura and Ichikawa\(^12\) demonstrated the effects of the chelating agents such as glycine and EDTA on the uptake and retention of \(^{60}\)Co in CoCl\(_2\) by short-necked clams. Although the occurrences of amino acids complexes with transition metals such as cobalt, copper and zinc in natural seawater have not yet been clearly identified, the possibility of the formation of such complexes in natural seawater has been suggested\(^13\). The authors\(^14,15\) also demonstrated the possible formation and some physicochemical characteristics of cobalt complexes with some amino acids such as glycine, alanine and aspartic acid in artificial seawater by means of adsorption on chelating resin, solvent extraction with dithizone and gel filtration chromatography and also paper electrophoresis. However, the biological availability of these amino acids complexes with transition metals by marine organisms has not yet been elucidated.

The present paper deals with comparative studies on the uptake and elimination of organic complexed \(^{57}\)Co in Co-trisglycinato complex and ionic \(^{60}\)Co in CoCl\(_2\) by mussel, Mytiliseptha virgatus under laboratory conditions.

**MATERIALS AND METHODS**

**Radiocobalt**

\(^{57}\)Co and \(^{60}\)Co were used in the experiments. Co-trisglycinato complex, \([\text{Co(NH}_2\text{CH}_3\text{COO})_3]\) labeled with \(^{57}\)Co was synthesized in accordance with the method described in the Chelate Chemistry\(^16\) (K. Ueno ed.), and was further purified with Chelex-100 resin (Na-form, 200-400 mesh) to remove ionic cobalt remaining in the specimen. In the preparation of \(^{57}\)Co-trisglycinato complex, cobalt carrier was added to the original \(^{57}\)Co solution. \(^{60}\)Co in CoCl\(_2\) was prepared by dilution of the original \(^{60}\)Co solution with distilled water.

**Mussel**

Mussel, Mytiliseptha virgatus (Murasaki-inkogai) was used in the experiments. The mussels were collected in the near shore waters at Uragami Bay, Wakayama Prefecture, Japan and were acclimated for 2 weeks under laboratory conditions. The average shell length and weight of the mussels were 3.6±0.8 (S. D) cm and 5.6±2.1
Rearing method

The mussels were reared in plastic vessels which held 20 liters of artificial seawater contaminated with each radiocobalt ($^{60}$Co in Co-trisglycinato complex and $^{60}$Co in CoCl$_2$) and were equipped with aeration and filtration apparatus. The artificial seawater was prepared by dissolving Aqua Marine (Yashima Chemicals, Ltd., Osaka), and the pH was adjusted to 7.8-8.2. The specific activities of $^{60}$Co in Co-trisglycinato complex and $^{60}$Co in CoCl$_2$ in the rearing waters were about 0.3 μCi/μg of stable complexed cobalt/1 and 0.8 μCi/μg of stable ionic cobalt/1, respectively. The rearing vessel had an inner basket made of polyethylene to prevent the uptake of excreta by mussels. The mussels were transferred to the inner basket in a group of 85 individuals after the radioactive concentration of the water reached approximately constant level. After about 40 days, attaining an apparent equilibrium of accumulation, the contaminated mussels in a group of 40 individuals were reared in non-active water in the same way as mentioned above to observe the elimination of the radiocobalt. The rearing waters were frequently changed to prevent a buildup of contaminants. In order to maintain a constant temperature of 15±1°C, the rearing vessels were placed in aquaria and bathed with a flow of water from a cooling unit. The mussels were reared without feeding throughout the experimental periods.

Determination of stable cobalt

In order to assure the specific activities of the radiocobalt in the rearing waters and to estimate the exchange of cobalt in the mussel, the stable cobalt contents in the prepared artificial seawater and also the soft parts of mussels were determined by spectrophotometry using nitroso-R salt in accordance with the method described by Fukai. Removing ionic cobalt in the specimen with Chelex-100 resin, the stable cobalt of the complexed form was determined after decomposition of the complex with conc. HNO$_3$ and H$_2$O$_2$. The dissected soft parts of mussels were combined and then ashed in an electric furnace for about 48 hours at 450°C. The ash was extracted with 2N HCl solution prior to the spectrophotometry.

Fractionation of radiocobalt in the rearing water

To elucidate physico-chemical state of the radiocobalt in the rearing water, the fractionation was carried out by means of filtration using Millipore HAWP filters (0.45 μm pore size) and high voltage paper electrophoresis during the uptake experiments. The experimental conditions for the electrophoresis were as follows: basic electrolyte, 0.1 N NaClO$_4$; filter paper strip (Toyo Roshi, No. 50), 40 x 5 cm; voltage, 1150 V; voltage gradient, 33.8 V/cm; duration of electrophoresis, 20 minutes. Two filter paper strips were run parallel at the same time. To prevent thermal effect during the electrophoresis, the inside of electrophoretic apparatus was maintained at
the temperature of 10±1°C using cooling tube immersed in carbon tetrachloride which filled the migration box.

Adsorption of cobalt on Amberlite XAD-2 resin and activated carbon

The batch method was used. To a 100 ml beaker were added 1 g of Amberlite XAD-2 resin or 100 mg of activated carbon (chromatographical grade) and 50 ml of contaminated seawater of pH 8.1 with each radiocobalt. The mixture was stirred for 5 hours at room temperature, and then centrifuged. One ml of the supernate was analysed by gross counting. The results are expressed in terms of the distribution coefficient (Kd). The Kd is represented by the formulation,

\[ K_d = \frac{C_0 - C}{C} \times \frac{V}{G} \]

where \( C_0 \) is the activity in the seawater before equilibrium (cpm), \( C \) is the activity in the supernate after equilibrium (cpm), \( V \) is the volume of the seawater (ml), \( G \) is the dry weight of the adsorber introduced into the system (g).

Measurement of activity

Three individuals of the mussels and 1 ml of the rearing water were taken for radioactive assay at appropriate time intervals. The mussels were wiped lightly with a filter paper and weighed. The byssus, the mantle, the gonads, the gills, the visceral mass, the adductor muscle and the shell were dissected out. In the dissection the body fluid was blotted with a filter paper. Each tissue of 3 individuals except the shell was combined and weighed in the fresh condition. The shell was cut into small pieces. Each dissected sample and also the body fluid blotted with filter paper were respectively put into a polyethylene test tube to a certain volume and its activity was measured in the fresh condition using Auto-well gamma system Model JDC-752 (Aloka Co. Ltd., Tokyo). The measurements were carried out three times and the calculated mean values of activities in the samples showed a standard deviation of less than 5%.

Estimation of rate of uptake, turnover rate and concentration factor

Although some proposals have been attempted for the modeling of the dynamics of radionuclide in aquatic organisms, an exponential model\(^{14}\) was assumed to fit the experimental data and the parameters, rate of uptake (\( u \)) and turnover rate (\( \beta \)) as well as concentration factor (\( u/\beta \)) were calculated using the least squares method. The basic differential equation for the change of concentration “\( Q_t \)” of particular nuclide in the organism with respect to time “\( t \)” (after proper correction of radioactive decay for radionuclide, if necessary) based on the exponential model\(^{14}\) may be given by

\[ \frac{dQ_t}{dt} = u \cdot S_t - \beta \cdot Q_t \] (1)
where \( S_t \) is the concentration of the nuclide in the environmental water, \( u \) is the rate of uptake per day and \( \beta \) is the turnover rate, \( 0.693/T_b (T_b: \) biological half-time in day).

Assuming \( S_t = K \) (constant) and \( Q_t = 0 \) at \( t = 0 \), the concentration at time \( t \) may be expressed as

\[
Q_t = \frac{u \cdot K}{\beta} (1 - e^{-\beta t}) \tag{2}
\]

The value of \( Q_t \) may approach asymptotically the equilibrium value \( Q_\infty = \frac{uK}{\beta} \) with the increase of time \( t \). At equilibrium state, \( \frac{dQ_t}{dt} = 0 \), and from the equations (1) and (2), the following relation may be obtained:

\[
\frac{u}{\beta} = \frac{Q_t}{S_t} = \frac{Q_\infty}{K} = \text{concentration factor} \tag{3}
\]

The numerical calculations were performed using YHP Model 97A microcalculator (Yokogawa Hewlett-Packard Co. Ltd., Tokyo).

RESULTS AND DISCUSSION

Fractionation of the radiocobalt in the rearing water

The fractionation of the organic complexed and ionic cobalt in the rearing waters using Millipore HAWP filters of 0.45 \( \mu \)m pore size showed that the activities retained on the filters were about 1% or less throughout the experimental periods. These results indicate that most of the cobalt, not only ionic but also organic complexed cobalt in Co-trisglycinato complex are of quite soluble form in seawater. Paper electrophoretic distribution of the radiocobalt in the rearing seawater is shown in Fig. 1.

A remarkable difference in the distributions between \(^{57}\text{Co}\)-trisglycinato complex and ionic \(^{60}\text{Co}\) in the rearing waters was pointed out. Although some changes in the distribution were observed during the course of rearing, the dominant species in ionic \(^{60}\text{Co}\) was cationic, while that in \(^{57}\text{Co}\)-trisglycinato complex was almost neutral. As can be seen in Fig. 1, the neutral species in \(^{57}\text{Co}\)-trisglycinato complex was more than 70% over the experimental period of 70 days. This fact might indicate that the synthesized complex was substantially stable at the temperature of about 15°C even in the rearing seawater for mussels. It has been suggested by Pentreath\(^{19}\) that careful consideration should be given to the use of filters in closed tank system in radiobiological studies for aquatic organisms, because of the possible changes in physico-chemical state of radionuclide by microbial action developed on filtration apparatus. In the present studies, however, no remarkable change in the dominant species was observed throughout the experimental periods. This presumably might be owing to relatively low water temperature of about 15°C to prevent microbial growth except obligate psychrophiles\(^{20}\).
Fig. 1. Paper electrophoretic distribution of radiocobalt in rearing seawater for mussels.

Adsorption of the cobalt on Amberlite XAD-2 resin and activated carbon

Neither $^{57}$Co-trisglycinato complex nor ionic $^{57}$Co in seawater was adsorbed on Amberlite XAD-2 resin, on the other hand, ionic $^{60}$Co was adsorbed slightly on activated carbon and much more adsorption was observed for $^{57}$Co-trisglycinato complex. The calculated distribution coefficients, $K_d$ values for $^{57}$Co-trisglycinato complex and
ionic $^{60}$Co on activated carbon were 263.8 and 28.8, respectively. Riley et al.\textsuperscript{31} and Sugimura et al.\textsuperscript{9} reported that some dissolved organic materials, especially organic compounds with aromatic structure were quantitatively adsorbed on XAD-1 or XAD-2 resin, while those with aliphatic structure had lower affinity to the resin, and none of inorganic or ions were adsorbed. These results indicate that it is difficult to recover quantitatively Co-trisglycinato complex using the adsorption technique on XAD-2 resin, although some adsorption on activated carbon may be expected.

**Uptake and accumulation of the radiocobalt by various tissues of the mussel**

The uptake and accumulation of $^{57}$Co-trisglycinato complex and ionic $^{60}$Co by various tissues of the mussel as well as the changes of radioactivities in the rearing

![Graph](image)

**Fig. 2.** Uptake of $^{57}$Co-trisglycinato complex by various tissues of mussels. The symbols denote data points; the lines are calculated curves.
Fig. 3. Uptake of ionic $^{60}$Co by various tissues of mussels. The symbols denote data points; the lines are calculated curves.

waters are shown in Figs. 2 and 3, respectively. The activity of ionic $^{60}$Co in the rearing water decreased exponentially with time, whereas that of $^{57}$Co-trisglycinato complex was almost constant. However, as can be seen in Fig. 3, the decreasing rate of ionic $^{60}$Co after the transfer of mussels into the rearing water was quite small. Therefore, the apparent concentration factor (the ratio of the radioactivity in organism to that in the surrounding water of the same weight at the same time) approached asymptotically an equilibrium value with the increase of time. Fig. 4 shows the changes of the apparent concentration factors in the whole-body of the
As already pointed out by Shimizu et al., the high accumulation of cobalt in the byssus is quite noticeable. The visceral mass including digestive tract and the gills followed the byssus. On the other hand, the accumulation of $^{57}$Co-trisglycinato complex in the shell was much smaller (Fig. 2), whereas that of ionic $^{60}$Co followed the gills (Fig. 3). It has also been reported by Lowman et al. that the uptake of ionic cobalt by the shell of clam, *Donax denticulatus* was higher than that of organic cobalt in cyanocobalamin. Furthermore, some differences in the uptake and accumulation between $^{60}$Co-trisglycinato complex and ionic $^{60}$Co by the gonads, adductor muscle and body fluid were observed as shown in Figs. 2 and 3, respectively. These dif-
ferences in the biological concentration between both the radiocobalt by the mussel might be somewhat attributed to their physico-chemical characteristics including electrophoretic behaviour revealed in Fig. 1, although further investigations would be required for electrophoretically separated radiocobalt. The curve passing through the observed values of uptake in each tissue was fitted using the estimated parameters, rate of uptake \((u)\) and turnover rate \((\beta)\) on the basis of the exponential model\(^{18}\), and the concentration factor in each tissue was estimated as the ratio \(u/\beta\). These results are shown together with the average of observed values of apparent concentration factors at apparent equilibrium in Table 1. Hiyama et al.\(^{23}\), Harrison\(^{24}\) and Shimizu\(^{25}\) pointed out carrier effect on the uptake and accumulation of radionuclides by marine organisms and reported that increasing the amount of added carrier raised in turnover rate and the concentration factor decreased. As is stated above, in the present experiments the specific activity of \(^{57}\)Co-trisglycinato complex in the rearing water was somewhat lower than that of ionic \(^{60}\)Co. This difference in the specific activities of both the radiocobalt might influence the experimental results. The concentration factors for \(^{57}\)Co-trisglycinato complex in various tissues as well as in the whole-body were lower than those for ionic \(^{60}\)Co. Furthermore, the concentration factor for ionic \(^{60}\)Co in the mussel was also somewhat lower than those for marine clams reported by other authors\(^{22-25}\) due to a higher cobalt content in the rearing water in the present experiments. However, as can be seen in Table 1, the turnover rates for \(^{57}\)Co-trisglycinato complex in both the soft parts and the shell were not necessarily higher than those for ionic \(^{60}\)Co. These results indicate that the effect of the increase in the amount of added carrier on the dynamics of radionu-

### Table 1

Rate of uptake, turnover rate and concentration factor for \(^{57}\)Co-trisglycinato complex and ionic \(^{60}\)Co in various tissues of mussels calculated from the uptake experiments

| Tissue            | Rate of uptake \((u)\) | Turnover rate \((\beta)\) | Concentration factor (\(u/\beta\)) |
|-------------------|------------------------|---------------------------|----------------------------------|
|                   | \(^{57}\)Co \(^{60}\)Co| \(^{57}\)Co \(^{60}\)Co | \(^{57}\)Co \(^{60}\)Co | \(^{57}\)Co \(^{60}\)Co | \(^{57}\)Co \(^{60}\)Co |
| Byssus            | 6.10 2560.43           | 0.21 5.40                 | 29.0 474.2 | 36.5 657.9 |
| Body fluid        | 54.71 32.99            | 59.02 15.36               | 0.9 2.1   | 1.0 2.4   |
| Mantle            | 0.15 0.64              | 0.20 0.15                 | 0.8 4.3   | 0.7 5.4   |
| Gonads            | 0.10 0.91              | 0.11 0.12                 | 0.9 7.6   | 0.8 8.8   |
| Gills             | 0.35 2.65              | 0.20 0.13                 | 1.8 20.4  | 1.8 24.5  |
| Visceral mass     | 1.00 5.81              | 0.29 0.11                 | 3.4 52.8  | 4.0 59.0  |
| Adductor muscle   | 0.14 6.82              | 0.17 1.09                 | 0.8 6.3   | 0.8 8.5   |
| Soft parts (except byssus) | 0.32 4.41 | 0.24 0.45 | 1.3 9.8 | 1.4 13.0 |
| Shell             | 0.05 1.39              | 0.05 0.14                 | 1.0 9.9   | 0.7 11.0  |
| Whole body        | 0.13 2.22              | 0.09 0.10                 | 1.4 22.2  | 1.6 26.2  |
clide in aquatic organism might depend on the chemical form of radionuclide as a matter of course. In addition to the turnover rates, the rates of uptake for $^{57}$Co-trisglycinato complex in both the soft parts and the shell were also smaller than those for ionic $^{60}$Co except the body fluid (Table 1).

Because the rates of uptake and the turnover rates for both the radiocobalt were estimated and the amounts of the stable complexed cobalt and ionic cobalt per ml of the rearing seawaters and also the amount of stable cobalt (0.71 μg, on an average) per gram of the soft parts of the mussel were known, the exchanged cobalt in the soft parts of the mussel could be calculated to be 0.26% for $^{57}$Co-trisglycinato complex and 1.93% for ionic $^{60}$Co on the basis of the equation (2) at equilibrium state, respectively. These results might suggest that $^{57}$Co-trisglycinato complex was less assimilated than ionic $^{60}$Co in the mussel, although the specific activity of the complex was smaller than that of the ionic in the rearing waters.

Elimination and distribution of the radiocobalt in the mussel

The elimination and distribution of $^{57}$Co-trisglycinato complex and ionic $^{60}$Co in the whole-body of mussel are shown in Fig. 5. The whole-body retention curves of both the radiocobalt at least consisted of the initial short half-life component and the following long one. However, the biphasic trend for ionic $^{60}$Co was less obvious than that for $^{57}$Co-trisglycinato complex, namely, the short-lived fraction for ionic $^{60}$Co was much smaller than that for $^{57}$Co-trisglycinato complex. The elimination of $^{57}$Co-trisglycinato complex was greater than that of ionic $^{60}$Co. The similar tendency was reported for $^{57}$Co-cyanocobalamin and ionic $^{58}$Co in clam, Donax denticulatus by Lowman et al.111. The activity distribution of $^{57}$Co-trisglycinato complex in the soft parts was slightly larger than that of ionic $^{60}$Co, however, the general tendency of the activity distribution of both the radiocobalt in the tissues was somewhat similar to each other (Fig. 5). Lowman et al.111 also reported that most of $^{57}$Co-cyanocobalamin was accumulated in the soft parts and ionic $^{58}$Co in the shell of the clam. However, no such remarkable tendency was observed in the distribution between $^{57}$Co-trisglycinato complex and ionic $^{60}$Co in the mussel in the present experiments, as is shown in Fig. 5, although some differences described in the previous paragraph were observed. These results indicate that the distribution of organic radiocobalt in bivalves also might depend partially on its chemical structure.

The biological half-lives, biological elimination rates and percent retention for both the radiocobalt in various tissues of the mussel were calculated in the first approximation by separating two components of the tissue retention curves using the least squares method. These results are summarized in Table 2, although some of parameters for the long-lived component could not be calculated due to much slower elimination. As can be seen in Table 2, in the long-lived component the biological half-lives in various tissues except the visceral mass for $^{57}$Co-trisglycinato complex were shorter than those for ionic $^{60}$Co, while that in the soft parts except the byssus was reverse. These results might suggest the affinity of $^{57}$Co-trisglycinato
complex to the visceral mass in spite of much more elimination of the complex by the mussel. The biological half-life for ionic $^{60}$Co in the soft parts except the byssus was about 173 days (Table 2). This value fairly agreed with 100–300 days which were reported by Harrison$^{24}$. On the other hand, the disagreement between the turnover rates from the uptake experiments and the biological elimination rates from the elimination experiments was pointed out. Such disagreement was also reported in the marine clam, Mya arenaria by Harrison$^{24}$, and she suggested that cobalt might follow different metabolic pathways during accumulation and loss. However, assuming the constant rates of uptake and turnover in the organism (organ or tissue) for the calculation of concentration factors on the basis of the exponential model$^{19}$, although the values of both the turnover rates and elimination rates did not necessarily agree, similar trends were observed in general between the concentration factors in the uptake experiments and the activity distributions in the elimination
Table 2
Biological half-life, biological elimination rate and percent retention for $^{57}$Co trisglycinato complex and ionic $^{60}$Co in various tissues of mussels calculated from the elimination experiments

| Tissue                | $r_1^2$ | $K_{b1}$ | $T_{b1}$ | $P_1$ | $r_2^2$ | $K_{b2}$ | $T_{b2}$ | $P_2$ |
|-----------------------|---------|----------|----------|-------|---------|----------|----------|-------|
|                       | $^{57}$Co | $^{60}$Co | $^{57}$Co | $^{60}$Co | $^{57}$Co | $^{60}$Co | $^{57}$Co | $^{60}$Co |
| Byssus                | 0.86    | 0.85     | 0.05     | 0.06  | 13.9    | 11.6     | 22.7     | 32.6   | 0.61  | 0.72 | 0.006 | 0.004 | 115.5 | 173.3 | 77.3 | 67.4 |
| Body fluid            | 0.85    | 1.00     | 0.47     | 0.13  | 1.5     | 5.3      | 84.5     | 68.6   | 0.82  | 0.81 | 0.012 | 0.011 | 57.8  | 63.0  | 15.5 | 31.4 |
| Mantle                | 0.86    | 0.82     | 0.19     | 0.14  | 3.6     | 5.0      | 80.6     | 70.7   | 0.68  | 0.61 | 0.003 | 0.002 | 231.0 | 346.5 | 19.4 | 29.3 |
| Gonads                | 0.91    | 0.86     | 0.13     | 0.12  | 5.3     | 5.8      | 73.8     | 68.4   | 0.42  |      | 0.004 |      | 173.3 |      | 26.2 | 31.6 |
| Gills                 | 0.78    | 0.67     | 0.28     | 0.82  | 2.5     | 0.8      | 43.2     | 31.8   |      |      |      |      |      |      | 56.8 | 68.2 |
| Visceral mass         | 0.74    | 0.87     | 0.07     | 0.19  | 9.9     | 3.6      | 54.0     | 53.7   | 0.63  | 0.72 | 0.0013 | 0.0014 | 533.1 | 495.0 | 46.0 | 46.3 |
| Adductor muscle       | 0.91    | 0.90     | 0.37     | 0.35  | 1.9     | 2.0      | 46.0     | 49.2   | 0.77  | 0.62 | 0.007 | 0.005 | 99.0  | 138.6 | 54.0 | 59.8 |
| Soft parts (except byssus) | 0.86 | 0.81     | 0.12     | 0.09  | 5.8     | 7.7      | 47.1     | 30.8   | 0.59  | 0.58 | 0.003 | 0.004 | 231.0 | 173.3 | 52.9 | 69.2 |
| Shell                 | 0.52    | 0.61     | 0.07     | 0.17  | 9.9     | 4.1      | 24.4     | 25.1   | 0.57  | 0.83 | 0.004 | 0.0038 | 173.3 | 182.4 | 75.6 | 74.9 |
| Whole body            | 0.82    | 0.63     | 0.13     | 0.04  | 5.3     | 17.3     | 55.2     | 24.9   |      |      |      |      |      |      | 44.8 | 75.1 |

$r_1^2$, $r_2^2$: Coefficient of determination, $P_1$, $P_2$: Percent retention (%), $P_1+P_2=100\%$.
$K_{b1}$, $K_{b2}$: Biological elimination rate (Day$^{-1}$), Suffix 1 and 2 denote the short and long components, respectively.
$T_{b1}$, $T_{b2}$: Biological half-life (Days).
experiments, that is, the same body parts had high and low concentration factors and high and low activity distributions except the shell.

Mass balance of the radiocobalt in the system

At the conclusion of the uptake experiments (78 days after the addition of the radiocobalt into the system), the experimental systems were disassembled and a mass balance of each radiocobalt in the system was calculated (Table 3). As can be seen in Table 3, a remarkable difference in the distribution between $^{60}$Co-trisglycinato complex and ionic $^{60}$Co in CoCl$_2$ is pointed out. More than 90% of $^{57}$Co-trisglycinato complex remained in the rearing water, while only 50% of ionic $^{60}$Co in the rearing water, and also the uptake and accumulation of $^{57}$Co-trisglycinato complex by the mussels, suspended matter and glass wool filter were much smaller than those of ionic $^{60}$Co. These results might be considered to be of fundamental importance to the radioecological implication of radiocobalt in the marine environment.

Table 3
Mass balance of the radiocobalt in the system on 78 days after the addition of the radiocobalt

| Component                        | $^{57}$Co-trisglycinato complex | Ionic $^{60}$Co in CoCl$_2$ |
|---------------------------------|---------------------------------|-----------------------------|
|                                 | Quantity (Wet weight) | Mass balance | Quantity (Wet weight) | Mass balance |
| Mussels                         | 165.4 g                     | 0.8%         | 159.2 g               | 7.3%         |
| (Soft Parts)                    | (68.3 g)                    | (0.6%)       | (68.7 g)              | (5.1%)       |
| (Shell)                         | (97.1 g)                    | (0.2%)       | (90.5 g)              | (2.2%)       |
| Glass wool filter including residue | 16.6 g                      | 1.6%         | 13.4 g                | 28.2%        |
| Rearing seawater                | 20000.0 ml                  | 92.7%        | 20000.0 ml            | 50.7%        |
| Suspended matter                | 2.0 g                        | 0.7%         | 1.6 g                 | 6.6%         |
| Experimental vessel             | 4.2 g                        | 4.2%         |                        | 7.2%         |
| Total                           | 100.0%                       |              | 100.0%                |              |

ACKNOWLEDGEMENT

The authors thank messrs. F. Kohgami and Y. Horie for their technical assistance throughout the experiments.

REFERENCES

1. G.G. Polikarpov (1966) Concentration of radionuclides of the eighth group of elements in the periodic system. In Radioecology of Aquatic Organisms, pp. 140-151, North-Holland Publ. Co., Amsterdam.
2. R. Ichikawa (1978) Concentration Factor. In Biological Concentration (in Japanese, N. Yamagata, ed.), pp. 21-40, Sangyo Tosho, Tokyo.
3. L.G. Sillen (1961) The physical chemistry of sea water. In Oceanography (M. Sears, ed.),
4. Lj. Marazović and Z. Pučar (1966) Electrodialysis of $^{106}$Ru, $^{56, 57, 58}$Co and $^{65}$Zn in sea water through ion-exchange membranes. *Croat. Chem. Acta*, 38: 183-191.

5. Lj. Marazović and Z. Pučar (1967) Two-dimensional electrochromatography of $^{106}$Ruthenium and some other radiomicroconstituents in sea water. *J. Chromatog.*, 27: 450-459.

6. Y. Honda, Y. Kimura and N. Tsuri (1972) Electrodialysis of $^{60}$Co, $^{106}$Ru and $^{144}$Ce in sea water through ion-exchange membranes. —On the effects of aging of $^{60}$Co, $^{106}$Ru and $^{144}$Ce in sea water—. *Radioisotopes*, 21: 269-275.

7. R. Fukai (1974) A Contribution to stability aspect of metal organic complexes in sea water. *Proc. Sympo. on Biogeochemistry*, Tokyo, Sept. 1970, 562-570.

8. Y. Honda (1975) Physico-chemical behaviour of radionuclides in sea water, Fundamental Aspects of Marine Radioecology (I), (in Japanese), *Proc. 2nd NIRS Seminar, Chiba*, 27-35.

9. Y. Sugimura, Y. Suzuki and Y. Miyake (1978) Chemical forms of minor metallic elements in the ocean. *J. Oceanogr. Soc. Japan*, 34: 93-96.

10. L.E. Ericson (1952) Uptake of radioactive cobalt and Vitamin B$_{12}$ by some marine algae. *Chem. and Ind.*, London, 34: 829-830.

11. F.G. Lowman and R.Y. Ting (1973) The state of cobalt in seawater and its uptake by marine organisms and sediments. In *Radioactive Contamination of the Marine Environment (IAEA-SM-158)*, IAEA, Vienna, pp. 369-384.

12. K. Kimura and R. Ichikawa (1970) Accumulation of radiocobalt by marine organisms (II). Abstract of the 13th Annual Meeting of the Japan Radiation Res. Soc., Tokyo, Oct. 1970, p. 236.

13. A. Siegel (1971) Metal-organic interactions in the marine environment. In *Organic Compounds in Aquatic Environments* (S.D. Faust and J.V. Hunter, eds.), Marcel Dekker, Inc. New York, pp. 265-295.

14. Y. Kimura and Y. Honda (1976) Interaction of radionuclides with organic matter dissolved in seawater, —Interaction of radiocobalt with some amino acids—. *Radioisotopes*, 25: 527-533.

15. Y. Honda and Y. Kimura (1978) Studies on the interaction of cobalt with organic matter in sea water, —Paper electrophoretic behaviour of cobalt in sea water media with or without glycine. *J. Faculty of Sci. and Technol., Kinki Univ.*, 13: 171-175.

16. M. Shibata (1975) Synthesis of metal complexes. In *Chelate Chemistry (5)*, (in Japanese, K. Ueno, ed.), Nankodo, Tokyo, pp. 385-386.

17. R. Fukai (1968) A spectrophotometric method for determination of cobalt in sea water after enrichment with solid manganese dioxide. *J. Oceanogr. Soc. Japan*, 24: 265-274.

18. Y. Hiyama and M. Shimizu (1969) Uptake of radioactive nuclides by aquatic organisms: The application of the exponential model. In *Environmental Contamination by Radioactive Materials (IAEA-SM-117)*, IAEA, Vienna, pp. 463-476.

19. R.J. Pentreath (1975) Radiobiological studies with marine fish. In *Design of Radiotracer Experiments in Marine Biological Systems*, Technical Report Series No. 167, IAEA, Vienna, pp. 130-170.

20. Y. Ishida (1974) Psychrophilic property of marine bacteria. In *Lectures on Oceanography (11)*, *Marine Microorganisms* (in Japanese, N. Taga, ed.), The Press of Tokyo University, Tokyo, pp. 16-34.

21. J.P. Riley and D. Taylor (1969) The analytical concentration of traces of dissolved organic materials from sea water with Amberlite XAD-1 resin. *Anal. Chim. Acta*, 46: 307-309.

22. M. Shimizu, T. Kajihara, I. Suyama and Y. Hiyama (1971) Uptake of $^{60}$Co by mussel. *J. Radiat. Res.*, 12: 17-28.

23. Y. Hiyama and J.M. Kahn (1964) On the concentration factor of radioactive I, Co, Fe and Ru in marine organisms. *Rec. Oceanogr. Works Japan*, 7: 77-106.

24. F.L. Harrison (1973) Accumulation and loss of cobalt and caesium by marine clam, *Mya*
arenaria, under laboratory and field conditions. In *Radioactive Contamination of the Marine Environment (IAEA-SM-158)*, IAEA, Vienna, pp. 453-478.

25. M. Shimizu (1975) Procedures for radioecological studies with molluscs. In *Design of Radiotracer Experiments in Marine Biological Systems, Technical Report Series No. 167*, IAEA, Vienna, pp. 121-136.