Development of a multi-target tissue approach for the prediction of non-uniform accumulation of radioactivity in fish

Kyeong Ok Kim[1], Roman Bezhenar[2], Vladimir Maderich[2], Hanna Kim[1], Mee Kyung Kim[1] and Kyung Tae Jung[1]
[1]Korea Institute of Ocean Science & Technology, Busan, Korea (kokim@kiost.ac.kr)
[2]Institute of Mathematical Machine and Systems Problems, Kiev, Ukraine

ABSTRACT

The present work is concerned with the development of a new dynamic modelling approach for the simultaneous calculation of concentration of a specific radionuclide accumulated in different tissues of fish. That is, as an extension of the previous single target tissue approach, the new model considers three-target tissues, flesh (muscle), bones (carcass), organs for each of fishes considered in the marine food web. The dynamic equation of concentration for each type of fish used in the single target tissue approach is split into three independent equations having different values of assimilation efficiency parameter and biological half-life. The target tissues were chosen based on the large differences in cell renewal time, namely biological half-life. Unlike pharmacokinetic models the new model does not consider the interaction between targets, considering substantial difference in biological half-life between considered tissues. Such simplification then requires much less number of parameters. The assimilation coefficients were basically defined using the experimental ratios between concentration of radionuclide in whole body of marine fish and concentration in specific tissue (Yankovich et al., 2010). Summing up the contribution of different tissues leads to estimation of total concentration of a radionuclide in each of fish.

For the validation purpose the model has been applied to simulate experimental results described by Baudin et al (2000). In detail, concentrations of the radionuclides 60Co, 54Mn, and 137Cs accumulated in fish (juvenile trout) are calculated and compared. The model has reproduced with reasonable accurately the accumulation of three radionuclides in fish.

INTRODUCTION

Noting that every radionuclide has the ability for preferential accumulation in a specific tissue of fish, Heling et al (2002) developed the BURN model where tissue with maximal concentration of radionuclide called "target tissue" was introduced. In the model, the target tissue is assumed to control the overall elimination rate of the nuclide in the organism according to biological half-life of this tissue; the accumulated radionuclide concentration in one tissue is predominantly large, whereas concentration in all other tissues is assumed very small and can be ignored. The single target tissue-based dynamic models usually adopt the following one-component equation.

$$\frac{dC}{dt} = aK_f C_f + bK_w C_w - \frac{\ln 2}{T_{0.5}} C, \qquad (1)$$

where C, C_f and C_w are the concentration values of activity in marine organism, their food and surrounding water, respectively, t is time, a is the food extraction coefficient (assimilation efficiency), b is the water extraction coefficient (in gills), K_f is the food uptake rate, K_w is the water uptake rate, and $T_{0.5}$ is the biological half-live of radionuclide in the body.

However, the single target tissue method works well only for radionuclides accumulating in muscle because mass fraction of muscle tissue is dominant in the organism. For radionuclides, which are accumulated at a significant rate in tissues other than muscle, we cannot ignore radioactivity in muscle, because even low concentration in muscle gives essential contribution in the total concentration of the fish body due to large mass fraction.

In this work, we present a new approach of simulating the accumulation of different radionuclides in different parts of fishes. As a first step of developing a generalized approach, a simplified multi-tissue approach is developed, neglecting the interaction between fish tissues. This approach is integrated in compartment model POSEIDON-R.

SIMPLIFIED MULTI-TISSUE APPROACH

The fact that a number of experiments show uneven elimination of activity from fish body can be explained by difference in time scale needed for depuration of different tissues (see Table 1). Therefore, in general case we need to take into account concentration of radionuclide in all tissues to obtain concentration in fish body C_{fish}

$$C_{fish} = \sum_{k=1}^{m} C_k \, f_k, \qquad (2)$$

where f_k is the mass fraction of tissue of type k (Table 1), C_k is concentration of radionuclide in the tissue of type k.

The new approach calculates concentrations of radionuclide in different tissues of fish simultaneously (multi-tissue approach). The equation (1) for each type of fish is split into three equations, which are responsible for accumulation of radionuclide in main fish tissues (carcass, muscle, organ). These tissues were chosen based on the large differences in cell renewal time (biological half-life). Biological half-life of organs (liver, kidney, stomach, gonads etc.) is much less than that of muscle, which in turn is much less than that of carcass (Table 1).

Subsequently we use a system of equations for each type of fish given below.

$$\begin{cases} \dfrac{dC_{bone}}{dt} = a_b K_f C_f + bK_w C_w - \dfrac{\ln 2}{T_{0.5(b)}} C_{bone} \\ \dfrac{dC_{flesh}}{dt} = a_f K_f C_f + bK_w C_w - \dfrac{\ln 2}{T_{0.5(f)}} C_{flesh} \\ \dfrac{dC_{organ}}{dt} = a_o K_f C_f + bK_w C_w - \dfrac{\ln 2}{T_{0.5(o)}} C_{organ} \end{cases} \qquad (3)$$

In the above, a_i values for different tissues (a_b for carcass, a_f for muscle and a_o for organs) represent the assimilation efficiency parameters. The water extraction coefficient b remains constant because the uptake of activity through water plays a minor role for most of radionuclides in comparison with uptake through food web. The a_i coefficients are computed based on experimental ratios between concentration of radionuclide in whole body of marine fish and concentration in specific tissue. Assimilation efficiency values obtained are shown in Table 2.

Table 1. Biological half-life and weight fraction for different tissues of fish used in POSEIDON-R model

Target tissue	Bone	Muscle	Organ
Biological half-life of tissues in non-piscivorous fish and demersal fish (d)	500	75	20
Biological half-life of tissues in piscivorous fish, bottom predatory fish and coastal predatory fish (d)	1000	150	40
Weight fraction f*	0.12	0.80	0.08

* Assumed from publications Yankovich (2003)

Table 2. Calculated assimilation efficiencies for different tissues of fish in dynamical food chain model

Target tissue	Bone	Muscle	Organ
a_i for isotopes of Cs	0.020	0.70	0.25
a_i for isotopes of Sr	0.300	0.20	0.35
a_i for isotopes of Co, Mn, Zn, Fe, Ni, Ag…**	0.005	0.05	0.50

** Median value among a wide range of values for each radionuclide

Table 3. Whole body Assimilation efficiencies (%) for different radionuclides extracted from Pouil et al. (2018) and estimated in current study.

Element	Median	Min	Max	Current model
Zn	22.2	4.0	40.3	
Mn	23.5	0.8	46.3	
Cu	13.6	9.1	17.9	
Cr	2.3	0.3	4.4	
Co	8.1	0.8	28.9	8.1
Cd	20.1	2.9	50.4	
As	9.6	8.1	10.6	
Am	6.8	1.0	10.2	
Ag	3.3	0.8	5.3	
Cs	76.2	61.4	88.6	58.2
Sr	-	-	-	22.4

Table 4. Standard and calculated from the model assumptions CFs, L kg^{-1}.

Radionuclide	IAEA(2004)	Non-piscivorous fish	Piscivorous fish
^{54}Mn	1000	1600	200
^{59}Fe	30000	130000	13000
^{60}Co	700	700	100
^{63}Ni	1000	1000	125
^{65}Zn	1000	3300	350
^{110m}Ag	10000	16000	1600
^{125}Sb	600	350	60

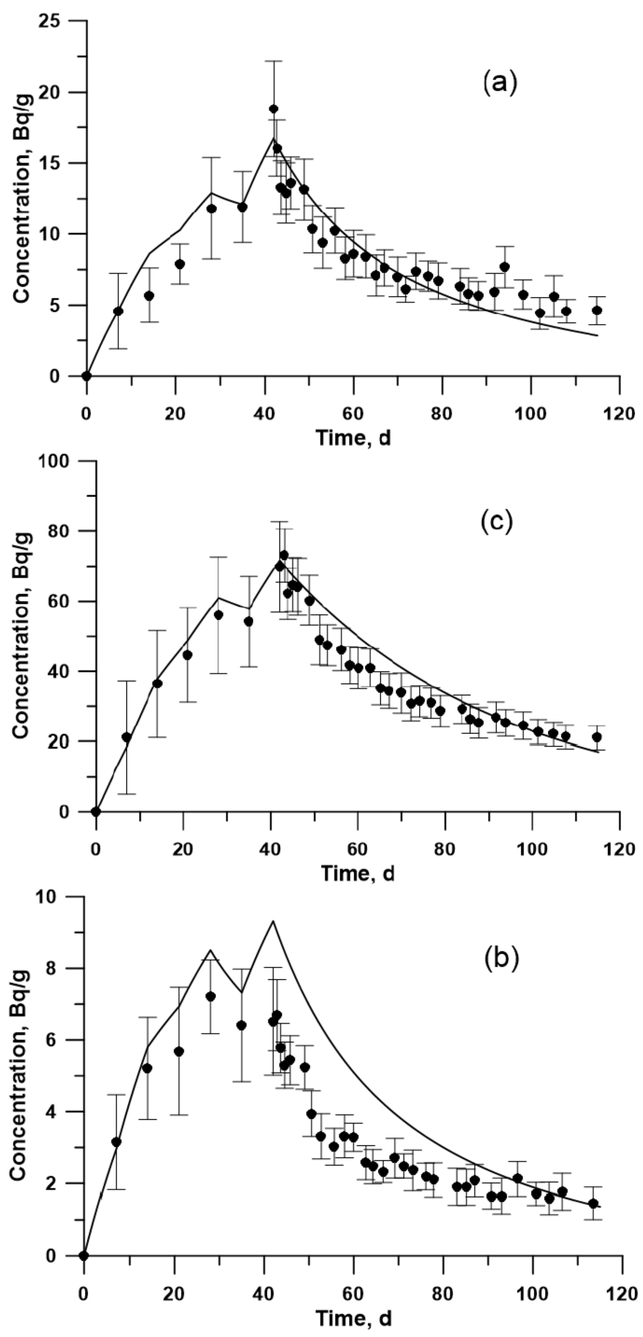

Fig. 1. Concentration of ^{60}Co (a) ^{54}Mn (b) and ^{137}Cs (c) in fish (juvenile trout) calculated by the new multi-tissue approach (lines) and measured during experiment (circles with confidence intervals) described in Baudin et al. (2000).

The whole body assimilation efficiency of radionuclide in fish (AE) could be estimated by taking into account sum of weighted assimilation efficiencies for different tissues:

$$AE = \sum_{i=1}^{3} a_i f_i, \qquad (4)$$

We have compared obtained AE for different radionuclides (Table 3) with data extracted from the literature. As we can see, the calculated AE values for the model are in the range of values for most of elements. It is noted that there is some underestimation of AE for Cs.

In general, various factors might have some influence on the assimilation efficiency of radionuclides in fish; however, we may conclude that this influence is not critical. Therefore the simplest case, when the value of a_i for certain radionuclide does not depend on the type of fish and its age, is used in the model. The calculated concentration factors for different types of fish and different radionuclides at equilibrium conditions are given in the Table 4. For most of radionuclides considered the standard concentration factor (IAEA, 2004) is in the range of obtained values.

MODEL VALIDATION using EXPERIMENTAL DATA

The experiment for assimilation of three radionuclides in fish during uptake phase and their retention during depuration phase is well described in Baudin et al. (2000). In the uptake phase of experiment, the 10 juvenile trout wish body mass of 11.3±1.2g were fed by contaminated food (young carp) during 42 days. After the uptake phase, trout were given uncontaminated food during 73 days. Periodically, all specimens were monitored for radioactivity measurements.

To reproduce the uptake and depuration of these radionuclides in fish, the developed multi-tissue approach were used with some adjustment. It is known that the biological half-life of ^{137}Cs in small size brown trout with mass 9 g and 24 g is around 40 days. This value is 3-4 times smaller than half-life of muscle tissue (where the ^{137}Cs is preferably accumulated) of adult predatory fish usually used in POSEIDON-R model (Table 1). Therefore we setup biological half-life for bone, muscle and organ tissues equal to 250, 40 and 10 days respectively to achieve experimental conditions. Estimated biological half-life for organ tissue in the juvenile fish (10 days) using such a simple method correlates with corresponding values for several organs ($T_{0.5}$ in a range from 5.7 days for liver to 8.8 days for kidney) of young brown trout during experiment with exposure by ^{54}Mn.

During the experiment, specimens of brown trout grew with average growth rate 0.007 d^{-1}. To reproduce the experiment we include in the equations (3) this parameter as additional retention term, which corresponds for decreasing of activity concentration in each tissue due to their growth.

Simulated concentration of ^{60}Co in fish agree well with measurements (Fig. 1a) both for uptake and depuration phases. In case of ^{54}Mn (Fig. 1b) we have good agreement for uptake phase and some overestimation of calculated concentration for depuration phase. However, the ratio between calculated and measured concentrations does not exceed two that could be acceptable for such complicated system. The assimilation of ^{60}Co and ^{54}Mn by fish differs from assimilation of ^{137}Cs because they are preferably accumulated in different tissues (^{60}Co and ^{54}Mn are accumulated mostly in organs while ^{137}Cs in muscle). Therefore, the good agreement between calculated and measured concentrations of ^{137}Cs in fish for uptake and depuration phases (Fig. 1c) confirms the adopted assumption about small biological half-life of different tissues in juvenile fish.

The application of the new multi-tissue approach to reproduction of the concentration of three radionuclides in juvenile predatory fish are found to be in good agreement with experimental results for both uptake and depuration phases. The model is advantageous in that it can be applicable to radionuclides preferably accumulated in different tissues of fish.

CONCLUDING REMARKS

Performance of the developed simple multi-target tissue model are encouraging in that radionuclides preferably accumulated in different tissues of fish can be modeled with considerable accuracy. The model can be used as a tool for assessment of the radiological consequences caused by the releases of radionuclides during normal operation from the various nuclear facilities or as a part of decision support system for the emergency response to the radioactivity release accident.

References

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