PAPER • OPEN ACCESS

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To cite this article: G V Lavrentyeva *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **487** 012012

Assessment of the radiation dose rate for a terrestrial mollusk during chronic Sr-90 irradiation

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Abstract. Radiation dose rate for a terrestrial mollusk *Fruticicola fruticum* was assessed under chronic Sr-90 irradiation in field conditions by three methods. The study-site is the territory nearby the radioactive waste storage facility in the Kaluga region. Due to a loss of integrity in one of the storage capacities, there was a leakage of radionuclides in 1998. Specific activities of Sr-90 in soil, plant and shells of terrestrial mollusk used as the input parameters for calculating the radiation dose rate are: 20±3 – 5203±785 Bq/kg; 22.3±13.4 – 10596 ± 195 Bq/kg, 76±11 – 17640±2646 Bq/kg, respectively. As a result of the calculations, the following radiation dose rates were obtained: from 10±2 to 1634±245 mGy/year with the J. Levinger and L.D. Marinelli formula, from 0.012±0.001 to 2.1±0.2 mGy/year with the Erica Assessment Tool, from 0.32±0.07 to 76±9 mGy/year by the Monte Carlo method. The Monte Carlo method gives the most adequate estimates, because the application of this method allows taking into account the maximum possible scenarios of mollusk irradiation, the maximum number of input parameters, including the weight and geometry of the organism, the dosimetric and physical features of the source of irradiation.

1. Introduction

In spite of the wide experimental and theoretical knowledge, methods for estimating radiation doses for biota are still under development. At the same time, many researchers work with the corresponding software packages. For example, the Erica Assessment Tool is most often used when assessing dose loads for reference animals and plants [1–5]. An application of the Erica Assessment Tool is recommended by the international organizations on the environment radiation protection. This methodology is developed in accordance with ICRP Publication 108 [6]; however, in view of the diversity of flora and fauna representatives, the possibility to estimate doses and dose rates by other methods is also not denied.

To calculate radiation doses, special mathematical models are also developed taking into account specific radioecological conditions and morphological features of an organism, which in some cases cannot be estimated with the Erica Assessment Tool [7–9].

In this paper, a comparative analysis is done for three approaches to calculate an absorbed radiation dose rate on an example of a terrestrial mollusk *Fruticicola fruticum*: the Erica Assessment Tool, a

IOP Conf. Series: Materials Science and Engineering **487** (2019) 012012 doi:10.1088/1757-899X/487/1/012012

classical computational method by the J. Levinger, L.D. Marinelli formulas, and the Monte Carlo method.

As study site in this work, the territory nearby the radioactive waste storage facility in the Kaluga region of Russia is considered. In 1998, there was a leakage of radionuclides from one of the storage capacities due to a loss of its integrity [10]. From the long period of observations (1998 – 2015), it has been well established that Sr-90 is the main radionuclide responsible for the radioecological situation in this study site [10].

2. Materials and methods

Samples of the soil, terrestrial mollusks *Fruticicola fruticum* and nettle *Urtíca dióica* (as the main food for mollusks) were taken from 42 local sites within the surveyed territory nearby the radioactive waste storage facility. Soil was selected by means of a specialized Edelman sampler ("Eijkelkamp", The Netherlands). Mollusks were collected from plants and from ground under plants in the amount of 25–30 individuals from one local site. Nettle was also sampled from the local sites.

Specific activity of Sr-90 in the samples of soil, plants and terrestrial mollusks was measured on the scintillation beta spectrometer BETA 01C after a preliminary radiochemical isolation of the radionuclide. It was carried out following the routine procedure to determine Sr-90 in environment media through β-radiation of its daughter radionuclide Y-90. Measurements of the Sr-90 specific activity were repeated 3 times.

To calculate the absorbed dose rate on a mollusk with the Monte Carlo method, the MCNP5 program was applied.

3. Results and discussion

Measurements gave the following values of Sr-90 specific activities: 20±3 – 5203±785 Bq/kg in soil, 22.3±13.4 – 10596 ± 195 Bq/kg in plants, and 76±11 – 17640±2646 Bq/kg shells of terrestrial mollusk. These data were used as the input parameters for calculating the radiation dose rate.

3.1. Assessment of the radiation dose rate with the Levinger and Marinelli formulas

This calculation is carried out taking into account the following sources of exposure of a mollusk.

The first source is a leaf of nettle. It is considered that a mollusk lives on a leaf during 155 days a year. The geometry of the irradiation source in this case is an infinitely thin plate. Radiation dose rate calculation is carried out according to the J. Levinger’s formula [11].

The second source is soil, the geometry of which is regarded as an infinitely thin plate. For a warm period, when a mollusk lives on the soil surface, the radiation dose rate is also calculated by the J. Levinger's formula [11]. For the cold period (an average of 155 days), when a mollusk appears in an anabiosis and stays inside the soil, the dose rate is estimated from the L.D. Marinelli’s formula [11].

The third source is a self-irradiation of a mollusk soft body from its shell. A shell is represented by the geometry of a sphere. The average parameters of mollusks inhabiting the study site are measured and taken into account. The average shell diameter is 1.4±0.1 cm, the average height – 0.8±0.1 cm, the radius – 0.72±0.01 cm, the square of a shell mouth – 6.16 ± 0.12 cm^2, and a shell volume of 1.44 ± 0.09 cm^3. To estimate the radiation dose rate on a mollusk soft tissue that is formed by external β-irradiation of Sr-90 and Y-90 containing in the shell, the formula is used for calculating the dose from the sphere radiation source to a point [11].

It is found that the radiation dose rate for a mollusk varies from 3.3±0.2 to 1634±245 mGy/year (table 1) along the local sites. At this, the radiation sources range in the following order: self-irradiation from shells (10±2 – 1189±178 mGy/year) > nettle (0.40±0.06 – 907±136 mGy/year) > soil (0.011±0.002 – 2.2±0.3 mGy/year). Important to emphasize that the largest contribution to the dose rate (over 95%) for a mollusk is brought by its self-irradiation from a shell.

3.2. Assessment of the radiation dose rate using the Erica Assessment Tool

When assessing the radiation dose rate for a mollusk using the Erica Assessment Tool, only one source of irradiation could be taken into account – the soil. Calculated values of the radiation dose rates vary from 0.012±0.001 to 2.1±0.2 mGy/year (table 1).

Table 1. The radiation dose rate for a mollusk (mGy/year) calculated by different methods.

Local site	J. Levinger and L.D. Marinelli formulas	Erica Assessment Tool	Monte Carlo method
1	41.2±0.3	0.10±0.04	1.41±0.04
1a	40.1±0.1	0.030±0.005	1.51±0.03
1b	18.2±0.2	0.11±0.01	4.71±0.04
2	50.3±0.5	0.31±0.01	3.41±0.04
2a	170±15	0.12±0.01	4.1±0.2
2b	34.3±0.3	0.10±0.01	20.0±0.6
2c	363±36	0.11±0.01	1.1±0.1
2d	1287±124	0.010±0.001	61±9
3	19.3±0.9	0.12±0.01	4.1±0.1
3a	912±43	0.031±0.001	49.2±0.5
3b	842±36	0.027±0.001	47.1±1.4
4	32.1±2.6	0.10±0.01	1.5±0.1
4a	512±27	0.052±0.001	24.3±0.7
4b	611±24	0.061±0.001	26.0±0.7
4c	499±19	0.053±0.001	25.0±0.6
6	105±24	0.31±0.01	2.7±0.1
6a	188±31	2.1±0.2	14.0±0.4
6b	648±85	0.21±0.02	32.0±0.7
6c	1533±185	0.10±0.01	10.0±0.4
7b	1634±245	0.9±0.1	76±9
10	378±81	0.23±0.04	11.1±0.5
10a	160±34	0.9±0.1	18.0±1.3
10b	76.2±14.3	0.011±0.001	3.1±0.1
10c	45.1±19.3	0.12±0.02	1.23±0.04
10d	30.0+11.2	0.12±0.01	1.10±0.05
10e	156±24	0.11±0.01	9.0±0.3
10l	327±84	0.32±0.02	12.1±0.3
11	667±94	0.9±0.2	10.0±0.6
Control	3.3±0.2	0.012±0.001	0.32±0.07

It should be noted that theses dose rates found with the Erica Assessment Tool are consistent with the results of the calculation with the D. Marinelli's formula for contribution of radioactive soil contamination (0.011±0.002 – 2.2±0.3 mGy/year). Despite the difference in the methods for calculating the radiation dose rate of a mollusk, the doses delivered from Sr-90 containing in soil are significantly correlated between two methods of estimation (r = 0.96).

3.3. Assessment of the radiation dose rate using the Monte Carlo method

An application of the Monte Carlo method is recommended by the ICRP [6] for terrestrial ecosystems when both a source and a target could be located in soil or on its surface, unlike aquatic ecosystems where target organisms' density is close to the water density. The Commission note that numerical simulations of particle transport through natural environments implemented by the Monte Carlo method have certain advantages. They include a possibility to model complicated geometry of a target and a source, an adequate consideration of radiation physics, low inaccuracy in the assessments. This method is widely used in international projects in the field of the environment radiation protection to resolve tasks of dose assessments.

Since Sr-90 is the main dose-forming radionuclide at this territory, the solution of the dosimetric problem reduces to an estimation of the radiation transfer of the β-source of Sr-90 and the β-, γ-source of its daughter radionuclide Y-90.

For the radiation dose rate calculation, physical and geometric models of a mollusk are necessary to use as well as all possible scenarios of a mollusk exposure should be taken into account.

The physical model of a mollusk could be represented by the following parameters: the shell material of a mollusk, consisting of $CaCO_3$, has a density of 2.7 g/cm^3; soft shellfish is represented by a 4-component ICRU system with a density of 1 g/cm^3 [12, 13].

The geometric model has the following parameters:

- a mollusk is represented by the geometry of a sphere with a radius of 1 cm;
- a mollusk shell has the geometry of a spherical layer, the thickness of the layer is 25 * 10^{-4} cm;
- the weight of a mollusk is 7.2 g, which corresponds to an average weight of mollusks inhabiting the study territory;
- the weight of a mollusk shell is 2.7 g (an average weight of the shells of the mollusks inhabiting the study site).

The calculations performed by MCNP5 program allow for accounting for 10^9 irradiation histories for each assumption. In calculations, nearly in all cases, a variance of less than 0.01% was obtained, in a few exceptional cases – less than 0.3%.

The following scenarios were considered at the assessment of the radiation dose rate for a mollusk.

Self-irradiation of an organism assumes the following assumptions:

- the source of radiation is deposited in a shell and soft tissue of a mollusk;
- the activities of Sr-90 in a shell and tissue are distributed in proportion to the Ca content in $CaCO_3$ (shell material) and in a mollusk tissue;
- the half-life of Sr-90 is not taken into account due to a short life cycle of a mollusk in comparison with the physical decay of the radionuclide.

The scenario when a mollusk lives on the soil surface assumes the following input parameters:

- the source of irradiation is enclosed in the volume of the soil, the geometry of the soil is represented by a cylinder;
- in the case of Sr-90, the cylinder has the following geometric parameters: radius – 10 cm, height – 6 cm; in the case of Y-90: radius – 14 cm, height – 8 cm. Taking into account different properties of Sr-90 and Y-90, different depth for the radionuclide deposition was used at the dose rate calculations;
- there is an air layer above the cylinder;
- the target (mollusk) is located in the center of the upper base of the cylinder.

The scenario of irradiation when a mollusk stays in anabiosis suggests the following:

- a mollusk is buried into the soil, the geometry of the soil volume is a cylinder with a radius of 19 cm and a height of 11 cm;
- a mollusk is located in the center of the cylinder along the radius and in the intermediate level (from 5 to 2 cm) along the height axis.

The scenario of irradiation when a mollusk is placed on nettle leaves during the vegetation period assumes the following input parameters and assumptions:

- the dose of irradiation is formed from the source of radiation distributed within the soil, the contribution to the dose from the source containing in the nettle is negligible;
- the target (mollusk) is at an altitude of 10 cm above the surface of the soil;
- for Sr-90 it is assumed that radiation is generated by the soil volume, represented by the geometry of the cylinder with a radius of 10 cm and a height of 10 cm;

- for Y-90, the radiation is assumed to be generated by the volume of the soil, represented by the geometry of two cylinders: with a radius and a height of 15 cm for β-radiation, and with a radius and a height of 20 cm for ɣ-radiation, respectively.

At further calculations of the radiation dose rate for a mollusk, the exposure time, animal weight and specific activity of radionuclides for all scenarios and at each local site were used.

As a result of all scenarios and assumptions, it is found that the radiation dose rate for a mollusk varies in the range from 0.32±0.07 to 76±9 mGy/year (table 1).

It is important to note that the radiation dose rate for a mollusk within nearly all the studied local sites is mostly formed from the self-irradiation of an animal that amounts to 0.3±0.02 – 48.6±0.4 mGy/year.

4. Conclusions

From the work done we can conclude that, among the methods considered, the most adequate estimates at the radiation dose rate calculations for a terrestrial mollusk could be received with the application of the Monte Carlo method. Such a conclusion is justified by the fact that the Monte Carlo method allows to take into account more possible scenarios of mollusk irradiation, maximum number of input parameters, including the weight and geometry of an organism, the dosimetric and physical features of a radiation source.

At the same time, the estimates obtained with the Erica Assessment Tool are the worst among the studied, because it is impossible to take into account an organism self-irradiation and contribution to the dose rate from radionuclides deposited in nettle leaves.

In turn, the assessment of the dose rate using the canonical formulas of J. Levinger and L.D. Marinelli allows considering all sources of an organism irradiation (soil, plant, self-irradiation). However, at this approach, such a very important input parameter as the weight of an exposed animal is not included in calculations. Since terrestrial mollusks are rather small biological organism with a low body weight (4–7 g), the weight omission can result in an overestimated value of the dose rate.

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