

Modeling of the Distribution of Radionuclide Concentrations in Organs and Tissues of the Human Body

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Received October 31, 2020; revised November 9, 2020; accepted November 10, 2020

Abstract—On the basis of previous studies carried out by the authors of this work, it was shown that the external environment of a person has a rather strong effect on the annual intake of radon and its daughter decay products into the human body. In this paper, the authors have presented a computational model and its software implementation in the form of a computer program that allows calculating the accumulated doses from various radionuclides in organs and tissues of the human body. This software and mathematical complex simulates the spread of radionuclides throughout the body, taking into account the experimental coefficients of transition from one organ to another. Such a mathematical calculation, based on the experimental accumulation factors and methods for calculating the ICRP doses, makes it possible to calculate the internal radiation doses of the corresponding organs and tissues. A mathematical model has been developed for the transport and accumulation of natural radionuclides in the organs of the respiratory and digestive systems of the human body on the basis of the accumulation and transition coefficients for the corresponding organs. The visualization of the accumulated doses of a certain organ is carried out against the background of a person's silhouette and the corresponding body system of this organ that is part of it. The degree of “highlighted” organs is normalized to the maximum doses of sanitary norms of the Republic of Kazakhstan for this organ and this radionuclide. In this simulation, the calculations of the accumulated doses from the concentrations of radionuclides in the respiratory and digestive systems of the human body are performed. This complex is designed, first of all, to perform preliminary estimated doses in organs from a wide range of radionuclides, both for diagnostic purposes and in the form of demonstration material in specialized courses at radioecological and medical centers or in higher education.

Keywords: radionuclides, accumulated dose, radioactive irradiation of organs and tissues, modeling of absorbed doses in the human body, external and internal human exposure

DOI: 10.1134/S106377882109012X

1. INTRODUCTION

Nowadays, special attention of public and international institutions is paid to reasoning and creating ways to ensure the safety of the population from natural radioactive radon. From a radiological point of view, radon is the predominant source of exposure for the population. The contribution of radon to the total dose of human exposure reaches more than 50%. Taking into account the medical consequences of the action of radon on the human body, it is worth considering that the International Agency for Research on Cancer classifies radon as a human carcinogen. Currently, the relationship between lung cancer and indoor exposure to radon is well established, while it is indicated that radon is the second most important (after smoking) risk factor for the appearance of pulmonary oncological pathology. According to the estimates of various reputable international institutions, from 3% to 14% of lung cancer cases are substantiated

by the exposure of people to the daughter products of radon decay in houses [1]. Taking this information into account, the protection of the population from radon is a necessary scientific and practical task, the solution of which not only is important in the framework of radiological aspects but also becomes widespread in the issue of public health.

The authors carried out studies of the mechanisms of temporal variations in the emanation of radon and its daughter decay products, as well as monitoring of natural beta radionuclides in the surface atmospheric layer [2–8]. A number of important conclusions were drawn from these studies. After the processes of radon emanation from the interior to the Earth's surface have taken place owing to the mechanisms of gas-kinetic diffusion, the mechanisms of radon diffusion into the atmosphere start. Mixing in the atmosphere occurs mainly due to the mechanism of turbulent diffusion [9]. This mixing is characterized by large varia-

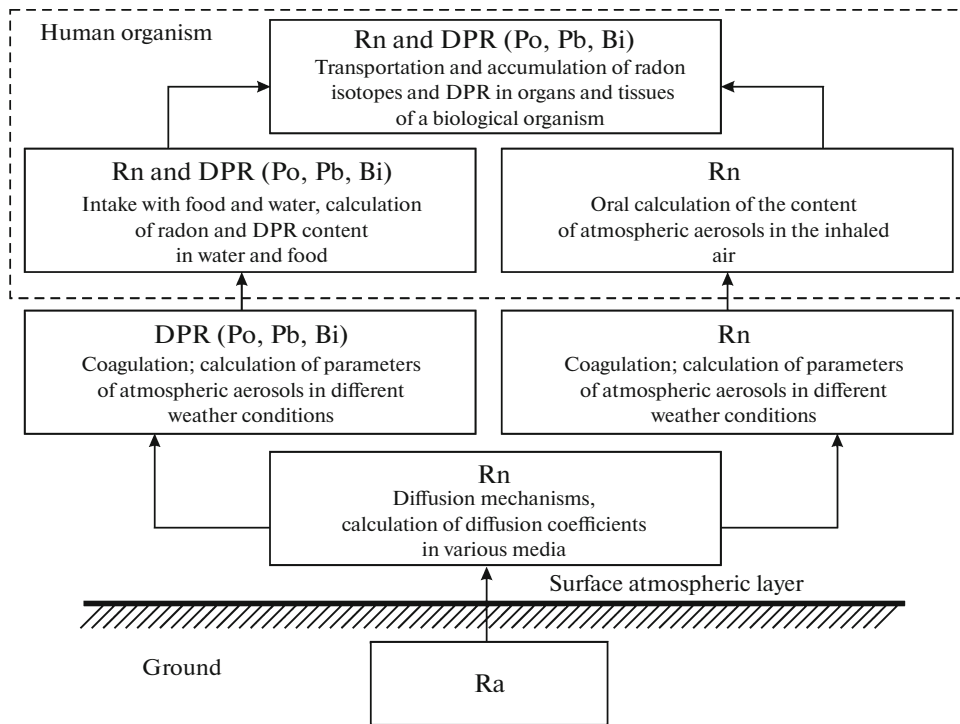


Fig. 1. Block diagram of the transport of radon isotopes and their daughter decay products from the source to the human body and the environment.

tions in amplitude, frequency, and spatial coordinates. Convection occurs owing to the uneven heating of the terrestrial surface by the Sun. Such unevenness can be local, regional, and global. The convection mechanism plays a significant role in radon migration, which arises as a result of the dynamics of air jets caused by changes in barometric pressure and temperature variations. Radon isotopes and their daughter decay products are sorbed by substances in various phase states. Adsorbed radon atoms are capable of concentrating in various substances [10] and such effects manifest themselves very well in carbon. This also applies to biological tissues, which significantly exacerbates the radon hazard and radon oncology.

The radon-absorbing properties of various substances significantly depend on the temperature, previously adsorbed other gases, moisture saturation, and many other parameters, which must also be taken into account when calculating the intake of radon and its daughters into the body. The authors carried out work concerning study of the influence of alpha radiation on living organisms [11].

It was shown in this work that, upon the occurrence of radiation effects on biological samples of *Drosophila melanogaster* during exposure to reference alpha sources simulating radon radiation, there is a satisfactory dependence of the occurrence of the corresponding effects on the radiation dose. Thus, the external environment of a person has a rather strong effect on the annual intake of radon and its daughters into the

human body. Figure 1 shows the methods of transportation and delivery of radon isotopes and their daughters into the human body.

The main natural radionuclides that enter the body and are formed owing to the long-lived isotope of radon from one of the three natural families of radioactive decay are presented in Table 1. The external conditions of the natural radiation background directly form the intake of natural radionuclides into the human body and, depending on their chemical properties, are concentrated in the corresponding human organs. By studying the accumulation of natural radionuclides in various human organs and their further influence on biological processes, it is possible to prevent and identify possible potentially dangerous radiogenic oncological diseases at an early stage [12–21]. In this regard, the problem to develop a model for the distribution of concentrations of natural radionuclides in organs and tissues of the human body was formulated.

In this work, the authors proposed a computer model making it possible to perform preliminary estimates of the doses of radionuclides in the organs and tissues of the human body.

2. DESCRIPTION OF THE ANALYTICAL MODEL

The distribution of chemical elements in individual living organisms (including the human body), as well

as in their totality, obeys the general geochemical laws of Mendeleev–Clark and Oddo–Harkins. In the world literature, such works are known as [22–26] in which measurements of the concentrations of chemical elements in various organs and tissues of the human body were carried out. From the point of view of the ingress and concentration of natural radionuclides on the diagram of the accumulation coefficients of elements in human organs and tissues according to Glazovsky (taken from [27]), the accumulation coefficient of lead isotopes, both final and bismuth—an intermediate product of decays of daughters of radon isotopes—is of interest.

The development of a model for the transportation and accumulation of natural radionuclides in the organs of the respiratory and digestive systems of the human body was carried out on the basis of the accumulation and transition coefficients for the corresponding organs obtained in [27].

The mathematical description of the model of ^{222}Rn intake into the human body, considering the decay of its daughters along the most probable decay chain, is described by nine differential equations

$$\begin{aligned} \frac{dN_1(t)}{dt} &= -\lambda_1 N_1(t), \\ \frac{dN_2(t)}{dt} &= \lambda_1 N_1(t) - \lambda_2 N_2(t), \\ \frac{dN_3(t)}{dt} &= \lambda_2 N_2(t) - \lambda_3 N_3(t), \quad \dots, \end{aligned} \quad (1)$$

which will make it possible to calculate the spectra of alpha radiation and fluxes of the corresponding energies of alpha particles, as well as the upper boundaries of the continuous spectra of beta radionuclides, which are formed in the course of a sequential series of radioactive decays of this long-lived isotope of radon ^{222}Rn . In the process of decay of radon and its transformation into daughter products of other chemical elements, considering the corresponding coefficients [27], the distribution and accumulation of radionuclides in the organs and tissues of the human body will occur. In this case, organs will be irradiated during the transport of the daughter radionuclide and accumulation in the final organ. Then the organ will absorb energy, depending on the current radionuclide undergoing the corresponding type of decay in the time interval characterizing its residence in this organ

$$\sum_i \left[A_i(k_T)_i (k_A)_i \sum_j E_j(\alpha, \beta, \gamma) n_{ij} \right] dt, \quad (2)$$

where A_i is the activity of a given radionuclide $A_i = \frac{dN_i}{dt}$ at the current time, n_{ij} is the intensity of the spectrum of a given radionuclide, $E_j(\alpha, \beta, \gamma)$ is the energy spectrum of radiation of the corresponding type of radiation, k_T is conversion factor from one

Table 1. Scheme of decays of ^{222}Rn daughters

Radio-nuclide	Type and probability of decay	Half-life	E , MeV	Radon daughter
^{222}Rn	α	3.8235 d	5.590	^{218}Po
^{218}Po	α 99.98%	3.10 min	6.115	^{214}Pb
	β^- 0.02%		0.265	^{218}At
^{218}At	α 99.90%	1.5 s	6.874	^{214}Bi
	β^- 0.10%		2.883	^{218}Rn
^{218}Rn	α	35 ms	7.263	^{214}Po
^{214}Pb	β^-	26.8 min	1.019	^{214}Bi
^{214}Bi	β^- 99.98%	19.9 min	3.272	^{214}Po
	α 0.02%		5.617	^{210}Tl
^{214}Po	α	0.1643 ms	7.883	^{210}Pb
^{210}Tl	β^-	1.30 min	5.484	^{210}Pb
^{210}Pb	β^-	22.3 yrs	0.064	^{210}Bi
^{210}Bi	β^- 99.99987%	5.013 d	1.161	^{210}Po
	α 0.00013%		5.036	^{206}Tl
^{210}Po	α	138.376 d	5.407	^{206}Pb
^{206}Tl	β^-	4.202 min	1.532	^{206}Pb
^{206}Pb		stable		

organ to another and into the blood [27], k_A is the accumulation rate in the relevant organ [27], and dt is the time interval. In this case, the speed of migration of the radionuclide formed as a result of a chain of sequential decays from one organ to another will depend on its chemical properties and the properties of this organ, which in this model correspond to the experimental coefficients of transfer and accumulation indicated above.

In the computer implementation of this mathematical model, only static processes are calculated, i.e., considering the coefficients of accumulation in the corresponding organs of the respiratory and digestive systems. The dynamic processes associated with the transportation of radionuclides in the human body are not taken into account. In this simplified implementation of the mathematical model, the calculation of the dose in the human body from the received radionuclide, considering its accumulation coefficient in organs and tissues, is calculated as

$$D = \frac{\varepsilon \bar{E} \times 1.6 \times 10^{-13} A(k_A)_i (k_R)_i}{m_j}, \quad (3)$$

where ε is the average efficiency of absorption of gamma quanta in the human body, \bar{E} is the average energy emitted by a radionuclide in one act of decay of a radionuclide, A is the radionuclide activity in Bq, k_A is the accumulation factor of elements in human organs and tissues for a given radionuclide [22], k_R is the dose exposure factor Sv/Bq [28–31], m_j is the

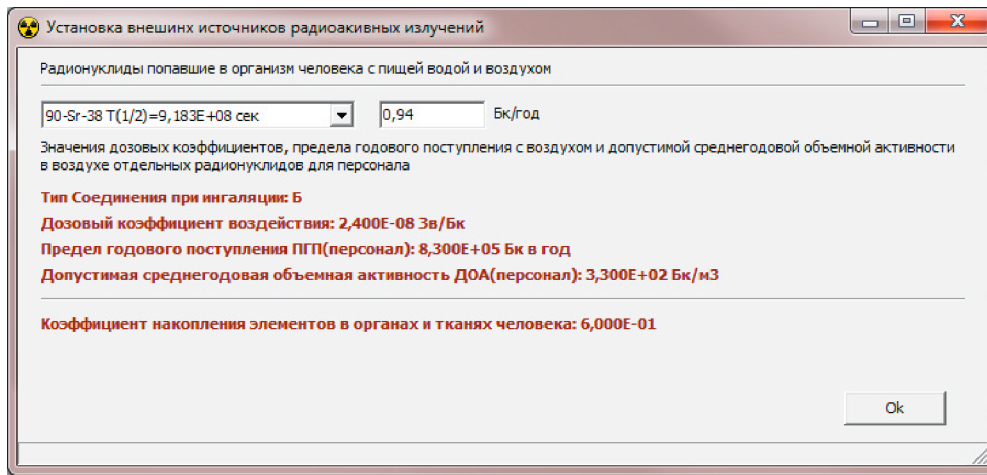


Fig. 2. Installation of external sources of radioactive radiation.

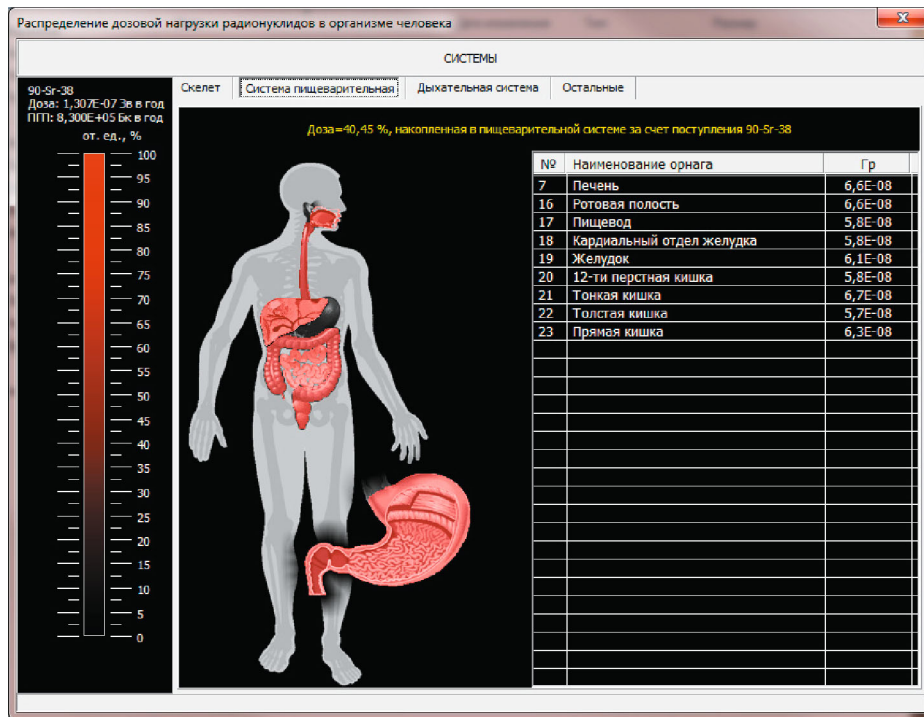


Fig. 3. Distribution of the dose load of radionuclides in the organs of the digestive system of the human body.

human organ or tissue mass, i is the radionuclide, and j is the organ.

The relative dose of the radionuclide in terms of the norm for “personnel” in percent is calculated by the formula

$$\bar{D} = \frac{D}{D_{AAL}} \times 100\%, \quad (4)$$

where D_{AAL} is the annual admission limit [28–31].

3. DESCRIPTION OF THE SOFTWARE IMPLEMENTATION OF THE MODEL

Currently, there are many different mathematical packages and programs that simulate the passage of nuclear radiation through a biological substance. So, for example, any linear accelerator designed for gamma radiation therapy in nuclear medicine is accompanied by a powerful specialized software package for planning the method of radiation exposure to a

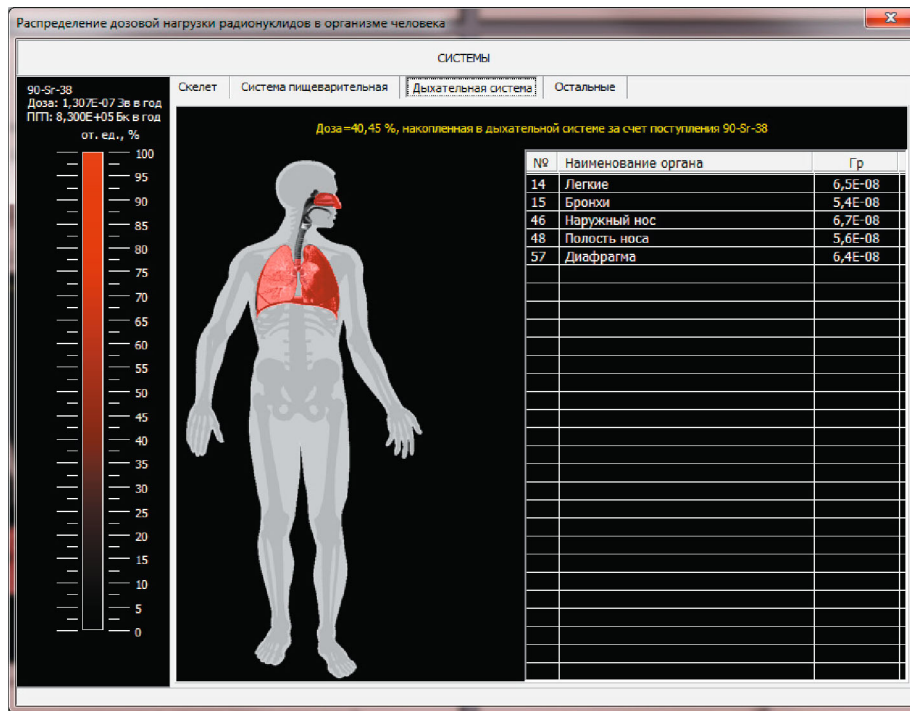


Fig. 4. Distribution of the dose load of radionuclides in the organs of the respiratory system of the human body.

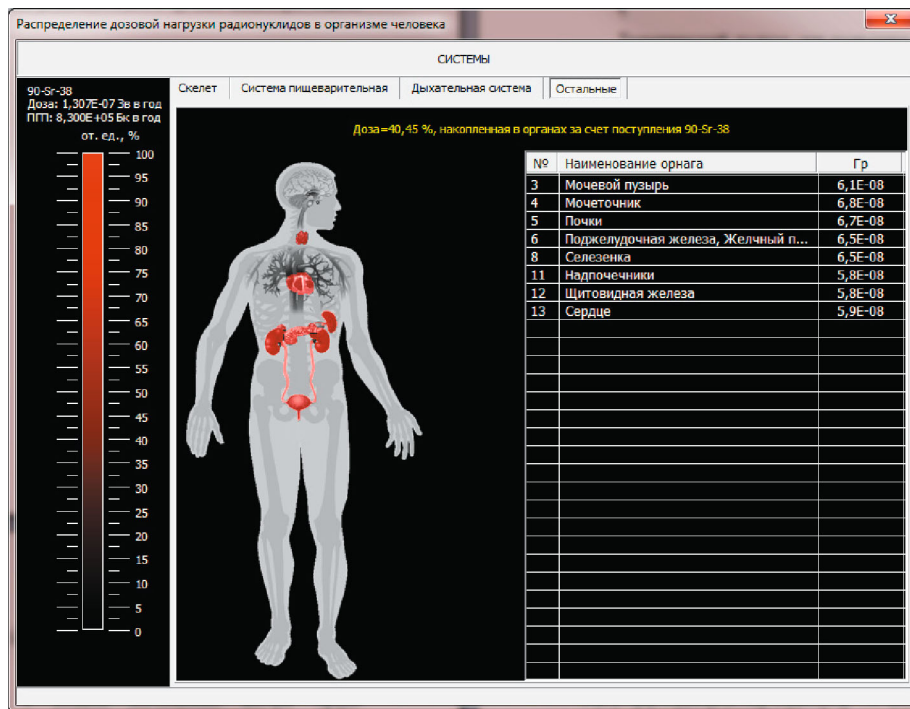


Fig. 5. Distribution of the dose load of radionuclides in other organs of the human body.

particular organ, taking into account the beam geometry and calculating the doses of organs that fall into the irradiated area. In addition to commercial similar software systems that simulate the interaction of radi-

ation with biological objects, there are, for example, Geant4-DNA and others [9]. Such software and computational systems are either unavailable or rather complicated.

The developed software and mathematical complex simulates the distribution of radionuclides throughout the body using experimental coefficients. Thus, a mathematical calculation based on the experimental accumulation coefficients makes it possible to calculate the internal radiation doses of the corresponding organs and tissues. Such modeling makes it possible to calculate the risks of oncological diseases owing to internal irradiation from incoming natural radionuclides.

Figure 2 shows the interface for selecting a radionuclide from the database [32, 33], which contains the values of dose coefficients [28–31] and other physical properties.

As a result of the calculation, the interpretation of the calculation results will be presented in the dialog box “Distribution of the dose load of radionuclides in the human body” (Figs. 3–5).

In this software version, gender differentiation is not considered, and other systems are not separated, and in this regard, the endocrine, cardiovascular, and genitourinary systems are partially located in the window for the rest of the organs (Fig. 5). One of the priority tasks of the software implementation of the model is the visualization of the main organs and tissues of the human body of the accumulated dose for a given radionuclide. The results in the display window can be conditionally divided into three main fields and tabs for various systems of the human body. The field in the left part of the window displays the color distribution scale depending on the accumulated dose. The scale is normalized to the annual intake limit for a given radionuclide. Above the scale, the calculated dose received by the human body from the selected radionuclide is displayed. The field in the central part of the window contains a profile of the human body, which, depending on the selected body system, depicts the corresponding organs. For visual demonstration, the organs are colored with the intensity of the accumulated calculated dose. Such visualization of the “highlighted” organs of the human body makes it possible to assess the degree of risk of radiogenic cancer.

4. CONCLUSIONS

The authors proposed a model for the transport and accumulation of natural radionuclides in the respiratory and digestive systems of the human body on the basis of experimental accumulation and transition coefficients for the corresponding organs [27]. The calculation results in the first approximation are in satisfactory agreement with the control examples performed by standard methods for calculating doses in organs and tissues.

In this simulation, the calculations of the accumulated doses from the concentrations of radionuclides in the organs of the respiratory and digestive systems of the human body are performed. This complex is

designed, first of all, to perform preliminary estimated calculated doses in organs from a wide range of radionuclides, both for diagnostic purposes and in the form of demonstration material in specialized courses at radioecological and medical centers or in higher education.

FUNDING

This work is carried out with the support of a state grant for fundamental research (project no. IRN AP09258978, AP09058404), on the basis of the performed research (project no. IRN AP05131884).

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Translated by P. Kuchina