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Model of the thyroid gland irradiation in the radiobiological experiment analysis

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Abstract. Radiation accidents at nuclear installations are usually accompanied by releases of volatile and biologically dangerous iodine radionuclides into the environment, which can lead to contamination of large areas and cause irradiation of the thyroid gland (TG) in the population and mammals. The reference representatives of biota in radioactive contamination of agricultural ecological systems can be agricultural animals. The basis for the selection of farm animals as reference species is the availability of data of constant veterinary control of animal health indicators and characteristics of their changes due to radiation exposure. To date, the regularities of radiation pathology of the thyroid gland in farm animals with the arrival of radioactive isotopes of iodine have been studied. At the same time, the computational base and software for quantitative analysis of dynamics of formation of radiobiological effects are not sufficiently developed. Using numerical models, namely: a) a compartment model of the $^{131}$I metabolism and (b) precise radiation transport model for the thyroid gland the radiobiological characteristics for calves’ thyroid irradiation is derived for the experimental conditions. As a result of experimental and calculated data comparison, critical dose resulting in rapid (within a day) radiation destruction of the parenchymal thyroid tissue was estimated.

1. Introduction

Radiation accidents at nuclear installations (nuclear power plants, nuclear chemical plants, research reactors) are usually accompanied by releases of volatile and biologically dangerous iodine radionuclides into the environment, which can lead to contamination of large areas and cause irradiation of the thyroid gland (TG) in the population and mammals.

Along with the objectives of human radiation safety, modern regulatory documents suppose an ecocentric approach to radiation protection [1]. Environmental quality standards in the vast majority of radiological situations are observed if hu-man radiation safety is ensured. At the same time, biological organisms, plants and animals, when polluting the environment with radionuclides, are most often exposed to large doses (comparatively with human doses) the knowledge of which provides additional information for assessing the quality of the environment and making decisions for the preservation of natural ecological systems, the gene pool of plants and animals.

Due to the large biological diversity of living organisms, it is impossible to estimate doses for each type of biota, so it is customary to assess a small set of representative organisms – reference species. These species are considered as biological objects with certain basic eco-logical and biological
characteristics. The reference representatives of biota in radioactive contamination of agricultural ecological systems can be rural animals. The basis for the selection of farm animals as reference species is the availability of data of constant veterinary control of animal health indicators and characteristics of their changes due to radiation exposure [2].

To date, the main radiation syndromes have been studied, the manifestation of which in animals can be expected for various scenarios of radioactive contamination. The regularities of radiation pathology of the thyroid gland in the admission of iodine radioactive isotopes were studied. The data on the state of health of animals in the areas of influence of radiation accidents have been received. At the same time, the computational base and modern software for quantitative analysis of the dynamics of the formation of radiobiological effects are not sufficiently developed.

The object of the present study is aimed at estimation the critical radiation exposure leading to radiation destruction of the calves thyroid parenchymal tissue, on the basis of a) compartment model of the 131I metabolism and (b) precise model of the radiation transport in the TG.

2. Materials and methods

For estimation of the $^{131}$I effect on the TG of farm animals at radiation accidents the experimental data for cattle’s young growth [3] have been used. The calves of 3-month age with weight ~ 60 kg took in $^{131}$I with two liters of milk daily during 6 days: at the first day 185 MBq, the activity of the next portions decreased in accordance with a radionuclide half-life period. On the 11th day of observations there was a sharp decrease in the dose rate of $\gamma$-radiation in the thyroid region [3], possibly due to radiation destruction of the parenchymal tissue of the TG and the $^{131}$I injection into the blood stream. Also, the possibility of radiation-chemical decomposition of thyroxins in the thyroid tissue is not excluded.

Calculation of the $^{131}$I radiation field characteristics was carried out by means of the MCNP5 [4] code. The TG morphology, tissue density, weight and the characteristic sizes are taken from [5].

To estimate the activity of $^{131}$I in TG, a compartment model of the $^{131}$I metabolism in the cattle organisms was used [6], modified in relation to the experimental conditions [3] (figure 1).

Figure 1. Compartment model of the $^{131}$I metabolism in the calves’ organism.
In General form, the dynamics of the iodine activity, received peroral, in an arbitrary compartment $q_i$ ($i = 1...n$) under the assumption of identical chemical form of $^{131}\text{I}$ in all the compartments during the whole observation time is formulated as follows:

$$\frac{dq_i}{dt} = -\lambda q_i + \sum_j k_{ij} q_j - \sum_j k_{ji} q_i + f(t) \cdot \theta_i$$

where

- $q_i$ – the $^{131}\text{I}$ amount in the $i$-th compartment (MBq);
- $\lambda$ – the $^{131}\text{I}$ radioactive decay constant (days$^{-1}$);
- $k_{ij}$ ($k_{ji}$) – the rate constants of the $^{131}\text{I}$ transport for compartment model (days$^{-1}$);
- $\theta_i = \begin{cases} 1, & i = 1 \\ 0, & i > 0 \end{cases}$
- $f(t)$ – rate function of the $^{131}\text{I}$ receipt from the external environment in barrier body.

At single oral consumption of the forage containing $^{131}\text{I}$, his receipt in barrier body (in this case – the GIT) sets by a starting condition: $q_1(t = 0) = q_0$.

Estimation of a range for rate constants $k_{ij}$ for calves was carried out with use of the parameters received in an experiment on dairy cows [7] without the Udder compartment and also the maximum parameters of metabolism more peculiar to a young animal, according to [8, 9].

3. Results and discussion

In figure 2 the TG sections which cover a trachea and consist of the cylindrical layers modeling a form of TG body are presented. According to [3], for calves of 3-month age with weight 60 kg averaged TG volume and weight are 11.6 cm$^3$ and 12.0 g correspondingly; except four main elements, Na, P, S, Cl, K and I enter into element composition. Iodine activity is distributed uniformly in the TG volume.

The current state of computational technologies for the transport of radiation allows accurate modeling of both the subject area and the functionals of the radiation field. The term ‘accurate modeling’ means that we can put the full extent of our knowledge into the models we construct. This approach in practice leads to a significant narrowing of the error corridor of modeling objects of the subject area and the processes of radiation transport.

| No. | External radius, cm | Height, cm |
|-----|---------------------|------------|
| 1   | 2.15                | 1.50       |
| 2   | 2.30                | 2.00       |
| 3   | 2.40                | 2.20       |
| 4   | 2.15                | 1.50       |
| 5   | 1.65                | 0.50       |

**Figure 2.** Radial (at the left) and axial section of the TG computational model (not to scale; received by visualization of the input file of the MCNP5 code). The table contains dimensions of TG cylindrical layers.
The current state of computational technologies for the transport of radiation allows accurate modeling of both the subject area and the functionals of the radiation field. The term “accurate modeling” means that we can put the full extent of our knowledge into the models we construct. This approach in practice leads to a significant narrowing of the error corridor of modeling objects of the subject area and the processes of radiation transport.

The thyroid gland is modeled by a two-dimensional axisymmetric body composed of nine segments, which are obtained by axial and radial sections. These segments are symmetrically located on the trachea and have different outer diameter and height. The same segments are joined in pairs to form four source bodies. The fifth source simulates the isthmus.

The task was formulated as follows:
1. Using the MCNP5 code, designed to calculate the radiation transport by Monte Carlo technique, to obtain an average dose in the model thyroid gland with a uniform volume distribution of the $^{131}$I activity.
2. Time-varying $^{131}$I content in the gland was determined using the compartment model.

To calculate total dose in TG, the problems with beta- and gamma-source in each of the five bodies (figure 2) were solved sequentially. Due to the additivity, the dose rates obtained from the two types of source were summed up taking into account mass/volume of the segments. Two components: 1) the dose rate from the beta source and 2) the dose rate from the gamma source combined to give the total dose rate, which was multiplied by the current activity of the gland. As a result, the dependence of the total dose rate on time was obtained. The integral of this dependence over the time interval from the beginning of the experiment allowed calculating the rate of dose accumulation.

Precise calculations were carried out for a) β-radiation transport in TG accompanied by production secondary radiation and its further transport taking into account all processes, including generation and transport of bremsstrahlung, Auger electrons, etc.; b) transport of $^{131}$I inherent γ-radiation, taking into account generation and transport of x-ray and fluorescent radiations, etc. Energy dissipation was monitored up to 1 keV, integral (energy) dose dispersion was throughout < 0.1 %.

It is shown by calculation that in these terms the contribution of γ-radiation produced by $^{131}$I inherent gamma-source (with all secondary radiations) in the total absorbed dose makes ~ 20%. The main result of calculations was the “conversion coefficient” from $^{131}$I activity (uniformly distributed in TG) to the average absorbed dose in TG (for these conditions of irradiation): 4.05 • $10^{-12}$ Gy/s per 1 Bq. Accumulative dose in the calves TG during time since which observed destruction of parenchymatous tissue was defined with use of $^{131}$I activity change in a TG.

Solution of the system of differential equations describing the iodine metabolism according to the presented compartment model (figure 1), by using a multifunctional interactive computing system PTC Mathcad Prime 3.1 has allowed to obtain a change in the $^{131}$I activity in TG after 6 one-time $^{131}$I revenues with milk in the gastrointestinal tract of calves. As a result, the dynamics of the absorbed dose accumulation in the thyroid gland of calves was calculated (figure 3).

The value of the absorbed dose accumulated in the TG of calves for the period of time through which rapid (within a day) destruction of parenchymal tissue was observed was ~ 330 Gy.

It is interesting to compare the result with the real situation in the acute period of the radiation accident at the Chernobyl NPP. In lactating cows of Khoyniki and Bragin districts in the Gomel region (the Republic of Belarus) after the Chernobyl accident in May 1986, the concentration of nuclear fission products was 3–4 orders of magnitude higher in the TG of cattle than in other organs and tissues (100–700 kBq/g).

The main factor of radiation danger during the first month after the Chernobyl accident was iodine isotopes. Their content in the mixture of release products ranged from 20 to 60 %. According to gamma-spectrometry, the content of $^{131}$I in samples of organs and tissues of cows in 5–12 days after the fallout was 65–90 %, and $^{134,137}$Cs 8–30% of the total activity. The average absorbed doses in the thyroid gland of animals from farms of Bragin and Khoyniki districts was 65.2±22.9 and 164.9±34.6 Gy, respectively [10–12].
Figure 3. The rate of dose accumulation simulated for experiment [3]; after 11 days accumulated dose ~ 330 Gy.

At autopsy of dead animals with maximum thyroid doses, signs of impaired thyroid structure were noted, that for the most polluted farms of Bragin and Khoyniki districts in dynamics manifested in the following way:

- during the first month a sudden impairment of circulation, hyperemia, stromal edema, hypervolemia of the capillaries of inter-follicle tissue, hemorrhage in interstitial tissue and the cavity of the follicle were observed in the TG;
- in the next 1.5–2 months the volume of the thyroid has changed, necronic and dystrophic changes of the follicles’ epithelium were founded, pyknosis of nuclei, destruction and desquamation of epithelial cells, the emergence of bands of connective tissue;
- external examination 5 months after the emergency release noted a decrease in the thyroid in volume, its seal and stratification on the cut. Histological examination revealed fibrosis of the organ;
- 8 months later, atrophy of the thyroid was noted. In thyroid’ localization the bands of connective tissue appeared.

In the next terms, morphological changes in the TG in the degree of severity were variable in animals of different farms and areas and depended on the density of radioactive contamination of the area and the time elapsed from the beginning of the accident.

The results obtained by us consider a more severe situation due to higher values of $^{131}$I peroral administered activity and the formation of high levels of thyroid irradiation. Apparently, the lower limit of the dose causing very rapid (within a day) destruction of the parenchymal thyroid tissue of calves corresponds to the value of the absorbed dose obtained in this work ~330 Gy.

4. Conclusion
The received results don't contradict the dosimetric data characterizing radiobiological consequences of radiation injury of a thyroid gland (~ 300 Gy) at the person [13] and sheep [11, 12].
The submitted analysis of formation of the absorbed dose in an organism of calves allows estimating the upper bound of the dose causing transient catastrophic destruction of parenchymatous tissue of thyroid gland and the source of $^{131}$I radiation localized in it. The intravital dosimetry of calves at a thyroid glands’ region convincingly shows this process: within a day after 11–12 days of observations the dose rate decreases sharply more than in 5 times. By this time in a thyroid gland the absorbed dose is close to 300 Gy.

It should be noted that the destruction of parenchymal thyroid tissue in cattle in the area of influence of the Chernobyl accident was also noted at lower absorbed doses (~150 Gy), but for a longer time (~3–5 months). The mentioned circumstances provide important information for the assessment of animal health in conditions of radioactive contamination of the environment by nuclear fission products.

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