Calculation of Radiation Doses in Cosmonaut's Body in Long-Term Flight Onboard the ISS Using the Data Obtained in Spherical Phantom

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The purpose of the paper is to develop a simplified calculating method for dose estimation in cosmonaut's body using minimum quantity of measurements based on the analysis of dose distribution in human body obtained in the spherical phantom onboard the International Space Station (ISS) during long-term orbital flights. The calculating method allows considerable decreasing of the labor to prepare the detectors and measure ionizing cosmic radiation doses in spaceflight. The presented results are based on data obtained in serial measurements in Service Module and module "Piers-1" of ISS using tissue equivalent spherical phantom. The measurements were performed with thermoluminescence detectors. General duration of the experiments carried out during expedition ISS-8, 9, 15, 16 is 710 days.

Introduction

Calculation and especially experimental on ground modeling of space radiation and its influence on a human is rather complicated problem. The problem is because of a variety of energy spectra of charged particles (up to 1019 eV/nucleon), complex ionizing radiation composition (ions from hydrogen to uranium, electrons, neutrons and other particles), and temporal and spatial variations of spectra and composition parameters. Estimation of shielding properties of a space vehicle, geometrical and physical features of its design and equipment is also a complicated task. It is difficult to develop an adequate theoretical model for calculation of radiation influence on human in conditions of long-term flights and to consider adequately the energy spectra and shielding features. Now, the estimation of radiation conditions onboard the International Space Station (ISS) is based on the data of the continuously functioning set of devices known as a radiation monitoring system similar to that originally used on "MIR" space station [1]. To consider the personal dose, the individual radiation control provided with set of the passive detectors located in pockets of flight suits of the crewmembers is used in addition. The measurements allow defining doses only in one point on a surface of the human body. Dose distribution in the body has not been measured. Effective dose that is a parameter considering non-uniformity of irradiation, accepted by the International Commission on Radiological Protection (ICRP) can not be derived from the measured values of individual doses.

The experiment description

Different models of the human body, namely phantoms [2], are used to estimate dose value in critical organs. A series of radiobiological experiments was carried out during 2004-2009 onboard ISS using tissue equivalent spherical phantom [3]. The initial data were received during space flights of crews ISS-8,9 (2004-2005 years, 425 days) in the Service Module of the Russian segment (SM RS) of ISS and crews ISS-15,16 (2007-2008 year, 285 days) in module "Piers-1" of ISS. Solar proton events did not occur during the time of experiments. Based on this data the values of the cosmonaut body dose were calculated and features of their distribution in a human body during long orbital flight were revealed [3,4,5]. The thermoluminescence detectors are used in our experiments as a basic measuring tool of the integral absorbed dose (IAD). About 300 detectors located inside and on the surface of the spherical phantom were used in each experiment in regular intervals. Besides the time of the detector exposure, the cycle of measurements also includes preflight preparation and after flight processing of the received data [6]. The measurements using passive dosimeters are rather labor consuming. Due to this fact, the purpose of the present work was revealing the laws and the interrelation of dose distributions inside and on the surface of the phantom and development of a simplified method of dose measurement and calculation for long spaceflights. The features of the considered periods are different duration of the measurements, and the phantom placing in different modules of ISS with various shielding of constructive elements.

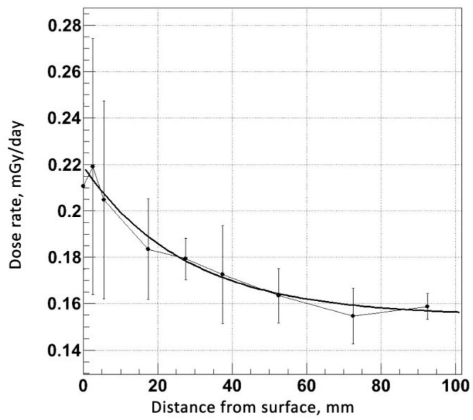
Main results

The most typical are the dependences of average IAD on depth in measurement points in the phantom. These dependences for the data obtained in the modules SM and "Piers-1" are presented in Fig. 1. Points note average IAD values; the interval designates the range of IAD values for the point at given depth.

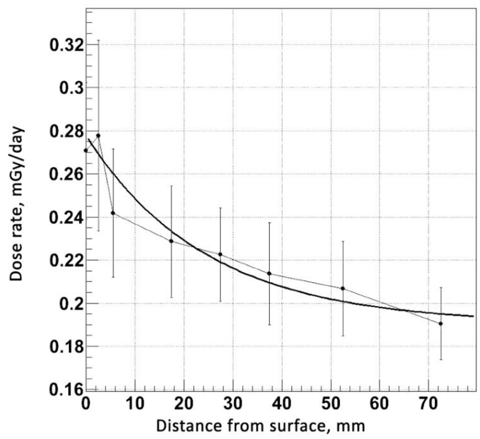
Despite the different conditions of the experiments, the mathematical law describing the dependences has appeared to be the same:

$$D_i(d) = D_{min}+(D_{max}-D_{min})\bullet exp(- k\cdot d) \qquad (1)$$

where D_{max} and D_{min} – the maximum and minimum IAD values in all measurements concerning corresponding experiment; $k \approx 0{,}035\pm0{,}003$ cm^2/g - constant coefficient for the two experiments (density of tissue equivalent matter of the phantom is 1.1 g/cm^3).



a) Service Module of ISS



b)"Piers-1" module

Fig. 1. Average dose rate (IAD/exposure time) dependence on distance from the surface of the phantom for corresponding measurement points (d) inside the phantom and functions approximating them for two cases of the phantom placing.

The approximation accuracy was estimated by Pirson's criterion and it is characterized by the 95 % confidential probability level.

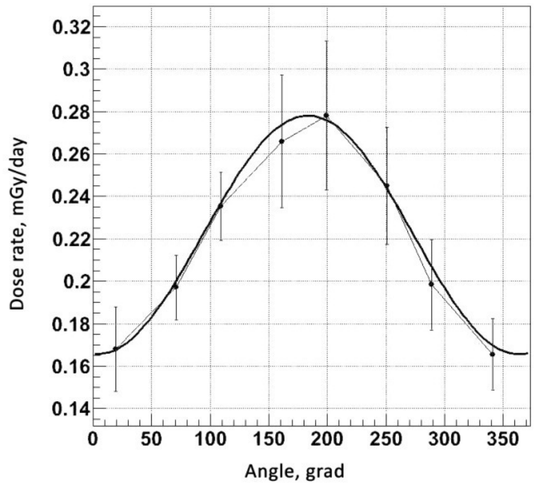
The physical meaning of the formula can be explained by the following:

- the average D_{min} is determined by the contribution of high-energy penetrating component of ionizing space radiation (ISR), which differs a little after passing through the substance of the phantom;

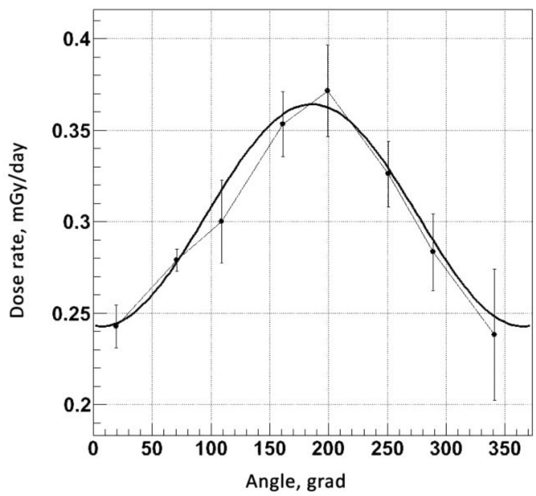
- the term $(D_{max}\text{-}D_{min})$ defines the dose on the phantom surface. The term decreases according to an exponential law when the thickness of tissue equivalent substance increases. Thus, the second item in the formula (1) can be considered as the contribution in ISR dose of low-energy ISR components.

-coefficient k can be considered as the parameter characterizing decreasing of the ISR influence by tissue equivalent substance.

In Fig. 2 dependences of the dose D_e, measured on the phantom surface, on the angle (φ), counted from "the equatorial line" , and also functions approximating these distributions are presented. "The equatorial line" is considered here as a line of conditional "zero" latitude in phantom's coordinate system. Points on graphs are the average doses in separate detector sets (from 5 to 9 TLDs in the set) and also mark corresponding maximum deviations from average values. Total amount of the detector sets, located in regular intervals on the phantom surface is 32. Approximation accuracy of empirical distributions was estimated by Pirson's criterion and characterized by 95 % confidential probability level.



a) Service Module of ISS



b)"Piers-1" module

Fig. 2 Average dose rate (Di/exposure time) dependences on the angle (φ) on the spherical phantom surface according to conditional "zero" latitude for two cases of the phantom locations.

The analysis of dependences presented in Fig.1 and 2 allows to note following features of the dose distribution:

1. Extrema of angular distributions and their phase shifts are defined by geometry of the phantom arrangement in ISS module relative to the direction of the external space radiation maximum (from the side of nearest approach to the external wall of the module). In two experiments, the phantom was oriented relative to the external wall of ISS module at $\approx 180^0$ shift. Due to this fact, on Fig. 2 (a, b) extremes are at antiphase. The minimum and maximum doses on the phantom

surface correspond to the points symmetrically located on the different parts of the phantom concerning its centre;

2. Changes of dose values both on the surface, and inside the phantom are monotonous, that is they do not contain obviously expressed deviations.

$$D_e(\varphi) = D_{\min'} + \frac{D_{\max'} - D_{\min'}}{2} + \frac{D_{\max'} - D_{\min'}}{2}\sin(\varphi - \varphi_0) \quad (2)$$

where φ - current angle (from 0 to 360 degrees), counted from any line on the phantom surface that belongs to the plane, passing through its centre, $D_{max'}$ and $D_{min'}$ are the maximum and minimum dose values on the phantom surface averaging-out along the chosen axis, φ_0 – angle, at which dose value is minimum. Besides that, it should be noted that the average dose of any of sixteen detector set pairs on the phantom surface, symmetrical relative to the phantom centre, was a constant coinciding with the average dose value for all surface [5]. Then, considering the formula (2) invariant relative to the choice of the line for counting out angle (φ), it is possible to define average dose for any "symmetrical" pair of detector sets on the phantom surface:

$$D_{av}(\varphi) = 0.5[D_e(\varphi) + D_e(\varphi + \pi)] = \frac{D_{\max'} + D_{\min'}}{2} \quad (3)$$

The obtained result allows making the important conclusion: average dose on the surface of the spherical phantom (D_{av}) can be defined with only one pair detector set if they are located symmetrical to each other on the phantom surface in different hemispheres.

If the phantom is regularly rotating at the rotation period much smaller than the exposure duration, the doses on its surface are the same. In the mathematical formula it corresponds to the following expression

$$\frac{D_{\max'} - D_{\min'}}{2} = 0$$

In this case, only one detector set measurements are necessary.

Analyzing expression (1) we can notice that at d=0, the dose value $D_i = D_{max}$ that corresponds to the average dose on the a phantom surface. That is,

$$D_i(0) = D_{\max} = D_{av(pair)} = \frac{D_{\max'} + D_{\min'}}{2} \quad (4)$$

As it was obtained in the experiments with the spherical phantom [5], the dose minimum values, measured inside the phantom and on its surface, are practically the same, that is $D_{min} \approx D_{min'}$. Thus, taking into account (1) and (4) it is possible to define the following dependence for the average dose calculation for the given depth:

$$D_i(d) \approx D_{\min'} + \frac{D_{\max'} - D_{\min'}}{2}\exp(-kd) \quad (5)$$

where $D_{max'}$ and $D_{min'}$ – the maximum and minimum doses measured on the phantom surface at any axis, $k \approx$ 0,035±0,003 cm^2/g for long orbital flight at ISS trajectory conditions. It is possible that the influence on the irradiation level of all attendant factors like shielding properties of the external equipment, flight conditions, composition and energy characteristics of the ionizing radiation, etc. is presented with three parameters only: $D_{max'}$, $D_{min'}$, and k.

Analysis of the results

Analyzing the data on dose distributions inside and on the phantom surface, and also average daily dose rates for the full periods of experiments on ISS trajectory (small variations of average daily dose rates in compartments for the long period are noted in [4]), it is possible to consider cosmonaut's presence under the influence of external ionizing radiation that is slightly varying in undisturbed conditions on the long period time scale.

Non-uniform distribution of structure elements and the equipment of ISS modules have the basic influence on the phantom irradiation heterogeneity in its location. It has an effect, that maximum and minimum doses have deviation as compared to the average values at given depths (see Fig. 1, 2). It is especially expressed for phantom layers lying on low depth where the contribution of the low-energy ISR component is higher. From the figures, it is evident that the interval, defining dose range relative to average values, is less in case when the phantom is placed in module "Piers-1" in comparison with the Service Module. It is because the bigger sizes of Service Module and considerable additional shielding with the compartment equipment (~ 5-10 g/cm^2) from one of the phantom sides in Service Module. The soft low-energy external ISR component is practically fully absorbed from the phantom side directed inside the Service Module [4, 5].

Calculations of the dose influences on a human body during longtime spaceflight, based on estimation of effective dose [7], demonstrate that using average IAD values for each organ with self-shielding higher than 5 g/cm^2 is quite reasonable. It is caused mainly by small dose deviations (within a measurement error) in the critical organ volume. For organs with self-shielding less than 5 g/cm^2 (skin, eye lens, testis), where the low-energy soft ionizing radiation contribution is notable enough, minimum and maximum IAD values deviation from the average value is about ±50%. Nevertheless, it is possible to use corresponding average values, defined by formula (5) while calculating dose in these organs. The influence of the body orientation of the averaged skin dose is low as when about 50% of skin has maximum irradiation, and then the other 50% has minimum irradiation. As for dose estimating in other "asymmetrical" organs, when human irradiation during longtime flight is like uniform rotating, it is reasonable to use average dose calculated by formula (5) in the given organ. Thus, formula (5) allows to calculate the doses of separate critical organs using only values of two dose measurements on the phantom surface, namely Dmax' and Dmin', decreasing thereby essentially labor input of the experiment. Development and detailed elaboration of the above presented dependences, including permanency of parameter k is a prospective subject of the nearest works. These researches and detailed elaboration can be realized both with the spherical phantom, and the cosmonauts' assistance.

Conclusion

A simplified calculating method for dose estimation in cosmonaut's body using minimum quantity of measurements is developed. The method is based on the analysis of dose distribution in human body obtained in the spherical phantom onboard the ISS in Service Module and module "Piers-1" during long-term orbital flights. The calculating method allows considerable decreasing of the labor to prepare the detectors and measure ionizing cosmic radiation doses in spaceflight.

Verification of the revealed laws may form the basis for working out a new technique of experimental dose estimation for human during long-term spaceflights.

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