STUDY OF SPATIAL DISTRIBUTION OF TISSUE DOSES WITH THE AID OF A PHANTOM-MANNEQUIN

L.N.Smirennyi, E.G.Litvinova, A.V.Khortsev
USSR

Abstract

In order to study in detail the radiation environment in a field of complex configuration, the procedure of computing doses in critical organs that takes into consideration real body shapes has been developed and a phantom-mannequin having the dimensions of a "standard man" has been manufactured from a tissue-equivalent material. The paper presents the results of computing doses in critical organs due to a solar flare with magnetic rigidity of 100 Mv and a flux of 10^{10} protons/cm^2. It also gives the doses and fluxes measured in the phantom-mannequin aboard the automatic interplanetary station "Zond-7" and the Earth artificial satellite "Kosmos-368".

Introduction

Problems related to the ensurance of radiation safety require detailed measurements of the doses affecting various organs of the human body. This is particularly important in cases of nonuniform shielding or attenuation of incident radiation and accumulation of the secondary radiation. The use of the doses estimated without taking into consideration the self-shielding of the body may give rise to a substantial error in the evaluation of radiation hazard. In the general form the solution of these problems is time- and labour-consuming. Therefore, one can measure depth doses experimentally, using phantoms, or compute dose distributions in simple geometric figures (infinite plate, sphere, cylinder, etc.). However, since the radiation field is appreciably nonuniform, these approximations are insufficient and may result in a significant error.

In order to measure depth doses, we made use of a complex approach, having developed a procedure of computing doses in the body of the "standard man" and having built a suitable phantom-mannequin.

Computation of doses in the body

Attempts of taking into consideration the real shape of the human body as precisely as possible were made elsewhere[1,2,3].

We devised methods of computing depth doses, taking into account real gepmetry of the body. The thickness distribution in relation to a given point was estimated with the aid of a computer, using coordinates of points on the phantom-mannequin surface that had dimensions of a standard man. In order to determine different arrangement of individual segments, the body was subdivided into the following parts: (I) trunk (with the head), (2) thigh, (3) shin, (4) shoulder, (5) arm (Fig. 1).

The mutual displacement of individual body parts was achieved by turning and transferring the coordinate system of the corresponding part in relation to the coordinate system of the trunk. The computations yielded the relationship of tissue thicknesses h_t from angles of ϑ and φ. Using the dose dependence on the thickness of the schielding tissue-equivalent substance $K(h_t)$, derived from the experimental findings (3), dose values in the critical organ can be obtained with the aid of the equation:

$$D=\int_0^{2\pi}\int_0^{\pi}\frac{dN(\vartheta,\varphi)}{d\Omega}K[h_t(\vartheta,\varphi)]\sin\vartheta\, d\vartheta\, d\varphi \qquad (1)$$

where $\frac{dN(\vartheta,\varphi)}{d\Omega}$ - proton flux, proton/cm^2 steradian;

$K[h_t(\vartheta,\varphi)]$ - dose as a function of the tissue thickness for a given proton spectrum, rad cm^2/proton;

As an illustration we estimated doses in different body organs induced by protons of the solar flare of the following spectrum: $N(P)=N_0 e^{-\frac{P}{P_0}}$ (2)

where: P - magnetic rigidity of protons, Mv, and P_0=100Mv. The computation results are given in Table I. The error of the dose computation for a given flux and spectrum depends on the error of assaying the relationship $K(h_t)$ and accuracy of measuring h_t.

In our computations the tissue thickness was estimated to an accuracy of 2mm which yielded an error of the dose in critical organs of approximately 15%.

Table I

Dose values in different organs of the human body (sitting) during isotropic irradiation with solar flare protons

$(P_o = 100, N_o = 10^{10} \frac{\text{protons}}{\text{cm}^2})$

Organ of the body	Dose, rads
Eye lens	3400
Gonads	400
Bone marrow (chest, at a depth of 3cm)	250
Bone marrow (vertebral column, at a depth of 3 cm)	270
Bone marrow (cranium, at a depth of 2.5÷3 cm)	440

As it follows from Table I, dose values for various organs differ significantly.

Dose values in different organs may depend on the position of body parts as related to one another. Our computations show that the turn of thigh that accompanies the transition from the sitting to the standing position changes the solid angle with a minimum thickness of 1÷2 g/cm^2 by more than an order for gonads. Accordingly, the gonad-absorbed dose induced by solar flare protons increases 5 times (Fig.2). Thus, the method described allows computations of the dose in ray approximation for any organ of the human body upon different position of its parts as related to one another.

Tissue-equivalent phantom-mannequin

The experimental investigations of the dose distribution within the human body were carried out, using a phantom-mannequin manufactured from the tissue-equivalent material. The weight composition of the material is given in Table 2 which indicates also the weight composition of the human muscular tissue.

Table 2

Composition of the tissue-equivalent material (% by weight)

Element	Tissue-equivalent material	Average composition of the biological tissue
Hydrogen	7.0	10.4
Carbon	50.0	18.7
Nitrogen	3.0	3.1
Oxygen	40.0	67.8

Our estimations showed that values of the doses absorbed in the material used and in the biological tissue for protons and γ -radiation did not differ by more than 5÷10% in the energy range of 1 to 1000 Mev and 0.1 to 3 Mev, respectively.

The phantom-mannequin was designed so as to resemble dimensionally the parameters of a "standard man" (5). It had movable joints (elbow,shoulder,pelvis,ankle) which allowed simulation of different postural positions of the human body.

The phantom-mannequin was equipped with 20 channels which were uniformly distributed along the whole body and allowed measurements of doses in critical organs by means of radiation detectors.

In our experiments we used as detectors thermoluminescent glasses and packeges of nuclear emulsions of various sensitivity (6). The procedures employed in our experiments to estimate fluxes and doses were described elsewhere (6).

Experimental

Experimental studies of the dose distribution within the human body were carried out during space flights of the automatic interplanetary station "Zond-7" and the Earth artificial satellite "Kosmos-368". In both cases the phantom-mannequin was exposed to the galactic corpuscular radiation and γ-irradiation from isotope sources that were part of the experimental equipment. The use of nuclear emulsions and thermoluminescent glasses helped to estimate dose contributions of individual radiations. Fig.Ia,b shows the distribution of fluxes and doses measured at a depth of 3 g/cm^2 from the ventral surface along the central axis of the body. Measurements of the dose distribution as a function of the body depth indicated that the ventral-to-dorsal surface gradient was about 20%, thus giving evidence for a significant rigidity of the radiation inside the modules. The head-to-pelvis gradient was the highest. The data shown in Fig.Ia,b demonstrate that onboard the "Zond-7" the γ-radiation dose increased greatly in the pelvic direction whereas fluxes of corpuscular radiations grew in the head area. "Kosmos-368" experiments also showed substantial variations of the fluxes and doses in the head-to-pelvis direction. The gradients of corpuscular fluxes can be attributed to the nonuniform shielding of the body by the space capsule walls and equipment. The nonuniformity of γ-radiation doses can be accounted for by local isotope sources and radiation attenuation by the phantom and equipment.

These findings clearly indicate that measurements with the aid of a phantom-mannequin are necessary to estimate radiation hazard in the field of a complex configuration.

References

1. D.L.Dye,Health Phys.,9,749-756,1963.
2. B.Liley a. S.C.Hamilton, Modified elemental volume dose program.(MEVDP),AFWL-TR-69-68,August 1969.
3. W.S.Snyder,H.L.Fisher et al.,Journal of Nuclear Medicine, pp.7-12,1969.
4. O.D.Brille et al.,Nuclear Interactions in the Spacecraft Shielding,Atomizdat,Moscow,1968.
5. O.A.Sidorov,Physiological Factors of the Man Determining the Arrangement of the Control Panel,Oborongiz,Moscow,1962.
6. Y.A.Akatov et al. in:Physical and Radiobiological Investigations onboard Earth Artificial Satellites,Eds. Y.G.Grigoryev a. E.E.Kovalev,Moscow,1971,p.25.
7. C.D.Zerby a. W.E.Kinney,Nucl.Instr.Meth.,36,125-140,1965.

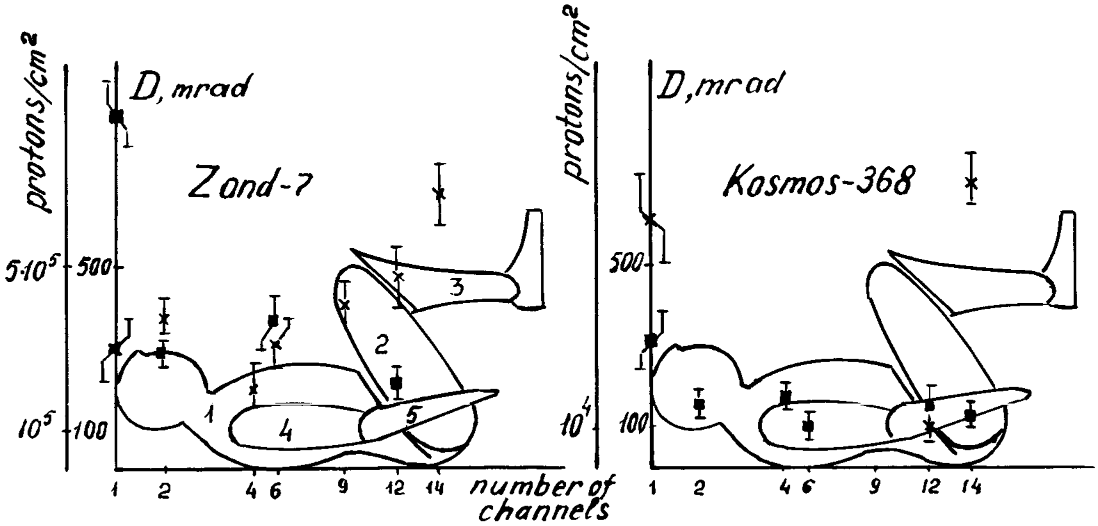

Fig.1. Results of measuring fluxes and doses in the phantom-mannequin during "Zond-7" and "Kosmos-368" flights. ■ -flux,proton/$_{\mathrm{cm}}$2, ✖ - dose,mrads.

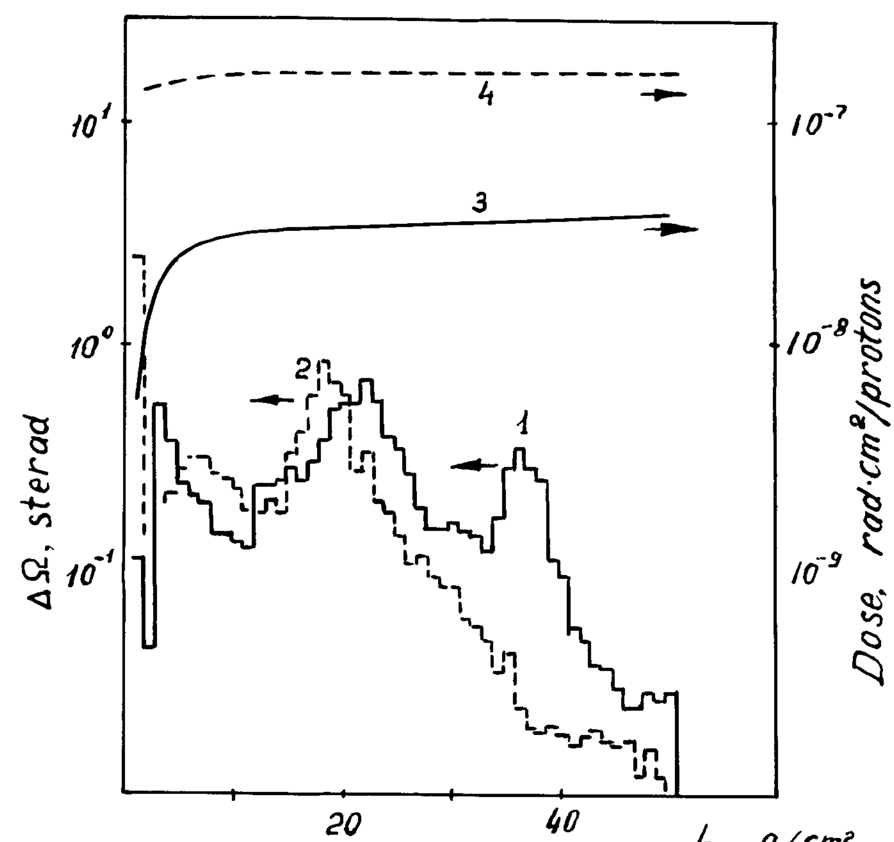

Fig.2. Results of computing the distribution of tissue thicknesses (1,2) as related to gonads and gonad-absorbed doses (3,4), ——— - sitting, -·-·- - standing.