Definition of a Permissible Dose for Primary Cosmic Radiation

By Hermann J. Schaefer
Naval School of Aviation Medicine, Pensacola, Florida

THERE ARE two sides to the problem of the exposure hazard from the primary cosmic radiation in flight at extreme altitudes. First, the scientific side: the mode of action of a novel type of radiation on living matter has to be investigated. Second, the official or legal side: what standpoint should be adopted by those who will be officially responsible for human's flying in the region of the primary radiation, or, to formulate it more precisely, in the heavy nuclei region?

To be sure, the second issue is anticipating future developments. The altitudes in which airplanes fly today are well below the region to which heavy nuclei even of the highest penetrating power can pass through. The particles which produce the ionization dosage in these lower regions are well known with regard to their biological effectiveness. At 35,000 feet, they produce a total ionization in tissue which corresponds to about 5 milliroentgens - equivalent - physical per twenty-four hours (mrep/24 hrs.), i.e., to 1/10 of the permissible dose.[3]

The novel quality of the heavy nuclei of the primary radiation which makes the evaluation of their ionization in terms of the biological effect a problematic issue is their extremely high specific ionization. The specific ionization or rate of energy loss (REL) of a particle characterizes the spacing of the ionization events along its path in the absorbing medium. It is well established that many of the effects of ionizing radiation on living matter and particularly those which are responsible for the so-called low-dosage long-term damage require smaller ionization dosages for radiations of a higher REL. The intensifying factor which expresses this relationship in quantitative terms is called the relative biological efficiency or RBE. It is that factor by which the ionization dosage measured in roentgen-equivalent-physical has to be multiplied to obtain the biologically effective dosage expressed in roentgens-equivalent-man (rem).

The biological dosage unit for ionizing radiations, the roentgen, has been originally defined for x-rays from 30 to 200 kilovolts. The energy dissipation of such x-rays in tissue or any other absorber is exclusively effected by secondary electrons released in collisions of the x-ray quanta with the atomic electrons of the absorbing medium. For the indicated energy range, the secondary electrons have a mean REL of 100 ion pairs per one micron of tissue. Thus, for this REL the RBE is equal to 1 per definitionem.

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Heavier particles and particles with multiple charge produce denser ionization columns. Protons, for instance, have a maximum REL of 1600 I.P./micron$_T$, alpha particles of 5500, and the ionization peaks of the heavy nuclei of the primary cosmic radiation range from 35,000 I.P./micron$_T$ for CNO nuclei to 100,000 I.P./micron$_T$ for Fe nuclei. The latter values demonstrate strikingly the great difference between cosmic ray heavy nuclei and terrestrial radiations.

The Recommendations of the International Commission on Radiological Protection list in the latest issue[1] in Appendix II a table of the RBE. Still more detailed information on the RBE is being prepared by the National Committee on Radiation Protection.[2] Radiologists unanimously agree that the relationship between the RBE and the REL is very complex and cannot be described, even for the same kind of ionizing radiation, by one general numerical value holding for the vast number of different biological test objects and reactions. Nevertheless, the data prepared by the National Committee have been selected and defined expressly for radiation safety practice. Therefore and because they carry official character, it seems worthwhile to investigate how far they seem applicable to the heavy primaries of cosmic radiation and what the shortcomings are of such evaluation.

Figure 1 shows the specific ionization of a heavy nucleus of $Z = 20$, i.e., a calcium nucleus, as a function of the residual range in living tissue. If such a nucleus enters the human body with an initial energy of 48.5 billion e-volts it has a residual range of 50 g/cm^2, i.e., since tissue has the density one, a range of 50 cm. Its REL at the beginning is 2,060 I.P./micron$_T$, that is about as much as that of an alpha particle of 5.5 million e-volts. The broken curve in Figure 1 indicates the RBE values. It is seen that the RBE is high along the full path of the particle. This fact should be emphasized in view of some misinterpretation in the literature. Even at relativistic speed, i.e., at minimum REL, a Ca-nucleus has an RBE of 12 corresponding to an REL of 2,000 I.P./micron$_T$.

When the nucleus slows down its REL increases and so does the RBE. Toward the end of the track, the REL grows more rapidly and finally reaches a steep and excessively high maximum immediately before thinning down to zero. The right hand graph of Figure 1 shows this terminal section of the track in higher resolution. The maximum REL is 72,500 I.P./micron$_T$. For such excessively high values of the REL no experimental data concerning their biological effectiveness are available. These values lie far beyond the range accessible to any artificial or natural terrestrial radiation source. The highest REL for which the Report of the National Committee[1] provides information is the value 5,000 I.P./micron$_T$ corresponding to an RBE of 20. In deriving the RBE curves of Figure 1, a moderate extrapolation has been performed beyond this limit to the RBE 26.5 corresponding to 10,000 I.P./micron$_T$.

To carry such extrapolation further seems not only not justifiable because of the temporary lack of experimental data but also for more fundamental

TABLE I.
COMPOSITION OF THE PRIMARY COSMIC RADIATION ON TOP OF THE ATMOSPHERE

Λ	M	H	He	CNO	Mg	Ca	Fe	TD
	Z	1	2	7	12	20	26	
55°	P	4,460	633	32	8.4	2.9	1.4	
	N	4,460	2,532	447	201	118	78	
	Dp	4.0	2.3	1.4	1.1	1.1	.90	10.7
	Dm	4.0	2.3	3.6	7.0	14.0	16.0	46.9
50°	P	3,100	459	23	6.1	2.1	1.0	
	N	3,100	1,836	322	146	84	56	
	Dp	2.4	1.4	.88	.69	.67	.54	6.6
	Dm	2.4	1.4	2.0	4 0	8.3	9.0	27.1
40°	P	1,620	226	11	3.0	1.0	50	
	N	1,620	904	154	72	40	28	
	Dp	1.2	.67	.41	.32	.31	.25	3.2
	Dm	1 2	.67	.90	1.8	3.7	4.1	12.3
30°	P	1,010	124	6.3	1.7	.58	.28	
	N	1,010	496	88	41	23	16	
	Dp	.81	.37	.23	.18	.17	.14	1.9
	Dm	.81	.37	.51	1.0	2.0	2.3	7.0

M: Type of Nucleus; Z: Atomic Number.
P: Frequency of Particles } traversing sphere of 1 cm^2
N: Frequency of Nucleons } cross section per hour from all directions.
Λ: Geomagnetic Latitude.
Dp: Ionization Dosage in millirep per 24 hours.
Dm: Biological Dosage in millirem per 24 hours.
TD: Total Dosage from all Components.

reasons. An ionization trail in tissue of such excessively high energy dissipation can be assumed in itself an above- threshold injury for tissue. The cells which happen to be exposed to such a heavy nucleus "hit" will suffer from severe radiation injury, and this injury cannot be adequately described with the common measuring units of mrep and mrem.

It is of course not possible at present to define the limit for the REL beyond which the common concept of the RBE can no longer be applied. This writer has suggested earlier[5] that the REL of 10,000 I.P./$micron_T$ be selected as a tentative limit in this respect. It is seen from Figure 1 that on this basis only the terminal four millimeters of the track, i.e., less than one per cent, have to be exempt from the ordinary procedure of evaluation. In other words, it is only a very small percentage of the total ionization of the heavy spectrum which cannot be assessed in common terms. This "very small percentage," however, due to its high concentration on small tissue volumes can be expected to produce severe damage to the cells affected. As to the nature and quantity of this damage no data are available at present.

Though the main question as to the exposure hazard from the heavy component remains unanswered it seems nevertheless interesting to carry out the evaluation for that part of the heavy spectrum in which the REL stays within the limits of the experience with terrestrial radiation sources. This evaluation is easily performed by subjecting the other components of the primary cosmic radiation to an analysis similar to Figure 1 and by combining the results with the data on the frequency of the different particles in the incoming cosmic ray beam. The final outcome, then, can be formulated in terms of a total biological dosage expressed in mrem/24 hrs. Table I contains these data for all components of the primary radiation. It is interesting to notice, in the first column, the very small percentages with which the heavy components are present in the primary beam if these percentages are expressed in frequencies of particles. This becomes different if they are expressed in frequencies of nucleons, i.e., of protons and neutrons making up the nuclei. If one goes again one step farther and calculates the ionization dosages, the heavy components become still more predominant. That is because the specific ionization is proportional to the square of the atomic number. For instance, the contribution to the total ionization dosage from an Fe nucleus is 676 times larger than from a proton.

Finally, the biologically effective dosage is obtained by multiplying the ionization dosage by the RBE. After this last conversion the situation is entirely reversed. The heavy components (CNO-Fe) now contribute about 85 per cent to the total biological dosage, and the heaviest components of them, Ca and Fe, are represented in this contribution with over 60 per cent. At 55° latitude, the total biological dosage is 46.9 mrem/24 hrs. For lower latitudes the dosage decreases substantially. Table I gives the pertinent values.

The dosage values of Table I represent strictly the contribution of the primary radiation. No allowance has been made for the star phenomenon nor for any other process of scattering or cascade formation. These dosages could actually be observed only in a very small tissue sample exposed entirely outside the atmosphere to the primary radiation. As soon as larger

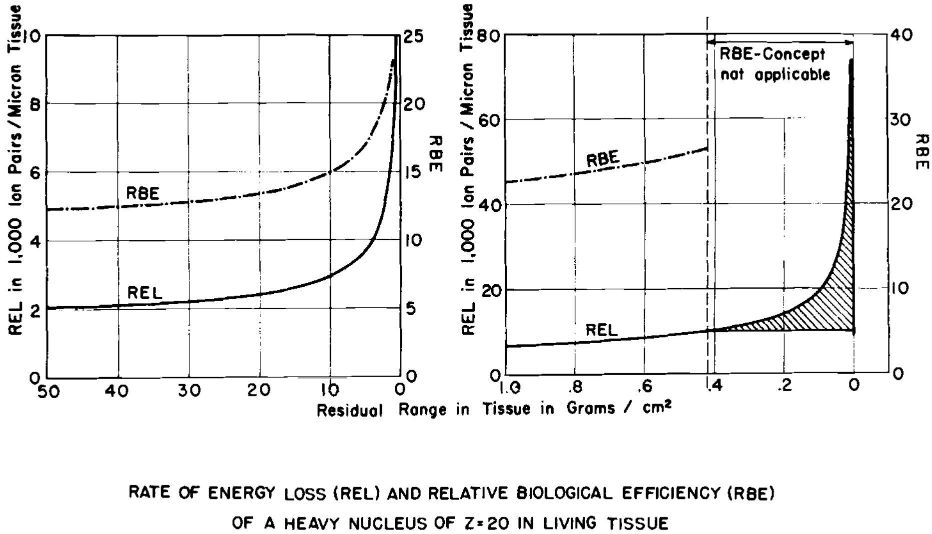


Fig. 1.

objects are involved the situation becomes very complex. On the one hand, the primary components and especially the heavy ones, become attenuated rather rapidly. Their contributions to the total dosage, therefore, decrease equally rapidly. On the other hand, nucleon cascades, photon-electron cascades and star formation create new contributions to the total dosage.

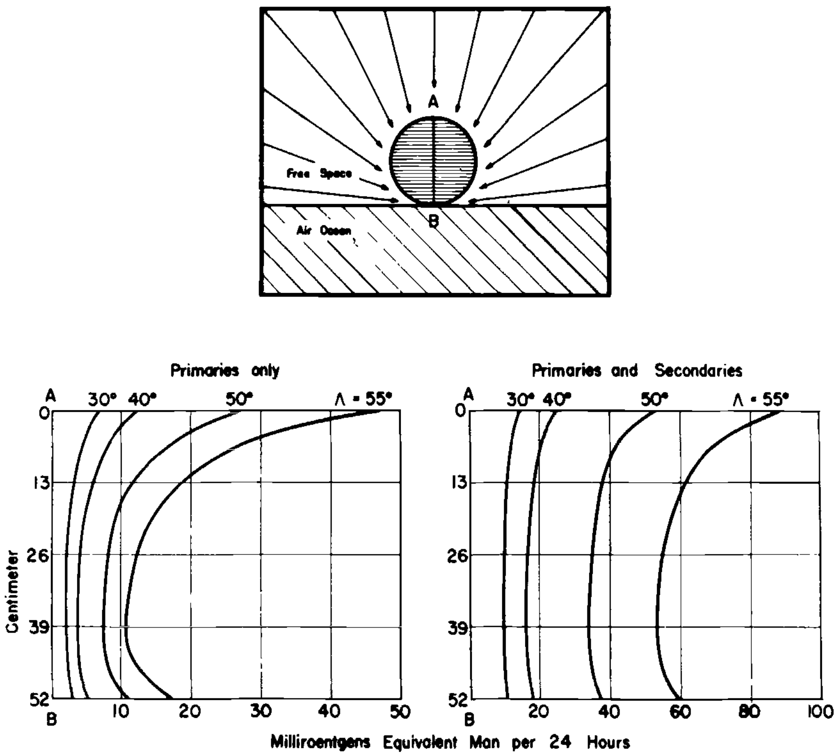
The upper graph of Figure 2 shows a model which has been used before[6] for a general treatment of this problem, namely, a sphere of density one and of 52 cm diameter, corresponding to a weight of 75,000 grams. This is, of course, only a very rough model of the human body. But it permits at least a first approximation.

For a clear understanding, it is useful to maintain temporarily the separate treatment of the primary components and to investigate how their contributions change in proceeding to deeper regions into the sphere. The left-hand graph in Figure 2 gives the depth dosages from the primaries in mrem/24 hrs. along the vertical diameter of the sphere. It is seen that the dosages decrease very rapidly inside the body. This is due to the circumstance that the components contributing most heavily to the biological dosage are, at the same time, those of the smallest penetrating power. The additional dosage due to secondaries can be expected to be rather large for a scattering body of the size under discussion. Unfortunately, this dosage cannot be calculated as accurately as the contributions from the primary components. For the region outside the atmosphere, experimental data on the scattering in large absorbers are entirely missing. For mountain and balloon altitudes, a few data are available from measurements of Van Allen, Fraser, and Ostrander.[7] On the basis of these, Van Allen has suggested a factor of 4 as a reasonable estimate for the increase of the ionization dosage due to production of secondaries. This estimate has been made by Van Allen expressly for the purpose of approximating the ionization in tissue-like absorbers.[8] This factor of 4, of course, has to be applied to the ionization dosage (mrep) and not to the biologically effective dosage (mrem). Since all secondaries are particles of single charge and the majority of them of relatively high energy, their RBE can be assumed close to one. With this assumption and using Van Allen's factor, one obtains a dosage distribution along the vertical diameter of the standard sphere as it is shown in the lower right of Figure 2. The largest value is the surface dose at the uppermost point of the sphere. It is 90 mrem/24 hrs. at a latitude of 55°, i.e., the permissible dose is clearly surpassed.

In proceeding from the surface to deeper regions inside the sphere, the dosage decreases substantially. One would expect that this circumstance would alleviate the situation considerably. However, the alleviation is more apparent than real so far as radiation safety practice is concerned as the official permissible dose, while defined in terms of the dosage at the surface of the body, has already taken the marked decrease of the dosage in the inner parts of the body into consideration.

As far as general conclusions are

concerned it can be said that the dosages, as they are obtained for the standard sphere, are higher than commonly anticipated. They represent the selves anything alarming. We have to realize that all the mrem-values in the graphs presented are 24 hr.-dosages. This implies a large margin of safety



SURFACE AND DEPTH DOSAGES ALONG THE VERTICAL DIAMETER OF A STANDARD SPHERE (HUMAN BODY) FROM COSMIC RADIATION OUTSIDE THE ATMOSPHERE

Fig. 2.

first detailed quantitative determination made possible by the accurate information now available on the composition of the primary radiation. They should replace the older rough estimates to which we have referred so far in dealing with the so-called total ionization.

On the other hand, I do not think that these new data represent in them- in as much as for many years to come nobody is going to stay that long in regions outside the atmosphere. As far as one can foresee today these outer regions will be accessible to us only with vehicles of the rocket type which will fly along free orbital trajectories after a short initial period of high acceleration. This type of flight, even if global distances are involved, will always last a few hours at the most. Moreover, we have to remember that even the 24 hr.-dosages exceeding the Permissible Dose of 50 mrem per day are limited to higher latitudes. In the equatorial region even a full twenty-four hours-stay would be permissible in terms of the official regulations.

On a very different footing stands, of course, the problem of tissue damage from the ionization-peak and thindown hits of low-energy heavy nuclei which has been discussed in connection with Figure 1. These hits represent the unknown quality which cannot be assessed in the common terms of the RBE. The situation about the tissue damage from them is aggravated by the circumstance that in the very region of latitude in which they occur the general background of total body exposure already is high. This further widens the basic difference with regard to the exposure hazard between the northern regions and the equatorial belt. Thus, the results of the presented analysis can be summarized in this conclusion: Whereas the concept of the permissible dose, as defined in the official regulations, after a moderate extrapolation, might be applied with reasonable confidence for the exposure of humans to the primary cosmic radiation in regions below 45 degrees latitude no adequate definition for a permissible exposure for the northern regions can be derived at the present time.

SUMMARY

Recently proposed amendments to the Recommendations of the International Commission on Radiological Protection contain detailed data on the relative biological effectiveness (RBE) of particle radiations. The possibility of extrapolating these data to the different components of the primary cosmic radiation is investigated.

It is shown that such extrapolation can be carried out only for the high and medium-energy part of the heavy nuclei spectrum, but cannot be extended to the low-energy part where extremely high values of the rate of energy loss (REL) occur in the terminal sections of heavy nuclei tracks.

This ionization-peak phenomenon is limited to northern regions above about 45 degrees latitude. It is this very region in which already without the contribution of the ionization peaks a maximum total exposure of 90 mrem/24 hrs. is obtained.

It thus seems appropriate to divide the region of extreme altitude in which the primary cosmic radiation predominantly contributes to the total ionization in two zones, one above and one below 45 degrees latitude. These zones differ basically with regard to the exposure hazard. Whereas for the equatorial zone the common concepts in the assessment of the radiation hazard can be extrapolated with reasonable confidence, no definition of a permissible exposure for the northern region can be derived at the present time.

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