Implications of Space Radiations in Manned Space Flights

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THAT ionizing radiations produce deleterious biological effects has been proven by sixty years of experience and experimentation. Qualitatively, the effects of all ionizing radiations, whether they are gamma rays or heavy primary cosmic particles, are the same and are a manifestation of the ionization produced in cells and tissues. Quantitatively, the effects are dependent on quality and nature of the radiation, on the specific biologic effect under consideration, and in many cases on the rate at which the radiation dose is delivered. Dose rate dependence is illustrated by the lethal effects of Co^{60} gamma radiation on mice. When delivered at the rate of 30 r per minute, about 700 r will result in death of 50 per cent of a large population of animals within 30 days. When delivered at a dose rate of 100 r per day, the LD_{50} dose is about 2000 r. Quantitative dependence of biologic effect on the characteristics of the radiation and the conditions of exposure make imperative the collection of more physical data on space radiations before their implications to manned space flight can be adequately evaluated.

EFFECTS OF IONIZING RADIATION

Acute Effects.—Radiation effects may be classified as acute, delayed, and chronic. Acute effects require moderately high doses of radiation delivered at relatively high dose rates. In man, the classical symptoms of acute whole body radiation are nausea and vomiting, diarrhea, drop in white blood cell count, alopecia, destruction of bone marrow resulting in anemia, hemorrhage, ulceration of the mucous linings of the gastrointestinal tract, gastric retention, sterility, and death.[8] The severity and time of onset of symptoms are in most cases dependent on the radiation dose. The acute LD_{50} dose of X or gamma radiation for man is not known but is variously estimated at from 300 to 750 r.[7,14,16,22]

The minimum sickness dose (lethargy, nausea) of radiation in man has been estimated at 100 to 225 r,[7,14,17] when the dose is delivered at high dose rates. At low dose rates, the minimum sickness dose may be somewhat larger. The lymphocyte count is considered by most authors to be the most sensitive indicator of acute radiation effect, and a transient drop in count may be demonstrated with radiation doses of 25 to 50 r.[4,9] Changes in other elements of the peripheral blood occur following relatively low acute radiation exposure.[9,10]

Chronic and Delayed Effects.—Signs of deleterious biologic effects may oc-

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Presented on January 27, 1959, at the 27th annual meeting of the Institute of the Aeronautical Sciences, New York, N. Y.

cur many years after acute radiation exposure. These delayed effects are qualitatively the same as those following chronic or repeated exposure to radiation doses too small to produce acute symptoms. Among the more important delayed or chronic radiation effects are cataracts of the lens of the eye, aplastic anemia, decreased life expectancy, increased incidence of malignant disease, i.e., leukemia, and increased incidence of genetic changes. The incidence of these effects in an irradiated population is proportional to the total radiation dose and their distribution is statistical in character. That is to say, whereas 225 r of whole body gamma radiation may shorten the average life expectancy of a large population by about three to six years, it cannot be said that the life of any specific individual in the population will be shortened by that amount.

The extent to which these statistically demonstrable effects are dependent on quality, nature, and intensity of the radiation is not known. Some believe that the incidence of such effects is independent of dose rate and dose fractionation, and related linearly only to the integrated dose (Fig. 1). If the linear hypothesis holds, it must be assumed that any amount of radiation, no matter how small, will carry a finite probability of risk.

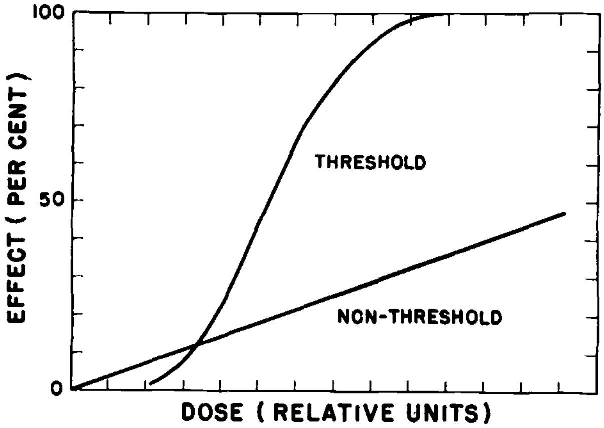

Fig. 1. Threshold and non-threshold response to ionizing radiation.

Others believe that chronic and delayed effects are dependent on factors other than total radiation dose, i.e., dose rate, and that the shape of the dose-responsive curve is sigmoid and similar in character to that for acute radiation effects and effects of other noxious agents (Fig. 1). In this case, it may be assumed that a practical threshold in the dose-response curve exists and that there is a maximum permissible radiation dose below which the probability of risk is, for practical purposes, zero. This uncertainty regarding the shape of the dose-response curve has led to adoption of very conservative maximum permissible exposure levels by National and International Commissions for Radiological Protection in order to make sure that jobs involving radiation exposure will carry no greater average probability of risk to workers than those involving no exposure.

Assuming the linear hypothesis for the dose-response relationship, 1 r of whole-body gamma radiation is believed to carry a statistical life shortening effect of about five to ten days[11] and an increased probability of development of leukemia of 1 to 2 $\times 10^{-6}$ per year.[3,13] The gamma radiation dose required to double the natural mutation rate is estimated to be 30 to 50 r.[6,15]

On the basis of the above data, a person who receives the equivalent of 150 r (assumed to be the minimum sickness dose[17]) of gamma radiation in a space mission will be placed in a population group which, if large enough, will have an average life expectancy approximately three years shorter than a similar group in the normal population. His probability of developing leukemia will be increased from the natural level of about 60 per million to about 360 per million per year. His probability of passing on a genetic mutation to his offspring will be increased by a factor of about five multiplied, of course, by the probability that he will father children.

To avoid the above speculations being taken too seriously, it should be pointed out that the quality and nature of the radiations were assumed to be that of gamma rays. The biologic effectiveness of various types of ionizing radiations is known to vary with the spatial distribution of the ions produced along the path of the ionizing event. Gamma rays are lightly ionizing, while particulate radiations produce dense ionization tracks in tissue resulting in relatively greater damage. Depending on the nature and type of radiation encountered in space, the actual effect may be greater than anticipated. On the other hand, it is possible also that the dose-response relationship is, indeed, of the threshold type in which case the actual effect may be smaller than predicted above.

SPACE RADIATIONS

Present physical measurements of ionizing radiations in space suggest two major potential radiobiologic problem areas in manned space flight. The first concerns the biologic effects of densely ionizing heavy primary cosmic ray particles, and the second concerns the effects of the particulate radiation belts, the so-called Van Allen layers, associated with the earth's magnetic field.

Heavy Primary Cosmic Rays.—The primary cosmic particles impinging on the top of the earth's atmosphere consist of about 80 per cent protons, 19 per cent alpha particles (helium nuclei), and about 1 per cent nuclei of elements of atomic number greater than 2. Distribution of the components of primary cosmic radiation somewhat parallels the composition of the universe. The energies of the primary radiation lie mostly between 10^9 and 10^{18} electron volts per particle.[12] There is a vast amount of information on cosmic ray intensity and its variation with altitude and latitude. The major portion of the cosmic radiation dose, up to an altitude of about 70,000 feet, is a result of secondary radiation produced by interaction of cosmic ray primaries with the earth's atmosphere.

At the northern latitudes, where the intensity is at a maximum, the secondary radiation dose rate is only about 100 mrad per week. Because this radiation is not unlike high energy gamma rays with regard to its specific ionization and biological effectiveness, the radiobiologic effects are not considered a significant problem in manned flights within the earth's atmosphere. Above the earth's atmosphere, the primary cosmic radiation dose rate drops to about 60 to 70 mrad per week. At great distances from the earth, the dose rate would approximately double.

Although the radiation dose in terms of ergs per gram of tissue seems insignificant, about 50 per cent of the dose is delivered by alpha particles and heavier nuclei with high average specific ionization.[18] In this case, the ions are not distributed throughout the tissue as with gamma rays but are in the form of dense ionization tracks. The potential biologic hazard of heavy primary cosmic ray particles in manned space flight becomes a question of the relative biologic effectiveness (RBE) of densely ionizing radiations. Unfortunately, no accelerators exist that are capable of producing particles in the laboratory analogous to the heavier high energy components of primary cosmic rays. Any knowledge, therefore, of their RBE must come from pure speculation and extrapolation from knowledge of other radiations vastly different in type and quality. Figure 2 shows a plot of the RBE of more conventional types of radiation against their linear energy transfer (LET) in kev per micron of track.

A number of points regarding the RBE of densely ionizing particles may be inferred from these data. First, they show that the RBE is dependent on the test system used and the biological effect that is observed. Second, RBE increases with LET, passes through a maximum at about 50 to 70 kev per micron, and decreases. Third, the upper curve for chromosomal aberrations[2] and the lower one for effects on mice[19] show the same general trend in RBE versus LET at the cellular and mammalian levels, respectively, and suggest an ability on the part of complex mammalian systems to repair or compensate for a portion of the radiation damage (perhaps by replacement of dead or damaged tissue from surrounding undamaged areas). Results from high dose irradiation of animals through perforated shields support this point.[20]

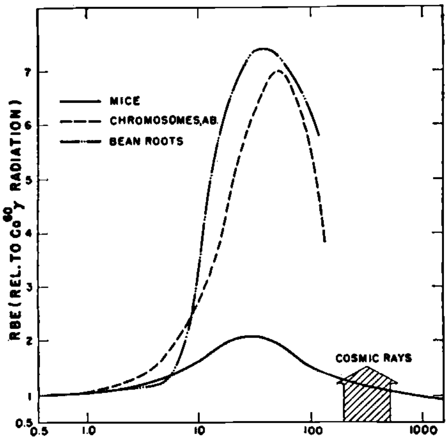

Fig. 2. Relative biologic effectiveness (RBE) as a function of linear energy transfer (LET).

From these data it may be concluded that heavily ionizing cosmic ray particles, although more damaging than conventional radiations, are not more damaging in direct proportion to their ionization density.[1,5] The above analysis of the problem is, of course, greatly oversimplified because of the complexities of LET calculations of heavy primary cosmic ray tracks and their associated delta rays.[18]

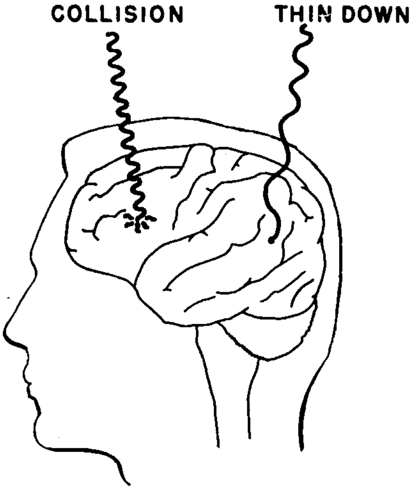

Fig. 3. Potential primary cosmic ray interactions with the central nervous system.

Especially questionable is the deleterious effect of such tracks if they occur in vital regions of the brain, such as the hypothalamus, and other tissues with little or no repair potential and where the destruction or damage of a few hundred cells could affect some vital function of the body or the function of a larger group of cells[21] (Fig. 3). Although such an effect of primary cosmic rays has never been demonstrated, its possibility has not been ruled out or its probability of occurrence established. Probability of gross effects from primary cosmic ray hits in vital areas should be demonstrable experimentally as a statistical decrement in viability of a large population of mice exposed in maximum duration balloon flights at an altitude of 100,000 feet or above. Life span, tumor incidence, graying and loss of hair, cataract incidence and cause of death of the exposed group could be compared with that of random controls exposed at ground level to the same environmental stress. Inasmuch as the brain of a man at 120,000 feet would receive only about 50 hits per hour from particles of atomic number of 6 or greater, intuitively the probability of a vital hit occurring during flights of short duration would seem quite low, especially in view of the particle energy distribution.

It seems unlikely that the existence of a heavy primary cosmic ray problem should be a deterrent to low-orbiting manned space flights of the near future.

Van Allen Radiation.—Measurements made with detectors in *Explorer* satellites[24,25] and the *Pioneer III* moonprobe[23] show the existence of high intensity radiation fields at altitudes greater than 500 miles. The radiation is believed to consist of charged particles, electrons and/or protons, confined in two rings around the earth by the earth's magnetic field. The relative composition of the radiation and the spectra of its components have not been established. Data from *Pioneer III* suggest that the first ring extends from approximately 1400 to 3400 miles above the earth, roughly in line with the earth's equator. The second ring, about 4000 miles thick, apparently begins at an altitude of approximately 8000 miles (Fig. 4). The maximum counting rates in the two belts, about

25,000 counts per second, were approximately equal. The radiation dose rate depends on the counter efficiency and the nature and energy of the radiation and cannot be estimated from counting rate alone. Estimations, however, based on assumptions of electrons with energies of 6 Mev and protons of 40 Mev, give maximum dose rates of the order of 10 and 100 rads per hour, respectively.[23]

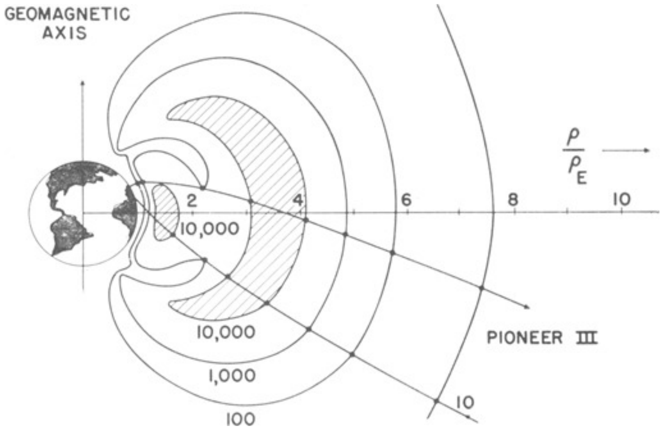

Fig. 4. The Van Allen radiation belt.

The general implications of the Van Allen radiation phenomenon to the early phases of manned space flight are, in principle, rather evident. The amounts of radiation that man can tolerate and not exceed a specific acceptable level of risk can be estimated with reasonable certainty. These estimates are dependent on the characteristics of the radiation and the exposure conditions. In manned space flight operations, exposures beyond acceptable levels of risk will have to be avoided. Avoidance may consist of rapid traversal of high intensity radiation fields, exit via the magnetic polar regions, or provision of adequate radiation shielding in space capsule design. From the engineering viewpoint, feasibility of shielding will be highly dependent on the characteristics of the radiation. When charged particles are stopped in matter, X-rays (bremsstrahlung) are produced. Electrons are worse than protons in this respect, since bremsstrahlung radiation is inversely proportional to the square of the particle mass. Electrons impinging on the capsule create essentially the same effect as electrons striking the target of an X-ray tube. The intensity of bremsstrahlung production, however, is directly proportional to the square of the particle energy times the atomic number of the target material. The use of low atomic number material, such as beryllium, as an ablation heat sink would provide shielding against electrons and decrease the bremsstrahlung radiation dose inside the capsule.

Until the characteristics of the radiations are determined, further discussion of the significance and alleviation of the potential hazards of the Van

Allen radiation belts would be nothing more than speculation. For this reason, further physical measurement of the nature, quality, and intensity of the radiation fields in terms amenable to biologic dose estimations is singularly the most urgent and important radiobiologic experiment that can be conducted with presently available satellite and probe payload capability. A widely orbiting satellite instrumented to measure both quality and quantity of radiation encountered would provide invaluable data for estimation of the potential hazard to man.

TABLE I. SOME PARAMETERS OF WHOLE BODY* RADIATION EXPOSURE AND EFFECT

Weekly Maximum Permissible Exposure	0.3 rem†
Yearly Maximum Permissible Exposure	5 rem
Permissible Exposure to Age 30	50 rem
Maximum Permissible Life-Time Exposure	225 rem
Acceptable Emergency Exposure	25 rem
Acute Minimum Sickness Dose	150 rem
Acute LD_{50}^{30}	450 rem
Acute Incapacitating Dose	5000 rem
Statistical Life Shortening (per rem)	5-10 days
Statistical Leukemia Incidence (per rem)	$1 - 2 \times 10^{-6}$ per year
Genetic Doubling Dose	30-50 rem

*Whole body irradiation is worse than partial body irradiation, except to the gonads in case of production of mutations.

†Dose in rem = dose in rad × RBE; 1 rem is that amount of any radiation required to produce the same degree of biological effect as 1 r of hard X or gamma radiation.

DISCUSSION

The question of acceptable levels of radiation risk in manned space flight seems worthy of further comment. Because of the inherent weight requirement of shielding and its interaction with the rest of the satellite system, radiation exposure limitations should be set realistically in early manned operations. Limitations that are too conservative will impose major engineering penalties and force compromises in other areas of the man-in-space program. Although not always directly applicable as acceptable radiation levels for manned space flight, maximum permissible levels and other exposure criteria (Table I) accepted by the atomic energy industry can serve as useful guides.

Maximum permissible levels of radiation exposure in industry are predicated on the assumption that a man will be potentially exposed for 45 years, 10 of which will be before age 30 (the average end of the reproductive age). These levels limit the whole body exposure rate to 5 r per year, 50 r by age 30, and 225 r per working lifetime. The limitation of 50 r to age 30 is for genetic reasons and limits the statistical probability of genetic manifestation in a worker's offspring to approximately twice the natural incidence. The lifetime exposure limitation confines the statistical average life shortening probability to no greater than three to six years. Application of these criteria to the early phases of manned space flight seems unrealistically conservative. The average life expectancy of conventional pilots is about 12 years shorter than that of the general population, and the early astronaut would not be expected to pursue his career for 45 years. With regard to the mutational effects of radiation exposure, the seriousness of increased probability of genetic manifestation in the offspring of a relatively small population exposed voluntarily and selectively should not be distorted by the present controversy over world-wide radioactive fallout from nuclear weapons tests. In the latter case, indiscriminate and involuntary exposure of the entire world population is involved. Exposure of the primary stock during permanent colonization of the moon and planets, however, should be considered in the latter context.

REFERENCES

1. Brustad, T., and Fluke, D. J.: Effect of stripped carbon and oxygen ions in lysozyme. *Radiation Research,* 9:95, 1958.
2. Conger, A. D., Randolph, M. L., Sheppard, C. W., and Luippald, H. J.: Quantitative relations of RBE in Tradescantia and average LET of gamma-rays, X-rays and 1.3-, 2.5- and 14.1-Mev fast neutrons. *Radiation Research,* 9:525, 1958.
3. Court-Brown, W. M.: Nuclear and allied radiations and the incidence of leukemia in man. *Brit. Med. Bull.,* 14:168, 1958.
4. Dunlap, C. E.: Effects of radiation on the blood and the hemopoietic tissues. *Arch. Path.,* 34:562, 1942.
5. Fluke, D. J., and Brustad, T.: Effect of stripped carbon and oxygen ions on bacterial spores and bacteriophage. *Radiation Research,* 9:115, 1958.
6. Glass, B.: In Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy. Congress of the United States, Eighty-Fifth Congress, First Session on The Nature of Radioactive Fallout and Its Effects on Man, June 4-7, 1957, Part 2, p. 1036.
7. Harris, P. S.: Estimation of radiation dose to the Japanese at Hiroshima and Nagasaki. Los Alamos Scientific Laboratory, 1957. (Unpublished report.)
8. Hempelmann, L. H.,, Lisco, H., and Hoffman, J. G.: The acute radiation syndrome. *Ann. Int. Med.,* 36:279, 1952.
9. Jacobson, L. O., Marks, E. K., and Lorenz, E.: The hemotological effects of ionizing radiations. *Radiology,* 52:371, 1949.
10. Jacobson, L. O.: *Radiation Biology,* Vol. 1, Part 2, McGraw-Hill, New York, 1954. p. 1029.
11. Jones, H. B.: In Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy. Congress of the United States, Eighty-fifth Congress, First Session on The Nature of Radioactive Fallout and Its Effects on Man (June 4-7, 1957). Part 2, p. 1123.
12. Korff, S. A.: The origin and implications of the cosmic radiation. *Am. Scientist,* 45:281, 1957.
13. Lewis, E. B.: Leukemia and ionizing radiation. *Science,* 125:965, 1957.
14. Medical Research Council of Great Britain: The hazards to man of nuclear and allied radiations. Her Majesty's Stationery Office, London, 1956, p. 12.
15. Müller, H. J.: In Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy. Congress of the United States, Eighty-Fifth Congress, First Session on The Nature of Radioactive Fallout and Its Effects on Man (June 4-7, 1957). Part 2, p. 1066.
16. National Academy of Sciences-National Research Council: Pathological effects of atomic radiation. Washington, D. C., 1956, p. 1.
17. Pickering, J. E. Biological aspects of nuclear propulson. Presented at Second International Symposium on the Physics and Medicine of the Atmosphere and Space, San Antonio, Texas, Nov. 10-12, 1958.
18. Schaefer, H. J.: In *Physics and Medicine of the Upper Atmosphere.* Univ. of New Mexico Press, Albuquerque, 1952, p. 290.
19. Storer, J. B., Harris, P. S., Furchner, J. E., and Langham, W. H.: The relative biological effectiveness of various ionizing radiations in mammalian systems. *Radiation Research,* 6:188, 1957.
20. Storer, J. B.: Personal communication.
21. Tobias, C. A., Mel, H. C., and Simons, D. G.: Cosmic radiation and space travel. *Science,* 127:1508, 1958.
22. United Nations: Report of the Scientific Committee on the effects of atomic radiation. Suppl. 17 (A/3838), United Nations, New York, 1958. p. 154.
23. Van Allen, J. A., and Frank, L.A.: Survey of radiation around the earth to a radio-distance of 107,400 kilometers. (Unpublished report.)
24. Van Allen, J. A., Ludwig, G. H., Ray, E. C., and McIlwain, C. E.: Observations of high intensity radiation by satellites 1958 (alpha and gamma). *Jet Propulsion,* 28:588, 1958.
25. Van Allen, J. A., McIlwain, C. E. and Ludwig, G. H.: Radiation observations with satellite 1958 Epsilon. Dept. Physics, State University of Iowa, SUI-58-10, 1958.