# *Radiation Hazards and Manned Space Flight*

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THE POTENTIAL medical hazards of man's venture into space will span a number of disciplines in regard to the pathology and deranged physiology to which the human body may be subject in travel beyond the earth's atmosphere. Not the least hazard is that having to do with the effects of radiation to be encountered in free space. This problem is one which is receiving considerable attention from astrophysicists, radiobiologists, and others interested in the effects of ionizing radiation on tissue.

The radiation in question can be divided broadly into three (3) categories. The first is cosmic radiation which apparently originates in interstellar space, and is therefore present in this galaxy and in others. The cosmic radiation has two (2) components both of which are particulate radiation. The largest component consists of protons (nucleus of hydrogen atom) comprising about 79 per cent of the radiation and alpha particles (helium nucleus) amounting to about 20 per cent of the total. The nuclei of heavy elements such as carbon, oxygen, nitrogen etc. up to at least iron comprise the remaining 1 per cent.[4] The cosmic ray particles are among the most energetic known. Energies range from a few million up to several billion electron volts.[5] As these particles enter the earth's atmosphere they interact with the atoms of air causing ionization with the production of a number of secondaries, (deflected particles and electrons) and eventually dissipate their energy so that the dosage at sea level from this radiation amounts to less than 100 milliroentgens per year.

The second source of radiation encountered is that designated as the trapped corpuscular radiation. This consists of two wide belts of particulate radiation surrounding the earth except in the polar regions. These are called the Van Allen belts after Van Allen who discovered them in 1958. The lower edge of the inner Van Allen belt varies from an altitude of about 450 kilometers above the earth's surface over Chile to an altitude of about 1400 kilometers over Australia. It extends outward into space to reach a maximum intensity at a little less than 4000 kilometers tapering off in the vicinity of 8000 kilometers. The outer Van Allen belt begins at an altitude of about 12000 kilometers and extends outward into space to about 55,000 kilometers with a maximum intensity at about 18,000 kilometers.[2, 4, 5] In both belts the maximum concentration occurs in the plane of the magnetic equator of the earth. The origin of these radiation belts is in doubt, although one popular theory is that the radiation belts represent particles trapped by the earth's magnetic field and deflected into a path travelling back and forth from North to South. The inner Van Allen belt consists of protons and electrons of high energies. The protons have energies ranging up to 700 Mev and the electrons attain a maximum of about 800 Kev.[4] The outer Van Allen belt appears to consist largely of electrons of much lower energy. This belt is greater in extent and depth than the inner belt. In addition the flux or intensity of flow of electrons is much larger than in the inner belt. Figure 1 depicts the Van Allen belts in relation to the earth.

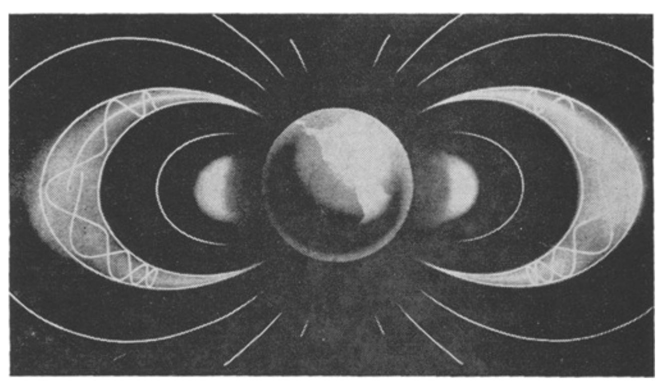

Fig. 1. Shows the general configuration of the trapped corpuscular radiation in the inner and outer Van Allen belts taken from Newell and Naugle,[5] Science, 132, 1960.

The third source of radiation in space is that due to solar flares. These are periodic surges of radiation consisting largely of protons of various energies originating from the sun and related to the cyclic sun spot activity. Again the energy of the protons can be very high and may extend into the billion electron volt (Bev) range.[4] These proton beams begin making their appearance at the polar caps of the earth about one (1) hour after a visible flare has occurred on the sun.

In addition to these sources of radiation above and beyond the earth's atmosphere, there occurs in interplanetary space lower energy particle radiation emitted by the sun consisting of protons and electrons and electromagnetic radiation in the x-ray range. The energy of this radiation is so low that it is not felt to create any radiation hazard.[2]

## RADIATION EXPOSURE RANGES

Dose rates delivered by the extra atmospheric radiation in free space have been estimated by a number of authors from measurements on high altitude balloons, rockets, and space probes.[2, 4, 5, 12] Beyond the protective effect of the earth's atmosphere the exposure rate from cosmic radiation in an unshielded situation would approach 15-20 millirads per day.[2, 4, 5] This is a relatively constant exposure rate due to the cosmic radiation. As one approaces the inner Van Allen belt through the area of maximum concentration at the magnetic equator of the earth, the dosage rate is increased sharply. Since the radiation in this zone consists of more energic protons and electrons, the penetration of such radiation is an important factor for space flights through this region. Without shielding in this region a surface dosage rate of 100 r per hour due to protons has been estimated.[4] This would lead to a probable depth dose at the center of an unshielded body in the vicinity of 100 millirads per hour. With the shielding of a space vehicle thick enough to provide a mass of 1 gram per square centimeter of surface area of intermediate atomic number material, the dosage rate is reduced to between 10 to 20 rads per hour.[2, 12] The slot between the inner and outer zones shows a fluctuation in radiation intensity although of a much lower order of magnitude when compared to the Van Allen belts themselves. The dosage rate when passing through the outer belt is several times higher than that in the inner belt. The outer belt shows very great variations in radiation intensity and spatial distribution of the particles, which is associated with solar activity. Surface dosage rates of the order of $10^4$ rads per hour[4] have been estimated to occur in the outer Van Allen belt. Shielding due to the "skin" of the space vehicle of the order of 1 gram per sq. centimeter would reduce this dosage rate to about 200 rads per hour inside the vehicle.[2] Because the radiation in the outer Van Allen belt is largely made up of less energetic electrons, the radiation dosage inside the space vehicle results from x-rays in the 20-100 Kv. range which are produced when the lower energy electrons are stopped in the material of the space craft (Bremsstrahlen radiation). The depth dose inside the body is therefore considerably lower when compared to the inner belt.

Solar flare phenomena contribute dosage rates in free space of the order of about $10\text{-}10^3$ rads per hour for a number of days due to protons under a 1 gm/cm $^2$ shield.[5] For a large flare and considering the radiation contributed by the lower energy protons as well, extrapolations from balloon data from the top of the atmosphere have estimated radiation levels as high as $3 \times 10^4$ roentgens per hour for free space without shielding during the peak of the radiation surge.[5]

It is to be emphasized that these data represent only orders of magnitude and these estimates and calculations may be in error by a considerable percentage.[2] A great deal depends upon the particular conditions at the time measurements are made, the size and intensity of the solar events considered, and whether or not these estimates are made for shielded or unshielded situations. The amount of shielding is obviously a pertinent factor as well. Schaefer[9] has demonstrated the transitions that may occur in relative depth dose (2 per cent-78 per cent) within a phanthom under increasing shield thicknesses and at decreasing intervals after the flare's onset. Figure 2 shows in graphic form the levels of

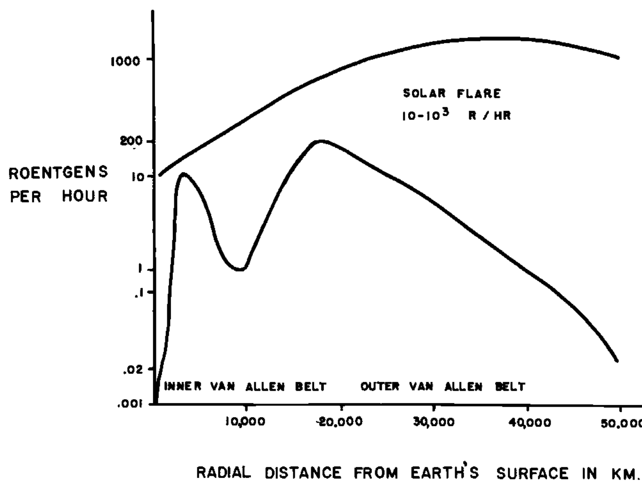


Fig. 2. Depicts in graph form the levels of radiation in roentgens per hour which might be encountered in free space at various altitudes behind a 1 gm./cm.$^2$ intermediate Z shield. The exposure rate due to cosmic radiation is shown at .001 r/hr, and that through the center of the inner and outer Van Allen belts at 20 and 200 r/hr. respectively, with 1 r/hr. in the "slot." Levels ranging from $10\text{-}10^3$ r/hr. are shown for a solar flare.

radiation exposure in free space that have been extrapolated or estimated from various sources for conditions of shielding equivalent to 1 gm./cm.$^2$ intermediate atomic number material.[4, 5, 12]

## BIOLOGICAL EFFECTS

The exposure rates above mentioned do not give information on the biological changes induced in the tissues by the radiation. The cosmic radiation particles consist mostly of protons and alpha particles, which produce, in tissue, ionization following patterns that are relatively well established, and the effects of which might be anticipated. For the smaller fraction of approximately one per cent of heavy nuclei in the cosmic radiation, the reaction in material and tissue is quite different. These heavy particles may react in two ways.

In the first case the heavy particle nucleus undergoes a collision with another nucleus resulting in the formation of a number of secondaries from the disintegration of the nucleus. This is called a star formation or spallation effect. The products of this interaction then cause ionization in the more familiar fashion. Most heavy particles of energy greater than one Bev tend to react in matter in this fashion. Particles of energy less than 100 Mev per nucleon have approximately a 90 per cent chance of terminating in so-called "thin downs."[10] In this case the heavy nucleus traverses matter or tissue causing a dense ionization in its wake from the number and distribution of the secondaries it produces. The most intense ionization occurs at the end of the particle track and is about 1 mm. in length. It can be as wide as 25 microns. In the center the ionization density is equivalent to doses of the order of 10,000 r.[2] It is estimated that a maximum of 15,000 mammalian cells would be involved in the volume of this intense ionization. A man weighing 70 kilograms might receive 100 such hits per hour in interstellar space.[2] Since only relatively small volumes of tissue would be affected by the intense ionization in the thin down, recovery from surrounding cells could be expected, and these thin downs are not felt to constitute a great radiobiological hazard. The classic work of Chase as described by Simons [10] in which black mice exposed in high altitude balloons sometimes showed localized grey streaks in their coats, was felt to represent damage to the hair follicles along the path of a densely ionizing heavy particle passing parallel to the skin surface causing loss of pigment production. Likewise investigations of such particles in heavy ion linear accelerators on tissue cultures have yielded suggestive evidence for single hit ionization events.[13]

However the experience with this type of radiation is very limited, and it is possible that such an effect, for example, in the lens of the eye may lead to the formation of a cataract; or if such a hit occurred in a vital nucleus in the central nervous system, it is conceivable that a serious or fatal injury might result. In addition living matter shows a much lower, or perhaps absent, threshold for effects due to these densely ionizing particles than for standard radiation.[10] The biological effects produced by the other radiation in space will be largely on an ionization basis, except for a small fraction of the more energetic protons found in solar flares. These have an RBE (relatively biological effectiveness) up to 10 times greater than standard radiation; and it is recommended that dosages received due to these be considered as cumulative and no allowance be made for recovery.[8] This radiation constitutes only a small fraction of the flare produced protons.[8]

## LESSENING THE RADIATION HAZARD

Thus, contemplated flights into space must take into account the radiation hazard involved to the crew or passengers. An obvious method of lessening this hazard is by means of shielding in the space vehicle itself. Considerations of weight and design will impose limits to the amount of shielding possible. Various composite shields may be more useful than heavier shields of high atomic number material. Cosmic radiation is not considered too great a hazard, so that shielding against the Van Allen belts and the solar flares will largely be of concern.[5] It is felt very likely that other planets which have a magnetic field will also have similar radiation belts of unknown intensities and energies surrounding their surfaces. The amount, intensity, and energy of the radiation to be encountered in travel through space has by no means been fully established. It will be impossible to provide shielding against all the radiation hazard. Sufficient shielding however, can be provided for flights through both Van Allen belts, if necessary, with exposures probably amounting to less than 10 roentgens.[6] It may be possible to avoid the Van Allen belts by choosing an orbit trajectory through the polar regions. Solar flares will be more difficult to shield against because of their unpredictable size and variable duration. However, the advent of a solar flare can be anticipated and the flare detected so that it may be possible to protect against it to a certain extent. In addition a storm cellar [5] has been suggested in part of the space vehicle. This would be a small compartment more heavily shielded into which an astronaut could secure himself for at least part of the radiation exposure. Schaefer [9] has shown the surface dose behind 2 gms./cm.$^2$ of shielding to remain above 4 r/hr. for a period of 28 hrs. during a typical solar flare. A skin dose of 200 r is reached in 58 hrs. and depth doses at 1, 2, and 15 cms. in a phanthom are 110, 70, 12 r respectively.

Therefore of the various radiation hazards in early space flights, solar flares and cosmic particles constitute the greatest threat because of their more energetic radiation and consequent depth of penetration. A saving in shielding weight can be accomplished if a common mass designed for the maximum is utilized against all radiation hazards. Various shielding materials e.g., metal, carbon and composite shields have been advocated. Further saving in weight may result from use of a partial body or trunk shield and employing water (some of which could be waste) as a shielding material. For short exposure flights this might amount to about 100 pounds per man.[14]

One of the major difficulties in assessing the problem fully, aside from the unknowns and uncertainties of exposure rates, is the biological effect of exposure to radiation in smaller doses over a relatively longer period of time. The effects of ionizing radiation upon man in acute dosages are known with more certainty. For example the MLD 50 for man is of the order of 450 r single exposure. Man may receive an acute total body exposure up to about 200 r without requiring medical attention in 90 per cent of instances.[3] There will be radiation sickness, but recovery without incapacitation can be expected. The problems of exposure on a more protracted or chronic basis are far less well documented. In initial space flights it seems possible that the recommended exposure of 25 r as a once per lifetime emergency dose for the ordinary individual may well be exceeded. The radiation acquired during a space flight is likely to be received over a period of weeks, months or years. What the limits of tolerance are and what the percentage of recovery becomes under such circumstances is unknown. It is known from work in clinical radiation therapy that total body exposures up to 200-300 r tissue dose may be delivered in certain cases of leukemia and lymphoma on a slow protracted basis over a 2-3 month period at a rate of 25 r per week without apparent somatic injury. The effects of such dosages in terms of genetic damage, shortening of life span, and possible carcinogenic effects are unknown and unobtainable as a rule from the study of such patients. While it is risky to extrapolate data from ill patients, such as these, to those in healthy condition, these points may serve as guide lines for estimating possible tolerances to radiation doses of small magnitude over a prolonged time. Rates of 1.5 r per day for a period of one year with one acute exposure of up to 200 r can be tolerated without somatic injury.[3] Between 1000 and 2000 r [11] can be accepted at a slow rate over a long time period ranging from one year upward with survival. It has been suggested that whole body doses of 100 r could be accepted for astronauts during space flights. Allowing a recovery period of 120 days, it was felt that four or five further such exposures could be permitted.[1] It may be that higher levels by a factor of 2 may be acceptable from the point of view of short term effects depending upon the rate of exposure and the over-all time period involved as recovery is occurring during a protracted low dose exposure. Genetic effects and long term effects at these dosage levels are unknown but likely to be significant. It is also true that man may unavoidably be exposed to more acute dosages in space. There is the additional point that radiation encountered in space may have components of different RBE than that ordinarily used in clinical practice. Likewise experience is lacking on the clinical effects of heavy nuclei. It appears that a price must be paid especially in early space flights for accomplishment of successful missions. How high this price will, or should, justifiably be is impossible to determine in the present state of knowledge regarding the radiation hazard in space. Obviously it must be kept as low as possible particularly from the point of view of late somatic and genetic effects. As mentioned above, doses in excess of 1000 r at a continuous rate over a year or more can be tolerated without immediate somatic effect and with survival expected. On the basis of N.C.R.P. recommendations regarding radiation hazards in fallout,[3] and previously allowed exposure for radiological workers, the early space explorers should probably be limited to 400 r total body exposure of penetrating radiation during their careers providing no acute exposure over 100 r occurs, in order to keep the risk of late somatic injury at a reasonable compromise level. For the space passenger of the future, the present suggested limit for radiological workers of about 200 r per lifetime should probably be considered as the maximum. A log including the accumulated total exposure of each space traveller will be as necessary as a passport until such time as an antidote for the effects of radiation is discovered, or it is possible to decrease exposure to presently accepted levels for the general population.

## SUMMARY

The three major components contributing to the radiation present above the earth's atmosphere in free space have been outlined and estimates on dosage levels in each of the areas have been given.

The biological assessment of the radiation has been discussed in general terms and the lack of specific data as to dosage rates and biological effects pointed out. The problems of tolerance and recovery for chronic exposures to radiation over longer periods of time, as conceivable in space flight, have been approached on the basis of clinical situations where total body radiation is given on a fractionated basis, information available from fallout studies, and exposures accepted by radiological workers.

The uncertainties and unknowns in the situation at present far outweigh the facts that can be stated with certainty.

Lifetime total body exposures of up to 400 r of penetrating radiation for early space explorers and up to 200 r for future space passengers have been suggested as compatible with a reasonable risk of late somatic injury in the present state of knowledge.

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The opinions presented are those of the author, a radiation therapist associated with the Royal Victoria Hospital, Montreal, Canada.