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Radiation protection in space*

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Abstract.

The challenge for planning radiation protection in space is to estimate the risk of events of low probability after low levels of irradiation. This work has revealed many gaps in our knowledge that require further study. Despite investigations of several irradiated populations, the atomic-bomb survivors remain the primary basis for estimating the risk of ionizing radiation. Compared to previous estimates, two new independent evaluations of available information indicate a significantly greater risk of stochastic effects of radiation (cancer and genetic effects) by about a factor of three for radiation workers. This paper presents a brief historical perspective of the international effort to assure radiation protection in space.

Introduction

Commercial air travel is recognized as statistically safer than travel by automobile. By comparison, space travel is acknowledged as a higher risk activity, primarily due to the greater number of hazards to be encountered. Radiation protection standards are set to prevent deterministic effects and to limit stochastic effects, in particular cancer, to a level considered "acceptable." The level of risk that is considered acceptable is the risk incurred in a number of occupations that are neither the most dangerous, nor the safest. This meeting has provided a concise review of emerging information on what is known about radiation fields in low earth orbits, and what measurements exist to predict radiation exposures in deep space. But knowing what the radiation exposure may be, and how to predict the response of individual space travelers are two separate but converging issues. Guidance on reassessing safe radiation exposure levels in space activities has undergone continual modifications during the last three decades. Recent changes are the result of additional information that has become available about radiation environments, and of new radiation risk estimates from exposed populations.

Historical review of space radiation safety standards

In 1961 an ad hoc working group was set up by the U.S. Space Science Board (SSB) of the National Academy of Sciences (NAS) to consider radiation safety for the space worker. In 1967 the committee issued its report on "Radiobiological Factors in Manned Space Flight" (NAS/NRC, 1967). The report dealt with both genetic effects and the appearance of both early - occurring (within 60 days) and late effects, primarily the risk of cancer.

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In 1969 the Radiobiological Advisory Panel of the SSB's Committee on Space Medicine was requested to formulate radiation protection guidelines for space missions. They proposed that the primary reference risk should correspond to an added probability of radiation-induced neoplasia over a period of about 20 years equal to the natural probability for the specific population under consideration. For men 30-35 years of age beginning their careers as astronauts, and based on available data, the recommendation was that 4 Sv (400 rem) would be the doubling dose for cancer risk. Tissue-specific radiation exposure limits were recommended for bone marrow, skin and the eye.

In 1972 the Committee on the Biological Effects of Ionizing Radiation (BEIR I) Report and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) Reports were both issued. These reports have been updated: UNSCEAR in 1977, and BEIR III in 1980. In light of differences in risk estimates from these various reports, the U.S. National Aeronautical and Space Administration (NASA) in 1986 requested the National Council on Radiation Protection and Measurements (NCRP) to re-examine the question of radiation risk.

The publication of NCRP Report #98 (Guidance on Radiation Received in Space Activities) in 1989, unfortunately did not include important information published in another UNSCEAR Report just before it in 1988, and also did not have the advantage of having the BEIR V Report (NAS/NRC 1990) or the ICRP Report #60 (ICRP 1991) available. NASA therefore requested the NCRP to again re-examine the question of radiation risk in near-earth orbits, especially within Space Station. They were also asked to reassess the risk to both women and men of various ages exposed to radiation in light of the new risk estimates of excess cancer and other radiation effects. The revision of NCRP Report #98 is not available yet, however an independent NCRP Committee Report #115 (Risk Estimates for Radiation Protection) was issued in 1993 dealing with safety standards for the general radiation worker. This comprehensive report is the most recent document available that reviews conclusions from all previous evaluations.

Since 1977 some important additional epidemiological data have become available from populations exposed to radiation. There has been an increase in the mortality data for the atomic bomb survivors (ABS), in particular, for those that were young at the time of exposure, a new dosimetry system, (DS86), has been used resulting in doses that are lower than previously used. All these changes have contributed to the increase in the estimates of the risk. The data now suggests that the dose-response relationship for solid cancer is linear.

Currently the risk estimates that are the basis of the recommendations for dose limits, are based almost entirely on the data from the atomic bomb survivors. There are concerns that this population has a distinct distribution of naturally occurring cancers that is different from that in the populations of the Western World. The atomic bomb survivors were exposed to very high dose rate radiation and suffered the stress and nutritional deficiencies of wartime. The appropriateness of basing dose limits for astronauts who are exposed to protracted low dose-rate irradiation, on the data from atomic bomb survivors must be examined.

UNSCEAR 1988 and BEIR V NAS/NRC 1990

Two independent panels of experts wrote the UNSCEAR 1988 and BEIR V Report of 1990. Several differences exist in the analysis of radiation risk by these panels. Each took a different approach to calculate life tables. In the UNSCEAR analysis, the calculated number of cancer deaths attributable to radiation was made in a standard population, whereas BEIR V estimated the number of excess deaths excluding those who died of a radiation-induced cancer who would have died at a later time from a cancer of natural occurrence. The RBE for neutrons was assumed to be 1.0 by the UNSCEAR committee and 20.0 by the BEIR V NAS/NRC committee. It is somewhat surprising that despite these differences, the final lifetime cancer risks for acute whole-body exposure to low-LET radiation estimated by these two panels was rather similar: $7.1 \times 10^{-2} Sv^{-1}$ by UNSCEAR and $8.8 \times 10^{-2} Sv^{-1}$ by BEIR V. These estimates however reflect increased risk coefficients compared to previous analyses. Their analyses also indicated less influence of sex of the individual on risk estimates, and a linear dose response for certain solid cancers. There was no agreement on the influence of dose rate and protraction. A dose-rate reduction factor (DREF) for low dose-rates was not applied by either committee, but both committees indicated that a factor of between two and ten might be appropriate.

ICRP and NCRP Reports

Both the International Commission on Radiological Protection (ICRP) 1990 and the National Council on Radiation Protection and Measurements (NCRP) 1993 published similar estimates of the risk of radiation-induced stochastic effects. Both these organizations considered that a DREF of two was appropriate and should be applied. This resulted in a coefficient of detriment caused by stochastic effects of $5.6 \times 10^{-2} Sv^{-1}$ for a working population (20 to 64 years of age) of which $4.0 \times 10^{-2} Sv^{-1}$ was attributed to fatal cancers. These estimates are greater by about a factor of three than those previously used for radiation protection purposes. Despite all the uncertainties and the assumptions that must be made, there is reason for considering lower career dose limits for those involved in space activities. A large number of factors must be considered before career limits, that hopefully can be applied internationally, are selected.

The effect of basing the career limits on risk estimates that are twice those used previously is shown in Table 1.

Table I

Career whole-body equivalent dose limit (Sv) for a lifetime excess risk of fatal cancer of 3% as a function of age at exposure.

Age	25	35	45	55
Male	0.75	1.25	1.7	2.0
Female	0.5	0.9	1.25	1.5

These limits range from 0.5 to 2.0 Sv compared to 1.0 to 4Sv recommended by the NCRP in 1989.

This degree of reduction would entail careful design of both space vehicles and long duration missions in the future.

Gaps in our knowledge

The improvements in risk estimates that are required will entail research in basic physics, the development and validation of transport codes, and the biological effects of space radiation and analytical methods of risk estimation. The concern is that there are virtually no data from studies of humans for either deterministic effects, or the induction of cancer by heavy ions or protons, in particular, with protracted exposures. Predictions of detrimental effects have had to be made by extrapolation from animal studies which itself is not without problems. The questions that remain to be answered either in part or entirely include:

1) What is the LET dependence of chromosome aberrations?

2) What are the risks of tissue damage that may result in infertility and loss of function of other tissues, for example the bone marrow.

3) Does the characteristic deposition of energy along the particle track of heavy ions cause multicellular damage that is distinct from the damage included by low-LET radiation? In the case of the central nervous system, this could be vitally important.

4) Is the potential interaction between irradiation and microgravity of concern, as has been suggested in the case of the immune system?

5) Does the fact that on missions of long duration, the radiation will be protracted, and at a low dose rate, pose special problems in the prediction of the risks? We do not know enough of how time influences the effects of radiation, whether it be the influence of age at exposure or whether irradiation at low dose rates is less carcinogenic, or as some claim in the case of high-LET radiation, increases the risk?

6) How should the estimates of the risk of cancer resulting from exposure to space radiation, especially heavy ions, be derived from either studies on experimental animals or from data from humans exposed to low-LET radiation?

7) Since risk estimates of cancer induction in humans exposed to low-LET radiation have to be used, the question of how to project risk estimates over time and how to transfer risk estimates from one population remains.

Summary

Numerous sources of uncertainty exist in estimating the risk of radiation-induced cancer. Dosimetry involves a complex reconstruction of the characteristics of the exposure and location of the exposure with inherent systematic and random errors. There are deficiencies in the epidemiological studies that make the estimates of risk at low-doses and low dose rates uncertain. Over 50% of the atomic bomb survivors are still alive and therefore a risk projection model must be used to obtain lifetime risks for the total population. It is not known if the risk will remain in excess for the lifetime of those exposed at a young age or will decrease in later life. There is no consensus about the difference in the risks from exposures at a low dose rate and a high dose rate. Finally, there is uncertainty of how to transfer the risk estimates based on Japanese populations to other populations with different rates of naturally occurring cancers. There is a major need for international collaboration to address the issues involved in the recommendation of radiation dose limits for those from many countries that will be involved in space activities.

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