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The U.S. National Research Council's views of the radiation hazards in space

Richard B. Setlow *

Biology Department, Brookhaven National Laboratory, Box 5000, Upton, NY 11973-5000, USA

Abstract

The author was the Chairman of a Task Group on the Biological Effects of Space Radiation formed as a result of discussions between NASA and the U.S. National Research Council's Committee on Space Biology and Medicine — a committee under the U.S. National Research Council's Space Studies Board. The Task Group was asked to review current knowledge on the effects of long-term exposure to radiation in space and to consider NASA radiation shielding requirements for orbital and interplanetary spacecraft. The group was charged with assessing the adequacy of NASA planning for the protection of humans from radiation in space and with making recommendations regarding needed research and/or new shielding requirements. This manuscript is a summary of the findings and recommendations of the Task Group. Beyond the protection of the Earth's atmosphere and its magnetosphere, the exposure to ionizing radiations far exceeds that on Earth. Of all the risks astronauts may face, this one is probably the most straightforward to control — by providing adequate shielding. However, because shielding adds weight, cost and complexity to space vehicles, it is important for designers to have a good quantitative understanding of the true risk and its degree of uncertainty so as not to under- or overshield spacecrafts. The extrapolations from our knowledge of ionizing radiation effects of low linear energy transfer (LET) to the risks from high-atomic-number high-energy energetic (HZE) cosmic rays are very uncertain because the necessary experiments on the effects of such particles have not been carried out and the extrapolation from low-LET to very high-LET has great uncertainties. These uncertainties were enumerated by the Task Group, and the types of experiments needed to minimize the uncertainties were described. The report found that, because of the small amounts of available time for biological research at HZE accelerators, it would take more than a decade of effort to obtain the answers to a narrow set of key questions that would facilitate reduction in risks and identification of the types of shielding needed. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

The Space Studies Board (originally the Space Science Board) of the U.S. National Research Council provides external and independent scientific and programmatic guidance to NASA. It is an advisory, consultative, correlating, evaluating body but not an operating agency in the field of space science. The Board has responsibility for strategic planning and oversight in the basic subdisciplines of space research. One of its committees, the Committee on

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* Tel.: +1-516-344-3415; fax: +1-516-344-6398.
E-mail address: setlow@bnl.gov (R.B. Setlow)

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Space Biology and Medicine, had undertaken to carry out a comprehensive review of the status of research in the various fields of space life sciences and develop a science strategy which could guide NASA in its long-term research and mission planning. One of its objectives was to develop the foundation of knowledge and understanding that will make long-term manned space habitation and/or exploration feasible.

I joined the Committee on Space Biology and Medicine in the summer of 1995. In the spring of that year, I attended a NASA Workshop, held at Brookhaven National Laboratory, devoted to space radiation effects. The workshop was held at Brookhaven because the laboratory had, and still has, the only accelerator capable of providing high-atomic-number high-energy energetic (HZE) particles, such as iron nuclei at an energy of 1 GeV/nucleon, suitable for irradiating biological samples. I picked up lots of useful information and I was asked to make a presentation to the Committee on Space Biology and Medicine of what was known in the general area of the health effects of the radiation environment in deep space. The cosmic ray flux above the Earth's atmosphere consists of a range of particles from protons to iron nuclei (atomic number 26) with a broad energy distribution going as high as 10^6 MeV/nucleon. The maximum in these distributions is between 10^2 and 10^3 MeV/nucleon. It has been estimated [1] that on a 3-year mission to

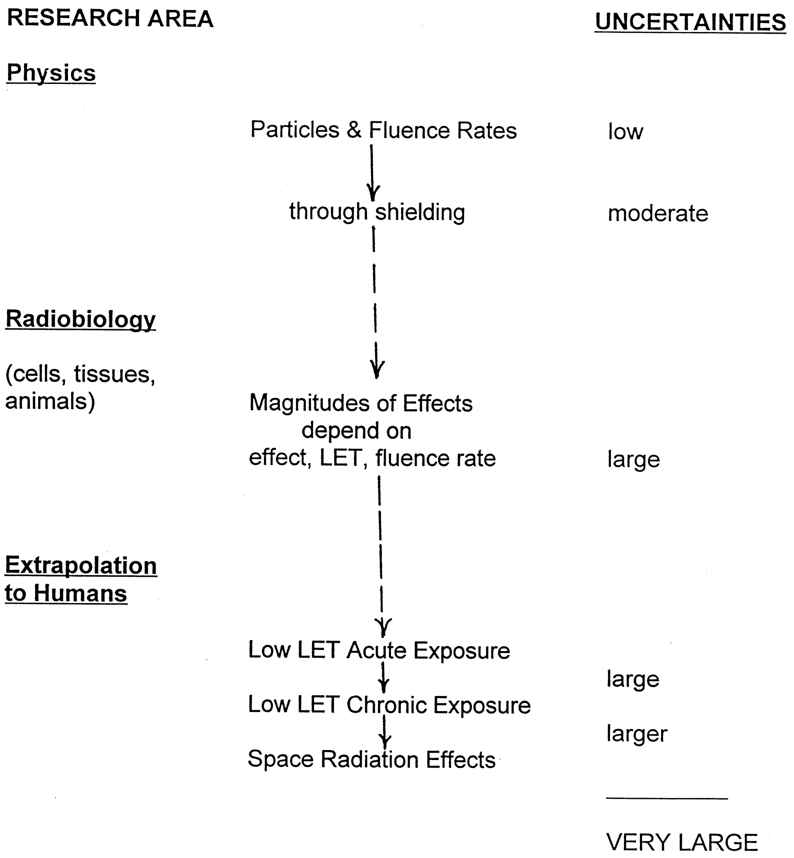

Fig. 1. The various scientific areas and the steps and extrapolations involved in estimating the effects of space radiation, especially HZE nuclei, on human health.

deep space, a mammalian cell nucleus of area 100 μm^2 behind aluminum shielding of 4 g/cm^2 would be traversed on the average by 400 protons, 0.6 carbon nuclei, and 0.03 ion nuclei. The latter number may seem small but it does represent 3% of cells in the body. Since the linear energy transfer (LET) of most of the energetic iron nuclei is in the neighborhood of 200 keV/μm and the energy of a primary ionization resulting from the passage of the iron nucleus through matter is somewhat less than 100 eV, 3% of the cell nuclei would have 2000 primary ionizations deposited in them during the 3-year flight. The probability of such a cell surviving unharmed is pretty small. Thus, from a cellular point of view, HZE particles could be devastating.

Shielding is necessary to protect humans on long outerspace exploration trips but the conventional type of shielding that we usually think about, lead or aluminum, is not appropriate. The dose behind a lead shielding actually increases even for densities up to 30 g/cm^3 and aluminum does not reduce the dose below 50% for the same mass per unit volume [2]. The reason for the apparent anomaly is that the impact between an HZE particle and a nucleus in shielding, especially a heavy nucleus, will give rise to spallation products of high energy that also have high-LET values. The best type of shielding would contain lots of hydrogen, since its nucleus will not produce spallation byproducts. Hence, the problem of shielding and the dose behind shielding is a difficult one as is the estimation of the biological effects of this complicated radiation field. My introductory summary of the state of knowledge is shown in Fig. 1. The extrapolations from various scientific fields to arrive at the effects on humans, and the uncertainties in estimates and extrapolations, are indicated. Thus, e.g., the particles and fluence rates in deep space are reasonably well-known, so that uncertainty is low. On the other hand, when HZE particles strike shielding, they cause extensive spallation of target nuclei and hence, the doses behind shielding are not well-known, so that these uncertainties are probably in the neighborhood of 20%. There are extensive data in the field of radiobiology but most of the data have been obtained on simple systems, such as the killing of cells in vitro or in vivo and the induction of chromosomal aberrations. Almost all these data indicate that the relative biological efficiency (RBE) increases with LET to a value in the neighborhood of 2–4 at LET values around 100–200 keV/μm. Above this value, the RBE decreases [3]. However, in the one investigation of the effects of HZE particles on tumor induction in experimental animals — the Harderian gland in mice — the RBE does not seem to decrease at high values of LET but remains at an approximate plateau with values of 20–40 [4] as indicated in Table 1. Hence, extrapolation to other tumor types exposed to high-LET radiation has a large uncertainty. The estimation of the effects of high-HZE particles on humans involves several extrapolations. Most of our risk estimates for cancer induction, e.g., come from studies of the

Table 1
Induction of Harderian gland tumors in mice by radiations of different LET's[a]

Radiation	Energy per nucleon (MeV)	LET (keV/μm)	Estimated dose (Gy) for 30% prevalence	RBE for 30% prevalence	RBE for initial slope[b]
^{60}Co γ-rays		0.23	3.0	1.00	1.00
^{1}H	250	0.4	1.6	1.9	–
^{4}He	226	1.6	2.0	1.5	2.3 ± 0.3
^{20}He	670	25	0.8	3.6	–
^{56}Fe	600	193	0.2	15	40 ± 11
^{56}Fe	350	253	0.3	10	20 ± 8
^{93}Nb	600	464	0.25	12	–

[a] This table is adapted from the data in [4].

[b] The initial slopes are Δprevalence/ΔGy ± SE. For missing values, the data were not sufficient to calculate an initial slope.

Japanese population exposed to atomic bombs [5]. These data represent the effects of a range of low-LET doses delivered in a minute instant of time, i.e., at a high dose rate. But space radiation is not a high dose rate phenomenon, but one in which doses are accumulated over months or years. Hence, one must extrapolate from acute exposures to chronic exposures over relatively long periods of time. This extrapolation is determined, to a large extent, from animal studies. Low dose rates are less efficacious in inducing biological effects than are acute exposures by a factor that ranges, depending upon the endpoint, from 2 to 10, although a nominal value of 2 is often used [5]. The final step is to extrapolate from low chronic LET exposures to high-LET chronic exposures. There are negligible data, but good guesses, for this extrapolation. Nevertheless, this extrapolation has larger uncertainties than the others. There are no very useful data. The net result is that estimates of the health effects of radiation on humans traveling through deep space have very large uncertainties, uncertainties estimated to be in the range of 4- to 15-fold [6].

It should be obvious from a glance at Fig. 1 that the major uncertainties are in the biological, not the physical, parameters. In a rational world — one that attempts to maximize the precision of predications for the level or resources committed — one would conclude that the resources should be proportional to the uncertainties. NASA's budget allocations do not follow this rule.

2. Formation of the task group

The Committee on Space Biology and Medicine felt that the need for additional data to minimize the present uncertainties in the biological effects of radiation in deep space, especially the HZE particles, would require the formation of a small Task Group to evaluate the state of knowledge and make recommendations for future research. The Task Group was made up of individuals knowledgeable about dosimetry and radiation effects on molecules, cells, tissues, animals, and humans. It received briefings and much useful information from Harry Holloway, Frank Sulzman, and Walter Schimmerling of NASA headquarters; John Wilson of NASA Langley Research Center; Amy Kronenberg of Lawrence Berkeley National Laboratory; and Gregory Nelson of the Jet Propulsion Laboratory. The Task Group included myself as Chair; John F. Dicello of Johns Hopkins University School of Medicine; R.J. Michael Fry of the Oak Ridge National Laboratory; John B. Little of Harvard University School of Public Health; R. Julian Preston of the Chemical Industry Institute of Toxicology; James B. Smathers of the University of California at Los Angeles; and Robert L. Ullrich of the University of Texas Medical Branch in Galveston. The Task Group was assisted most ably by staff of the Committee on Space Biology and Medicine including Sandra J. Graham, the Study Director who organized the task group and its meetings and kept the feet of the group to the fire so as to produce a report entitled, ''Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies'' published by the National Academy Press in 1996.

The report reviewed the state of knowledge of both deterministic and stochastic effects of radiation and made numerous recommendations so as to reduce the risk and the uncertainty in the risk estimates. It outlined priority research questions and the strategies that could be followed to answer them. A compact description of the report is included in the Executive Summary that gives the task group's conclusions, its recommendations for future experiments, and its estimates of the time needed to carry out these experiments.

3. Summary of the report

This summary is taken from the Executive Summary of ''Radiation Hazards to Crews of Interplanetary Missions,'' National Academy Press, 1996.

(1) The principal risks of suffering early effects as a result of exposure to radiation in space arise from solar particle events (SPEs). It is not too difficult a task to provide appropriate shielding or storm shelters to protect against exposure during SPEs, but surveillance methods to predict and detect SPEs from *both* sides of the sun relative to a spacecraft must be improved.

(2) The kinds of biological effects resulting from exposure to the ionizing radiation encountered in

deep space do not differ from those resulting from exposure to X-rays. However, the quantitative difference between the risks posed by X-rays (low-LET radiation) and by heavy high-energy nuclei (high-LET radiation) may be large, and the magnitude of the human biological effects is largely unknown. An understanding of these effects — including cancer induction, central nervous system (CNS) changes, cataract formation, heritable effects, and early effects on body organs and function — as well as of the shielding necessary to mitigate these effects for crew members, is essential for the rational design of space vehicles built for interplanetary missions.

(3) The Task Group members generally agreed that the potential late effects of radiation are the major concern in estimating risks to crew members. Of the known late effects, cancer is currently considered to be the most important. However, experimental data suggest that exposure to HZE particles may also pose a risk of damage to the CNS. Since it is estimated that during a 1-year interplanetary flight each 100-μm^2 cell nucleus will be traversed by a primary energetic particle of atomic number greater than 4 [1], further experimentation is essential to determine if CNS damage is a significant risk.

(4) To estimate the cancer risk posed by exposure of humans to radiation such as HZE particles, for which no human data are available, it is necessary to use data on the Japanese atomic bomb survivors exposed to acute low-LET radiation and then extrapolate, based on experimental data, to estimate the risks posed by high-LET radiation. At present, the only comparative data for cancer are for studies on the induction of Harderian gland tumors in mice. Additional research is required to reduce the uncertainties of the assumptions inherent in this approach. To calculate risks associated with exposure to low-fluence-rate HZE particles, it is assumed, based on cell and animal studies, that there is not a large dose-rate effect.

(5) Biophysical models and data for cell killing and mutagenesis indicate that as the LET increases, the biological effect of the radiation increases to a maximum near a LET of 100 keV/μm and then decreases at higher LET [3]. However, no such decrease was observed in one animal tumor for which data were obtained using a number of heavy ions with increasing LET [4]. This discrepancy creates uncertainties in estimates of risks associated with exposure to particles at these higher LETs. To resolve these uncertainties, additional systematic studies are needed on the induction in animals of other radiobiologically well-characterized cancers, such as leukemia and breast cancer. From a practical point of view, sufficiently accurate data can only be obtained from ground-based experiments using acute doses.

(6) The background frequencies of the heritable changes in humans, which might be increased by exposure to radiation, range from $\sim 10^{-5}$ to 3×10^{-3} per genetic locus [7]. The minimum chronic dose that would double these values is $\sim$ 4 Sv [8], a value greater than that given in NASA's current lifetime exposure guidelines. Hence, the genetic risk — the absolute increase in the frequencies of heritable changes — to an astronaut will be low. The risk to the gene pool of the overall human population will of course be far lower due to the relatively small number of space-faring humans.

(7) The doses of radiation to which crews are exposed in space are not expected to induce early deterministic effects, with the possible exception of skin damage and a temporary reduction of fertility. Skin damage is likely only following exposure at high doses outside the spacecraft. Experimental studies in dogs indicate that any reduction in fertility per unit dose of radiation may be greater for low-dose-rate, protracted exposure than for acute exposure [9].

(8) The space vehicles used for missions of short duration in low Earth orbit have required minimal optimization of radiation shielding for crew protection purposes. In contrast, optimization of shielding for prolonged interplanetary trips will be a major factor in the design and cost of space vehicles. It will be necessary to know, for protons and HZE particles, the basic nuclear cross-sections for interactions and fragmentation in shielding. Such data will be used to calculate the particle distributions and energies present behind different types of shielding as a result of the incident radiation passing through the shield material. Such transport calculations must be verified by ground-based experiments.

(9) A knowledge of the particle types and energies present behind types of shielding should be used, with appropriate risk models, to calculate biological effects — cell killing, mutations, chromosomal changes, and tumor induction — in animals

exposed to radiation. NASA investigators should also obtain parallel experimental data for the same radiation types and energies and compare these to the results calculated with models. This research is best accomplished at ground-based facilities.

(10) Microgravity has little effect on the responses of simple cellular systems to radiation [10], and uncertainties about the effects of microgravity seem negligible compared with the other uncertainties regarding risk (see 11 below). Doing cell biology and cancer induction experiments in space is costly and difficult and would require that a source of radiation be carried in the spacecraft. Because only a limited number of animals could be investigated, the results would not be statistically significant. Hence, for the study of living systems, radiation experiments in space should have a very low priority compared with ground-based research.

(11) The estimated overall uncertainty in the risks of radiation-induced biological effects ranges from a factor of 4- to 15-fold greater to a factor of 4- to 15-fold smaller than our present estimates because of uncertainties both in the way HZE particles and their spallation products penetrate shielding (particle transport) and in the quantitative way in which these types of radiation affect biological functions [6]. In the absence of precise data and calculations, the shielding would have to protect crew members against the higher, but uncertain, estimated risk. The cost of this possibly unnecessary shielding has been estimated by NASA researchers to be in the range of US$10 billion to US$30 billion [11]. In comparison, the cost of a ground-based, dedicated HZE particle research accelerator was estimated in 1996 to be US$18.7 million, with an annual operating cost of about US$4 million for 2000 operating hours per year [12,13]. The disparity between the excess cost of additional shielding and the annual NASA budget for biology and space radiation physics indicates the need for a significant increase in the research budget for these areas.

(12) Major radiation facilities — including both specialized radiation sources and animal colonies — have been shut down in recent years. At present, there are severe limits on the availability of radiation particle types and particle energies for HZE particle research. NASA can no longer rely on the Department of Energy and the Department of Defense for expertise, research, and facilities. If the necessary facilities, expertise, and funding were available now, it would take approximately 10 years to provide data that NASA needs to assess the best way to provide appropriate safeguards for its spaceflight crews.

(13) Unless NASA obtains access to a reliable source of HZE particles with an appropriate support staff for a significant fraction of each year, it will take well over 10 years, perhaps over 20 years, depending on the level of effort, to reduce the present large uncertainties in particle transport behavior and in the biological response functions for cancer induction. Such a delay will postpone the design of necessary shielding or may result in the use of excess shielding (at a higher cost) and possibly delay any planned Mars mission beyond the next quarter century.

(14) In Chapter 4, the task group outlines its recommendations for research priorities that NASA should follow to obtain the information needed to evaluate the biological risks faced by humans exposed to radiation in space and to mitigate such risks. The research priorities recommended by the task group include extensive physical and biological experiments, including animal studies using light and heavy nuclei up to 1 GeV/nucleon. Such experiments could take more than 20 years at NASA's present utilization rate of approximately 100 h/year of accelerator time at Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS), the only source for HZE particles supported by NASA.

(15) To carry out needed research expeditiously, NASA should explore a number of possibilities, including international collaborations, so as to increase the research time available for experiments with HZE particles and protons at energies over 250 MeV. Such possibilities include a combination of more running time at the AGS and at lower-energy accelerators, expansion of existing facilities, the commissioning of new beam lines at existing facilities, and the construction of a new facility. A 1992 National Research Council letter report, to the Secretary of Energy and the Administrator of NASA, emphasized the need for a dedicated HZE particle facility.

The fact that the present report reaches conclusions similar to those in the 1989 report of the National Council of Radiation Protection [3] underscores the need for additional resources and facilities in order to understand quantitatively the radiation biology associated with interplanetary flights.

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