BIOLOGICAL EFFECTS OF SPACE RADIATION

G. Reitz
DLR, Institut für Luft- und Raumfahrtmedizin, Abteilung Strahlenbiologie, D-51140 Köln

1. SUMMARY

The radiation exposure in space missions can be reduced by appropriate measures, but it cannot be prevented. The reason is that space radiations due to their high energy deeply penetrates in matter. In comparison to the shielding thickness of the atmosphere of approximately 10 meter water equivalent, a spacecraft provides only 1-30 cm shielding depending on the equipment installed inside the spacecraft. Much more shielding cannot be provided due to mass constraints. A small shelter may be constructed, but the shielding thickness is still far away from that what the atmosphere provides. In the orbit of the International Space Station (ISS) the radiation exposure due to galactic cosmic radiation and the radiation belts results for long term missions in an considerable access risk for cancer mortality. In extravehicular activities (EVAs) due to solar particle events exposures may occur resulting in acute radiation effects. Since risks from this exposures cannot be eliminated, they are treated as occupational hazard. Highest possible accuracy on information is therefore essential concerning the radiation environment and their biological effects for the evaluation of the radiobiological risk.

2. INTRODUCTION

Radiation is an acknowledged primary concern for manned spaceflight and is a potentially limiting factor for interplanetary missions. Results from numerous space probes demonstrate heightened radiation levels compared to the earth's surface and a change in the nature of the radiation field - particularly the presence of high energy heavy ions. To date the waste majority of crewmembers having exposures in flights with a duration of less than two weeks. Only a few Russian cosmonauts have been exposed for one year, but still at levels for which the excess risk of fatal cancer, is lower than the recommended risk limit for US spaceflight activities, namely 3 percent for the career. However, very little is really known concerning the biological effects of human low level radiation exposure in space. Studies using lower life forms demonstrate a synergistic interaction between microgravity and radiation. More experiments are needed to confirm these findings, as are measures to counteract potentially harmful medical effects. Plans to extend man's activities to visits of nearby planets and to spend significant periods of time on the lunar surface demand a reassessment of presently available databases and the potential for adverse medical outcomes.

Some exposure levels are given together with the mean annual exposure for a normal individual and the exposure limits for radiation workers and astronauts in table 1. Doses encountered in space may a factor of 100 or more higher than on earth. For deterministic effects the eye is the most sensitive target, repeated long duration stays may lead to detectable opacities and cataracts, next sensitive are the testes with temporal sterility and the bone marrow with depression of hematopoesis as effect. The mean excess cancer mortality risk per mSv exposure accounts to 0.005 %, for a one year stay on MIR station this is equal an excess risk of about 1%. In comparison, the cumulative

Values	mSv
Mean annual effective dose from Natural sources to the public	2.4
Mean annual effective dose by Medical treatments	1.5
Mean annual dose equivalent on MIR station during solar minimum	216
BFO dose equivalent of August1972 solar flare behind 1 g cm^{-2} Al shielding	480
BFO dose equivalent of Februar 1956 solar flare behind 20 g cm^{-2} Al shielding	60
Annual effective dose limit for occupational exposure on earth Maximum effective dose in 5 years	50 100
30 day BFO dose equivalent limit and annual BFO dose equivalent limit for space activities	250 500

Table 1. Radiation exposures and U.S. exposure limits. (BFO is blood forming organs).

cancer mortality rate in Germany is 20.5 ± 0.2 %. Such predictions of radiation risks has some short comings, as example they base on gamma-radiation observations at high doses, do assume additivity of effects of different radiations and do not include environmental effects on the expression of radiation effects.

Although galactic cosmic heavy ions contribute to less than 1% of the total absorbed dose of cosmic radiation, their biological importance cannot be

neglected ‘Grahn (1973)’. They induce extremely high ionisation densities in highly localised cylindrical volumes around their trajectory through matter and are capable to damage a number of contiguous cells located along their track. Since the nonuniformity of energy distribution in this case is so great that a group of cells is heavily affected while the rest is untouched, the concept of mean dose to a critical tissue as used in radiation protection issues on earth loses its conceptional base. The assessment of the potential significance of heavy ions therefore calls for a new approach.

Regarding the important question of a modification of the radiation response by spaceflight parameters, especially microgravity, no conclusive results exist so far. Some findings indicate synergistic effects, others show no influence at all. The results requires further elaboration and additional experiments until answers can be given with some confidence.

3. RADIOBIOLOGICAL EFFECTS

3.1 Space findings

No space findings exist on the biological effects of other radiations than heavy ions, since dose rates are lower by orders of magnitudes compared to typical dose rates used in terrestrial experiments. The first effects of heavy ions were detected with mice in high altitude balloon flight in the 1950ies. The biological effects observed - grey spots and streaks in the fur - were ascribed to the passage of single cosmic heavy ions, and the lateral extension of these streaks were much larger than any physical explanation in terms of ionisation pattern around the particles` trajectories might provide for. In subsequent experiments these studies were extended to histological examinations in brains of mammals exposed to cosmic heavy ions in high altitude balloon flights. Again the large lateral extension of track-like regions found in these brain sections stimulated speculations about the biophysical mechanisms responsible for this "long range" effect. However, apart from potential artefacts from the preparative techniques these findings were affected - as well as the earlier ones - by the lack of a firm geometrical correlation between the observed biological effects and independent information on the trajectories of the presumably causative single heavy ions, although physical track detectors had been employed for this purpose in most of these experiments. This crucial methodological prerequisite was fully accomplished in the subsequent Biostack space flight experiments, where a variety of biological test organisms in resting state could be attached in monolayers to the surfaces of thin sheets of visual nuclear track detectors in such a way that a permanent and precise correlation between the positions of individual test organisms and the trajectories of single heavy ions could be recorded. Evaluation of the effects observed in bacterial spores, in plant seeds, and animal embryos demonstrated that single heavy ions induce in all these test organisms, although with varying efficiency, significant biological perturbations comprising gross somatic mutations, severe morphological anomalies, and complete inactivation of development ‘Bücker (1974), Horneck (1988a), Reitz (1995)’. Biophysical analysis of some of these results again yielded the conclusion that the magnitude of these effects could not be explained in terms of accepted mechanisms, and, in particular, that the lateral extension of effectiveness around the trajectories of single particles exceeds the range, where secondary electrons could be considered to be effective. Investigations on yeast cells in Russian space flight experiments, which were set up similarly as the Biostack experiments, produced also in these organism effects of an inexplicably large lateral extension around the trajectories of single heavy ions.

In order to get a magnitude of the biological effect of a single heavy ion, one can calculate the ratio of effects from hit to non-hit biological objects. The ratio is shown in Figure 2. A ratio of one indicates that a hit sample has no higher probability of showing the effect than a non-hit sample. Most of the

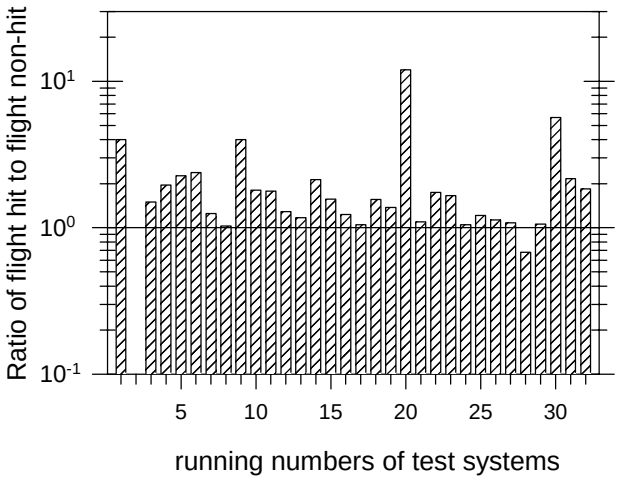

Figure 2. Relative effects of hit and non-hit objects flown on the Biostack experiments. Major effects are: loss of germination of Bac. subtilis spores (no. 1), lethal mutations in Arabidopsis thaliana seeds (no. 9), larval anomaly in Artemia salina cysts (no. 20), and malformations of Carausius morosus insects hatched from exposed eggs (no. 30).

biological systems used show a higher ratio than one. The findings in space flight experiments as well as those from recent terrestrial investigations reveals one common denominator: The radiobiological mechanisms of heavy ions (high linear energy transfer (LET) radiation) are qualitatively different from those of low LET radiation like X-rays, photons and electrons under virtually every aspect.

3.2 Terrestrial findings

3.2.1 Biological effects of heavy ions

The findings to be discussed are (1) the effects of accelerated heavy ions on cells and tissues, (2) the observation of microlesions engendered in various tissues by irradiation with a single heavy ion, (3) the non-additive effect on tissue cultures of sequential irradiation with heavy ions and sparsely ionising radiation, (4) the different kinetics of expression of late effects in mammals, and (5) the reversed dose rate effect observed in the life shortening of mice and the induction of neoplastic transformations in tissue cultures by high LET radiation in the context of other endpoints and systems.

Extensive ground control work with spores of Bacillus subtilis corroborated the Biostack findings in two independent ways. On the one hand, analysis of the effects of single accelerated heavy ions on single cells reproduced the essential features of the spaceflight results. On the other hand, the conventional analysis of the inactivation cross-section corroborated the conclusions of the spaceflight results that current quantitative models of radiobiological heavy ion effects do not reproduce the observed cross-sections. As far as the "long range" effect is concerned also results of accelerator experiments with this organism and with yeast cells were indicative in its operation.

One of the most spectacular finding so far in terms of radiobiological heavy ion effects, namely the microlesions produced by single heavy ions, were, once again, discovered first via space flight experiments as channel-like or tunnel lesions in the retina of rats. In subsequent accelerator experiments these microlesions have been shown to be caused by the passage of single heavy ions through various biological tissues. Although the quantitative interpretation of these results in terms of physical "quality" parameters remains somewhat controversial, these observations unequivocally represent unique radiobiological responses to the penetration of single heavy ions.

One of the implicit assumptions of those assessing space radiation environment hazards has been the independence or additively of the effects of sparsely and densely ionising components. However, when this basic postulate was subjected to experimental testing, it was found to be incorrect. Pre-irradiation with either X-rays or heavy ions rendered V79 cells more sensitive to subsequent irradiation with the other radiation modality, with X-ray pre-irradiation resulting in greater synergism than vice versa. Results displaying this nonadditivity in cultures of the same mammalian cell line irradiated with such light ions as deuterons or helium ions were also described and even for simultaneous irradiation with fast neutrons and gamma rays.

In the experiments reviewed so far the radiobiological endpoints under investigation can vaguely be classified as early effects. The increasing importance of radiobiological late effects adds additional weight to recent experimental findings concerning late effects of densely ionising radiation. In a series of heavy ion experiments the temporal distribution of the incidence of late effects in various rabbit tissues was investigated and compared with corresponding findings for sparsely ionising radiation. Apart from the reduced amount of recovery, an acceleration of the development of late effects together with an increased severity of these effects was observed in the heavy ion experiments as compared to the X-ray results.

In the already mentioned investigations on the additively and the kinetics of damage expression the observation was reported that fractionation of the high LET irradiation did not result in the reduction of the radiobiological effects, as in the case of protraction of X-ray and other low LET radiation exposures - with the telling exception of a particular class of biological endpoints to be discussed below. To the contrary, fractionation of heavy ion exposures resulted in an enhancement of the radiobiological early and late effects.

3.3 Radiation effects on man

The primary database pertains in the overwhelming majority of cases exposures to photons and electrons under terrestrial exposure conditions only. As far as radiation protection of man is concerned, the subcellular and cellular radiation effects mentioned above are relevant only insofar as they finally give rise to deterioration of tissue or organ functions with the expression of clinically observable symptoms. Symptoms becoming manifest from within minutes to 30 to 60 days subsequent to exposure are classified as early effects. Radiation effects not occurring within this period generally do not become manifest for many months or even years of a latent period and these effects are then classified as late or delayed effects. Among late effects those, which do not become manifest in the

irradiated individual but in its progeny, are classified as genetic or more properly as hereditary effect and they arise if radiation damage either directly or indirectly affected the cells of the germline. Non genetic effects are the result of radiation damage to the soma and hence are called somatic effects.

Radiation effects in complex organisms are further divided into stochastic and deterministic radiation effects. For deterministic radiation effects the magnitude or severity of effect depends on dose with a possible lower threshold dose below which no response at all will be produced for stochastic radiation effects, instead, no threshold dose exists and here the probability for the manifestation of a radiation effect rather than its magnitude becomes a function of dose.

To the extent that universal findings can be obtained for the relations observed in animal systems between dose-modifying factors, such as radiation quality or dose-rate, and cell killing or transformation, these findings might tentatively be drawn upon to supply the information lacking for human response data, which are available only for radiation qualities and exposure conditions vastly different from those prevailing in the space radiation field.

The most important source of human exposures for the dose-effect relations for stochastic radiation effects, i.e. radiation induced cancer, is the Japanese atomic bomb survivors. But even this source suffers from severe restrictions concerning either the dosimetry and/or the medical or epidemiological methodology.

For early (acute) radiation effects part of the same data base as used for stochastic effects and, in addition, findings from therapeutic exposure in cancer therapy and from accident victims in the nuclear industry constitute the respective data base.

The primary and secondary sources of human exposures are reviewed and updated by national and international committees as well as ad hoc study groups constantly. The UNSCEAR reports are most widely recognized as the most through and balanced summaries of the field 'UNSCEAR (1993)'.

3.3.1 Early effects

Manifestations of early effects in man usually appear to be threshold phenonomena and occur only after acute exposures to comparatively high doses, which under terrestrial standards would have been ruled out as impermissible under regular circumstances. In the still pioneering era of manned spaceflight, however, the hazards of exposure to space radiation had to be evaluated in the context of the high competing risks of those missions. Appraisal of these hazards therefore focussed on the possibilities that radiation effects might impair performance of crew members and thereby might result in failure of the mission. Thus early radiation effects assumed prime importance. Although radiation protection standards for the space station era will primarily be based on late radiation responses as the limiting effect, inclusion of early effects is still warranted by the non negligible probability for high exposures during emergency situations such as failure in orbit control or large solar particle events especially on polar orbits or during extravehicular activities, which at least during the construction phase of a space station conceivably will form a substantial part of the work schedule.

Apart from early mortality that is rarely to be expected at instantaneous exposures below 2 Sv, early forms of radiation sickness, which occur already at lower doses and might impair the functional performance of space personnel have to be considered as relevant effects. The threshold, below which no symptoms of the prodromal symdrom - the most sensitive symptom complex - such as anorexia, nausea, fatigue, vomiting and diarrhea should occur is about 200 mSv if the model of the NUREG report 'Evans et al. (1985)' is taken with parameter values for instantaneous exposure. The risk drops below 5% around that dose value. Another report, the PSR report ' Anno et al. (1985)' uses a higher threshold of 500 mSv (free-in-air!), below which no early radiation related symptoms should be observable.

3.3.2 Delayed or late effects

Radiation protection standards for a permanently manned space station in near Earth orbits refer to late radiation effects rather than to early effects as the limiting risk from exposure to space radiation. Future crew populations will be larger in size, will comprise both males and females of substantially younger age than in earlier missions , and will spend a larger fraction of their occupational life time in the space environment. Thus life shortening as the most severe consequence of exposure to ionizing radiation will be the primary reference risk for which acceptable risk levels and therefrom exposure limits are to be determined.

3.3.2.1 Stochastic effects

Life shortening, the primary reference risk, is presently considered to be mainly due to either the induction or the acceleration of appearance of neoplastic diseases. Hence the dose-response relationship for cancerogenesis is the basic empirical datum from which exposure limits are to be derived. The human data base, again, consist mainly of observations on the atomic bomb victims. Less specific data on general life shortening exist for

the shortened life expectancy of American radiologists prior to 1950 while data on the induction of leukemia can be supplemented by observations on patients irradiated for ankylosing spondylitis.

Detailed information on the estimates of probability for fatal cancers and expected years of life lost from fatal cancer is described in 'ICRP (1991)' . The fatal probability coefficients for different organs per Sv are given in Table2.

Organ	Fatal Probability coefficient (10^{-4} Sv^{-1})
Bladder	30
Bone marrow	50
Bone surface	5
Breast	20
Colon	85
Liver	15
Lung	85
Oesophagus	30
Ovary	10
Skin	2
Stomach	110
Thyroid	8
Remainder	50
Total	500

Table 2. Lifetime mortality in a population of all ages from specific cancer after exposure to low doses

Genetic manifestations will never place a limit on radiation exposure as far as population dose is concerned, due to the vanishing contribution of the space crew population to the gene pool of the general population. However, on an individual basis the gonads have to be considered as an additional critical organ.

For genetic effects, the human data base consists practically entirely of the experience from the atomic bombings of Hiroshima and Nagasaki. To date these studies do not demonstrate a statistically significant increase in the incidence of genetic defects in the survivors`children. Risk estimates therefore are based in the main on extrapolations from animal studies .

3.3.2.2 Deterministic late effects

Secondary or ancillary reference risks relating to distinct organs are "late" cateractogenesis in the ocular lens and permanent or late skin effects.

The thresholds for deterministic effects in man are given in Table 3. Temporary sterility appears to be around 0.15 Sv of low-LET radiation and about 0.4 Sv if exposure is fractionated. In case of higly fractionated exposures cataract formation is the most important deterministic effect. The latent period varies from about 0.5 to 35 years with an average of about 2 to 3 years.

Dose response relationships for late skin effects, other than cancer, such as late loss of reproductive capacity of fibroblasts are not available.

Tissues and effects	Treshold	
	Total dose equivalent received in a single brief exposure (Sv)	Annual dose equivalent rate if received yearly in highly fractionated or protracted exposures for many years (Sv y^{-1})
Testes		
Temporary sterility	0.15	0.4
Permanent sterility	3.5 – 6	2.0
Ovaries		
Sterility	2.5 – 6	> 0.2
Lens		
Detectable opacities	0.5 – 2.0	> 0.1
Visual impairment (cataract)	5.0	> 0.15
Bone marrow		
Depression of hematopoeisis	0.5	> 0.4

Table 3. Estimates of the thresholds for deterministic effects in the adult human testes, ovaries, lens and bone marrow.

4. INTERACTION OF SPACEFLIGHT ENVIRONMENT AND RADIATION

During spaceflight man is exposed to several stressors: (1) flight dynamic factors, such as, above all microgravity, acceleration and vibration, (2) work environment factors, such as hypoxia, hyperoxia, hypo- and hyperthermia and noise, (3) internal body factors, such as exercises, trauma, infection, altered biorhythms and psychological and (4) cosmic radiation. The interrelationship between the pathologies of radiation syndrome and the influence of external and internal factors, so far, is merely understood at the level of two factor combinations. Up to now, only a few data on the interaction of the first three factors with radiation for humans are available. Most of the investigations are done using cellular systems, plant seeds and animal systems, like insect eggs, larvae pupae and adults as well as rat and mice and dogs. Irradiation was performed with gamma sources before or after spaceflight or with an onboard source. The combination of microgravity and radiation yields, mostly an additive interaction by use of pre- or postflight irradiation, whereas in experiments with onboard irradiation synergistic effects (greater than the sum of the effects of each factor) dominate 'Horneck (1988b)'.

Regarding the important question of a modification of the radiation response to heavy ions by microgravity, one important result has been obtained by the use of the Biostack concept in combination with the 1-g centrifuge of BIORACK. For the investigation eggs of the stick insect *Carausius morosus* were exposed in the D1 mission and allowed to continue their development during spaceflight. After retrieval, hatching rates, growth kinetics and anomaly frequency were determinated. A synergistic action of heavy ions and microgravity was established in the unexpectedly high frequency of anomal larvae. Neither cosmic radiation nor microgravity alone produced an effect of similar extent nor was this extremely high anomaly rate reached by adding up the effects of the two parameters. Although suggestive, this result requires further elaboration and additional experiments until answers can be given with some confidence.

The combined influence of different spaceflight factors is one of the key problems in space medicine; it is of particular interest to understand the mechanisms underlying the interaction of radiation and microgravity. Along the radiobiological chain of events , every step is affected by internal and external modifiers, thereby influencing the final radiation response. Concerning the observed synergistic effects of microgravity and radiation, microgravity may exert its influence: (1)at the molecular level, e.g. by changing diffusion controlled processes, (2) at the cellular level, e.g. by modifying repair processes or by changing the metabolic/physiological state and/or (3) at the tissue and organ level, e.g. by modifying self-assembly intercellular communication, cell migration, pattern formation, or differentiation.

It is unlikely that microgravity interferes with the number of primary molecular radiation lesions. Cellular enzymatic processes, such as DNA repair, are more likely to be gravity-dependent. This hypothesis was tested during the IML1 mission with X-ray preirradiated yeast cells. The results suggest that DNA double strand repair is inhibited or al least delayed under microgravity. A replication of this experiment on the SMM-03 mission could not confirm the previous result. Again no effect of microgravity could be observed in an third yeast experiment using an on board radiation source. The effectiveness and kinetics of DNA repair in preirradiated bacteria (*E. coli*, *B. subtilis* and *D. radiodurans*) and human fibroblasts remains unchanged under microgravity.

4. RADIATION PROTECTION LIMITS

The first radiation guidelines for US manned spaceflight were recommended by the 'Space Science Board's Committee on Space Medicine (1970)'. The panel considered it reasonable to recommend limits based on doubling the natural risk of cancer over a period of 20 years which resulted in a 2.3% lifetime excess risk. This resulted in a career limit of 4 Sv; as annual limit 750 mSv was recommended. Due to new radiobiological data a reappraisal of the guidelines became necessary. NCRP set up its Scientific Committee 75 which produced the NCRP Report 98 "Guidance on Radiation Received in Space", which was issued in 1989 'NCRP (1989)'. Based on risk estimates derived from the National Institute of Health (NIH) ad hoc working group (the committee compares the risks of fatal cancers with fatality data from accidents in various occupations) 'Rall et al. (1985)' . Although spaceflight is considered by most experts as a risky occupation, the committee found a lifetime excess risk for fatal cancer due to radiation exposure of 3% reasonable, taken into account that space crews have besides radiation risk other serious risks. This risk of 3% is comparable with the risk in less safe, but ordinary industries, such as agriculture and construction, and it is lower than for the more highly exposed radiation worker on the ground, corresponding to a lifetime risk of 5%. Finally, NCRP recommends based on a 10-year career, age and sex dependant limits which are given in Table 4a, the limits

for protection against deterministic effects are given in Table 4b.

Still, as a larger segment of the population asked to participate, this 3% level may found to be unacceptable and means for its lowering instituted. A more acceptable fatality risk level may be that of 1% working lifetime which occurs with automobile travel in the US and radiation workers generally. The radiation protection limits are currently under revision by the Scientific Committee 75.

Age at Exposure	Effective Dose - Sv	
	Female	Male
25	1.0	1.5
35	1.75	2.5
45	2.5	3.2
55	3.0	4.0

Table 4a. Recommended career dose equivalent limits(based on three percent excess lifetime risk)

	Bone marrow	Eye	Skin
Carreer	See Table 4b	4.0	6.0
Annual	0.50	2.0	3.0
30 days	0.25	1.0	1.5

Table 4b:Recommended dose equivalent limit in Sv for all organs

6. FUTURE RESEARCH NEEDED

Current practices from radiation protection are empirical and based on extrapolating potential for harm from experiences during ground-based exposures. These have proved useful to date, but have provided little information for predicting adverse effects due to unique particles encountered when weightless (heavy ions, high-energy protons, neutrons). The permanently manned international space station and interplanetary travel within the next century is forcing a reassessment of the many gaps present. Resolution will require definition of the biological effects for space encountered protons and neutrons, as well as the potentially specific effects of heavy ions. Specific information on the biologic effects of heavy ions carries the highest priority especially the resolution of the dangers from produced microlesions in various types of body cells.

For the radiobiologist the next several decades provides the challenge of resolving radiobiological effectivity for space-based radiation, with particular emphasis on long-term or late effects (predominately carcinogenesis). Resultant data will be critical in defining the relevance of Earth-based models and determining whether presently recommended exposure limits can be broadened or restrained. Involved is a careful assessment of potential interactions between radiation and weightlessness.

In the Biostack experiments it was demonstrated first and corroborated on further spaceflight experiments with lower organisms in resting state, that single heavy ions of the cosmic radiation produces significant biological damage at absorbed doses which are in the conventional sense are totally negligible. Since the effects are poorly understood, further investigations on individuell cells have to be done. A significant improvement of theoretical models has to be achieved, as well as a empirical data base has to be obtained to evaluate the radiobiological consequences of heavy ions. Suitable techniques have already been developed and applied successfully. More studies including animal, tissue and cell cultures with well-defined biological end points, such as cell kinetics, cell inactivation, cell transformation, cell regulation and effects on cell regulation are needed to provide dose and particle flux/response information for each kind of radiation. Endpoints of primary interest are effects of partial whole body irradiation, such as life span studies, carciogenesis, cataracts, teratogenesis, effects on central nervous system, and eye morphological and functional effects and microlesions. Not all this investigations can be tackled in space, most of them are difficult to handle even in ground-based laboratories. A careful balance between ground and space studies shall be achieved, where the latter should concentrate on specific endpoints. Predictions from ground based studies need to be verified by appropriate space experiments, especially effects of spaceflight factors has to be taken into account.

Dosimetry will be critical and needs to be continued and expanded to provide real time measurements of exposure, as well as absolute levels and information about the physical characteristics of the radiation, energy and charge spectra and the particle's fluence. Radiation monitoring devices like tissue-equivalent proportional counters (TEPCs), particle and LET spectrometer and passive environmental and personal devices are needed to obtain these data. In the end these activities will lead to improved methods of shielding, assurance as to whether a great segment of the population can participate, and ability to handle radiation based emergencies, should they occur.

Although considerable dosimetric data has been accumulated from several spaceflight experiments, it is not yet possible to provide a quantitative description of the radiation field, especially at the

edge of the radiation belt, because of its highly complex composition regarding the particles present and their energy spectra. It was shown that current models of the radiation belts need revision. Accurate models are necessary to improve predictions for long term missions. This is of special importance for planning EVAs which are much more frequent as ever before in the construction phase of the space station.

For extended and interplanetary mission prediction of the radiation risk is an important prerequisite. This calls for an improved forecast of the changes in the radiation environment due to solar particle events.

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