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Space radiation research in the new millenium – from where we come and where we go

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Abstract

Space radiation research had a significant impact in the past. The physical interaction of heavy charged particles with living matter and the development of models, including microdosimetry, were stimulated by problems encountered in space. New phenomena were discovered. Advanced dosimetric techniques had to be developed and computational methods to describe the radiation field in space. The understanding of the radiobiology of heavy ions, necessary for a well-founded risk assessment and prompted by space radiation research, constitutes also the basis for heavy ion radiotherapy. So far unknown areas like the interaction of microgravity and radiation were opened. The space station will give even more opportunities. For the first time it will be possible to investigate animals for a longer time under the influence of both microgravity and radiation. Living systems can be exposed under well defined conditions with parallel physical measurements. Solar particle events are still an unsolved problem. Significant improvement in their predictability and quantitative description can be expected. All this will not only give exciting opportunities for research but will also translate into immediate benefit for human beings. This paper will attempt to give an overview of the past achievements and glance into the future.

KEYWORDS: Radiation protection, LET, particles, space station.

1. Introduction

Space radiation research began around 1910 when the Austrian physicist Victor Franz Hess (1883-1964) launched a balloon with detectors to study the decrease of terrestrial radiation with altitude. Contrary to expectation he found an increase which he interpreted correctly as radiation coming from space: His work was awarded the Nobel prize in 1936. With the advent of space travel cosmic and solar radiation became a more important issue but some time elapsed before it was identified as a mayor hazard to astronauts. This problem is now at the centre of interest, and it has grown to a new dimension because of plans for human exploration of Mars involving more than a year of travel in outer space. Thus space radiation research concentrates on the question how to assess the risk to humans. The problem is manifold, its solution requires the co-operation of many disciplines, physics, basic radiation and cell biology as well as epidemiology, to name just a few. The actual needs have been summarised by R.B. Setlow [1] and W. Schimmerling [2].

The system of radiation protection on Earth is rather far advanced and based on solid scientific evidence of epidemiological investigations as recently summarised in the 2000 UNSCEAR report [3]. The main source is still the follow-up of the survivors in Hiroshima and Nagasaki who were, however, acutely exposed to essentially low-LET radiation. The situation in space is different: the initial field is mainly composed of particles and the fluence rates are comparatively small. How to extrapolate from one environment to the other is still not known in spite of considerable work which has been done. It is historically interesting that at the same time when the interest in space radiation started also the development of powerful accelerators made the study of particle effects on biological systems possible. The centre of this new discipline was undoubtedly the Lawrence Berkeley Laboratory, an overview was given by one of the leading pioneers, Cornelius Tobias (1917-2000) [4]. It is more than just a coincidence that at the same time the potential of accelerated heavier particles for tumour radiotherapy was realised, a connection which persists until today and flourishes.

Table I – The current problems of space radiation research (after Setlow [1]).

Discipline	Problem
Physics	Particle fields behind shielding Solar events
Basic biology	Influence of LET, fluence and fluence rate
Human biology	How to extrapolate from low LET acute exposure to space radiation effects

It may sound paradoxical but most of space radiation research has to be performed on Earth. It requires sophisticated techniques, both physical and biological, to understand the underlying phenomena which are not available on satellites or the space station. Also astronauts whose time is very limited cannot be trained to be experts in all fields. This means that space experiments shall be restricted to very special objectives which are to be defined after extensive groundwork. This has not always been realised by grant-giving agencies who supported only space experiments without giving at least equal weight to ground laboratory work. This unfortunate situation lead quite often to ill-defined space investigations and to a loss of credit in the scientific community. Fortunately this seems to have changed now, and the times have gone that just sending a biological specimen up was thought to be a scientific endeavour. But even today the logistic problems and the very careful establishment of control experiments are often underestimated.

This paper is not intended to give a comprehensive review which would also not be possible within the space allotted but represents a rather personal view. Although omissions were not at all planned they are bound to exist – a single person is not as balanced in its judgements as a carefully selected committee.

2. The primary field and initial interactions

The primary space radiation field is now fairly well known [5] but there are still uncertainties concerning interactions with spacecraft materials and inside the human body [6]. Fragmentation processes and the generation of secondary radiations modify it so that inside a satellite the composition may be quite different. This requires careful dosimetry, particularly because the biological effectiveness may be greater than outside. Programmes for the International Space Station (ISS) are already far advanced to achieve this goal [7].

A largely unsolved problem are solar flares. They may lead to doses far in excess of those which are normally encountered in space and can approach levels where even deterministic effects cannot be excluded [8]

Also the human body modifies the field in such a way that not only the doses but also the composition of radiations in interior organs may be quite different from that at the surface. This has to be assessed with the help of realistic human phantoms. Some have already been flown on shuttle missions but more will be expected from the ISS [9].

3. Basic radiation biology

Much is already known about the action of heavy particles on mammalian cells but we are still far away from understanding the effects in a quantitative predictable way. The relationship between physical particle properties and endpoints like killing, mutation induction and neoplastic transformation is not yet understood. Track structure is studied by Monte Carlo-calculations [10] and the results are used to predict DNA damage [11]. Another approach – sometimes called the “amorphous track model” – was initiated by R.B. Katz [12] where the radial dose distribution around the track is used to compute the biological outcome [13]. The study of particle effects created a new discipline, microdosimetry, by H.H. Rossi (1918-2000) [14] whose potentials seem not yet to be fully explored for radiation risk analysis in space. In spite of the different efforts described a comprehensive theoretical understanding of particle interactions with biological systems has still to be achieved.

Also in the field of experimental studies there is still much to be done. Mutation induction by different particles has been extensively investigated and there seems to be a fairly acceptable agreement of the LET-RBE relationship with the ICRP recommendations [15] but far less data are available for neoplastic transformation which are mainly due to the work of T.C. Yang (1938-1998) [16]. For cancer formation in animals there are virtually only the experiments with the Harderian gland in mice [17]. Even if more animal data were available there is still the problem how they can be extrapolated to the human situation [18].

Although ambient doses are comparatively high in space the actual particle fluence rates are low so that the action of single traversals becomes important. With newly developed ‘microbeams’ interesting results have been achieved [19 , 20] but this seems to be still the beginning of a fascinating field. It originated from space related problems when H. Buecker (1926-1997) developed his BIOSTACK [21] approach where single particle traversals are identified by track detectors attached to the biological specimens.

The problem of low radiation doses is by no means only important for space but even more urgent on Earth. There seems to be now wide-spread agreement that solutions cannot be expected from epidemiological investigations but must come from a better understanding of fundamental mechanisms. Radiation risk assessment in space is thus not isolated but intimately connected to terrestrial questions, and techniques developed also have their immediate applications, particularly with particle interactions. There is a direct link, e.g. to the ‘radon problem’. A better understanding of radiation carcinogenesis will also help to unravel the yet unsolved mystery of cancer development and thus make a significant contribution to human health.

Biology offers now a wealth of new techniques which are yet to be fully explored for our field. An example are ‘DNA chips’ which can help to understand the phenomena of radiation mutagenesis. The analysis of chromosomal aberrations by advanced ‘fluorescence in situ hybridisation’ (FISH) has not only a fundamental aspect but has already been used to assess personal doses to astronauts [22].

4. Problems and potentials of the new space era

With the completion of ISS and the human Mars exploration in sight there will be no really new problems but the old ones are intensified. Rational risk assessment becomes more important with extended stays in space, and the design of appropriate shielding materials. This has not only a scientific but also an economical component since every kilogram of added material increases the cost of the mission. It has also to be critically discussed whether the system of radiation protection which has been quite successful on Earth is really the best way also for the space situation [13, 23] A fundamental assumption is that all radiation effects can be scaled to those of low-LET radiations using appropriate quality or weighting factors. If space particles were found to cause specific effects not observed with gamma- or X-rays the RBE for this would be infinite, and no weighting factor could be applied. The – still unproved – concept of microlesions [24] has to be mentioned here.

The environment in space is quite different from that on Earth and the interaction with radiation effects has to be seriously considered. The most important factor is microgravity. It appears to be clear that cellular repair of DNA double strands is not affected [25, 26] although it cannot be excluded that repair fidelity may be compromised. More important are changes at the systemic levels [26] and particularly a possibly reduced immune response [27]. There are suggestions that radiation induced developmental malformations are more frequent under microgravity [28]. The ISS should allow to study animal colonies over extended periods of time and assess this and also radiation carcinogenesis under conditions of reduced gravity.

There may be still quite a number of unforeseen surprises to come. An example were the light flashes seen by the Apollo astronauts [29] although they were predicted long before by Tobias who also later confirmed their existence in a brave experiment on himself at the BEVALAC [30].

5. Conclusions and final remarks

There is no new space radiation research just because a new millenium begins but there are exciting new opportunities linked, however, to new problems as sketched above. They create challenges to experimental designs and the way of thinking – with other words, an Eldorado for bright scientists. It is our task to gather the best of them and attract the young generation. Space radiation research requires the integration of physics and biology making use of the most advanced techniques available. As already indicated there will be ample 'spin-offs' for the situation on Earth, the 'radon problem' is an example, the close connection to the radiation therapy of cancer by heavy particles another.

Science is always international but space research has an additional specific flavour. The ISS will be a truly international laboratory where all have to cooperate under rather restricted conditions and to rely on each other. All who had already the opportunity to have experiments on shuttle missions will remember the same spirit, and Kennedy Space Center has been a good fore-runner. There are great times to come for our field, it is ours to face the challenges and use the opportunities!

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