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Space radiation effects on plant and mammalian cells

C. Arena [a,*], V. De Micco [b], E. Macaeva [c,d], R. Quintens [c]

[a] Department of Biology, University of Naples Federico II, Via Cinthia 4, 80126 Naples, Italy
[b] Department of Agricultural and Food Sciences, University of Naples Federico II, via Università 100, 80055 Portici, Naples, Italy
[c] Radiobiology Unit, Institute of Environment, Health and Safety, Belgian Nuclear Research Centre, SCK●CEN, Boeretang 200, B-2400 Mol, Belgium
[d] Department of Molecular Biotechnology, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium

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ABSTRACT

The study of the effects of ionizing radiation on organisms is related to different research aims. The current review emphasizes the studies on the effects of different doses of sparsely and densely ionizing radiation on living organisms, with the final purpose of highlighting specific and common effects of space radiation in mammals and plants. This topic is extremely relevant in the context of radiation protection from space environment. The response of different organisms to ionizing radiation depends on the radiation quality/dose and/or the intrinsic characteristics of the living system. Macromolecules, in particular DNA, are the critical targets of radiation, even if there is a strong difference between damages encountered by plant and mammalian cells. The differences in structure and metabolism between the two cell types are responsible for the higher resistance of the plant cell compared with its animal counterpart.

In this review, we report some recent findings from studies performed in Space or on Earth, simulating space-like levels of radiation with ground-based facilities, to understand the effect of ionizing radiation on mammalian and plant cells. In particular, our attention is focused on genetic alterations and repair mechanisms in mammalian cells and on structures and mechanisms conferring radioresistance to plant cells.

1. Introduction

Understanding the effect of ionizing radiation on organisms is a relevant and complex topic of current research which can be aimed to reach different endpoints within various contexts. The Chernobyl disaster and the more recent one at Fukushima-Daiichi have aroused interest in radioecology which aims to both comprehend the consequences of radiation exposure on living organisms in ecosystems and unravel the mechanisms by which plants and animals are able to counteract the effects of ionizing radiation [1,2,3]. Other fields of ionizing radiation application are in breeding programs to obtain selected plant cultivars [4,5] and in microbial decontamination methods alternative to conventional procedures [6]. In addition, the increasing use of ionizing radiation in medicine, whether for diagnostics or therapy, also supports the need for a better understanding of the long-term health effects of radiation exposure in humans.

Another important field of interest related to the studies on the effects of radiation on living organisms is space research. Humans in space are subjected to galactic cosmic rays (GCR) and solar particle events (SPE) that

* Corresponding author. Tel.: +39 081 679173; fax: +39 081 679233.
E-mail addresses: c.arena@unina.it (C. Arena), demicco@unina.it (V. De Micco), emacaeva@sckcen.be (E. Macaeva), rquinten@sckcen.be (R. Quintens).

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cause significant but poorly understood risks of carcinogenesis and degenerative diseases [7]. The GCR spectrum is composed primarily of high-energy protons and atomic nuclei, namely about 87% high energy protons, 12% alpha-particles and 1% heavier ions up to iron (HZE) [8]; SPE consist of low to medium energy protons and alpha-particles. Numerous flight and ground-based experiments have been performed to expand the knowledge on the biological effects of cosmic radiation on humans in the perspective of manned space missions [9–11], although many questions still remain unanswered. At present, radiation risk represents the major constraint for manned exploration and colonization of the Solar system [12,13]. Indeed, the radiation risk in Space is still accompanied by a high degree of vagueness linked to the uncertainty not only of the levels of radiation likely encountered by organisms, but also of the degree of danger associated with different radiation types and organisms [14]. Ionizing radiation may have different outcomes on organisms depending on the radiation quality, the dose (rate) and/or cell characteristics [15,16]. The biological effects of cosmic radiation on other organisms (animals, plants and bacteria) are even less well characterized, but their understanding may be of equal importance in the view of future interplanetary missions aiming to establish permanent inhabited bases because bioregenerative life support systems, which will be needed to sustain such missions, heavily rely on the relationships between humans (animals), plants and bacteria [17–19].

Following the exposure to radiation, a latent period is expected in which the biological effects may not be immediately observed. The extent of the latent period may vary from a few minutes to decades, mainly depending on the irradiation dose and the intrinsic radiosensitivity of the organism. Irradiation at very high doses may cause immediate death or irreversible damages to cells, while both acute and prolonged irradiation with low doses may lead to the development of tumors in animals even decades after the exposure [16]. In addition, the biological effect of ionizing radiation may not only be limited to the organism exposed to irradiation but may also involve next generations. However, transgenerational effects of radiation appear to be very much dependent on the organism. For instance, it has been demonstrated that radiation exposure in mice can lead to increased frequencies in germ cell mutations, followed by malformations and dominant lethal mutations in the offspring [20]. In contrast, in humans no direct evidence of hereditary effects caused by radiation has been reported yet [21].

Generally, the term “high dose” is much different for plant cells than for mammalian cells [22]. The differences in structure and metabolism between the two cell types account for the higher resistance of plant cells compared to mammalian cells. It has been recently demonstrated that doses of X-rays up to 10 Gy do not induce any detrimental effect in leaf anatomical traits of bean plants when irradiation is directed to mature adult tissues [23]. In contrast, a whole body irradiation with such a dose in humans would cause death within days or weeks, mostly due to infections resulting from a depletion of white blood cells. With regard to tissue effects in humans, it is assumed that the threshold dose, below which no deterministic effects occur, is 0.1 Gy for both low- and high-LET (Linear Energy Transfer) radiation [24]. Therefore, for radiation protection in humans doses above 0.1 Gy are considered as high doses. However, despite the evident differences between the two systems, one of the most important common effects is the disruption of cell division. In animal cells, the exposure to radiation even at relatively low doses (below 0.1 Gy) induces a temporary interruption of the cell cycle. Higher doses may cause DNA mutations and chromosomal reorganization which may result in complete cessation of division or destruction of the cells [25]. Because of particular ionization patterns, high-LET ionizing radiations (*e.g.* protons and heavy ions) are more dangerous than low-LET ones (*e.g.* X- and gamma-rays), thus generating more cell death and mutations in both plant and mammalian cells [7,15,26]. High-LET radiation research is of particular importance in understanding the biological effects of cosmic radiation since they represent a very large fraction of cosmic radiation.

In this review, we summarize some recent findings related to the effects of low-LET and high-LET ionizing radiation on plant and mammalian cells. In particular, we focus on the main alterations triggered by radiation in mammalian and plant cells, on DNA repair processes in mammalian cells and on structures and mechanisms conferring radioresistance in plant cells.

2. Effects of space radiation on mammalian cells

As mentioned in the introduction, space radiation consists of fairly well described [9] GCR and SPE, of which especially heavy ions are expected to have an important negative impact on the astronaut's health [27]. Effective shielding might seem to be the easiest and most obvious solution. However, with the current technology, passive shielding is only effective for SPE, whereas it is limited for GCR due to severe mass constraints in spaceflight. Therefore, genetic and biomedical approaches could represent one of the solutions to GCR radiation protection issues [28]. In addition, it is noteworthy that the reduction in primary radiation due to shielding might be counteracted by secondary species (*e.g.* neutrons) which are formed when primary radiation interacts with the space-craft material. Such a secondary radiation might be even more biologically hazardous [7].

Up to now, the assessment of radiation risk for astronauts is almost completely based on extrapolation from terrestrial experimental and epidemiological data. This situation is unlikely to change in the near future as the number of individuals involved in real space flights is too low and thus comprehensive models are needed [29]. Two excellent reviews have provided an overview of ground-based studies relevant to space flight health risk assessment with respect to cancer [7] and non-cancer effects [30].

It is a well-established fact in radiobiology that physical differences between high-LET and low-LET ionizing radiation have a significant impact on the damage caused in mammalian cells. Because of their physical nature, high-LET particles deposit their energy within a comparatively small volume, thus causing more complex DNA damage and overall biological effects when compared to low-LET radiation of the same energy [31,32]. This, together with

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