Life Sciences in Space Research 8 (2016) 52–67

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

# Reference field specification and preliminary beam selection strategy for accelerator-based GCR simulation

Tony C. Slaba [a,*], Steve R. Blattnig [a], John W. Norbury [a], Adam Rusek [b], Chiara La Tessa [b]

[a] NASA Langley Research Center, Hampton, VA 23681-2199, USA
[b] Brookhaven National Laboratory, Upton, NY 11973, USA

ARTICLE INFO

*Article history:*
Received 29 May 2015
Received in revised form 27 October 2015
Accepted 13 January 2016

*Keywords:*
Space radiation
Galactic cosmic rays
Radiobiology
Astronaut risk

ABSTRACT

The galactic cosmic ray (GCR) simulator at the NASA Space Radiation Laboratory (NSRL) is intended to deliver the broad spectrum of particles and energies encountered in deep space to biological targets in a controlled laboratory setting. In this work, certain aspects of simulating the GCR environment in the laboratory are discussed. Reference field specification and beam selection strategies at NSRL are the main focus, but the analysis presented herein may be modified for other facilities and possible biological considerations. First, comparisons are made between direct simulation of the external, free space GCR field and simulation of the induced tissue field behind shielding. It is found that upper energy constraints at NSRL limit the ability to simulate the external, free space field directly (i.e. shielding placed in the beam line in front of a biological target and exposed to a free space spectrum). Second, variation in the induced tissue field associated with shielding configuration and solar activity is addressed. It is found that the observed variation is likely within the uncertainty associated with representing any GCR reference field with discrete ion beams in the laboratory, given current facility constraints. A single reference field for deep space missions is subsequently identified. Third, a preliminary approach for selecting beams at NSRL to simulate the designated reference field is presented. This approach is not a final design for the GCR simulator, but rather a single step within a broader design strategy. It is shown that the beam selection methodology is tied directly to the reference environment, allows facility constraints to be incorporated, and may be adjusted to account for additional constraints imposed by biological or animal care considerations. The major biology questions are not addressed herein but are discussed in a companion paper published in the present issue of this journal. Drawbacks of the proposed methodology are discussed and weighed against alternative simulation strategies.

Published by Elsevier Ltd on behalf of The Committee on Space Research (COSPAR).

## 1. Introduction

Exposure to galactic cosmic rays (GCR) on long duration missions presents a serious health risk to astronauts (NCRP, 2006; NRC, 2006) with large uncertainties associated with the biological response (NCRP, 2012; Cucinotta et al., 2013). In order to reduce these uncertainties, radiobiology experiments are performed to elucidate the basic mechanisms through which cancer and other endpoints are initiated by space radiation exposure. An important goal, and complicating feature, of the experiments is to collectively span the broad range of energies, particle species, low exposure rates (~1–2 mSv/day, Zeitlin et al., 2013) and total mission exposures (~1 Sv, Zeitlin et al., 2013) characteristic of the GCR environment on a long duration deep space mission. Individual experiments have typically considered a small number of particle species or energies. This approach is guided in part by the desire to gain a basic understanding of the mechanisms through which radiation interacts with biological targets but also by limitations with particle accelerator facilities and cost.

The NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) and other facilities such as the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) have been supporting radiobiology experiments for over a decade. Additional facilities are being built elsewhere with overlapping research interests (Durante et al., 2007), such as the Facility for Anti-proton and Ion Research (FAIR) at GSI. The accelerator at NSRL has generally matured to a point where simulating a broad spectrum of particle types and energies encountered in deep space within a single experiment is feasible from a technology and cost perspective. The main purpose of such an experiment, referred to herein as a GCR simulation, would

* Corresponding author at: 2 West Reid St., Mail stop 188E, Hampton, VA 23681-2199, USA. Tel.: 1 757 864 1420.
*E-mail address:* Tony.C.Slaba@nasa.gov (T.C. Slaba).

http://dx.doi.org/10.1016/j.lssr.2016.01.001
2214-5524/Published by Elsevier Ltd on behalf of The Committee on Space Research (COSPAR).

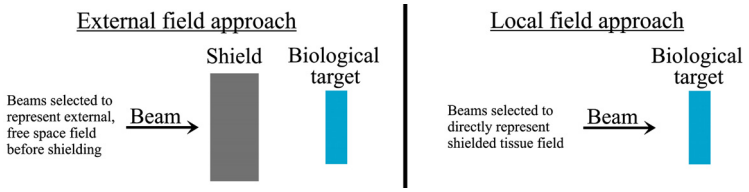


**Fig. 1.** External and local tissue field approaches for selecting beams in the GCR simulator.

be to deliver the radiation environment encountered by astronauts in deep space to biological targets in a controlled laboratory setting. These experiments may be used to study a variety of topics associated with mixed radiation fields including countermeasure development and testing, carcinogenesis, and cardiovascular and central nervous system (CNS) effects.

Many of the details associated with designing a GCR simulator will depend on the biological question and endpoint being studied. However, certain aspects of the simulator may be standardized across experiments to enable subsequent cross comparisons and validation. Such standardization efforts also lead to improved efficiency and reduced costs but need to be carefully developed and implemented so future research efforts are not hindered or unnecessarily constrained. The present work focuses on two aspects of GCR simulator design at NSRL that allow some level of standardization: reference field specification and a general beam selection strategy. The term reference field is used here to describe the space radiation environment being represented in the GCR simulator. The beam selection strategy described herein includes accelerator facility constraints that are specific to NSRL as well as animal constraints related to tissue-shielding provided by mouse models. The strategy could be easily adjusted for other facilities and additional biological constraints when they are defined.

It is important to note that the beam selection approach is not being presented here as a final design for the GCR simulator, but rather a single step within a broader design strategy. In this first step, it is shown that the beam selection methodology is tied directly to the reference environment, allows facility constraints to be incorporated, and may be adjusted to account for additional constraints imposed by biological or animal care considerations. The major biology questions are not addressed herein but are discussed in a companion paper published in the present issue of this journal (Norbury et al., 2016).

Two basic strategies for beam selection are discussed presently and are depicted in Fig. 1. In one approach, the external, free space GCR spectrum is represented by discrete ion and energy beams and delivered onto a shielding material placed within the beam line, in front of the biological target. The shielding material is used to modulate the primary beams in a manner similar to vehicle or habitat shielding for a deep space mission. This approach is referred to throughout this paper as simulating the external GCR environment directly, or the external field approach and has been discussed by Kim et al. (2015). The key feature is that the accelerator facility provides the ions and energies necessary to accurately reproduce the unmodified, external, free space GCR spectrum. In the other approach, models are used to characterize the induced radiation field found within a representative tissue of an astronaut behind shielding. The induced (or local) tissue field is then represented by discrete ion and energy beams and delivered directly onto the biological target. This approach is referred to throughout this paper as simulating the local tissue field, or the local field approach. Note that in either approach, a reference field is required to guide beam selection. In the external field approach, the reference field is a representative free space GCR spectrum (e.g. unmodified, free space solar minimum environment). In the local tissue field approach, the reference field is a representative shielded tissue spectrum found in space (e.g. average tissue fluence behind vehicle shielding during solar minimum).

Certain advantages and disadvantages of the two approaches are collectively described in this paper and by Kim et al. (2015) and Norbury et al. (2016). Further work is needed to explore hybrid methodologies as well. Such hybrid procedures, utilizing a combination of the local and external field paradigms, might result in optimal exposure conditions that cover a broader range of energies and particle types than what can be achieved with either method singularly.

In this work, two aspects of simulating the GCR environment in the laboratory are studied: reference field specification and general beam selection strategy. First, a reference environment for the laboratory simulation is identified. This includes analysis and discussion related to the external, free space environment, the induced environment behind shielding and tissue, as well as the impacts of shielding and solar activity. Second, sensitivity analysis results are given to identify the ions and energies of greatest importance in the reference field for exposure quantities of interest (e.g. dose and dose equivalent). The impacts of accelerator facility constraints are also considered with an emphasis on lower energy limitations of the experimental design and upper energy limitations of the accelerator. Third, an approach for simulating the reference field at an accelerator facility is presented. The approach considers the hydrogen ($Z = 1$) and helium ($Z = 2$) energy spectra individually, and heavier ions are represented by considering the associated linear energy transfer (LET) spectrum from the reference environment. This combined approach allows the full reference environment to be approximately represented with relatively few discrete ion and energy beams. Other quantities such as dose equivalent and the track structure parameter spectrum (Cucinotta et al., 2013) are used to independently verify that certain characteristics of the reference field are maintained by the beam selection. Increasing the number of discrete ion and energy beams is shown to systematically improve the representation of the reference environment. Drawbacks of the proposed methodology are discussed and weighed against drawbacks of alternative strategies.

## 2. Reference environment

In this section, a reference environment is identified for the laboratory simulation. The first part examines whether the external field approach or local tissue field approach is more appropriate given current accelerator constraints and other factors. It is found that NSRL energy constraints limit the ability to simulate the external, free space GCR field. Drawbacks of simulating the shielded tissue field are similarly discussed. Other strategies for experimentally delivering the GCR environment could also be considered (i.e. some combination of the above mentioned strategies), and are likely to impose added complexity requiring further analysis to ensure the field being delivered is fully understood.

The second part of this section examines variation of the induced radiation field as a function of tissue location within the body, shielding thickness, shielding material, and solar activity. This quantifies the expected variation in the physical description