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Modelling the Influence of Shielding on Physical and Biological Organ Doses

FRANCESCA BALLARINI[1,2]*, MARCO BIAGGI[1,2], ALFREDO FERRARI[3], ANDREA OTTOLENGHI[2,4], MAURIZIO PELLICCIONI[2] and DOMENICO SCANNICCHIO[2,4]

Monte Carlo / Space radiation / Shielding / Dose distributions / Human phantom

Distributions of "physical" and "biological" dose in different organs were calculated by coupling the FLUKA MC transport code with a geometrical human phantom inserted into a shielding box of variable shape, thickness and material. While the expression "physical dose" refers to the amount of deposited energy per unit mass (in Gy), "biological dose" was modelled with "Complex Lesions" (CL), clustered DNA strand breaks calculated in a previous work based on "event-by-event" track-structure simulations. The yields of complex lesions per cell and per unit dose were calculated for different radiation types and energies, and integrated into a version of FLUKA modified for this purpose, allowing us to estimate the effects of mixed fields. As an initial test simulation, the phantom was inserted into an aluminium parallelepiped and was isotropically irradiated with 500 MeV protons. Dose distributions were calculated for different values of the shielding thickness. The results were found to be organ-dependent. In most organs, with increasing shielding thickness the contribution of primary protons showed an initial flat region followed by a gradual decrease, whereas secondary particles showed an initial increase followed by a decrease at large thickness values. Secondary particles were found to provide a substantial contribution, especially to the biological dose. In particular, the decrease of their contribution occurred at larger depths than for primary protons. In addition, their contribution to *biological* dose was generally greater than that of primary protons.

INTRODUCTION

Estimates of space radiation health risk and the development of efficient countermeasures are key issues for manned space exploration, in particular for long term missions on the International Space Station and possible missions to Mars. Accurate risk estimates require a detailed investigation of both the physical aspects of the problem (essentially the fluences of the various primary-radiation components and of the secondary particles produced by interactions with the spacecraft walls, the shielding structures and the human body) and the radiobiological aspects, i.e. the effects of mixed fields on biological targets at different levels, from DNA and cells up to tissues, organs and organisms.

In the framework of a collaboration supported by the Italian Space Agency, the research groups of Naples, Rome and Milan performed experiments to investigate how shielding can modulate the effectiveness of space radiation at inducing chromosome aberrations[1)], DNA damage and cell killing, whereas the group of Pavia/Milan addressed the same problem by developing theoretical models and Monte Carlo codes to be compared with such experimental results. In particular, a mechanistic model and a MC code able to simulate the induction of chromosome aberrations by different radiations is under development[2–4)], as are models and codes aimed to investigate the induction of cellular and sub-cellular endpoints starting from "event-by-event" track structure

*Corresponding author: Phone: +39–02–50317399
Fax: +39–02–50317630
E-mail: Francesca.Ballarini@mi.infn.it
[1] Università degli Studi di Milano, Dipartimento di Fisica, via Celoria 16, I-20133 Milano, Italy
[2] INFN (National Institute of Nuclear Physics)
[3] CERN, Geneva, Switzerland
[4] Università degli Studi di Pavia, Dipartimento di Fisica Nucleare e Teorica, via Bassi 6, I-27100, Pavia, Italy

simulations[5–7]. Indeed chromosome aberrations are a particularly relevant endpoint, since they are positively correlated with most cancer types and they can be used for applications in the field of biological radiation dosimetry[8]. Furthermore, the FLUKA transport code was modified to allow integration of radiobiological data taken either from event-by-event simulations[9], or from experimental work[10]. FLUKA is a Monte Carlo code able to transport hadrons and leptons in any material with a "condensed-history" approach[11]. Presently, hadron-hadron and hadron-nucleus interactions are available in FLUKA in the energy range 0-100 TeV, whereas nucleus-nucleus interactions are available in the range 5 GeV/u-10,000 TeV/u. The implementation of nucleus-nucleus interactions below 5 GeV/u is under development, in order to compare a fully Monte Carlo approach with analytical codes such as HZETRN[12]. Relativistic Quantum Molecular Dynamics (RQMD) models[13] are under investigation to assess their reliability in the energy range of interest. Successful tests will lead to the interface of one of these codes with FLUKA, while awaiting the development of an original model based on the description of hadron-nucleus interactions presently adopted in FLUKA.

Similarly to the track-structure model of Katz and coworkers[14], the integration technique has the aim of replacing the use of radiation quality factors recommended by ICRP[15]. A detailed description of this technique can be found in reference 16. In this work, a specially-developed version of the FLUKA code was coupled with a model geometrical human phantom within an aluminium shielding box and dose distributions in various organs were calculated for different values of the shielding thickness. The phantom is provided with different organs whose masses are in accordance with the ICRP data on reference man; further details can be found elsewhere[10]. The integration of the yields of DNA "Complex Lesions" (see below) provided distributions of "biological" dose, as well as physical dose.

MATERIALS AND METHODS

The FLUKA code was coupled with a geometrical human phantom inscribed into a shielding box of variable shape, thickness and material. As an initial test simulation, the phantom was inserted into an aluminium parallelepiped and was irradiated with 500 MeV protons isotropically emitted from an external sphere. Distributions of "physical" and "biological" dose in various organs (e.g. liver, lung, ovaries and testes) were calculated for different values of the aluminium shielding thickness, from 0 to 64 cm; the "biological dose" was modelled as the yield of "Complex Lesions" (CL) per cell, regardless of the cell nucleus shape. CL yields were taken from a previous work, in which a CL was operatively defined as "two or more DNA single-strand breaks on each strand within 30 base-pairs" and yields of CL/Gy/Dalton were calculated for different radiation types and energies by coupling an event-by-event Monte Carlo track structure code with a geometrical DNA model[5]. The integration into a version of FLUKA modified for this purpose of the yields of CL/(Gy·Dalton) due to the various radiation components provided the distributions of CL/Dalton (and thus CL/cell) in different organs. The contributions of primary protons and secondary particles were calculated separately.

RESULTS AND DISCUSSION

Calculated distributions of physical and biological dose per particle fluence (protons/m^2) in the liver after a simulated 500 MeV proton irradiation are shown in Figs. 1a and 1b for different values of the Al shielding thickness (from 0 to 64 cm). The contributions of primary protons (black bar) and secondary hadrons (white bar) are shown separately; the black bar and the white bar don't add up to the grey bar (total dose) because also secondary electrons contribute to total dose.

The dose modulation by the Al shielding thickness was found to be organ-dependent. Indeed each organ showed a "critical" shielding thickness corresponding to a maximum dose (both physical and biological), but the value of such thickness was found to vary from organ to organ. For the liver, the maximum dose was found after 6 cm Al shielding. The change in critical thickness is related to the fact that the various organs have different positions within the human body, as well as different compositions, shapes and masses. Position plays an important role because of the self-shielding of the body, so that the radiation fields in internal organs are modulated by the intervening material.

Secondary hadrons were found to make a substantial contribution to the dose. As a general trend, the contribution of secondary hadrons initially increased with thickness and then started to decrease at larger depths with respect to primary protons. The contribution of secondary hadrons to biological dose was found to be larger than that of primary protons. This is mainly due to the presence of low-energy (secondary) particles, which have a high biological effectiveness.

To associate the concept of Complex Lesions to other types of biological damage and more generally to health

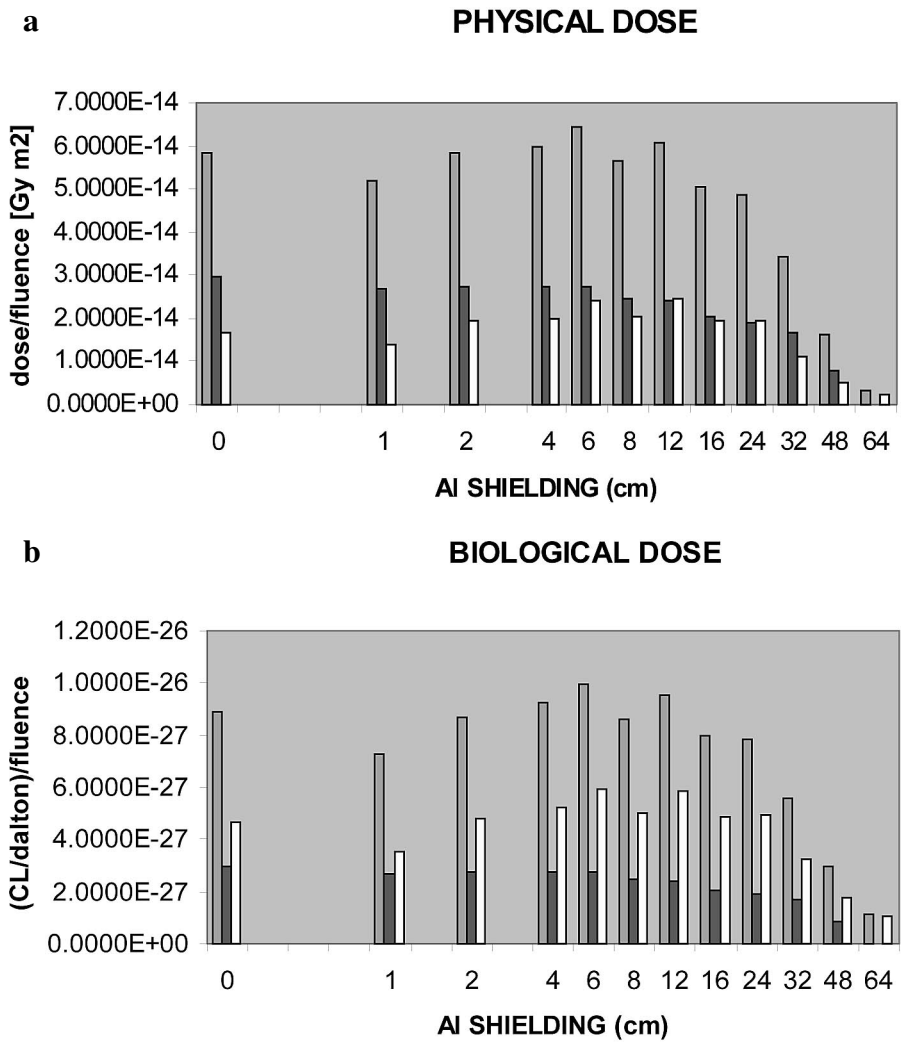

Fig. 1a. Calculated physical dose (divided by particle fluence, expressed as protons/m^2) for different values of Al shielding thickness after irradiation of liver with 500 MeV protons. Grey: total dose; black: contribution of primary protons; white: contribution of secondary particles.

Fig. 1b. Calculated biological dose (divided by particle fluence, expressed as protons/m^2) for different values of Al shielding thickness after irradiation of liver with 500 MeV protons. Grey: total biological dose; black: contribution of primary protons; white: contribution of secondary particles. See the text for details on biological dose calculation.

risk, it can be helpful to "convert" CL yields into more familiar endpoints such as chromosome aberrations. By assuming for primary protons a fluence rate of 3.5 particles cm^{-2} s^{-1} (that is the 87% of the maximum total particle fluence rate of GCR at solar minimum, protons comprising 87% of the GCR ions), corresponding to 3×10^9 particles m^{-2} day^{-1}, and by taking into account that the DNA contained in a human cell nucleus has a mass of about 4.2×10^{12} Dalton, a biological dose of 10^{-26} (CL/dalton)/fluence (that is the order of magnitude of total biological dose, see Fig. 1b) corresponds to 1.3×10^{-4} CL $cell^{-1}$ day^{-1}. Since one can reasonably assume that 2 CL lead either to a dicentric or to a reciprocal translocation with equal probability[2], this would imply that during a six-month mission at solar minimum the 2.3% of the liver cells would carry a CL and therefore about the 0.6% of the liver cells would carry a translocation if the space radiation consisted of monoenergetic 500 MeV protons. Translocations are particularly relevant in terms of risk, since they are known to be strictly correlated with cancer[17]. It has to be emphasised that the aim of this calculation is not to provide a quantitative estimate of space radiation risk, but it is simply to provide a key for reading the vertical scale of Fig. 1b. Reliable estimates can be made only by using GCR spectra and by taking into

account the low dose rate characteristic of GCR exposure. The possible occurrence of Solar Particle Events (SPEs) also has to be taken into account. Indeed in the near future the work described herein will be repeated for one or more specific SPEs, which are characterised by much higher fluence rates and broad energy spectra. Different materials and shapes will also be tested for the shielding structure. Furthermore the FLUKA code will be coupled with a "voxel" phantom developed at GSF (Muenchen, Germany), in which the various organs are described by means of voxels with linear dimensions of the order of millimetres[18], and the resulting dose distributions will be compared with those obtained with the geometrical phantom.

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