

A Monte Carlo code for a direct estimation of radiation risk

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Abstract

An example of pragmatic approach for predicting mixed field effects is presented. The method was initially applied adopting the following, commonly used, assumptions: a) radiation risk (typically cancer) is correlated with chromosome aberration induction; b) radiation-induced chromosome-exchange yield can be well described by a linear-quadratic dependence on particle fluences (mostly linear with high-LET radiation), with parameters depending on particle types and energies. Information on monochromatic field radiobiological effects was integrated in a condensed-history Monte Carlo transport code (FLUKA), able to simulate nuclear interactions. The integrated code provides the chromosome aberration yield (and thus an estimation of radiation risk) in each voxel of any irradiated volume, given any external mixed-field irradiation; in the present work, the method was tested for neutron irradiation of a water phantom. FLUKA was then coupled with a geometrical human phantom provided with different radiation shielding, in order to apply this approach to estimate radiation risk in manned space missions.

KEYWORDS: Monte Carlo simulations, radiation risk, mixed fields, human phantom.

1. Introduction

A detailed knowledge of the action of mixed fields can be of great help for different applications, such as the development of tumour treatment plans with hadrons and the estimate of health risk after exposure to space radiation, which mainly consists of charged particles of high energies. Indeed space radiation risk estimates are further complicated by many factors (e.g. presence of heavy ions, very low dose rates, interaction between radiation and microgravity); the present work is focussed on the techniques to predict the effects of mixed fields.

Average quantities such as dose and RBE do not allow one to take into account the highly-stochastic aspects characterising the action of mixed fields, whereas mechanistic models based on Monte Carlo transport codes can provide a more adequate approach. However, performing event-by-event track structure simulations in large volumes (e.g. organs such as liver and lung) would require unreasonable CPU times; on the other side, condensed-history codes, alone, cannot provide a complete description of biological damage induction, which is initiated by events occurring at the nanometer scale, i.e. the linear dimensions of the DNA. A possible solution to this problem is represented by 'mixed' approaches, consisting in integrating into condensed-history codes information on the early stages of damage induction obtained from event-by-event simulations. An example of application of this kind of approach can be found in [1], in which the proton beam used at the Paul Scherrer Institut (Villigen, Switzerland) for the treatment of human ocular tumours was characterised from a physical and biophysical point of view. More specifically, assumed that 'Complex Lesions' (calculated in [2] as 2

or more DNA ssb on each strand within few base pairs with an event-by-event track-structure code) play a fundamental role in inducing cell inactivation, the yield of CL per cell was integrated in FLUKA, a condensed-history Monte Carlo code able to transport electromagnetic particles and hadrons of different energies in various materials, taking into account nuclear interactions [3, 4]. The spatial distribution of dose measured at PSI was faithfully reproduced, and very good agreement was found between the (calculated) ratio of proton-induced CL to X-induced CL and the (measured) ratio of proton-induced lethal lesions to X-induced lethal lesions at 2 Gy.

Since the linear increase of CL with dose does not allow reproduction of the dose-dependence observed in RBE measurements, in the work presented herein a new approach was adopted on the basis of the approach of Rossi and Zaider [5], who stated that a biological system following the postulates of the Theory of Dual Radiation Action must show synergism when exposed to more than one radiation. This implies that the total number of lesions is always more than the sum of the lesions produced by each single beam component, since sublesions produced by one radiation interact not only among themselves but also with sublesions produced by all other radiation types. This synergistic effect was mathematically demonstrated by the authors in the case of a sequential exposure to two doses D_1 and D_2 (with the subscripts referring to the two radiation types), for which the yield of lesions was expressed as $\varepsilon(D_1, D_2) = \alpha_1 D_1 + \beta_1 D_1^2 + \alpha_2 D_2 + \beta_2 D_2^2 + 2(\beta_1 \beta_2)^{1/2} D_1 D_2$; α and β are the parameters of the linear-quadratic equation $\varepsilon(D) = \alpha D + \beta D^2$. A similar approach to that of Rossi and Zaider was adopted by Belli et al. [6], who calculated the variations in the

inactivation RBE along the Bragg peak of therapeutic proton beams starting from biological data obtained from monoenergetic beams. More specifically, the parameters determining the linear-quadratic fitting functions for the survival curves were derived starting from experimental data obtained with different proton energies. Two functions of the energy were fitted to experimental data, one for the linear coefficient $\alpha(E)$ and one for the quadratic coefficient $\beta(E)$, to obtain these parameters for all the energy values of the proton spectra of the simulated beam. Thus the usual relationship representing cell survival as a function of the dose D , $S(D) = e^{-\alpha D - \beta D^2}$, was generalised to take into account the effects of protons of different energies. This provided the absorbed dose corresponding to a given surviving fraction in the case of protons, whose energy distribution at any depth along the track was provided by a Monte Carlo simulation. Therefore, the RBE at each given depth could be calculated as the ratio between the dose of X-rays needed to give the same effect and the proton dose calculated as above.

In the present work, a method for calculating the linear and quadratic coefficients (α and β , respectively) describing chromosome exchange induction by mixed fields was developed; the method was tested in the case of dicentric chromosome induction in human lymphocytes by neutrons, which represent an excellent benchmark for this kind of studies. Indeed neutron interactions with matter produce a well-known mixed field of charged particles directly reproducible using codes like FLUKA [3,4], and there exists a large number of experimental data sets on dicentric induction both by neutrons and by different charged particles.

2. Methods and Results

The following assumptions were adopted to model health risk induced by mixed fields: a) radiation risk (typically cancer) is linearly correlated with chromosome aberration induction [7]; b) radiation-induced chromosome exchange yields can be well described by a linear-quadratic dependence [8], with the linear and quadratic coefficients α and β depending on particle types and energies: $Y = \alpha D + \beta D^2$ (1). Thus, by integrating information on monochromatic-field biological effects in the condensed-history code FLUKA, it is possible to provide the chromosome aberration yield (and consequently an estimate of the radiation risk) in each voxel of any irradiated volume, given any external mixed-field. More specifically, the values of α and β determining the aberration yield can be obtained by generalising the approach proposed by Rossi and Zaider [5] and “averaging” the values of α and $\sqrt{\beta}$ due to the different beam components, similarly to what reported in [1] for the yield of CL/cell. Different voxel arrays (in this case three) are used; every time an energy E is deposited in a voxel, the following quantities are added in the corresponding array

element: E (first array); $\alpha \times E$ (second array); $\sqrt{\beta} \times E$ (third array), with α and β corresponding to the type and kinetic energy of the particle depositing the energy E (α and β can be obtained by interpolating input tables). At the end of the simulation, for each voxel one can calculate the values of α and $\sqrt{\beta}$ (and thus β) by dividing each element of the second and third arrays by the corresponding element of the first. The aberration yield in each voxel can then be obtained by applying equation (1).

Given experimental values of α and β describing the yield of dicentric chromosomes induced by protons, electrons and in general by charged particles of different types and energies, the method described above was tested by simulating irradiation of a water phantom with neutrons of different energies. Since no input data were available for the linear coefficient in the case of protons of energies lower than 1 MeV, the yield of Complex Lesions, purposely re-normalised on the basis of α values relative to energies higher than 1 MeV, was used as input for the FLUKA code. The values of α and β for dicentric induction by neutrons were calculated as described above, and compared with experimentally-derived values. The good agreement found between the calculated and measured α coefficients for neutrons of different energies showed that the neutron linear coefficients can be well reproduced by integrating in FLUKA the information on chromosome aberrations induced by the recoil ions and the products of nuclear interactions. By contrast, since the β values observed for neutrons are generally higher than the observed quadratic coefficients of the recoil ions and most of the nuclear interaction products, there is no apparent way to obtain the neutron quadratic coefficient by folding the β values of the recoil ions and the nuclear interaction products. This might be due to one or more of the following reasons: a) the presence of very short secondary ion tracks, which can induce DNA lesions sparsely distributed in the cell nucleus; b) the presence of very effective slow secondary ions, which at high doses can significantly influence the *observed* aberration yield by increasing phenomena such as apoptosis and cell cycle perturbations; c) problems in measuring and/or estimating the physical doses delivered by neutrons. Moreover, the high negative correlation between the linear and quadratic coefficients makes very ticklish the fitting procedure and the determination of α and β .

In order to simulate astronauts irradiation in space missions, the FLUKA code is also coupled with a geometrical human phantom provided with different shielding structures. The phantom is located in an external region and the code was modified to map the phantom geometry inside shields of various shapes, thickness and materials. Specific modules of the code are devoted to test different criteria to take into account the various components of mixed fields in critical organs. A representation of the phantom is reported in Figure 1.

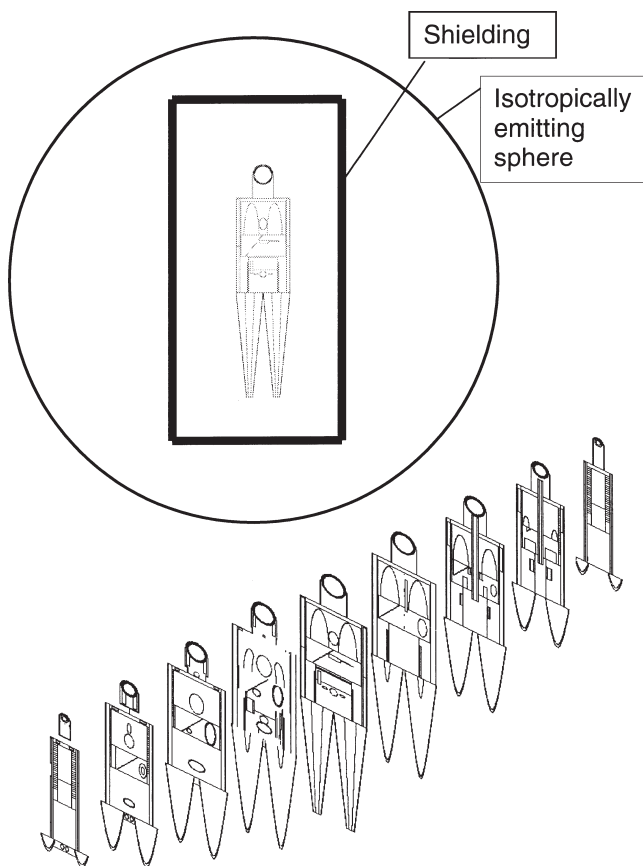


Fig. 1 – representation of the human phantom, which can be dynamically mapped inside shields of various shapes, materials and thickness.

3. Conclusions and future developments

A method to estimate biological effects (and thus health risks) induced by mixed fields was developed, consisting in integrating radiobiological information obtained from experimental data and event-by-event simulations, into condensed-history transport codes. The test of the method in the particular case of dicentric chromosome induction by neutron beams indicated that the linear coefficient describing dicentric yields vs. fluence can be regarded as a ‘convolution’ of the different neutron beam components, whereas

other mechanisms have to be considered for interpreting the experimental quadratic coefficients. The approach described above can be applied to the irradiation of human phantoms with different mixed fields; a geometrical phantom was already coupled with the FLUKA transport code, and a voxel phantom is planned to be adopted for future works. This will provide a practical tool for interpreting biodosimetry data and predicting the risks – typically cancer – for critical organs and tissues (e.g. liver, lung and blood forming organs) in case of specific missions, such as long permanence on the International Space Station and manned missions to Mars.

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