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Application of optimized geometry for the Monte Carlo simulation of a gamma-ray field in air created by sources distributed in the ground

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HIGHLIGHTS

- We apply an optimized geometry model for Monte Carlo simulation of gamma radiation field in air due to ground sources.
- Emission geometry is considerably reduced.
- We calculate conversion factors for different source configurations and for different emission energies.
- We achieve better accuracy than the calculations based on classical geometry.
- We achieve good agreement with the Monte Carlo results adopted by ICRU.

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ABSTRACT

An optimized geometry for the Monte Carlo simulation of a gamma-ray field in air created by any source distribution in the ground is applied. The soil–air medium of propagation is modeled using an optimized geometry that depends on the soil depth as the sole parameter. When this geometry is implemented, it is possible to track only those photons that are most likely to be detected. The variance in the radiation estimators is consequently reduced. The absorbed dose rates in air at 1 m from the ground for a uniform source distribution are studied. The conversion factors for the natural series of ^{232}Th, ^{238}U and ^{4}K are calculated and compared with previous calculations and with experimentally deduced values. The conversion factors for ^{137}Cs sources exponentially distributed in the ground are calculated based on the results for planar sources at various depths. According to the optimization performed here, infinite planes are reduced to discs of decreasing radius. The obtained results are in agreement with the reference studies, although the size of the geometry-detector system was considerably reduced in this work. For the uniform distribution, the best agreement was achieved with the Monte Carlo results adopted by the International Commission on Radiation Units and Measurements (ICRU), although the emission volume of soil used in our case was 30,000 times lower.

1. Introduction

Environmental gamma-ray radiation originate predominantly from homogeneously distributed natural radioactive series of ^{238}U, ^{232}Th and ^{4}K in the ground and from radionuclides released into the environment from nuclear facilities, either during normal operations or in accident scenarios. The knowledge of the distribution of a gamma radiation field in air is important for the estimation of absorbed dose rates from a given source concentration. The absorbed dose rate in air is the key quantity for the assessment of the external exposure of the human body and for the estimation of approximate concentrations of radionuclides in the soil.

To obtain detailed knowledge of such an external gamma-ray radiation field, numerical models that describe gamma-ray transport in the environment are used. In the literature, two basic approaches have been followed. The first approach is to calculate the gamma-ray field by solving the Boltzmann transport equation in the media of propagation. One of the most important studies of this type was conducted by Beck and Planque (1968). They used a combination of P-3 and DP-1 polynomial expansion matrix

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equation methods to solve the one-dimensional transport equation in soil–air media. The second approach is to obtain information regarding the energy and angular characteristics of the radiation field in air using Monte Carlo techniques through the random-walk model (Saito and Jacob, 1995; Likar et al., 1998; Clouvas et al., 2000). The fraction of photons that hit the detector is the expected value of a properly selected random variable. The Monte Carlo simulation of a gamma radiation field in the air created by sources distributed in the ground is a large-scale geometry problem in which the convergence is slow and the variance is high because the detector is typically small. The efficiency of a Monte Carlo simulation is affected by the history-scoring efficiency and the dispersion of non-zero history scores.

Several approaches have been proposed in the literature to efficiently simulate events that contribute positively to the detector response. The emphasis has been placed on the selection of an appropriate source geometry and on appropriate scoring to achieve better accuracy. For (Saito and Jacob, 1995), the soil and the air were assumed to contact each other through an infinite plane with cutoff boundaries at 2000 m in height above the ground and 5 m deep in the ground. Infinite planes lying horizontally in the air were utilized to detect photons. Whenever a photon crossed these planes, its energy, position and direction were recorded in addition to the exposure it provides. A vertical line source was considered instead of an infinite-volume source. The results obtained in this previous study are presently used as reference values (ICRU, 1994). For (Clouvas et al., 2000), the source geometry was modeled as a cylinder of 40 m in radius and 1 m in depth. These dimensions were believed to be sufficient for the consideration of the photon-emission geometry as a half-space geometry. The authors also used a large virtual disc detector of 2 m in radius placed at 1 m from the ground to count each crossing gamma photon. Likar et al. (1998) have calculated the absorbed dose rate in air by summing all energy deposited by the scattered photons and the secondary electrons and positrons generated in a box of air as large as 2 km. Based on symmetry arguments, the primary photons were generated along vertical axes below the ground level to account for a volume source distribution in the soil.

Despite the success encountered in reproducing radiation-field parameters, the discrepancies among the various Monte Carlo calculations that have been performed up to now remain important. The overall discrepancy exceeds 20% for the energy spectrum of interest. In our view, the accuracy of these Monte Carlo calculations requires further investigation.

In the present work, a method is proposed to improve the Monte Carlo simulation of the radiation field in the air caused by gamma-ray emitters distributed in the soil. When an optimized geometry is implemented to describe the medium of propagation, it is possible to track only those events that are most likely to be detected. This allows the variance in the calculated results to be reduced. CERN's Geant4 toolkit system with the low-energy electromagnetic physics package was used in this calculation. Gamma-dose-rate conversion factors were calculated for uniform and exponentially distributed sources in the ground. FLUKA Monte Carlo code was also used to benchmark our calculation for the exponential source distribution in the ground. The results were compared with those of previous Monte Carlo calculations. A comparison was also performed with results obtained by solving the transport equation and with experimentally obtained results. The contribution of direct and skyshine radiation to the absorbed dose rate was also studied for the natural radioactive series.

2. Methods

For a gamma radiation beam of intensity I, the amount of radiation, $\mathrm{d}I$, that is absorbed by an absorber of thickness $\mathrm{d}x$ is proportional to both I and $\mathrm{d}x$; thus,

$$\mathrm{d}I = -\mu I \mathrm{d}x \tag{1}$$

where μ is the linear attenuation coefficient, which depends primarily on the photon energy and the material properties. By integrating, we obtain the exponential law of attenuation:

$$I = I_0 e^{-\mu x} \tag{2}$$

where I_0 is the initial gamma-ray intensity. The term μx is the linear attenuation factor, which expresses the total attenuation when the radiation crosses a thickness x of matter.

Consider now a two-layer model with the Earth as an infinite half-space of constant density and a radioelement concentration overlain by a non-radioactive layer of air of constant density. A gamma ray emitted from a point source within the earth at a distance of $x_s + x_a$ from the detector experiences a total attenuation factor of $\mu_s x_s + \mu_a x_a$. This factor expresses the probability that the emitted radiation will reach the detector. Because the gamma ray is strongly attenuated in the soil within a nominal depth d, equivalent to a few tens of centimeters of soil thickness, a cut-off can be defined for the probability for emitted radiation to reach the detector. If the detector is at a distance h from the ground level, the attenuation factor for a reference point source at the nominal depth d on the vertical axis that contains the detector is $\mu_s d + \mu_a h$ (Fig. 1). Thus, for an emitted gamma ray approaching the detector, the total attenuation factor satisfies the following inequality:

$$\mu_s x_s + \mu_a x_a \le \mu_s d + \mu_a h \tag{3}$$

In other words, the probability for a radiated photon to reach the detector is strongly correlated with the thickness of matter that separates the emitter from the detector. The contributions of the cross sections of the physical interactions undergone by the photons are accounted for through the linear attenuation coefficient.

It has been demonstrated (Askri et al., 2008) that the set of useful sources that emit the radiation of interest are contained in a volume bordered by the surface defined by the equation

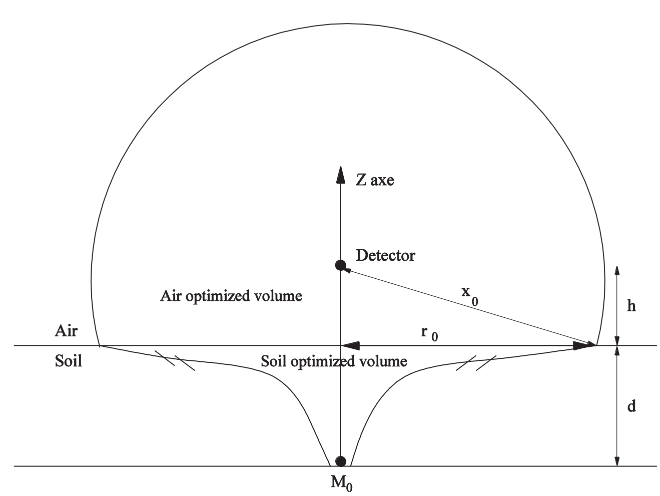

Fig. 1. A sketch of the geometrical layout showing necessary parameters to define the optimized volume of the soil–air medium.