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Evaluation of the Fluence to Dose Conversion Coefficients for High Energy Neutrons Using a Voxel Phantom Coupled with the GEANT4 Code

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Crews working on present-day jet aircraft are a large occupationally exposed group with a relatively high average effective dose from galactic cosmic radiation. Crews of future high-speed commercial flying at higher altitudes would be even more exposed. To help reduce the significant uncertainties in calculations of such exposures, the male adult voxels phantom MAX, developed in the Nuclear Energy Department of Pernambuco Federal University in Brazil, has been coupled with the Monte Carlo simulation code GEANT4. This toolkit, distributed and upgraded from the international scientific community of CERN/Switzerland, simulates thermal to ultrahigh energy neutrons transport and interactions in the matter. The high energy neutrons are pointed as the component that contribute about 70% of the neutron effective dose that represent the 35% to 60% total dose at aircraft altitude. In this research calculations of conversion coefficients from fluence to effective dose are performed for neutrons of energies from 100 MeV up to 1 GeV, irradiating MAX with mono-energetic beams in the mode Anterior-Posterior. An alternative methodology is developed too, using the atmospheric neutrons spectrum simulated with GEANT4 code at aircraft altitude instead of the traditional method that uses mono-energetic beams. To obtain the neutrons spectrum 1.5×10^5 extensive atmospheric showers are simulated by cosmic rays interactions with atmospherics atoms. The main characteristics of the spectrum are in agreement with literature confirming the validity of GEANT4. For 100 MeV energy the conversion coefficient calculated with spectrum shows a decrease of 8%, pointing out the importance of the environment influence.

I. INTRODUCTION

In 1912 Hess discovered, in manned balloon flights, a component of natural radiation for which the intensity increases with altitude [1]. This radiation in the atmosphere arises from high energy particles of cosmic origin which continuously impinge on our earth. Life is shielded against this radiation by $10^{30} gcm^{-2}$ of air which is comparable to a water layer of 10 m thickness. As a result at sea level the cosmic rays contribute less than 10% to the total dose rate of natural radiation to which man has always been exposed [2]. However, at higher altitudes in the atmosphere or in space where shielding is less effective, cosmic rays are the dominating radiation fields. They have been taken into account in risk estimations since the beginning of space flights and of supersonic flights in the upper atmosphere, but were always a specific problem for a limited number of people. During recent years higher flight altitudes have been used frequently by modern commercial aircraft and at the same time the recommended limits for acceptable dose to individuals were reduced. This changed situation led to the necessity for a detailed and more precise investigation of these aspects of cosmic radiation by dedicated experiments and by model calculations, which will be discussed here.

II. METHODOLOGY AND METHOD

Galactic cosmic rays particles, i.e. particles which come from far outside our solar system, are impinging in isotropic way on top of the atmosphere. All information about the direction of their sources is lost, since these charged particles have been scattered by irregular interstellar magnetic fields. The energy of cosmic rays particles extends from thermal energy up to 10^{21} eV. The primary composition depends on the energy interval [3]: - at energies lower than 20 GeV the primary spectrum is modulated by solar magnetic wind and geomagnetic field and the composition too; - for 20GeV¡E$\leq$ 100GeV cosmic rays are constituted by 92% protons, 6% helium, 1% heavier nuclei, 1% electrons and 0.1% gamma rays; - for 100GeV¡E¡1PeV the composition become heavier with 50% protons, 25% helium, 13% CNO (i.e. Carbon, Nitrogen and Oxygen) and 13% Iron; - for higher energy the experimental data are not definitive. Above solar modulation the primary spectrum follows the following power law: $dN/dEKE^{-\gamma}$ where γ is the exponent index of value (2.7 ± 0.1) up to TeV and K the normalization constant.

A. High Energy Neutrons Spectrum

In the atmosphere cosmic rays particles collide with the atoms of the air. They lose energy in ionization interactions and thus are slowed down continuously [2]. In each collision a proton loses on average about 50% of its energy, which is spent on the production of new particles like protons, neutrons, π e κ mesons and so on. These secondary particles may have a wide spectrum of energies, extending up to the energy of the primary cosmic rays. The neutron spectrum has two picks: - the first appears around 1 MeV due evaporation by target nuclei; - the second is located around 100MeV produced from knock-on source.

B. GEANT4 Particles Transport Simulation Code

In the past, theoretical predictions of atmospheric particle fluences have been subject to large uncertainties. The primary spectrum was known only within a factor of 2 and the demand in computing power for three-dimensional Monte Carlo simulations made systematic studies of all aspects of the radiation field almost impossible. Recently, however, the situation has greatly improved as detailed experimental information on the primary cosmic ray spectra is now available and powerful CPU has become relatively inexpensive. In addition, results of systematic experimental studies performed aboard aircraft, balloons and on the ground exist with which the model predictions can be compared.

The worldwide knowledge about cosmic rays energy spectra, which is available from measurements and models, has been incorporated into particles transport code as GEANT4, based on Monte Carlo simulation [4]. This code was developed in the CERN Laboratory under a worldwide collaboration of about 100 scientists, coming from over 40 institutes and HEP experiment groups in 15 countries. The first version of GEANT4 was released in 1998 as general-purpose simulation toolkit for particles detectors. This code provides basic functionality of simulation as to describe detector geometry and materials, to transport particles, to describe detectors response and to visualize simulations related information. It is also doted with extensive physics models to describe interactions of particles with matter across a wide energy range.

The design goal of GEANT4 was to create a flexible and extensible simulation toolkit exploiting object-oriented methodology and C^{++} language technology. Achievement of transparency of the physics implementation and hence the possibility of validating the physics results with available experiments data was another important success. Therefore, the GEANT4 collaboration takes into account the requirements from space and cosmic rays applications, nuclear and radiation computations, heavy ions and medical applications.

C. The male adult voxel phantom MAX

The basic dosimetric quantity related to the probability of the appearance of stochastic radiation effects as recommended by the International Commission on Radiological Protection is the effective dose, which is the sum of the weighted equivalent doses in 23 tissues and organs of the body, defined as [5]:

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \quad (1)$$

where H_T is the equivalent dose in tissue or organ T, w_T is the weighting factor for tissue T, w_R is the radiation weighting factor and $D_{T,R}$ is the energy absorbed in the specific tissue or organ T due R radiation.

Most of the dosimetric data for adult published by the ICRP [6] and the ICRU [7] have been compiled with MIRD5 (Medical Internal Radiation Dose) mathematical phantoms. In these simplified heterogeneous human phantoms, the size and form of the body and its organs are described by mathematical expressions representing combinations and intersections of planes, circular and elliptical cylinders, spheres, cones, tori, etc.

Energy (MeV)	$CC = E/\Phi$ (pSvcm^2)
100	508
200	446
300	745
400	791
500	624
600	891
700	969
800	919
900	925
1000	936

TABLE I: Fluence to effective dose CCs for AP exposure of MAX voxel-based phantom with 10^5 mono-energetic neutrons from 100 MeV up to 1 GeV with relative error $\Delta CC/CC = 1.5\%$.

For the present, tomographic or voxel phantoms represent the last step in the improvement of computational models. Tomographic phantoms are based on digital images recorded from scanning of real persons by Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). Compared to the mathematical phantoms, voxel phantoms are more adequate to represent the human body internal structure. A voxel based phantom is constituted by a three-dimensional matrix of cubic volumes with 3.6 mm side. Each volume, depending on location, receives an organ volume identification (ID) number by tomographic segmentation. Tissues and organs composition and density used for the construction of MAX are taken from or based on the ICRU-44 [8]. With a body height of 175.3cm, a weight of 74.6kg and the most radiosensitive organs and tissues masses being equal or very close to the reference masses, the MAX phantom corresponds better to the anatomical data of the ICRP Reference Man than any other currently existing human voxel phantom. Details and differences between MAX and the Reference Man [9] can been encountered in [10].

III. RESULTS

Conversion Coefficients (CCs) from fluence to effective dose are calculated for AP irradiation of MAX using 10^5 mono-energetic neutrons parallel beams for 100 MeV up to 1 GeV. The radiation factor adopted here is $w_R = 5$. The results are showed by Table 1 with relative error of $\Delta CC/CC = 1.5\%$.

With GEANT4 toolkit the high energy neutrons spectrum is obtained at air flights altitude of $300 gcm^{-2} \sim$ 12km, simulating extensive air showers produced by protons that impinge vertically on atmosphere with energy interval (20GeV¡E¡1PeV) and follow the experimental law above reported. In the Figure 1 is visualized a typical extensive air shower generated by an incident proton of 100 GeV energy. A cylinder with 40 km height and 10 km radius represents the

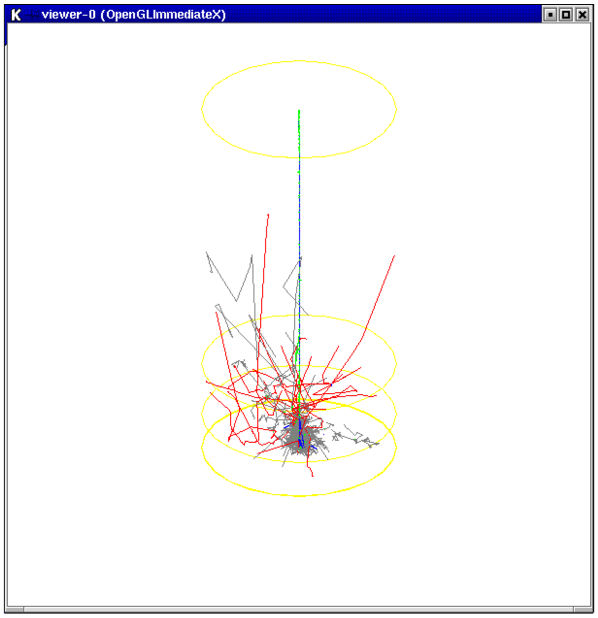

FIG. 1: Simulation of a typical extensive atmospheric shower produced from a proton with energy of 100 GeV using the GEANT4 toolkit and the graphic software Open GL.

atmosphere above air flights altitude. Each color corresponds to a particles type: - blue for positive charged particles; - red for neutrons; - grey for neutral and green for negative.

The main characteristics of the simulated neutrons spectrum are in agreement with literature [11, 12]. With 1.5×10^5 extensive air shower is achieved an experimental distributed spectrum of 3.0×10^4 neutrons with (80-120) MeV energy. The AP irradiation of MAX provides for the energy interval centered on 100 MeV the following Conversion Coefficient from fluence to effective dose: $CC = E/\Phi = (468 \pm 13)\,pSvcm^2$.

IV. CONCLUSIONS

With the increasing popularity of air travel and its revised radiation safety standards the dose received by airline personnel and frequent flyers from secondary cosmic radiation has become the subject of intensive discussion. As a result, the assessment with theoretical and experimental methods arose as an indispensable necessity, especially for high energy due data absence.

The Conversion Coefficients from fluence to effective dose are calculated for Anterior-Posterior irradiation of MAX voxel-based phantom using 10^5 mono-energetic parallel neutrons beams covering the energy range from 100 MeV to 1GeV. The results are in good agreement with literature [13, 14].

A new methodology is developed here too, allowing to calculate the effective dose directly from the atmospheric neutrons energy spectrum simulated with GEANT4 toolkit for estimation about the environment conditions and their influence. The difference of the two methods results in 8% for 100 MeV energy showing a decrease of CCs when detailed exposure conditions are taken into account.

[1] W. Hess, W. Patterson, and R. Wallace, Phys. Rev. **116**, 445 (1959).
[2] W. Heinrich , S. Roesler, and H. Schraube, Rad. Prot. Dos. **86**, 253 (1999).
[3] S. Paganini, Os muons observados com o detector central do EASCAMP, *Tese de Doutorado*, UNICAMP - SP (2001).
[4] Geant4 Home Page, http://geant4.web.cern.ch/geant4.
[5] ICRP-60. 1990 Recommendations of the International Commission on Radiological Protection. *ICRP Publication 60*, Pergamon Press, Oxford, (1991).
[6] ICRP-74. Conversion Coefficients for Use In Radiological Protection Against External Radiation. *ICRP Publication 74*. Pergamon Press, Oxford (1996).
[7] ICRU-57. Coefficients for Use in Radiological Protection Against External Radiation.. *ICRU Publications Report* **57**, Bethesda, MD (1996).
[8] ICRU-44. Tissue substitutes in radiation dosimetry and measurement. *ICRU Publications Report* **44**, Bethesda, MD (1989).
[9] ICRP-89. Report of the Task Group on Reference Man,.*ICRP Publication* **89**, Pergamon Press, Oxford (2003).
[10] R. Kramer, W. Vieira, H. Khoury, F. Lima, and D. Fuelle, Phys. Med. Biol. **48**, 1239 (2003).
[11] P. Goldhagen, M. Reginatto, T. Kniss, J. W. Wilson, R. C. Singleterry, I. W. Jones, and W. Van Steveninck, Nucl. Instr. and Meth. in Phys. Res., A **476**, 42 (2002).
[12] H. Schraube, G. Leuthold, S. Roesler, and W. Heinrich, Adv. Space Res., **21**, 1727 (1998).
[13] M. Pelliccioni, Radiat. Prot. Dosim. **88**, 279 (2000).
[14] S. Iwai, N. Yoshizawa, O. Sato, S. Takagi, S. Furihata, J. Funabiki, T. Uehara, S. Tanaka, and Y. Sakamoto, J. Nucl. Sci. Technol. **1**, 865 (2000).