Radiation Physics and Chemistry xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Monte Carlo calculation of the neutron dose to a fetus at commercial flight altitudes

M.C. Alves[a,*], D.C. Galeano[b], W.S. Santos[c], John G. Hunt[d], Francesco d'Errico[e,f], S.O. Souza[a], A.B. de Carvalho Júnior[a]

[a] Departamento de Física, Universidade Federal de Sergipe, Sergipe, Brazil
[b] Hospital Universitário Júlio Müller, Universidade Federal de Mato Grosso, Cuiabá, MT, Brazil
[c] Instituto de Física, Universidade Federal de Uberlândia (INFIS/UFU), Uberlândia, MG, Brazil
[d] Divisão de dosimetria, Instituto de Radioproteção e Dosimetria, Rio de Janeiro, Brazil
[e] School of Engineering, University of Pisa, Largo Lazzarino 1, Pisa, Italy
[f] School of Medicine, Yale University, New Haven, CT, USA

ARTICLE INFO

Keywords:
Monte Carlo
Pregnant phantom
Conversion coefficients
Fetus dose rate

ABSTRACT

Aircrew members are exposed to primary cosmic rays as well as to secondary radiations from the interaction of cosmic rays with the atmosphere and with the aircraft. The radiation field at flight altitudes comprises neutrons, protons, electrons, positrons, photons, muons and pions. Generally, 50% of the effective dose to airplane passengers is due to neutrons. Care must be taken especially with pregnant aircrew members and frequent fliers so that the equivalent dose to the fetus will not exceed prescribed limits during pregnancy (1 mSv according to ICRP, and 5 mSv according to NCRP). Therefore, it is necessary to evaluate the equivalent dose to a fetus in the maternal womb. Up to now, the equivalent dose rate to a fetus at commercial flight altitudes was obtained using stylized pregnant-female phantom models. The aim of this study was calculating neutron fluence to dose conversion coefficients for a fetus of six months of gestation age using a new, realistic pregnant-female mesh-phantom. The equivalent dose rate to a fetus during an intercontinental flight was also calculated by folding our conversion coefficients with published spectral neutron flux data. The calculated equivalent dose rate to the fetus was 2.35 μSv.h^{-1}, that is 1.5 times higher than equivalent dose rates reported in the literature. The neutron fluence to dose conversion coefficients for the fetus calculated in this study were 2.7, 3.1 and 3.9 times higher than those from previous studies using fetus models of 3, 6 and 9 months of gestation age, respectively. The differences between our study and data from the literature highlight the importance of using more realistic anthropomorphic phantoms to estimate doses to a fetus in pregnant aircrew members.

1. Introduction

Cosmic rays are about 90% protons, 9% alphas, and 1% heavier nuclei in the polar regions, and approximately 83% protons, 15% alphas and 2% heavier nuclei near the equator (ICRU, 2010). They penetrate the Earth's atmosphere and interact with atmospheric constituents yielding secondary radiations that contribute to exposures at flight altitudes (European Commission, 2004; Ferrari et al., 2001; ICRU, 2010). Indeed, aircraft crew members are exposed to ionizing radiation nearly 100 times more than a person at sea level (Chen et al., 2005). At commercial flight altitudes, neutrons, protons, photons, electrons, positrons, and muons contribute to the radiation exposure of aircrew members. According to publication 84 of the International Commission on Radiation and Units (ICRU, 2010), neutrons contribute 50% of the total radiation dose during flights at temperate latitudes. Additional concerns arise for pregnant women travelling at aircraft altitudes, because of the high radiosensitivity of the embryo and fetus, which may lead to biological effects, including death (ICRP, 2000, 2001, 2003). The International Commission of Radiation Protection (ICRP) recommends that, for pregnant aircrew members, the equivalent dose to the fetus not exceed 1 mSv during pregnancy (ICRP, 2007).

Dose estimates for aircrew members can be obtained by folding fluence-to-dose coefficients for cosmogenic radiations at flight altitudes with the energy spectrum of these radiations. The ICRP recommends that radiation dose estimates for aircraft crew members be made using isotropic or semi-isotropic geometries (ICRP, 2010). Sato et al. (2011) calculated fluence-to-dose coefficients for isotropic, semi-isotropic and

* Corresponding author.
E-mail address: alves.materia@gmail.com (M.C. Alves).

http://dx.doi.org/10.1016/j.radphyschem.2017.03.041
Received 1 October 2016; Received in revised form 22 March 2017; Accepted 26 March 2017

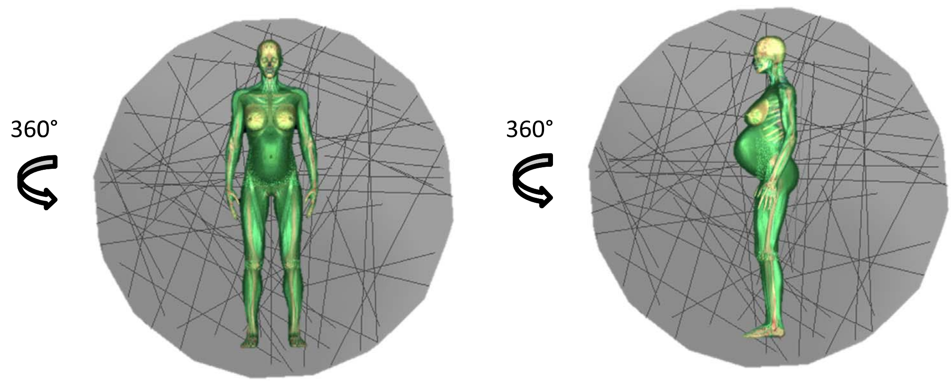

Fig. 1. Representation of isotropic irradiation geometry with the pregnant female phantom MARIA.

two additional irradiation geometries simulating exposure conditions of aircrew members to neutrons and protons of 1 MeV to 100 GeV. They observed that an isotropic geometry approximates the geometric condition inside an aircraft at cruising altitudes better than a semi-isotropic geometry.

To date, only Chen et al. (2004), Chen (2006, 2007), and Taranenko and Xu (2008) have calculated neutron fluence-to-dose coefficients for a fetus. To calculate the doses to an embryo and fetus, Chen et al. (2004), and Chen (2006, 2007) used a mathematical phantom to describe the body of a pregnant female and her embryo/fetus at four different gestation ages (8 weeks, 3, 6, and 9 months). Taranenko and Xu (2008) used realistic models named RPI-P3, RPI-P6, and RPI-P9, which represent a pregnant female at the end of the three, six and nine-month gestational periods, respectively. These models were developed using the boundary representation (BREP) method where the anatomy is represented and adjusted in an organ-based surface geometric domain involving a mixture of 3D data structures of polygonal meshes and non-uniform rational b-splines (NURBS) (Xu et al., 2007; Xu and Eckerman, 2010). However, only Chen et al. (2005) and Chen and Mares (2008), using a stylized pregnant-female phantom, calculated the equivalent dose to a fetus from cosmic radiation exposures during commercial flights. It was reported that the equivalent dose to a fetus may exceed the dose limit of 1 mSv after, e.g., 15 round trip flights between Canada and Europe (Chen et al., 2005).

Based on the female adult mesh phantom (FASH) (Cassola, (2009, 2010)), the numerical dosimetry group of the Federal University of Pernambuco recently developed a model, named Maria, for a female at the end of the second trimester of pregnancy. Some modifications of the FASH model were made to represent a pregnant woman at 6 months of pregnancy. A realistic fetus model was developed using a polygon mesh and then introduced in the female model (Cabral et al., 2015a). The aim of this study was assessing neutron fluence to equivalent dose conversion coefficients and equivalent dose rates for a fetus using the pregnant female model by Cabral et al. (2015a) and Cabral (2015b). Neutron fluence-to-equivalent dose conversion coefficients for a fetus for neutrons from 0.001 eV to 100 GeV were calculated in an isotropic geometry and results were compared with values reported by Chen (2007), and by Taranenko and Xu (2008). The fetal dose rate was obtained folding the fluence-to-fetal dose coefficients with a neutron spectrum measured in a commercial flight from Trenton, Canada, to Koln, Germany, as presented in Chen et al. (2005) and results were compared with values reported in that paper.

2. Material and methods

The general purpose Monte Carlo transport code MCNPX ver. 2.7.0, developed at Los Alamos National Laboratory (LANL), was used in this study. The code can simulate the transport and interactions of neutrons, protons, electrons, photons, heavy charged particles and other 30 types of particles of a wide range of energies (Pelowitz, 2011). Our numerical dosimetry group has ample experience using MCNPX to obtain organ and effective dose conversion coefficients (Alves et al., 2014; Galeano et al., 2016).

The Maria model simulating a pregnant female in standing posture at the end of the second trimester of pregnancy (6 months) was implemented in MCNPX in order to obtain neutron fluence to equivalent dose coefficients. The phantom presents cubic voxels of $(1.2\times1.2\times1.2)$ mm^3 and contains a fetus model with a total soft tissue mass of 633 g. Additional details concerning the Maria phantom and the fetus can be found in Cabral et al. (2015a) and Cabral (2015b).

The phantom was simulated *in vacuum* and irradiated by isotropic monoenergetic beams of neutrons, as illustrated in Fig. 1. A spherical surface source was defined emitting particles inward independent of direction and location, and containing the phantom within its volume. For the primary monoenergetic neutron beams, 39 different energy groups from 10^{-3} eV to 100 GeV were used. For each energy, 10^8 neutron histories were simulated, yielding a statistical uncertainty below 1%. In order to obtain accurate energy deposition estimates, eight main secondary radiation types were considered: photons, protons, neutrons, electrons, deuterons, tritons, alphas, and ^{3}He. The low-energy cut-off values were 10^{-9} MeV for neutrons, 10^{-2} MeV for photons, electrons, and positrons, 1 MeV for protons, 2 MeV for deuteron, 4 MeV for alphas, and 3 MeV for tritons and ^{3}He particles. The MCNPX default physical models were employed to simulate nuclear interactions via the mix-and-match feature in the energy region where no cross-section data are available. Neutron cross-section data based on the evaluated nuclear data file (ENDF) are available for the most abundant isotopes up to 150 MeV. The CEM03 model was used in the intermediate energy range. Above 3.5 GeV, LAQGSM was used to handle all heavy-ion interactions as well as all light-ion interactions (Pelowitz, 2011). The S(α,β) thermal scattering treatment for hydrogen in light water at 294 K based on the SAB2002 library (ENDF/B-VI.3) was employed for all materials in order to model thermal neutron interactions with the molecules of the body.

Energy deposition scoring (in MeV/g) in the fetus model was accomplished via the F6 tally, which is a track-length estimation tally yielding the energy deposition averaged over the tissue or organ mass. The energy deposition was then normalized to the incident particle fluence to obtain the absorbed dose per unit fluence coefficient. The equivalent dose rate to the fetus was calculated by folding the spectral neutron fluence rates with the neutron fluence to absorbed dose conversion coefficients and the radiation weighting factor for neutrons.

In order to obtain the dose to a fetus in a commercial flight, we used the neutron spectrum measured during a flight from Trenton, Canada, to Koln, Germany, on May 9, 1995 at a latitude of 55°N and an altitude of 11.3 km, as reported by Chen et al. (2005). The spectral particle fluence rate was also obtained from the Excel-based Program for calculating Atmospheric Cosmic-rays Spectrum (EXPACS ver. 3.01) for the same latitude, altitude, and date of spectrum presented in Chen et al. (2005). EXPACS is capable of calculating neutron spectra for any