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Evaluation of uncertainties in lung measurement of actinides due to non-uniform distribution of activity in lungs

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ABSTRACT

Various parameters can introduce uncertainties in the lung activity measurements of actinides. In this study, uncertainties due to non-uniform distribution of activity in the lungs are evaluated. To study the effect of non-uniform distribution, lungs of ICRP male thorax voxel and resized phantoms are divided into upper and lower parts of both right and left lungs as well as into anterior and posterior lung regions. Simulation of uniform and non-uniform distribution of activity in lungs is carried out using thorax voxel phantoms in FLUKA for Phoswich and an array of three HPGe detectors for 18–238 keV photons. Source sampling for non-uniform distribution of activity is carried out by selecting the source points by varying the weightage to 0.4, 0.5, 0.6 and 1 in different parts of lungs. Uncertainties in lung activity estimation at different energies are quantified in the form of scattering factors (SFs) which are geometric standard deviations. The SFs due to non-uniform distribution of activity of the order of 0.4–0.6 in different parts of the lungs are found to be ~ 1.25 for Phoswich and HPGe array detectors above 18 keV.

1. Introduction

Assessment of internal contamination due to actinides in the lungs of the radiation workers is carried out in totally shielded steel room using Phoswich and/or HPGe array detectors (Pendharkar, and ICRU et al., 2008, 2003). The actinides are alpha emitters but also emit low energy, low yield photons; these are attenuated in the tissues overlying the lungs (ICRU, 2003). The composition of the overlying tissues also affects the transmission of low energy photons (LEPs) of energies less than 50 keV (ICRU, 2003). Therefore, lung monitoring systems used for quantification of actinides are calibrated as function of muscle equivalent chest wall thickness (MEQ-CWT) using realistic physical thorax (IAEA, 2003) or voxel (ICRP, 2009) phantoms with activity uniformly distributed in lungs. In physical thorax phantoms such as Lawrence Livermore national laboratory (LLNL) and Japan atomic energy research institute (JAERI), lung sets for various radionuclides are used along with different MEQ-CWTs to estimate counting efficiencies (CEs) as a function of MEQ-CWTs (IAEA, 2003).

There are several factors that can introduce uncertainties (ISO, 1995) in the lung activity estimation of actinides, such as MEQ-CWT, detector positioning, counting statistics and variation in the activity distribution. There are studies (NCRP, 2009; Gómez-Ros et al., 2008; EURADOS, 2013) where uncertainties in the form of scattering factors (SFs) due to these parameters are given for in vivo measurements of radionuclides emitting low ($E < 20$ keV), intermediate (20 keV $< E <$ 100 keV) and high ($E > 100$ keV) energy photons. SF is a geometric standard deviation (GSD) assuming that lung activity follows lognormal distribution (NCRP, 2009; Gómez-Ros et al., 2008; Limpert et al., 2001). Authors have estimated SFs due to variation in detector positioning, MEQ-CWT and variation of detector background of an uncontaminated adult male in standard lung monitoring geometry using theoretical simulations and experimental measurements for Phoswich and HPGe array detectors (Nadar et al., 2014a). NCRP in its report (2009) has given SFs for in vivo measurements of radionuclides due to variation in activity distribution as 1.3 for energies less than 20 keV and 1.05 for energies between 20 and 100 keV for HPGe detector. However, SFs are not provided for specific energies encountered in lung monitoring of actinides. There is a need to simulate non-uniform distribution of activity in the voxel phantom as physical phantoms have lungs with uniform activity distribution. Non-uniform distribution of activity in lungs is one of the many parameters that can introduce uncertainty in lung activity measurements and will propagate in committed effective dose (ICRP, 1997). There is also a need to estimate detector and energy specific SFs as well as consider variation of morphological parameters, so that all the factors that can contribute to uncertainty due to non-uniform distribution of activity can be taken

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into account. Therefore, International Commission of Radiation Protection (ICRP) reference male thorax voxel phantom (ICRP, 2009) and two resized phantoms obtained from the reference phantom are used in this paper. Source is sampled uniformly as well as non-uniformly in the lungs to obtain counting efficiencies (CEs) for phoswich and HPGe array. Variation in the CEs due to non-uniform activity distribution in ICRP reference voxel phantom and two resized phantoms is studied. CEs are used to estimate SFs for each of the three phantoms at different energies and used to predict combined SFs due to non-uniform distribution of activity in lungs.

2. Materials and methods

2.1. Detection systems

The detection system consists of HPGe array and Phoswich detector. HPGe array has three HPGe detectors, each of 7 cm diameter and 2.5 cm thick with a 0.8 mm thick carbon entrance window. Phoswich is a 20 cm diameter detector with 1.2 cm thick NaI (Tl) and 5 cm thick CsI (Tl) with a 0.5 mm Beryllium window. The details about the HPGe array with its schematics and Phoswich detector can be found in author's earlier work (Nadar et al., 2013). The details of the experimental detection system consisting of both HPGe array and Phoswich are geometrically configured and simulated in Monte Carlo code FLUKA. FLUKA (Fasso` et al., 2005; Battistoni et al., 2007) is a Monte Carlo code for simulation of particle transport and interaction of radiation with matter.

2.2. ICRP male thorax voxel phantom and resized phantoms

ICRP reference male voxel phantom of in-plane resolution 2.137 mm and slice thickness of 8 mm is described by three dimensional voxel array arranged in columns, rows and slices (ICRP, 2009). Columns correspond to X co-ordinates and vary from right to left; rows correspond to Y co-ordinates and vary from front to back and slices correspond to Z co-ordinates that vary from toes to the vertex of the body (ICRP, 2009). The thorax voxel phantom used in this study is derived from ICRP reference male voxel phantom by cutting it in X-Z planes and removing the voxels above the skin layer in X-Y plane. This modification was required to position the detectors at ~ 1 cm from the phantom chest for simulating the actual geometry of measurement (Nadar et al., 2014a). The co-ordinate system of voxel phantom is used for defining detector geometry in FLUKA.

By varying in-depth resolution of thorax voxel phantom to 1.923 and 2.35 mm and keeping the voxel height at 8 mm, two resized phantoms are obtained having same height. The weights, MEQ-CWTs and lung volumes of three voxel phantoms used in this study are given in Table 1. The MEQ-CWT (IAEA, 2003) of voxel phantom is estimated by taking into account the average CWT, the thicknesses of adipose and muscle tissues present over the lungs at various locations over the chest and considering the attenuation of photons in those mediums at 60 keV.

2.3. Measurement geometry

In the standard geometry used for lung monitoring of radiation workers, detector center is kept on the midline of the body and one end

Table 1
The details of the three thorax voxel phantoms used in the study.

In-plane resolution mm	Weight kg	MEQ-CWT cm	Lung volume cm3
2.137	73	2.25	2891
1.923	59.1	2.025	2340
2.35	88.3	2.47	3496

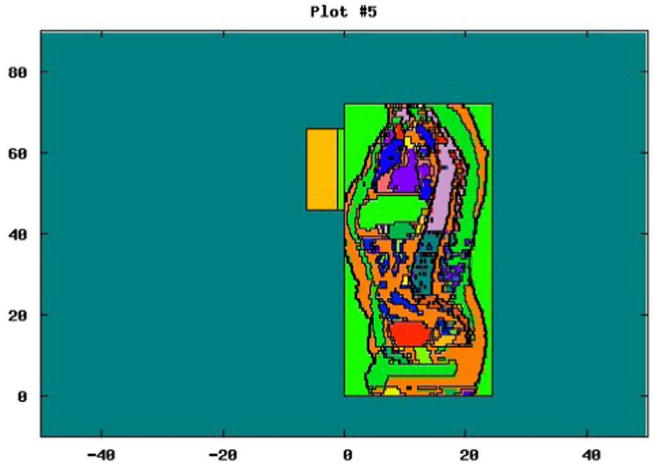

Fig. 1. Phoswich detector positioned over the chest of the ICRP male thorax voxel phantom as viewed by Flair.

is positioned tangential to the supra-sternal notch over the chest (Pendharkar et al., 2008). Fig. 1 shows phoswich detector positioned over the chest of voxel phantom as viewed by Flair. Flair (Vlachoudis, 2009) is an advanced user interface of the FLUKA and has been used for creation of input file and visualization of geometry.

2.4. Source sampling in the Monte Carlo code FLUKA

For uniform source distribution, a point is randomly chosen in the lung voxel, which itself is chosen randomly (Brown, 2005) from the known voxels of the lungs. The isotropic directional distribution of emitted photon is sampled from a uniform distribution of direction cosines (Dunn and Shultis, 2011). The lung has been divided into four regions namely, upper right, lower right, upper left and lower left regions in this study. The lung voxels in each region are identified and arranged in sequence for assigning weightage to a particular region laterally. The total lung voxels are 79,130 and the number of voxels in upper right, lower right, upper left and lower left lung regions are 18,796; 24,312; 17,264 and 18,758 respectively. Each region is assigned with a weightage of 0.4, 0.5, 0.6 and 1 and CEs are evaluated. For example, when weightage of 0.6 is required for upper right lung, voxel is chosen randomly 60% of the times from 18,796 upper right lung voxels and 40% of times from the remaining 60,334 lung voxels. Fig. 2 shows source points due to weightage of 0.6 given to the upper

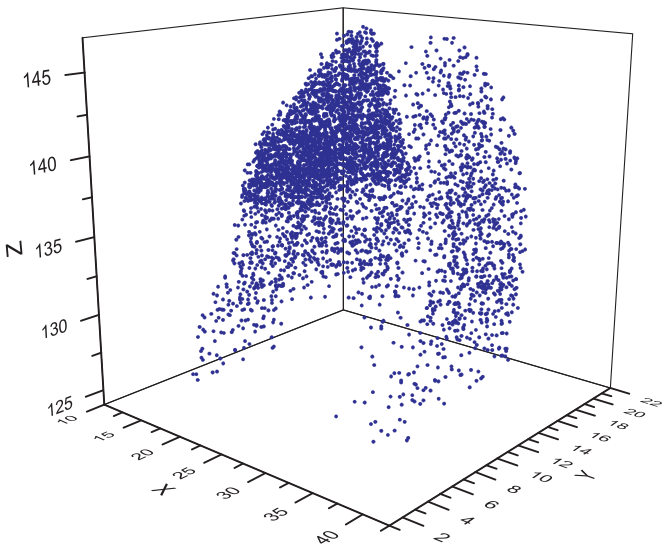

Fig. 2. Sampling of source points in upper right lung with weightage of 0.6.