

ABSTRACT

Whole-body-counting gamma-spectrometry is one of the specialized techniques for monitoring internal exposure to various radionuclides. Calibration of these systems is based on the use of tissue equivalent plastic phantoms which contain a known amount of activity of specific radionuclides. Although this technique has broad application, questions arise about the accuracy of results obtained using *in vivo* measurement methods and techniques. These questions might be resolved by developing computational phantoms representing the variation of radionuclide concentration in the human skeleton. These voxel geometries can be incorporated into a Monte Carlo code to estimate detector response. In this study, the United States Transuranium and Uranium Registries' (USTUR) Case 0102 Americium-241 Leg phantom was created using a real human skeleton. The phantom serves as a realistic standard for intercomparisons of whole body counting systems at US DOE facilities and other laboratories world-wide. The post mortem radiochemical analysis of the Case 0102 skeleton showed a significant variation of ²⁴¹Am concentration within and among different bones. This paper describes an approach of modeling the radionuclide concentration distribution for use in a Monte Carlo simulation. A 3D voxel model of the phantom has been developed. DICOM (Digital Imaging and Communications in Medicine) images of the phantom have been segmented using Eclipse® radiotherapy planning software. Each Dicom image was segmented into multiple regions of interest. Additionally, all bones of the voxel phantom were divided into multiple sections to represent samples used in the radiochemical analysis. A method of simulating photon emission from the non-uniformly distributed ²⁴¹Am source is presented. Once the voxel representation of the phantom is imported into the Geant4 Monte Carlo code, experimental response of external planar germanium detectors can be simulated for various distributions of ²⁴¹Am concentration in the human bones of the phantom.

INTRODUCTION

The purpose of *in vivo* lung measurements is to estimate the quantity of radioactive material deposited in the respiratory tract. In case of presence of any activity in the bone, adjustments to account for crossfire from the thoracic skeleton are necessary (Neton, 1988). These adjustments are based on the use of realistic tissue equivalent phantoms which contain a known amount of activity of specific radionuclides.

There are various types of anthropometric leg phantoms available for geometric efficiency calibration, including the most advanced phantoms with realistic bone structure and radionuclide distribution (Spitz, 2000). The United States Transuranium and Uranium Registries' (USTUR) Case 0102 ²⁴¹Am Leg phantom was created using a real human skeleton and was intended to serve as a unique standard for intercomparisons of whole body counting systems at United States DOE facilities and other laboratories world-wide. The advantage of this phantom is a realistic distribution of ²⁴¹Am in the real human skeleton with known values of activity in different bone sections of the right pelvis, leg, and foot as dissected prior to the radiochemical analysis.

Geant4 Monte Carlo simulation toolkit was used for the radiation transport modeling of the project. This software is based on object oriented technology. It allows a flexible approach for incorporating the different geometries into the code. The Geant4 simulation toolkit has been developed to model mathematical phantoms through the variety of Geant4 solid models, while the voxel phantoms take advantage of the "nested parameterization" technique to optimize simulation performance. Voxels can be parameterized according to various features, for instance, their material composition. Nested parameterization allows for efficient navigation across the voxel geometry of a phantom, thus speeding up the simulation process. Geant4 also allows one to employ both, mathematical and voxel geometries, either individually or in mixed configurations. This allows sufficient customization of the phantom model to meet the requirements of this specific experimental application (de Souza e Silva et al., 2009).

The objective of this project is to divide all bones of the voxel phantom into multiple sections to represent samples used in the radiochemical analysis. A method of simulating photon emission from the non-uniformly distributed ²⁴¹Am source is presented. Once the voxel representation of the phantom is imported into the Geant4 Monte Carlo code, experimental response of external planar germanium detectors can be simulated for various distributions of ²⁴¹Am in the human bones of the phantom.

MATERIALS AND METHODS

VARIFICATION OF DETECTOR GEOMETRY AND PHYSICAL MODEL

Before the actual phantom is imported into the Geant4 code, accuracy of the gamma detector construction and physical processes associated with the radioactive decay of ²⁴¹Am has to be verified. This is achieved by a simple ²⁴¹Am point source experiment. The simulated detection system consists of Canberra¹ low energy germanium detector (LEGe) operating at the PNNL whole body counting facility, Richland WA. Sizes and materials of various components of the detector are shown on Fig. 1. Digital models of detector and source geometries are placed in the air. The source dimensions, material, and radionuclide composition are also considered in the simulation to improve accuracy.

Once the radioactive material, in this case ²⁴¹Am, is introduced into the source volume, the Geant4 physical model describing the interactions of low energy photons, charged particles, and other ions with matter can be used for further radiation transport and interaction purposes. Electromagnetic interactions of photons and electrons cover energies down to 250 eV, and protons, ions and antiprotons less than 1 keV (Pia, 2004). This range allows the simulation of the 59.5 keV full energy peak as well as lower energy x-ray peaks from the ²⁴¹Am distributed in the skeleton of the USTUR Case 0102 phantom.

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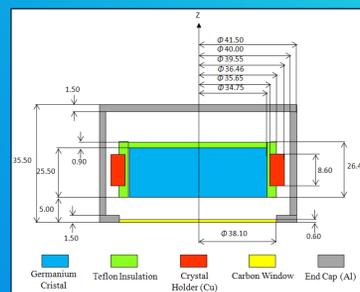


Figure 1. Cross-sectional view of the Canberra LEGe detector with dimensions (mm) and materials.

MODELING ²⁴¹Am DISTRIBUTION IN BONES OF THE VOXEL PHANTOM

The radiation source in the USTUR Case 0102 phantom, Americium-241, is present in the skeleton. Total activity in the leg phantom is 1243.4±10.9 Bq (USTUR, 2010). This value is a sum of activities of different bone sections of the right pelvis, leg, and foot as dissected prior to the radiochemical analysis. The activity values are scaled based on results from the right leg. The radiochemical analysis data shows that ²⁴¹Am concentration varies among the anatomical structures of the bone. These values will be used to model the activity distribution in bones of the virtual phantom. Different bone sections of the right pelvis, leg, and foot are shown in Fig. 2.

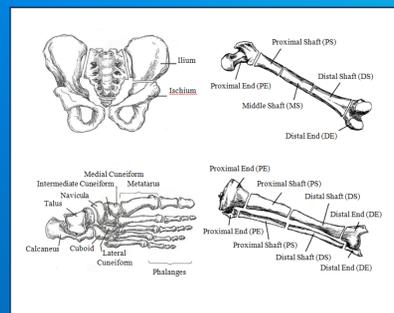


Figure 2. Pelvis, Leg, and Foot dissection prior to the radiochemical analysis (McInroy et al., 1985)

RESULTS

²⁴¹Am POINT SOURCE MEASUREMENT

The point source experiment was performed with a source lying at a fixed distance (19.05 cm) from the central surface point of the LEGe, along its main axis. The source and background were both counted for 10 minutes; corresponding energy spectrum is shown on Fig. 3.

The external gamma detector geometry is modeled using the Geant4 with detector specific volume and dimensions, as provided by the manufacturer (Fig. 4). Computational model of the ²⁴¹Am source was also created using the radionuclide information and physical descriptions available in the source certificate of calibration.

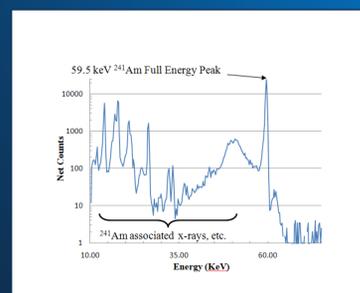


Figure 3. Experimental response of the LEGe to externally positioned ²⁴¹Am point source .

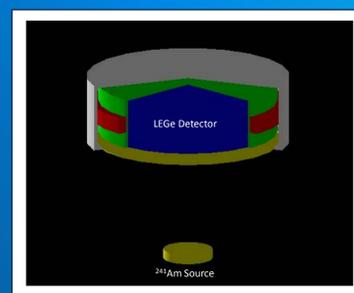


Figure 4. Geant4 cross-sectional view of the Canberra LEGe detector and ²⁴¹Am Source

USTUR CASE 0102 VOXEL PHANTOM GEOMETRY

Bone and tissue equivalent structures of the USTUR Case 0102 ²⁴¹Am Leg phantom have been successfully contoured using the Eclipse auto-segmentation algorithm. The three-step segmentation procedure involved: defining the regions of interest and establishing the HU (Hounsfield Unit) values for different anatomical structures; auto-segmenting; and finally, manually checking and as necessary re-segmenting certain regions. To represent activity variation in different bone sections, new regions of interest were objectively contoured in skeleton of the phantom (Fig.5.). The final geometry has been exported to the DICOM-RT format so that it can be incorporated into the Geant4 code. The DICOM-RT data format is similar to the DICOM data format; however, it additionally contains application specific information. In this case, ranges of HU units and positions of the contoured structures are stored in the dataset.

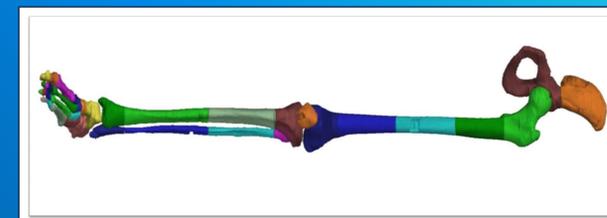


Figure 5. Three-dimensional voxel image of segmented bone regions in the USTUR Case 0102 leg phantom

FUTURE WORK

- Verification of detector geometry and physical processes associated with the radioactive decay of ²⁴¹Am.
- Development of an appropriate algorithm to introduce ²⁴¹Am uniformly within the bone structure, and to take into account the variation of activity and concentration in each section of bones of the phantom skeleton.
- Verification of the accuracy of the model by comparing the results of the simulation with experimental measurements.
- Calculating the ratio of detection efficiency of ²⁴¹Am concentrated in each bone section to the efficiency from the total skeletal distribution.

CONCLUSION

In this study a 3D voxelized phantom has been developed, using the Eclipse radiotherapy planning software, which provides a basis for tracking ²⁴¹Am distribution across the skeleton. Geant4 proves to be a useful tool for modeling simple solids as well as implementing complicated voxelized geometries. Using the object-oriented programming, raw DICOM data may alternately be incorporated into the Geant4 code, thus skipping some image processing steps required when building the geometry file format necessary with other Monte Carlo simulation codes. Thus, all necessary image manipulation steps can be done within the code. The ability to model radioactive decay is a great feature of the code which allows avoiding all decay products to be modeled individually.

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