



# USTUR Case 0102 CT Image Processing Techniques For Voxel Phantom Development

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## ABSTRACT

A 3D voxel model of the United States Transuranium and Uranium Registries' (USTUR) Case 0102 <sup>241</sup>Am phantom has been developed. The phantom which was created using half the skeleton from Case 0102 has served as a unique standard for intercomparison of external counting systems at United States DOE facilities and other laboratories world-wide. High resolution (0.5mm) Computed Tomography (CT) images of the USTUR Case 0102 phantom provide the physical basis for precisely defining the internal structure of the bones in the donor subject. DICOM (Digital Imaging and Communications in Medicine) images of the phantom (head, torso, arm, and leg) have been segmented using the Eclipse® radiotherapy planning software. This has a robust automatic segmentation feature. The three-step segmentation procedure involved: defining the regions of interest and CT numbers for different anatomical structures; auto-segmenting the Dicom images, and; manually correcting any errors in the auto segmentation results. Each Dicom image was segmented into the following regions of interest: air pockets, cortical bone, bone cavities (marrow/trabecular spongiosa), and soft tissue. Soft tissue was subdivided into 'light' and 'regular' regions to represent inhomogeneities (artifacts) that occurred when the phantom was cast in nominal ICRU tissue equivalent plastic. The range of CT numbers in each region of interest was replaced by a single characteristic CT number. All structures of the phantom were exported to the DICOM-RT format. The voxel representation of the phantom is now ready for use in the Geant4 Monte Carlo code to simulate the experimental response of external planar germanium detectors.

## INTRODUCTION

Whole body counting gamma spectrometry is one of the specialized techniques for monitoring internal organ content of various radionuclides. This technique, performed with high-purity germanium detectors (high counting efficiency), allows a fast assessment of the activity in the body for a wide energy-range of gamma emitters. Calibration of a whole body counting system is usually based on the use of plastic phantoms which contain a known amount of activity. However, questions about the adequacy of calibration for individuals of different body size and shape consistently arise.

This question might be resolved by developing computational phantoms representing individuals of various body types (ectomorphs, mesomorphs, and endomorphs). These voxel geometries can be incorporated into a Monte Carlo code to estimate detector efficiencies.

The two most widely used classes of an anthropomorphic computational phantom are; stylized and voxel phantoms. While flexibility for changes in organ shape and positioning can be best achieved with stylized phantoms, they are limited by their inability to fully capture complex anatomic structures. Voxel phantoms can better describe anatomical complexities, but are limited when defining (contouring) organs within low resolution CT images (Lee et al., 2007).

The USTUR Case 0102 voxel phantom for use in the Geant4 Monte Carlo code can be modified (scaled) to represent individuals of different body types. Using this voxel representation counting efficiency can be calculated for detectors variously positioned over the extremities of the phantom (head, torso, arm, and leg phantoms).

## MATERIALS AND METHODS

Monte Carlo Simulation of radiation transport in the voxelized geometry can be handled using different codes including: EGS, MCNP, and Geant. Regardless of the code used, the following two steps are encountered. First one must build the voxel geometry. Second one must define the source and the detector. Based on the Monte Carlo code used for the particular application, the file format of the input geometry may vary. A raw DICOM data set undergoes multiple image processing steps, including: the segmentation (classification into different regions of interest) of the DICOM images, development of a 3D surface model (Non-Uniform Rational B-Spline, NURBS), and image voxelization. These steps simplify a voxel geometry in order to reduce the computer resources and time of the simulation process.

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. When using Geant4, voxels are characterized independently, meaning that additional organ or structure information is not necessary. The radiation source in the USTUR Case 0102 phantom, Americium-241, is present in the embedded bones. So for more accurate source characterization, all structures of the phantom have to be contoured. This is a process in which voxels are grouped into structures.

## DICOM IMAGE PROCESSING

Image contouring is perhaps the most time consuming step of the process. During the contouring, organs are defined within the image using the manual or automatic contouring technique. Several different programs are commonly used for segmentation: IDL (Interactive Data Language), 3D Doctor, and Eclipse. However, the Eclipse Treatment Planning System<sup>1</sup> has more robust contouring algorithms than IDL or 3D Doctor – and a 3-dimensional voxel image of the regions of interest in the USTUR Case 0102 <sup>241</sup>Am phantom has been successfully created<sup>2</sup> using this auto-segmentation algorithm. The auto-segmentation process is shown on Fig.1.

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. Each DICOM image was segmented into the following regions of interest:

- Air Pockets
- Cortical Bone
- Bone Cavities - Marrow/Tabecular spongiosa
- Tissue – Light and Regular



Figure 1. USTUR Case 0102 head phantom contouring performed with Eclipse Treatment Planning System

Tissue regions are subdivided into Light and Regular due to inhomogeneities that occurred when the USTUR Case 0102 head phantom was cast in nominal ICRU tissue equivalent plastic.

The following structures were objectively defined using the CT data alone: Air Pockets, Light Tissue, Regular Tissue, and Osseous. The HU guidelines used for the contouring were as follows:

- Air (-1000 to -500)
- Light Tissue (-500 to -100)
- Tissue Equivalent (-100 to 250)
- Osseous (250 to 3071)

The following structures were manually contoured:

- Osseous
- Cortical Bone (540 to 3071)
- Bone Cavity (contoured using a boolean operation of Osseous minus Cortical Bone)

Certain discontinuities were observed in the segmented phantom. The Bone Cavity contains trabecular bone and marrow and, the Osseous structure has a skeletal appearance instead of containing the density defects that are present in the actual DICOM phantom data. A segmented image of the USTUR Case 0102 phantom is shown on Fig. 2. After the segmentation of the phantom is complete the data are exported into the DICOM-RT format. 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, positions of the contoured structures, and dose distribution curves within the phantom images are stored in the dataset. The dose distribution curves are automatically generated during the segmentation process and they have no possible use in this project, therefore they were ignored.

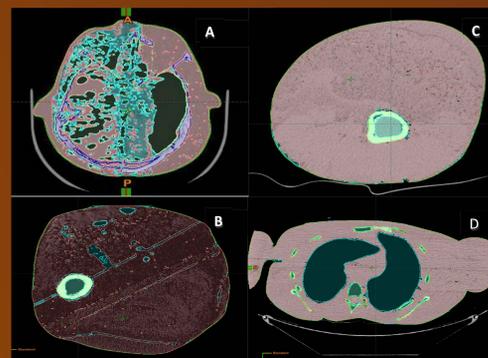


Figure 2. USTUR Case 0102 A) head, B) leg, C) arm, and D) torso phantom contouring performed with Eclipse Treatment Planning System

## EXTERNAL GAMMA DETECTOR RESPONSE SIMULATION

The objective of this project was to build a 3-Dimensional voxel geometry of the Case 0102 <sup>241</sup>Am phantom in order to simulate the experimental response of external planar germanium detectors variously positioned over the head, knee, ankle, and wrist of the phantom.

Geant4 software is based on object oriented technology. It allows a flexible approach for incorporating the different geometries into the code. The Geant4 simulation toolkit was 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).

DICOM file type structures vary among manufacturers. Hence, it often becomes necessary to develop a new DICOM file “reader” for each file format. A DICOM interface for Geant4-based simulation has been developed by Kimura et al. The code is able to handle DICOM data files and it allows target volume modeling. Furthermore, the ability to handle the DICOM-RT format was specifically incorporated into this code (Kimura et al., 2004).

After the USTUR Case 0102 DICOM images were imported into the Geant4 code, the source and detector terms needed to be defined. The Geant4 Simulation Toolkit includes a model to describe the interactions of low energy photons, electrons, hadrons and ions with matter. 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 60 keV photons emission from the <sup>241</sup>Am source which is distributed in the skeleton of the USTUR Case 0102 phantom.

The external gamma detector geometry is represented using detector specific volume and dimensions, as provided by the manufacturer. This allows the counting efficiency of different detector types and configurations to be modeled. The counting efficiency of each detector is determined by taking the ratio of the number of events generated within the source region to the number of interactions recorded within the detector volume.

The counting efficiency of the external detectors can also be simulated for people of various anatomical build and body size differing from the USTUR Case 0102 phantom. This is achieved by adding a virtual layer of the tissue equivalent material on to the existing geometry of the voxel phantom. Two methods considered for creating an additional layer are: 1) adding a solid layer of tissue equivalent material to the voxel geometry; 2) “cloning” the existing tissue voxels of the phantom to reach a predefined thickness.

## RESULTS

The CT-images of the USTUR Case 0102 phantom have been successfully segmented with the Eclipse Radiotherapy Treatment Software. The contouring of the Air Pockets, Light Tissue, Regular Tissue, and Osseous structures was achieved by using a predefined range of HU values. The Osseous structure was modified manually across all slices of the CT data to more precisely describe the bone anatomy. Using the contouring algorithms, the Cortical Bone was captured in the structure called Bone by first using the range of 540 HU to 3071 HU and then limiting the structure to and logically within the Osseous structure. The Marrow Cavity that contains the trabecular bone and bone marrow was defined by subtracting the Bone structure from the Osseous. The final geometry has been exported in the DICOM-RT format. Fig. 3 shows a 3-dimensional voxel images of the regions of interest in the USTUR Case 0102 phantom.

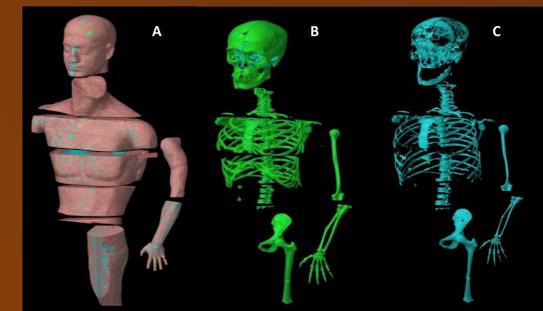


Figure 3. Three-dimensional voxel images for A) all regions of interest, B) cortical bone voxels only, and C) marrow/trabecular spongiosa voxels only.

## WORK IN PROGRESS

The USTUR Case 0102 segmented data set (DICOM-RT) is being imported into a data file structure compatible with Geant4. The external gamma detector geometry is being built for several different detector types. An appropriate algorithm will be developed to implement the voxelized phantom and a detector geometry within the code. The source will be introduced uniformly in the skeleton of Case 0102 phantom. The fact that only half of the skeleton contains <sup>241</sup>Am will be taken into account.

The purpose of the project is to determine the counting efficiency for external gamma detectors. Detector efficiency will be calculated for various detector designs and locations external to the extremities of the voxel phantom. Results of the simulation will be compared to experimental data to verify the accuracy of the model. Finally, estimates of the counting efficiency for different size individuals will be generated.

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<sup>1</sup>Developed by the Varian Medical, Palo Alto, CA

<sup>2</sup>This software is used for advance radiotherapy treatment planning at Portneuf Medical Center, Pocatello, ID