CT2MCNP: An Integrated Package for Constructing Patient-Specific Voxel-Based Phantoms Dedicated for MCNP(X) Monte Carlo Code

A. Mehranian[1], M.R. Ay[1,2,3], and H. Zaidi[4,5]

[1] Tehran University of Medical Sciences, Research Center for Science and Technology in Medicine, Tehran, Iran
[2] Tehran University of Medical Sciences, Department of Medical Physics and Biomedical Engineering, Tehran, Iran
[3] Tehran University of Medical Sciences, Research Institute for Nuclear Medicine, Tehran, Iran
[4] Geneva University Hospital, Division of Nuclear Medicine, Geneva, Switzerland
[5] Geneva University, Geneva Neuroscience Center, Geneva, Switzerland

Abstract— **We introduce a fast and well-structured package for constructing voxel-based computational phantoms as MCNP(X) input file based on CT DICOM images. Our program which has been implemented under a graphic user inter-face provides several basic image processing tools for manipulating images. The MCNP materials are interpreted from the CT numbers of DICOM images. Two modes of phantom creation have been provided using individual cells and lattice. In the former, the program uses a fast merging algorithm for reducing the number of cells and in the latter, an optimized approach has been followed. This software has strong potential in applications in radiologic, dosimetry and therapeutic MCNP- based Monte Carlo studies.**

Keywords— **anthropomorphic phantoms, voxel-based models, Monte Carlo simulation, MCNP.**

I. Introduction

Anthropomorphic computational phantoms have recently served an important role in improving the effectiveness of radiation treatments in radiotherapy and the correctness of image processing algorithms in diagnostic radiology [1, 2]. They can be defined by either mathematical functions (stylized phantoms) or digital volume arrays (voxel-based phantoms) [3] or a combination of both (hybrid phantoms) [4]. The stylized phantoms are approximate mathematical fits to the shape and volume of actual organs. They do not faithfully represent realistic organ anatomy as exits in individual patients. Whereas voxel-based phantoms, constructed from segmented tomographic medical images such as magnetic resonance (MR) images or computed tomography (CT), can more realistically describe the human anatomy than afforded via stylized equation-based phantoms. By increasing the computing power of micro-processors and expanding the memory capacity of computers, the voxel-based phantoms has attained so popular acceptance that ICRP Publication 110 is recently published to recommend replacing the stylized phantoms by voxel-based computational phantoms [5]. Integrating the anatomical characteristics of specific patients into Monte Carlo radiation codes is now an integral part of modern radiotherapy treatment planning systems where patient's CT images is used for treatment planning, localization and dose assessments.

A number of groups have developed programs for creating voxel anthropomorphic model geometry into Monte Carlo code. We describe a new program called CT2MCNP (Computed Tomography to MCNP Monte Carlo radiation transport code) with enhanced features in creating voxel-based phantoms from DICOM CT images into 3-dimensional Cartesian coordinate system of MCNP(X) geometry. This software which is written under MATLAB (Math Works Inc., Natick, MA, USA) reads a sequence of tomographic scans from DICOM files and prepares the geometry and material sections into an MCNP or MCNPX input file. Basically, the creation of a tomographic model involves four general steps: (a) Acquire a set of medical images, (b) classify and segment the organs or tissues of interest for the application at hand (e.g., lungs, liver, skin, etc.) from the original images by assigning voxel with unique identification numbers, (c) specify tissue type (e.g., soft tissue, hard bone, air, etc.) and composition to organs or tissues, and (d) implement the geometric data into a Monte Carlo code to calculate radiation transport and score quantities of interest (e.g., dose in each of the organs of interest) [6].

In the following sections we first introduce the MCNP code and its geometry definition package and then about the above basic steps implemented in CT2MCNP and supplemental features fed into this software.

II. MCNP Monte Carlo Code

MCNP is a general-purpose and internationally recognized code for Monte Carlo (MC) radiation transport, developed and maintained at Los Alamos National Laboratory [7]. It uses a flexible scheme in geometry definition in which geometrical volumes, known as cells, are primarily defined by Boolean combination of signed half-spaces

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which are delimited by first, second and fourth degree surfaces in a three-dimensional Cartesian coordinate system. In this geometry definition, surfaces are in turn designated by special characters followed by appropriate coefficients needed to meet the surface equation. As an example, a cube can be defined by Boolean intersection of six planes (first degree surfaces). Cells are the basic tool for the geometric construction for any problem in MCNP and, as said, comprise of combinations of surfaces. Furthermore, MCNP employs a special feature called Repeated Structures whose basic concept is that generic geometrical shapes can be built by the repetition of one or a group of cells. Using this feature, even irregular shapes can be reproduced. In repeated structures feature, each cell can be filled with a *universe*, which can represent a lattice or collection of cells. To each universe, an identification number (ID) is assigned so that every cell belonging to this universe is associated with this number. This feature has been used for constructing voxel-based phantoms such that each cell, or strictly speaking, each *universe* to which cell belongs represents one voxel of human body[8]. The geometry and graphical capabilities of MCNPX do not fundamentally differ from the standard MCNP code and thus remains the same.

III. DICOM STANDARD

The DICOM (Digital Imaging and COmmunications in Medicine) standard is the fundamental standard in digital medical imaging and communicating [9]. As such, it provides all the necessary tools for the diagnostically accurate representation and processing of medical imaging data. In the first step of construction of a patient-specific phantom, CT2MCNP reads patient's CT DICOM images which may consist of either a series of files each containing a single image or a single file that contains multiple image frames. When importing a series of files, it first verifies that each file or files has a Service-Object Pairs Class UID that corresponds to a CT image. It then checks several features of each file to verify that they belong to the same image study, by comparing the Series Instance UID, Study ID and the Series Number. Each file is then consistency checked by comparing various fields such as pixel rows, pixel columns, pixel spacing, etc. to make sure that the image presentation is identical for each image file.

IV. IMAGE MANIPULATION FEATURES

Initially, some basic image processing tools have been predicted in our software and impeded into a user graphic interface (GUI). At this section we treat to some of the implemented tools.

A. Windowing

To improve display contrast visibility, window level (WL) and window width (WW) setting is provided for user along with Window/Level Presets that are a scrollable list of available presets that can be applied with a single click to the image display window.

B. Image Cropping

Image slices can be cropped by a rectangular crop region to remove unwanted portions from an image or for a set of images. Thus pixels outside the crop region are not used when generating MCNP geometry. Furthermore, it has planned to improve this feature by cropping with user-defined region of interest (ROI) to remove those portions.

C. Image Reslicing

Reslicing a series of DICOM image is often required to visualize the three orthogonal views: transverse, coronal, and sagital. CT2MCNP provides reslicing option by which user can observe images in these orthogonal views at different slices.

D. Image Resizing

The image matrix sizes may keep the default CT resolution (512x512) or it can be reduced to a 256 × 256 or 128 × 128 matrixes. Resizing images (down-sampling) may be accomplished by nearest- neighboring, bilinear and bicubic interpolation methods or pixel binning (summing the intensities together).

V. MCNP INPUT GENERATION

Each pixel in medical images represents a tissue volume in a 2-D plane. The 3-D volume of the tissue is termed a voxel (volume element), and it is determined by multiplying the pixel size by the thickness of an image slice. Unlike stylized whole-body models, a tomographic model contains a huge number of tiny cubes grouped to represent each anatomical structure. In the next step of generation of a voxel-based phantom to each voxel of image dataset a unique tissue/organ ID is assigned which is then interpreted as an MCNP material.

A. Material Mapping

The MCNP materials are interpreted from Hounsfield Unit (HU) values or CT numbers in the DICOM dataset. The CT numbers are grouped into 6 subsets that are dosimetrically

equivalent and then an identification number is assigned to each of them. Therefore each pixel's CT number is mapped to a specific ID representing a material. The composition fractions and density of each material is then loaded from a material library derived from ICRU 44 [10] and imported to MCNP input file in the form of material card number followed by atomic number and atomic fractions.

B. Conversion Modes

The specification of phantom geometry, its composition and radiation source must all be put together in three main blocks on MCNP deck input file, namely, cell card, surface card and data card. When CT numbers in input images were mapped to ID numbers, CT2MCNP provides two schemes for defining the geometry of phantom into MCNP input file called XYZ intersection and Lattice method.

- XYZ intersection method

In this mode, individual rectilinear cells are defined from arrangements derived from the tissue ID-mapped DICOM dataset by Boolean intersection of six planes (first-degree surfaces). In this method, to reduce the total number of cells without scarifying the anatomical details and thus increasing the efficiency of the MCNP, a very fast cell merging algorithm is used to combine cells in to a larger cell. Cells are merged if they share a common boundary, are bounded by the same surfaces in the directions perpendicular to the common boundary, and contain the same material. The cell merging algorithm first searches for candidate cells with common boundaries in the X direction, then in the Y direction, and then Z direction (between slices). The cells along with their attributes (cell number, material, density and particles' importance) are written on cell block of input file. The surfaces bounding cells along with their coefficients required to meet the equation of each surface are then written in surface card and finally material card is written in data card. Figure 1 shows the operation of this conversion mode Zubal phantom [11] in which each color represent a unique material by which organs are delineated. This image has been depicted in MCNP4C code. Zubal phantom is a computational human body model derived and segmented from CT image. It consists of a 3-dimensional array of 128 × 128 × 246 (4,030,464) cubic voxels, 4 mm on each side. Multiple internal organs and structures were identified by Zubal *et al.* and related to an index number for each voxel. The XYZ intersection module defines this phantom into MCNP environment by 52,634 cubic voxels in a fairly short time (~15 seconds on a Pentium IV dual core PC with 2.6 GHz CPU and 2 GB RAM).

- Lattice method

The repeated structures representation is employed in this mode of conversion which eliminates the MCNP's limit for the number of cells in the phantom model. The definition of the rectangular space lattice of voxels is the heart of the voxel phantom setup. The procedure is initiated by defining a lattice whose number of rows, columns and its third dimension is the same as those of the processed DICOM volumetric dataset. The dimensions of the phantom elementary voxel are determined based on patient dimensions, slice thickness and the amount of image size down-sampling. In the next step, each voxel (cell) is filled by a universe to which an ID or material number has been assigned. Based on the IDs on the slices of the image, the algorithm written for this mode construct an fill array comprising of a large number of IDs by which MCNP fills each voxel by the universe to which the ID belongs. When one row of the lattice was filled, the next rows are in turn filled. Fig. 2 shows a cut of an anthropomorphic Zubal phantom defined into MCNP using lattice method.

The particle tracking in lattice-base geometry is slightly slower than in conventional surface-sensed geometry. To speed up the tracking and consequently decreasing MCNPs' execution time, the filling universes were defined by a

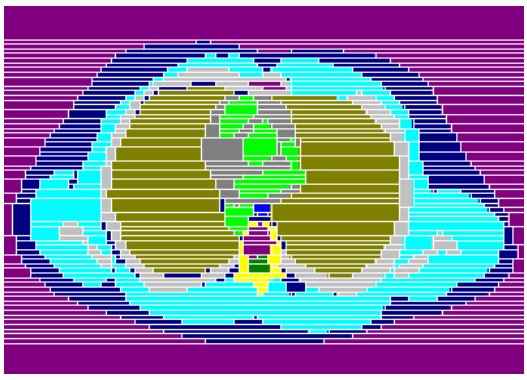

Fig. 1 An MCNP transverse geometry plot from the anthropomorphic phantom converted by XYZ intersection module

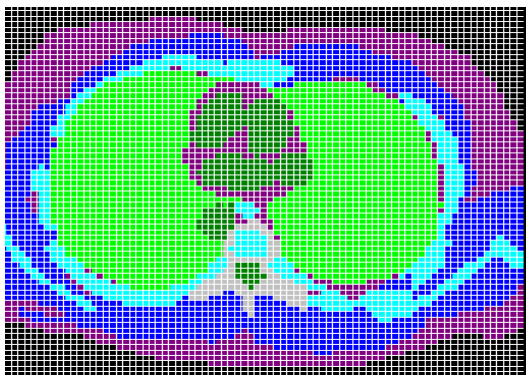

Fig. 2 An MCNP transverse geometry plot from the anthropomorphic phantom converted by lattice module

single plane far away from phantom's body. Traditionally a single spherical cell and a space out of it is used for defining universes which is take more memory and slows down the speed of execution.

Phantoms defined by lattice mode are of importance for internal dosimetry where the distribution of dose to organs near an internal radiation source or plotting isodose curves is sought. Whereas phantoms defined by XYZ intersection mode may find applications in absorbed dose in each organ for external irradiation in a faster simulations. Fig. 3 shows CAD visualizations of the lung and heart of Zubal's phantoms converted by XYZ intersection mode. As seen in cut-away views, the merging algorithm combines neighboring cells in an optimized way in three directions. The CAD visualization was translated from MCNP input file using MCAM software, an integrated interface program between CAD systems and Monte Carlo simulation codes (FDS Team, China [12]).

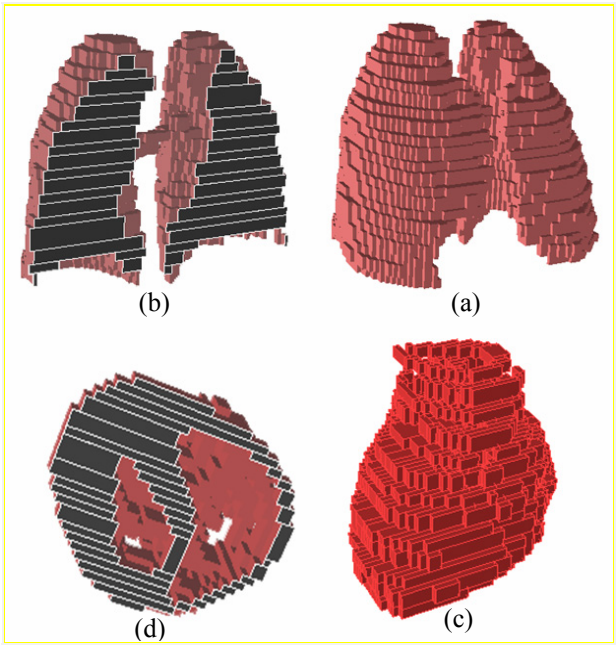

Fig. 3 CAD visualization of the performance of XYZ intersection conversion mode. (a) 3D views of lung and (b) its coronal cut-away view, (c) heart and (d) its transverse cut-away view

VI. Conclusions

CT2MCNP provides a MATLAB-based graphical user interface to create voxel-based phantom from CT DICOM images into MCNP's environment. It employs two conversion modes called XYZ intersection and Lattice methods which exploit optimized algorithms in geometry definition. The program provides some basic image processing tools. It is currently under the evaluation and development and soon will be enhanced with new features such as segmentation tools, measurement and displaying tools along with tallying capabilities.

References

1. Williams G, Zankl M, Abmayr W, et al. (1986) The calculation of dose from external photon exposures using reference and realistic human phantoms and Monte Carlo methods. Phys Med Bio 31:449–452
2. Peter J, Tornai M, Jaszczek R. (2000) Analytical versus voxelized phantom representation for Monte Carlo simulation in radiological imaging. IEEE Trans Med Imaging 19:556–564
3. Huh C, Bolch WE (2003) A review of US anthropometric reference data (1971–2000) with comparisons to both stylized and tomographic anatomic models. Phys Med Biol 48:3411–3429
4. Lee C, Lodwick D, Hasenauer D, et al. (2007) Hybrid computational phantoms of the male and female newborn patient: NURBS-based whole-body models. Phys Med Biol 52:3309–3333
5. ICRP Publication 110 (2009) Adult reference computational phantoms. 39(2):1–166
6. Zaidi H, Xu X G, (2007) Computational Anthropomorphic Models of the Human Anatomy: The Path to Realistic Monte Carlo Modeling in Radiological Sciences. Annu Rev Biomed Eng 9: 471-500
7. Briesmeister J F, (2000) MCNP–A general Monte Carlo N-particle transport code. Los Alamos National Laboratory LA-13709-M
8. Yoriyaz H, Santos A, Stabin M G, Cabezas R, (2000) Absorbed fractions in a voxel-based phantom calculated with the MCNP-4B code. Med Phys 27:1555–1562
9. Digital Imaging and Communications in Medicine (DICOM) at http://medical.nema.org.
10. ICRU Publication 44 (1989) Tissue Substitutes in Radiation Dosimetry and Measurement.
11. Zubal G, Harrell C, Smith E, et al, (1994) Computerized three-dimensional segmented human anatomy. Math Phys 21:299-302
12. Wu Y, (2009) CAD-based interface programs for fusion neutron transport simulation. Fusion Eng Des 84:1987–1992

Author: Mohammad Reza Ay
Institute: Tehran University of Medical Sciences
Street: Pour Sina
City: Tehran
Country: Iran
Email: mohammadreza_ay@tums.ac.ir