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DETERMINISTIC 3D RADIATION TRANSPORT SIMULATION FOR DOSE DISTRIBUTION AND ORGAN DOSE EVALUATION IN DIAGNOSTIC CT

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ABSTRACT

Over the past quarter century, there has been an impressive growth both in the number of diagnostic x-ray examinations and the introduction of newer, very valuable imaging modalities and equipment. However, this dramatic evolution of imaging has also resulted in a significant increase in the population's cumulative exposure to ionizing radiation. There is therefore a serious demand for more accurate, patient specific dose evaluation methods for diagnostic imaging. To serve this goal, we developed PENTRAN-MP, a specialized code package for medical physics applications based on deterministic radiation transport simulations that proved to be, in certain circumstances, a more convenient alternative to the popular, in the field, Monte Carlo methods. This work presents the whole body dose distribution and doses to the most radiosensitive organs resulted from a simulated abdomen CT scan using the PENTRAN-MP code system and one of the UF Series B tomographic human phantoms (11 year old male).

KEYWORDS: diagnostic imaging, 3D dose distribution, organ dose, deterministic radiation transport simulation

1. INTRODUCTION

Ionizing radiation has been used for diagnostic purposes for more than a century. The benefits are immense and certainly exceed the risks. The more recent development of remarkable equipment such as multidetector row computed tomography (MDCT) along with other new modalities revolutionized the practice of medicine, but also significantly increased the patient dose. Consequently, there is increasing interest in the scrutiny of radiation dose from imaging procedures and hence need for accurate, patient-specific dose evaluation methods. Although Monte-Carlo-based radiation dose calculation is considered by many to be the only accurate method for computing radiation doses in human tissues, the Monte Carlo technique may be too computationally expensive for use in many applications, and may not provide desirable accuracy when the computations employ approximation necessary to carry out radiation-dose calculations within the time constraints imposed by real-word applications.

An alternative to Monte-Carlo-based radiation dose calculation is the deterministic solution of the Boltzmann equation that models radiation transport through materials. A common approach for calculating radiation doses using the Boltzmann equation is known as "discrete-ordinates." This approach discretizes the radiation-transport problem in space (finite-difference or finite-element), angle (discrete-ordinates), and energy (multi-group cross sections), and then iteratively solves the differential form of the transport equation in a discrete, multi-dimensional space.

In this work we present whole body dose distribution and doses to the most radiosensitive organs resulted from a simulated abdomen CT scan using the PENTRAN-MP code system and one of the UF Series B tomographic human phantoms (11 year old male).

2. METHODOLOGY

To conduct accurate patient dose attribution, we performed 3D deterministic radiation transport simulations in a highly detailed anatomical model obtained from one of the high-resolution voxelized human phantoms in place at UF.

2.1. UF Series B Pediatric Phantoms

The UF Advanced Laboratory for Radiation Dosimetry Studies (ALRADS) has a very well established background in work with detailed human phantoms and phantom data. Following the development of their *CT-Contours* segmentation software, and the construction of their first tomographic dosimetry model (UF Newborn), ALRADS research team focused on constructing an expanded series of pediatric tomographic phantoms (Series B Phantoms), this time using live patient CT images from the Shands image archive. A total of five additional phantoms have been constructed from CAP (chest – abdomen - pelvis) and head CT scans of pediatric patients examined at the University of Florida (UF) Shands Children’s Hospital. Patient inclusion criteria included those patients displaying normal or near-normal anatomy at their respective age and gender (e.g., avoidance of regions of tumor, edema, organ enlargement). After completion, the resolutions of the phantoms for the 9-month, 4-year, 8-year, 11-year and 14-year were set at 0.86mm×0.86mm× 3.00 mm, 0.90 mm × 0.90 mm × 5.00 mm, 1.16 mm × 1.16 mm × 6.00 mm, 0.94 mm × 0.94 mm × 6.00 mm and 1.18 mm × 1.18 mm × 6.72 mm, respectively. While the previous phantoms preserved the body dimensions and organ masses as seen in the original patients who were scanned, comprehensive adjustments were made for the Series B phantoms to better match International Commission on Radiological Protection (ICRP) age-interpolated reference body masses, body heights, sitting heights and internal organ masses.

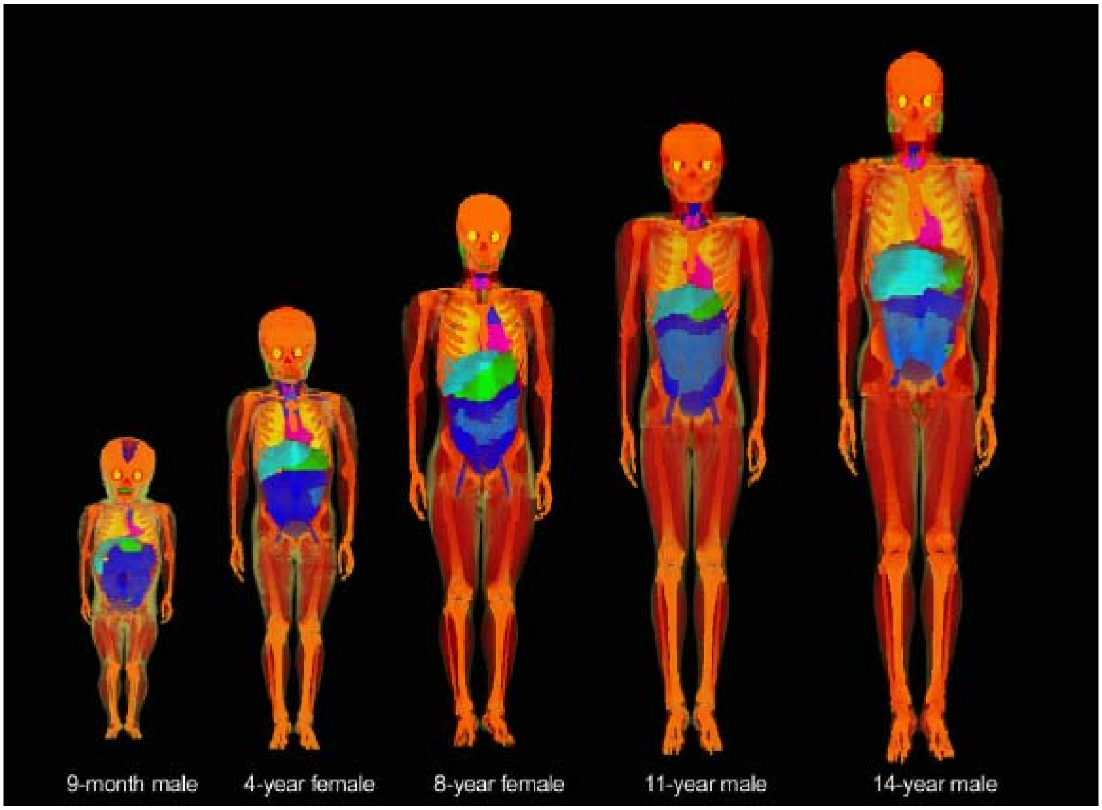

Figure 1. The UF Series B pediatric phantoms series (9-months, 4-years, 8-years, 11-years and 14-years old patients).

2.2 PENTRAN-MP Code System

Currently, the PENTRAN-MP code system contains pre-processing algorithms that include the GHOST-3D phantom voxel collapsing (back-thinning) code, the DXS x-ray source generation code, the PENMSH-XP 3D mesh distribution, material balance, and problem input generator code, and the CEPXS (a product of Sandia National Laboratories) assisted by GREPXS to generate multigroup cross sections.

2.2.1 Benchmarking of PENTRAN-MP calculations by equivalent MCNP5 simulations

A preliminary validation of our deterministic methodology was done by performing two sets of transport simulations on similar models, employing the MCNP5 Monte Carlo and PENTRAN S_N methods, respectively.

Calculations were performed to compare the S_N and Monte Carlo results for the scalar fluxes along the source central axis and in the source region along the z axis at different depths for different energy groups. Fig. 2 depicts a 3D scalar flux distribution computed by PENTRAN for the reference case. This simulation was based on the use of an S_{32} angular Legendre-Chebychev quadrature (1088 directions/mesh) with

As shown in Fig. 2, the PENTRAN results with S_{32} Legendre-Chebychev quadratures, P_3 scattering anisotropy and 8 energy groups are in very good agreement with the parallel MCNP5 meshtally in source region converged to <6 % and typically < 2% for most of the results for the reference case. Overall, this figure shows that deterministic techniques are capable of producing accurate results within the statistical error of Monte Carlo methods where Monte Carlo methods can produce a solution with an acceptable stochastic error.

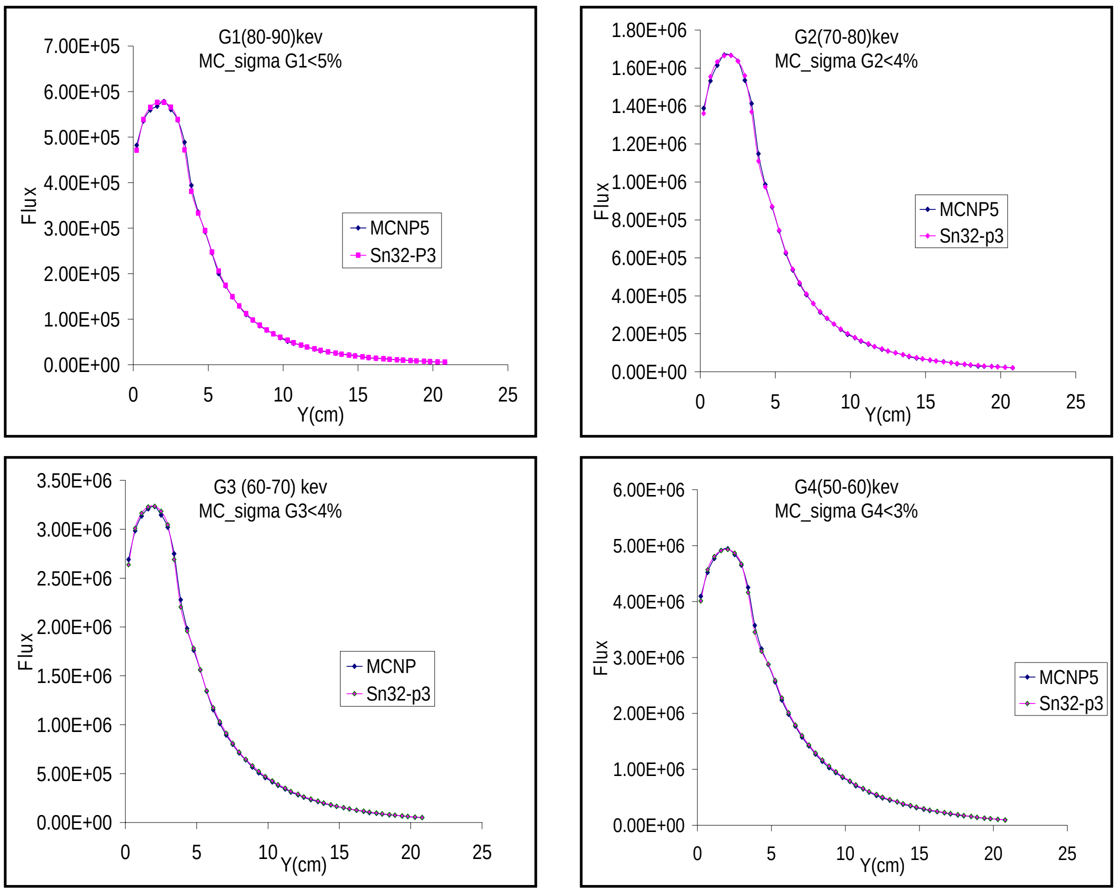

Figure 6. Angular flux distributions using S_{32} with P_3 scattering anisotropy in PENTRAN using the CEPXS library vs MCNP5 Monte Carlo results for energy groups 1, 2, 3 and 4 along the source central axis.

2.3 CT scan computational model

3. RESULTS AND DISCUSSION

4. CONCLUSIONS

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