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Calculation of absorbed doses from computed tomography in pelvic phantom using Monte Carlo Simulation

Janejirarak Ritpanja[1,4] **Phiphat Phruksarojanakun**[2] **Waraporn Sudjai**[3] **Chayanit Jumpee**[4*]

[1]*Department of Diagnostic Radiology, Lampang Cancer Hospital, Lampang Province, Thailand*
[2]*Office of Atoms for Peace, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand*
[3]*Thailand Institute of Nuclear Technology (Public Organization), Nakorn Nayok Province, Thailand*
[4]*Department of Radiologic Technology, Faculty of Associated Medical Science, Chiang Mai University, Chiang Mai Province, Thailand*

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ABSTRACT

Background: Computed Tomography (CT) is an effective diagnosis method which deposits high absorbed doses on internal organs; therefore, it is necessary to understand dosimetry nature of this method.

Objectives: To improve CT absorbed dose estimation by using a more appropriate phantom representing a human body and a Monte Carlo transport code.

Materials and methods: The Monte Carlo N-Particle transport code Version 5 or MCNP5 is used in this study to simulate a Rando phantom representing pelvic section of a patient in a CT procedure. Absorbed doses of various internal organs from MCNP5 are compared with standard experimental measurements based on the InLight nanoDot dosimeters.

Results: CT absorbed dose between MCNP5 simulation and standard experiment measurement are mostly in reasonable agreements within 10-percent discrepancy except those at skin positions.

Conclusion: Further study is recommended for calculating absorbed doses at skin positions, MCNP5 is practically reliable for estimating absorbed doses in a number of internal organs. The MCNP5 simulation is one of alternative method to evaluate patient radiation dose which helps radiology team manage diagnosis and treatment planning.

Introduction

In recent years, computed tomography (CT) is one of the most important image modalities for medical diagnosis since its image outputs can provide a physician thorough understanding of internal organ that cannot be achieved through a traditional 2-D imaging method. However, this practice inevitably comes at the expense of high-level X-ray exposure from many different radiation angles. Effective doses resulting from CT scan can vary from 2 to 16 mSv, depending on organ range examination.[1] As an alternative measurement of effective dose on a particular organ, an absorbed dose has recently been used to assess a radiation risk on a patient.[2] Traditionally, CT dose index (CTDI) is employed to calculate CT absorbed doses. However, CTDI is limited by its physical geometry as it only contains two cylindrical objects made of homogeneous polymethyl methacrylate (PMMA) phantom (CTDI phantom) representing head and trunk. This study aimed to improve CT absorbed dose estimation by using a more appropriate phantom representing a human body and a Monte Carlo transport code.

* **Corresponding author.**
Author's Address: *Department of Radiologic Technology, Faculty of Associated Medical Science, Chiang Mai University, Chiang Mai province, Thailand.*
** **E-mail address:** chayanit.j@cmu.ac.th
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Materials and methods

Absorbed Dose Measurement in Rando phantom

The InLight nanoDot dosimeters which is a crystal of $Al2O3:C$ compound of Optically Stimulated Luminescence Dosimeter (OSL nanoDot) were positioned inside the Pelvic-Rando phantom (10 slices, 2.54 cm/slice) to represent 19 position of internal organs (Table 1). Rando phantom is modelled after anatomical characteristics of the reference man and consists of a real human skeleton embedded in soft tissue equivalent material. Figure 1 shows all slabs of pelvic Rando phantom (Left) and dosimeter holder together with OSL nanoDot (Right). The duplicate 19 OSL nanoDot were irradiated using 64 slices CT scanner of the Aquilion64 (Toshiba) from the department of Radiologic Technology, faculty of Associated Medical Sciences, Chiang Mai University, Thailand. The scanning protocol is shown in Table 2. Subsequently, all OSL nanoDot samples were evaluated by Thailand Institute of Nuclear Technology (Public Organization), Nakorn Nayok, Thailand and reported in an organ absorbed dose that expressed in unit of centigray (cGy).

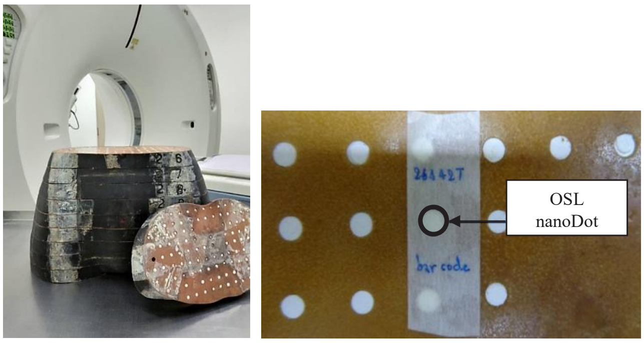

Figure 1. *Pelvic Rando phantom.*

Table 1 Sociodemographic data of stroke participants.

Equivalent organ	Number of OSL	Coordination (X,Y,Z)* [cm]
Rt. Ovary	1	(-6,0,15.24)
Lt. Ovary	1	(6,0,15.24)
Bladder	6	(-3,4.50,15.24), (3,4.50,15.24), (-3,4.50,17.78), (3,4.50,17.78), (-3,0,20.32), (3,0,20.32)
Uterus	1	(0,2,12.70)
Prostate	2	(-1.50,-1,22.86), (1.50,-1,22.86)
Skin	8	Outside (anterior, posterior, right, left) Z = 8.39, 13.97
Total	19	

Note: *Coordinate of Rando phantom center is X=0, Y=0 and Z=12.70, cm: centimeter*

Table 2 CT scan protocol for irradiations of the Rando phantom.

Parameter	Value
kVp	120
mA	tube current modulation mode
rotation time	0.5 sec
slice thickness	0.5x64 cm.
scan length	20 m.

MCNP Simulation

The Monte Carlo N-Particle transport code Version 5 (MCNP5) with F6 tally that is deposition energy (MeV/g. photon) in each cell was used to simulate a set of direct measurements based on 19 OSL nanoDot dosimeters in pelvic RANDO phantom including X-ray source structure of CT scanner (Figure 2). The 120 kVp X-ray source with energy spectrum shown in Figure 3 was located on 36 positions on circumference of 50 cm CT gantry. As shown in Figure 4, each position was equally spaced out as its radial line made a 10-degree angle to another adjacent radial line. This source placement was an attempt to model a spiral continuous movement of X-ray tube rotation about CT gantry. The collimator was also included in model to collimate a cone beam from X-ray source into a fan-shaped beam with an angle of 49.2 degree and 1-cm thickness. The results of F6 tally, which is energy deposition averaged over a cell in unit of MeV/g, are normalized per a simulated photon particle. In order to obtain absorbed dose to current, it was necessary to multiply the MCNP5 results, a source strength which is given in a unit of a number of photons per current-time (photon/mAs). In this study, source strength was chosen as 1.75E+11 photon/mAs from preliminary study that was calculated from equation (1) according to G Jarry *et.al.*[3]

$$\text{Source strength} = \left[\frac{\text{Air kerma}_{\text{measured}}}{\text{Air kerma}_{\text{MCNP5}}}\right]/\text{mAs} \qquad (1)$$

Air $\text{kerma}_{\text{measured}}$ is absorbed dose measured in air using ionization chamber detector at the isocenter of CT scanner and Air $\text{kerma}_{\text{MCNP5}}$ is absorbed dose simulated using MCNP5 transport code at under the same condition of experimental measurement.

To ensure that whole pelvic section of the Rando phantom was accounted, absorbed doses covering 20-cm scan length were calculated by MCNP5 and reported in unit of cGy. The number of histories for all simulations, were appropriately adjusted to ensure that relative errors of the results were always less than 5 percent.[4] In this study, only MCNP5 results that were within 10-percent discrepancy with OSL nanoDot measurements were acceptable.

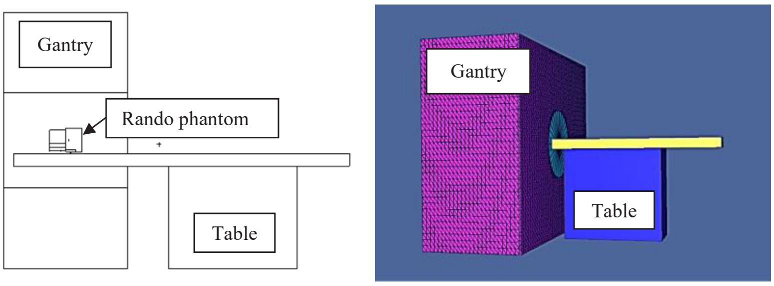

Figure 2. *2D (left) and 3D (right) MCNP5 simulation geometry of radiation measurement in Rando phantom.*

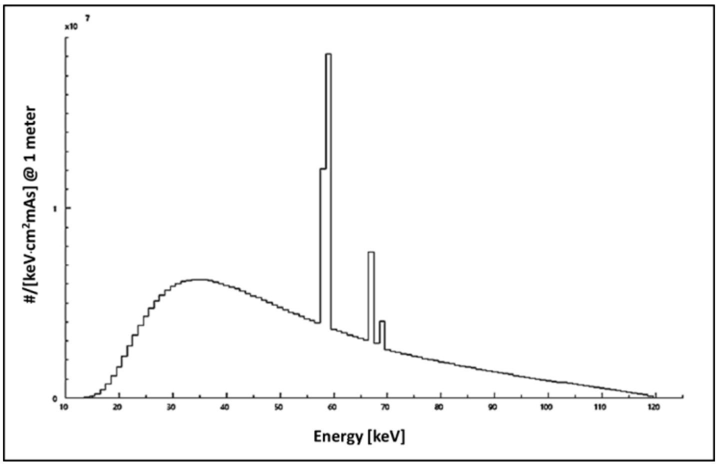

Figure 2. *120 kVp X-ray source spectrum (SpekCalc program).*

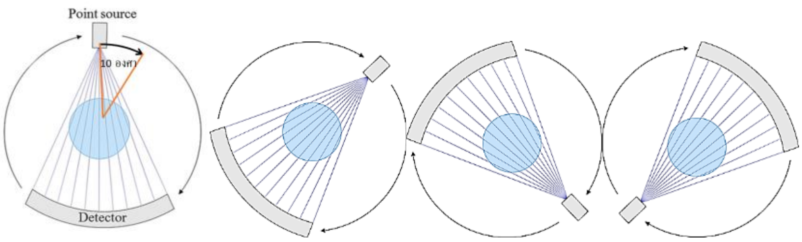

Figure 4. *Movement simulation of X-ray source from CT scanner.*

$$\% \text{ Difference} = [(D_{MCNP5} - D_{OSL}) / D_{OSL}] \times 100 \quad (2)$$

Results

Absorbed doses from MCNP5 calculation (D_{mcnp5}) and OSL nanoDot (D_{OSL}) measurement are compared then % difference of them were calculated following the equation (2) which exhibited in Table 3. Eleven absorbed doses of internal organs (No. 1 to 11) are in good agreements with less than 10 percent differences. However, eight absorbed doses from skin areas (No. 12 to 19) are observed with higher than 10 percent differences, especially in cases of left and right side (No. 14, 15, 18 and 19). It is believed that a shorter distance between a radiation source and a detector contributes to large discrepancies observed as illustrated in Figure 5. Similar discrepancies have also been observed by several studies performed by Thomas M. *et al.*[5] and Kara U[6] as shown in Table 4. Uncertainties of OSL nanoDot measurements caused by angular dependence also significantly impact on both efficient measurement and results, especially at the position of 90° and 270° (i.e., right and left side of skin).[7] In addition, Kazuki Takegami *et.al.*[8] indicated that there were a great deal of uncertainties with roughly 30% when using OSL nanoDot for patient entrance surface dose (ESD) measurement. Therefore, radiation doses recorded by OSL nanoDot might be lower than the actual values.

Table 3 Absorbed dose of equivalent organs and percentage difference.

No.	Equivalent organ	Absorbed dose (cGy)		%Difference
		MCNP5	OSL nanoDot	
1	Uterus	3.31±0.25	3.48±0.14	-5.06
2	Bladder1	4.36±0.45	4.47±0.23	-2.43
3	Bladder2	4.63±0.38	4.39±0.35	5.52
4	Bladder3	3.86±0.73	4.20±0.44	-8.11
5	Bladder4	4.37±0.73	4.05±0.32	7.72
6	Bladder5	2.20±0.19	2.37±0.10	-7.23
7	Bladder6	2.20±0.09	2.43±0.44	-9.65
8	Prostate gland1	1.98±0.12	2.02±0.06	-2.21
9	Prostate gland2	1.99±0.09	2.14±0.07	-7.12
10	Right ovary	3.03±0.57	3.01±0.33	0.87
11	Left ovary	3.23±0.43	3.08±0.24	5.03
12	Skin ($Z_{8.89}$, anterior)	8.54±0.59	4.42±0.41	93.27
13	Skin ($Z_{8.89}$, posterior)	7.03±2.14	3.68±0.78	91.17
14	Skin ($Z_{8.89}$, right)	7.42±0.34	3.50±0.21	112.24
15	Skin ($Z_{8.89}$, left)	17.94±8.60	3.23±0.23	455.39
16	Skin ($Z_{13.97}$, anterior)	9.04±1.16	5.26±0.81	71.75
17	Skin ($Z_{13.97}$, posterior)	4.66±0.42	3.96±0.29	17.66
18	Skin ($Z_{13.97}$, right)	10.65±3.55	3.58±0.85	197.08
19	Skin ($Z_{13.97}$, left)	17.82±8.34	3.82±0.81	366.90

Note: *Coordinate of Rando phantom center is X=0, Y=0 and Z=12.70, cm: centimeter.*

Table 4 Absorbed dose ratio of skin to ovary (skin/ovary) .

Condition	This study	Thomas M. *et.al*[9]	Kara U. *et.al*[10]
Absorbed dose ratio (skin/ovary)	48.88-469.33%	47.47%	58.33%
Measurement method	MCNP	OSL + post-mortem	MCNP
CT model	Aquilion64, Toshiba	Aquilion ONE, Toshiba	Lightspeed, GE

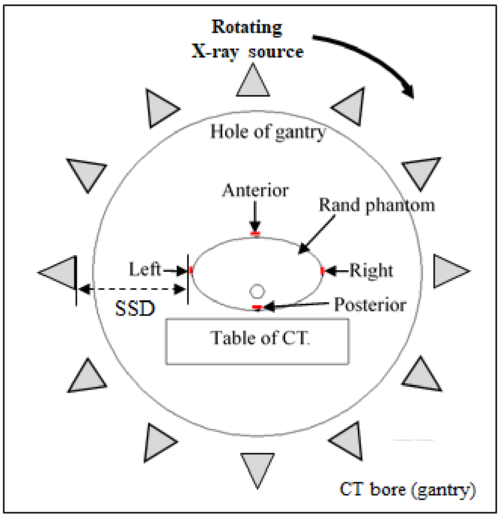

Figure 4. *Simulated setup for radiation measurement at Rando phantom surface (skin dose). The dosimeters were placed at surface of Rando phantom (4 red dots).*

Conclusion

The MCNP5 model can be used to estimate absorbed doses on internal organ from CT scanning. MCNP5 results would be normalized by machine-specific normalization factor to obtain appropriate absorbed doses. It is conceivable to provide efficient and safe CT procedure for both a radiation physicist and a physician in radiation diagnosis plan for the patients. However, the significance of difference of absorbed doses between MCNP5 calculation and OSL nanoDot measurement for skin positions should be further investigated to verify that MCNP5 calculation is reliable for predicting absorbed doses on skins or near-surface organs. More number of OSL nanoDot measurements should be contacted for statistical reliability.

Acknowledgments

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