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Review paper

Monte Carlo simulation of eye lens dose reduction from CT scan using organ based tube current modulation

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ABSTRACT

Purpose: To investigate lens dose reduction with organ based tube current modulation (TCM) using the Monte Carlo method.
Methods: To calculate lens dose with organ based TCM, 36 pairs of X-ray sources with bowtie filters were placed around the patient head using a projection angle interval of 10° for one rotation of Computed Tomography (CT). Each projection was simulated respectively. Both voxelized and stylized eye models and Chinese reference male phantoms were used in the simulation, and tube voltages 80, 100, 120 and 140 kVp were used.
Results: Dose differences between two eye models were less than 20%, but large variations were observed among dose results from different projections of all tube voltages investigated. Dose results from 0° (AP) directions were 60 times greater than those from 180° (PA) directions, which enables organ based TCM reduce lens doses by more than 47%.
Conclusions: Organ based TCM may be used to reduce lens doses. Stylized eye models are more anatomically realistic compared with voxelized eye models and are more reliable for dose evaluation.

1. Introduction

The lens is sensitive to ionizing radiation but cancer due to radiation is rare, so when the International Commission on Radiological Protection (ICRP) defines thresholds for radiation for the eye, the lens is excluded [1]. High-dose ionizing radiation is thought to increase the risk of cataracts [2,3], but only when reaching a particular threshold of 0.5–2.0 Gy for a single brief exposure or 5.0 Gy for highly fractionated or protracted exposures [1]. Studies show that threshold doses were less than 1.0 Gy for detectable opacities [4,5]. Based on a review of epidemiology and mechanisms of radiation cataract genesis from the Health Protection Agency (HPA) [6], a report released by ICRP indicates that a threshold dose for lens effects is defined as ∼0.5 Gy, and there are no data to suggest that protracted doses are less damaging [6,7]. A prospective cohort study among US radiologic technologists suggested an increasing likelihood of cataract formation with increasing radiation exposure, but with no apparent threshold [8,9]. Even so, because of the rapidly expanding application of CT procedures, concern about lens radiation from CT scans has been raised [10,11]. Lens radiation doses are reported to vary from 10 to 60 mGy depending on the CT scanner type and protocol. A recent study of 2776 patients undergoing head and neck CT scans compared with 27,761 non-exposed individuals suggested that repeated exposure to head and neck CT was significantly associated with increased risk of cataracts [10]. Therefore, it's important to reduce lens dose from CT scan, and new techniques like organ based TCM without impacting image quality [12] which has been implemented by angular modulation was believed to be an effective way. To precisely report the eye lens radiation dose is the primary work to evaluate the effectiveness of organ based TCM. As the volume of the eye lens is too small, doses to the eye lens could hardly be measured directly, reported literatures use dosimeters placed over the center of the eye to measure the eye lens dose [13], which might bring more uncertainty. Monte Carlo simulations with appropriate eye models may be used to determine eye lens dose [14–16] as the voxelized eye model cannot represent detailed eye structures due to their low resolution. Thus, it is very important to construct a detailed eye model for accurately assessing lens dose and radiation risk. We incorporated a stylized eye model into the polygon-mesh version of the Chinese reference adult male whole-body surface model. Simulations of the dose to the lens from CT scan were made using a voxelized eye model and stylized eye model and 36 projections of CT X-ray tubes for one rotation were simulated individually to investigate the lens dose reduction using organ based tube current modulation.

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Table 1
Data from Hu [18](reprinted with Panpan Hu's permission).

Organ		Curvature Radius (mm)	Thickness (mm)
Eye	/	12.10	/
Cornea	Front Surface	7.75	0.55
	Back Surface	7.20	
Atria	/	/	3.00
Lens	Front Surface	12.50	4.00
	Back Surface	8.00	
Vitreum	/	/	17.20

2. Materials and methods

2.1. Lens of Chinese reference male phantom

We developed an anatomical mesh phantom of a Chinese reference male based on the Anatomium™ 3D [17] model. To use the phantom in the Monte Carlo transport code, the mesh phantom was processed into a voxel structure. The minimum voxel size is set at $2.7 \times 2.7 \times 2.7\ mm^3$, leading to voxel volume of $19.7\ mm^3$, considering the memory size and addressing limitations of code. The voxel size effectively limits the construction of the detailed lens. Due to low resolution, detailed eye structures cannot be represented. To provide accurate computational modeling, a stylized eye model was incorporated into Chinese reference male phantom. Structural data from Hu [18] appear in Table 1 with explicit permission from the author. This stylized model of the human eye provides the dimensions and geometry of the cornea, lens, anterior chamber, sclera, choroid, retina, vitreous humor, macula and the optic nerve. The model was divided into two parts which describe sensitive and insensitive lens portions. Sensitive regions are mainly positioned near the front surface of the lens at the outer region, near to equator [19]. Both stylized and voxelized eye models were used in this study and Fig. 1 shows differences between each model. The density and composition of stylized eyes were taken from Charles and Brown [20]. The density and chemical composition of each organ of Chinese human phantom were obtained from the ICRP89 report [21].

2.2. CT scanner model and Monte Carlo simulation

A GE Light Speed Pro 16 CT scanner model (General Electric Healthcare Corporation, Waukesha, WI), was used. The Monte Carlo CT scanner model includes variables that specify source geometry, source movement, X-ray energy spectrum, bow-tie filter and beam shape [22]. The scanner model was developed and benchmarked against physical measurements under various bowtie filters, tube voltages, and beam collimation combinations, and each combination agreed to within 10% [23]. The lens dose simulations were performed using Monte Carlo N-Particle eXtended (MCNPX) code version 2.7.0[24]. Xcomp5r was used to generate spectra at different kVp for X-ray source modeling. Because X-ray energy is less than 140 keV in CT diagnostic imaging, it is assumed that secondary electrons generated deposit their energy locally. The *F8 tally was employed to record the energy deposit to the lens both models. For acceptable statistical uncertainty (relative errors < 2.5%), 10^8 source photons were initialized in each run.

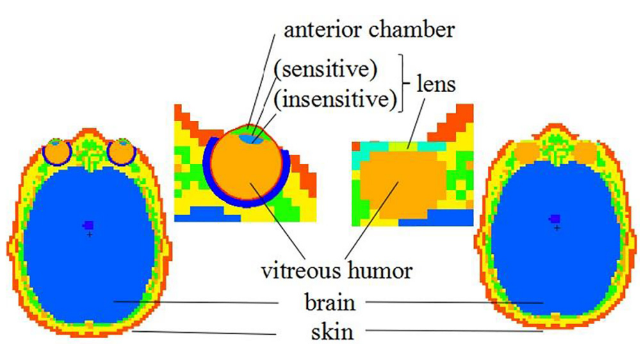

Fig. 1. Transverse slices of the head of the Chinese reference male phantom across the eyes with both (left) voxelized and (right) stylized eye models.

Many CT protocols have lens coverage or partial coverage over the scan range, such as head orbit, or sinus CT scans. To simplify estimation of lens doses, an orbit CT scan protocol was selected for this study, and scan lengths and positions were chosen from the mid-maxillary sinus to the frontal sinuses. Both voxelized and stylized eye models of Chinese reference male phantoms were placed at the *iso*-center of the CT scanner model with a head bowtie filter and 5 mm beam collimation selected for the simulation. To estimate lens dose reduction using organ-based TCM, 36 X-ray sources and bowtie filters were placed around the patient head with a projection angle interval of 10° for one rotation of the CT scan, and each projection was simulated respectively. Also, 0° was defined as anterior-posterior (AP) direction, and 180° was defined as posterior-anterior (PA) direction. Tube voltages (80, 100, 120, and 140 kVp) were used in the MCNPX code as well.

To transform results into MeV/particle reported by *F8 tally Card into dose unit MeV/gram/particle, all simulated results were divided by lens mass. To transfer the dose results unit MeV/gram/particle to mGy/100 mAs, the MCNPX output results were adjusted by the measured air kerma from the scanner. The conversion factor (CF) to convert the tally output to absorbed dose in units of mGy/100 mAs [22], is defined as Eq. (1).

$$(CF)_{E,NT} = \frac{((CTDI_{100})^{Measured}_{in-air,mGy\ per100\ mAs})_{E,NT}}{((CTDI_{100})^{Simulated}_{in-air,MeV/g\cdot source\ particle})_{E,NT}} \tag{1}$$

where $((CTDI_{100})^{Measured}_{in-air,mGy\ per100\ mAs})_{E,NT}$ is the measured air kerma $(CTDI_{100})_{in-air}$ values by using the ionization chamber in air at the CT scanner *iso*-center for a single axial scan using 100 mAs and different beam energies and beam collimations; $((CTDI_{100})^{Simulated}_{in-air,MeV/g\cdot source\ particle})_{E,NT}$ is the corresponding air kerma values acquired by simulating the ionization chamber in the MCNPX code under the same CT scan scenario. The units of $(CF)_{E,NT}$is expressed in units of (mGy gram source particle)/(MeV 100 mAs). The final results were normalized by $CTDI_{vol}$ and the units of absorbed dose was mGy/per $CTDI_{vol}$.

For eye scan CT protocols, the organ based TCM technique used with the CT scanner decreases the tube current by 75% from the reference value for an angular range of 120° over the anterior surface, and increased the tube current by 25% for the remaining 240° of the scanning range [12,25] (Fig. 2). In this manner, the tube current time product applied over a 360° CT scan can be maintained with image quality. The lens dose components from each projection were calculated with simulated results multiplied by the corresponding mAs, and the lens dose from the protocol was obtained by adding all components together.

3. Results and discussion

3.1. Comparison between two kinds of eye models

The doses for the lens of the stylized eye model were calculated and differences between the two values were reported relative to the voxelized eye model as noted in Eq. (2).

$$Difference(\%) = \frac{D_{stylized} - D_{voxelized}}{D_{stylized}} \times 100 \tag{2}$$

To investigate the lens dose differences between the two models, dose results from orbit CT scans all voltages appear in Table 2. As the lens dose results are bilaterally symmetrical, the results of the projection angles ranging from 0 to 180° were listed for comparison. Note that AP directions are the most important irradiation scenario for lens dose