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Lens of the eye dose calculation for neuro-interventional procedures and CBCT scans of the head

Zhenyu Xiong, Sarath Vijayan, Vijay Rana, Amit Jain, Stephen Rudin, and Daniel R. Bednarek

Toshiba Stroke and Vascular Research Center, University at Buffalo, Buffalo, New York

Abstract

The aim of this work is to develop a method to calculate lens dose for fluoroscopically-guided neuro-interventional procedures and for CBCT scans of the head. EGSnrc Monte Carlo software is used to determine the dose to the lens of the eye for the projection geometry and exposure parameters used in these procedures. This information is provided by a digital CAN bus on the Toshiba Infinix C-Arm system which is saved in a log file by the real-time skin-dose tracking system (DTS) we previously developed. The x-ray beam spectra on this machine were simulated using BEAMnrc. These spectra were compared to those determined by SpekCalc and validated through measured percent-depth-dose (PDD) curves and half-value-layer (HVL) measurements. We simulated CBCT procedures in DOSXYZnrc for a CTDI head phantom and compared the surface dose distribution with that measured with Gafchromic film, and also for an SK150 head phantom and compared the lens dose with that measured with an ionization chamber. Both methods demonstrated good agreement. Organ dose calculated for a simulated neuro-interventional-procedure using DOSXYZnrc with the Zubal CT voxel phantom agreed within 10% with that calculated by PCXMC code for most organs. To calculate the lens dose in a neuro-interventional procedure, we developed a library of normalized lens dose values for different projection angles and kVp's. The total lens dose is then calculated by summing the values over all beam projections and can be included on the DTS report at the end of the procedure.

Keywords

lens dose; Monte Carlo; EGSnrc; DTS; CBCT; neuro-interventional procedure

1. INTRODUCTION

Cataract is a clouding of the lens in the eye leading to a decrease in vision. Recent studies has suggested that the dose threshold for cataracts is lower than previously believed or even that the effect is stochastic without a threshold (Cucinotta et al. (2001)¹; Worgul et al. (2007)²; Chodick et al. (2008)³). These have lead the ICRP to recommend a reduction of the annual equivalent dose limit for the lens of the eye from 150 mSv in a single year (ICRP, 2007)⁴ to 50 mSv in a single year or 20 mSv per year over five years (ICRP, 2011)⁵.

Neuro-interventional procedures and head CBCT scans can result in relatively high doses to the patient's eyes so it is very important to know the lens dose in these procedures. We have previously developed a dose tracking system (DTS) ⁶ to provide a real-time color-coded 3D-

mapping of skin dose (Figure 1). The purpose of the present work is to add the capability to determine lens dose to the DTS software. We thus simulated CBCT and neuro-interventional procedures and calculated lens dose using Monte Carlo code and compared the results with measurements made with radiochromic film and ionization chambers. The proper functioning of the code was validated by comparison to the results of PCXMC⁷.

2. METHOD AND MATERIALS

2.1 Monte Carlo simulation of X-ray tube and spectra

To generate the spectra used for CBCT and neuro-interventional imaging, the x-ray tube of the Toshiba Infinix C-Arm System was modeled by BEAMnrc, which is an EGSnrc-based Monte Carlo code. All parts of the tube were simulated according to the manufacturer's specifications. We used the XTUBE component module (CM) of the BEAMnrc⁹ code library to simulate the tube target. The SLABS CM was employed to simulate inherent filtration and additional filtration. The JAWS CM was set to simulate two pairs of lead collimators which can adjust the field of view.

To enhance photon fluence production and increase the simulation efficiency, we used the variance reduction technique known as directional bremsstrahlung splitting (DBS) with a splitting number of 1000. The anode bremsstrahlung cross-section enhancement (BCSE) was increased by a factor equal to 200. The Russian Roulette (RR) was set outside the DBS field of interest, the DBS splitting field radius was 15 cm and the SSD of the splitting field was 60 cm. The photon energy cut-off was set to 1 keV for range rejection and the electron energy cut-off was set to 521 keV including the electron rest mass energy. Material data were generated by the PEGS4 code developed at NRC¹⁰. We also turned on the following low energy physics options for accurate simulation: electron impact ionization, bound Compton scattering, photoelectron angular sampling, atomic relaxation, Rayleigh scattering and simple bremsstrahlung angular sampling. The NIST data were used for all bremsstrahlung cross section simulations and XCOM was used for photo-absorption and Rayleigh-scattering total cross sections. We implemented the EXACT boundary crossing algorithm which utilizes a single scattering mode to cross boundaries. The distance from the boundary at which the chosen BCA algorithm comes into effect (skin depth for BCA) is 3 electron mean path lengths. The PRESTA-II electron-step algorithm was employed to calculate lateral and longitudinal corrections. A parallel rectangular monoenergetic beam of 5×10^9 electrons is incident on the target region.

A phase space file (PHSP), which contains the spatial and directional information with energies for all the x-ray photons, was obtained at a source-to-surface distance of about 60 cm. We have used the phase space files to find the spectra and percent-depth dose (PDD) and HVL of the simulated beam. We verified the validity of the x-ray spectra that were simulated using the BEAMnrc by comparing the results with those of SpekCalc¹¹ as shown in Figure 2. Then we compared the PDD simulated by EGSnrc using the BEAMnrc spectrum with the measured PDD for the Toshiba x-ray tube using a 0.6 cc Farmer chamber in solid water (Figure 3).

Our group has previously calculated organ dose in diagnostic examinations such as CBCT and interventional procedures by using PCXMC¹⁵. However, PCXMC does not provide lens dose calculation since it is not needed for the effective dose calculation. Nevertheless, we can still use it to calculate the dose to other organs and thus we compared it with the results calculated from EGSnrc to test the proper functioning of the code. We simulated a DA procedure over the abdominal region of the torso for PA projections. The field size is $10 \times 10 \text{ cm}^2$, the peak voltage is 80 kVp and the air kerma given is 1000 mGy. The results of the EGSnrc simulation were compared to the results of the PCXMC simulation under the same exposure parameters as seen in Figure 8.

2.2 Lens dose calculation in CBCT

The x-ray photons in the PHSP were transported to the voxel phantom generated with the anthropomorphic phantom CT data in DOSXYZnrc¹² user code. After the BEAMnrc simulations were completed, phase space files from the BEAMnrc were used to run DOSXYZnrc user code in order to determine the relative dose deposited per simulated particle in cylindrical CTDI phantom and an anthropomorphic virtual phantom derived from a patient-specific CT scan. In each DOSXYZnrc simulation, the number of histories run was equal to the number of photons stored in the PHSP file. We used a source type 8 (phase-space source from multiple directions) to simulate the rotational irradiation of the CBCT scans.

We simulated a cylindrical CTDI PMMA head phantom with DOSXYZnrc code and directed the PHSP file photons towards the phantom voxels to calculate the dose distribution. To measure the surface dose, we covered the CTDI head phantom with Gafchromic film (type XR-RV3, ISP Corp, Wayne, New Jersey) and performed a CBCT head scan. For both simulation and measurement, we set a CBCT scan protocol with a source to iso-center distance of 69 cm, a peak voltage of 80 kVp, a tube current of 250 mA, a rotation range of 206 degrees and the number of frames at 103. To obtain a dose within the dynamic range of the film, we repeated this scan protocol 10 times. Then we compared the surface dose distribution between measurement and simulation as shown in Figure 4.

For comparisons simulating a head, we used the Zubal CT torso+head Phantom¹³ for dose calculation of the same CBCT scan. This phantom was developed based on a whole-body CT scan of an adult male whose radiosensitive organs and tissues, including the eye lens, were individually segmented. The weight and the height of the patient model were 70 kg and 178 cm, respectively. The torso+head phantom consists of isotropic voxels with dimensions of 4 mm. Each voxel in the phantom was assigned a tissue type, described by elemental composition and mass density. An .egsphant file was constructed to describe the Zubal CT torso+head Phantom by using a Visual C++ program. This file includes the coordinate, material and density information. Then we modified the DOSXYZnrc code so that in the computational voxel phantom simulation, more media can be used and the MXMED can be changed to 100 or more. The same CBCT scan was performed on an SK150 anthropomorphic head phantom (Phantom Laboratory, Salem, NY) which was similar in dimensions to the virtual phantom and the surface dose at the positions of the right and left lens and for the back of the head were measured by using a 0.6 cc ionization chamber. The

results of the simulation and the measurements are shown in Figure 5. DOSXYZ_SHOW user code¹⁴ was used to find the axis locations of the individual cavities in the CT phantoms to extract the point dose values from the .3ddose files (Figure 6).

To determine the effect of the projection angle on lens dose, we did a simulation to get the ratio of lens dose to the entrance dose at the center of the FOV for the Zubal CT torso+head Phantom. We set the beam size to 15×15 cm at the iso-center distance of 69 cm and the peak voltage at 80 kVp; simulations were carried out at a projection angle interval of 5° around the head phantom. The results are shown in Figure 7.

2.3 Lens dose calculation in neuro-interventional procedures

For a clinical neuro-interventional procedure, the exposure and geometry parameters are expected to change throughout. To reduce the computation time, exposure events may be able to be grouped so that a single computation can be performed depending on the magnitude of the parameter change and its effect on lens dose. We had used this grouping method previously when using PCXMC to determine organ dose for simulated cardiac procedures resulting in a substantial reduction of computation time.¹⁵

The degree of variability of lens dose with exposure parameters was evaluated so that appropriate grouping of exposure events can be made to reduce computation time. We thus did a series of simulations of normalized lens dose values as a function of different parameters like tube voltage, beam size, and LAO/RAO, CAU/CRA angulation. This allowed us to produce a library of lens dose values to quickly determine the lens dose for a given set of conditions.

For investigating the change in lens dose with change in kVp, the simulation were carried out to find the ratio of eye lens dose to the head phantom entrance dose with peak voltage interval of 10 kVp from 50 kVp to 120 kVp. All of the projection angles were PA and beam size was 15×15 cm at the 69 cm iso-center distance. To compare the effect of different filtration in the tube, we used the minimum added beam filtration (1.8 mm Al) and maximum added beam filtration (0.5 mm Cu) to do the simulation. These simulations were also validated with measurement on the head phantom by using a 0.6 cc ionization chamber (Figure 9).

To investigate the change in lens dose with beam size, simulations were carried out to find the difference to eye lens dose with different beam FOV's from 4.5 cm beam width to 18 cm beam width. All of the projection angles were PA, beam peak voltage is 80 kVp and source to iso-center distance is 69 cm. We normalized every lens dose at the different FOV's to the lens dose for a beam width of 4.5 cm (Figure 10).

To investigate the change in lens dose when the location of the beam was moved farther (i.e., inferior) from the lens, simulations were done with the center of the beam location changed from the center of the lens to 12.8 cm below the lens. Beams were projected in a parallel direction with a beam size of 15×15 cm at the 69 cm iso-center distance and a beam peak voltage of 80 kVp. The results are illustrated in Figure 11.

To investigate the change in lens dose with gantry projection angles, the ratio of lens dose to the air kerma at 15 cm from isocenter were calculated for various angles in the RAO/LAO and CRA/CAU directions (Figure 12). The beam peak voltage was set to 80 kVp and the beam size to 15×15 cm at the 69 cm iso-center distance.

3. RESULTS AND DISCUSSION

Comparison of the SpekCalc simulated x-ray spectrum with the spectrum calculated using the EGSnrc/BEAMnrc is shown in Figure 2. The characteristic peaks are shown superimposed on a continuous spectrum. In general, the agreement between the shape of the bremsstrahlung spectra acquired from the EGSnrc/BEAMnrc simulation and the SpekCalc simulation is good.

Figure 3 shows the comparison of the transmission curve produced by the EGSnrc/BEAMnrc simulation and experimental measurement with the 0.6 cc Farmer chamber for a solid water phantom at 80 kVp. Both transmission curves were normalized to their maximum value. It was found that the simulated transmission curve is slightly higher than the measured transmission curve for all thicknesses but the difference was generally less than 5%.

The HVLs for the EGSnrc/BEAMnrc simulation and measurement with the ion chamber are 3.25 and 3.1 mm Al, respectively; the HVL from direct measurement using the ion chamber was thus consistent with the HVL calculated using the simulated spectra.

Figure 4 compares EGSnrc simulation and Gafchromic film measurement surface dose results over 360° of the CTDI head phantom for a CBCT scan. 0° and 360° were defined as the anterior side of the phantom, while 180° was defined as the posterior side of the phantom. The two lens locations would be approximately at 20° and 340° . The minimum dose was located at 0° and the maximum dose was located at 180° . The lens location entrance dose to the posterior location entrance dose is about 1: 3. Since the rotation range is from 77° to 283° with an interval of 2° , the dose at the lens location was due to attenuated primary and scattered radiation. EGSnrc simulation and Gafchromic film measurement dose profiles match well.

Figure 5 shows the entrance dose profiles for a CBCT scan simulated by EGSnrc for the Zubal CT torso+head Phantom as well as the entrance dose measured by an ionization chamber at the lens positions and the posterior location of the SK150 anthropomorphic head phantom. The minimum dose was located at 0° , which is the same as with the simulation and measurement on the CTDI head phantom. However, the maximum dose values were located at about 130° and 230° , which is different from 180° on the CTDI head phantom. This may due to the different structure between the CTDI head phantom and the anthropomorphic head phantom. Additionally, the ratio of the lens-location entrance dose to the posterior-location entrance dose is about 1: 12, which is 4 times lower than the ratio on the CTDI head phantom. There are two possible reasons for this. First, the diameter off the CTDI head phantom is 16 cm while the distance from the anterior to the posterior sides is about 20 cm for the anthropomorphic head phantom, and thus the transmission of the

anthropomorphic head phantom will be lower. In addition, the anthropomorphic head phantom contains skull bone which has a higher density than PMMA, and this also can decrease the transmitted and scatter dose to the lens location. Figure 6 shows the dose distribution through an axial and sagittal sections which highlight the higher energy absorption in the skull bone.

To determine the effect of different projection angles on lens dose, we did a simulation to get the ratio of lens dose to the entrance dose at the center of the FOV as a function of projection angle at an interval of 5° . Figure 7 shows that, when the eye is in the primary beam, the ratio is about 1.0 but the ratio drops rapidly as the primary beam moves away from the lens location

Figure 8 generally shows excellent agreement between the organ dose calculation of PCXMC and the software used here. The disagreement of the values for the kidney is likely due to differences in the anatomic organ models used in the two simulations.

Figure 9 shows that the radiation doses to the lens increases as the tube voltage is raised from 50 kVp to 120 kVp and that the radiation dose to the lens also increases with increased beam filtration. According to Figure 10, the lens dose increased as the field size increased from the 4.5 cm beam width, which just covers the two eye lenses, to the 18 cm beam width. However, the rate of increase of lens dose was lower with the larger beam sizes since the scatter dose contribution was less from the greater distance to the lens. Figure 11 shows the subterminal lens dose was decreased by approximately 90% when the beam location was displaced a full 1.5 cm away from the eye lens (inferior). It should be noted that moving the beam edge 1.5 cm resulted in a geometry such that the lenses are just out of the primary beam. The dose drop off is obvious once the lens is outside the primary beam.

Figure 12 shows the variation of lens dose to the right eye as a function of beam angulation and Figure 14 provides an illustration of the relation between the LAO/RAO angulation of the beam and the position of the lenses within the head phantom. As seen in Figure 12, at a given CRA/CAU angle, the lens dose decreased when the projection changes from 90° LAO to 50° LAO, and then increases until at 35° LAO, the lens dose was nearly that at 90° LAO. This may be because the thickness of bone between the upper zygomatic bone and lower frontal bone is relatively thin as shown in Figure 13 and, when the beam projection angle is at about 55° LAO, it will go through this thin bone and go straight to the subterminal eye. Then the lens dose decreases becoming a minimum at 0° LAO because the attenuation at this angle is the highest. The lens dose increases until it peaks at about 70° RAO, likely because of the lower attenuation. For the same RAO/LAO angle, the lens dose from 30° CAU to 30° CRA is nearly the same, except for a few locations where the skull attenuation varies.

Data such as shown in Figure 9 to Figure 12 can be used to produce a library of lens dose per entrance skin dose values for the various parameters of the exposure. Using this library, a Monte Carlo calculation will not need to be performed for every exposure event during the procedure and the lens dose determination can be performed more quickly. Furthermore, the exposure events in the neuro-interventional procedure are recorded in the DTS log and they can be grouped depending on their similarity and the variability of lens dose with the

parameter changed; the amount of grouping used will depend on the degree of accuracy needed and the calculation time constraints. A total procedure lens dose can then be obtained by adding the lens dose for all groups.

4. CONCLUSIONS

We have successfully used EGSnrc to calculate the lens of the eye dose for simulated procedures of neuro-interventions and CBCT of the head. Our simulation results have good agreement with measurements and other Monte Carlo simulations. This work expands the dose information that can be provided by our dose tracking system (DTS).

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Figure 1.

The DTS tracks the x-ray beam in real-time and provides a color-coded mapping of skin dose during fluoroscopically-guided interventional procedures⁸.

Figure 2.
X-ray spectrum at 80 kVp using BEAMnrc for simulation of the Toshiba Infinix beam compared with the spectrum generated by SpekCalc.

Figure 3.

Comparison of the 80 kVp PDD curve simulated by EGS and that measured in solid water using a Farmer chamber.

Figure 4. Comparison of entrance dose profiles for a CBCT scan of the CTDI head phantom as simulated by EGSnrc and measured by Gafchromic film. The insert shows the color-coded dose distribution through an axial section of the phantom.

Figure 5. Entrance dose profile for a CBCT scan simulated by EGSnrc for the Zubal CT torso+head Phantom compared to ion chamber measurements on an SK150 anthropomorphic head phantom. The insert shows the color-coded dose distribution through an axial section of the phantom through the lens.

Figure 6. Head dose distributions of the CBCT scan for the Zubal phantom. Axial and sagittal views are presented with percent dose level and density bar (g/cm³).

Figure 7.
Ratio of lens dose to the entrance skin dose at the center of FOV for different projection angle.

Figure 8.
Comparison of organ doses for 80 kVp PA radiography of the abdomen calculated by EGSnrc and by PCXMC.

Figure 9. Ratio of lens dose to the head phantom entrance skin dose versus kVp for different beam filtration compared to measurement with an ionization chamber.

Figure 10.

Lens dose variation with different beam size, normalized to 1.0 for the beam size of 4.5×4.5 cm. All beams included both lens.

Figure 11.

The effect of moving the beam location farther from the eye lenses. All of the lens doses were normalized to the dose of the subterminal lens which is just at the edge of the beam.

Figure 12.

A 3- D surface plot of the ratio of lens dose to the entrance air kerma at 15 cm from isocenter as a function of CRA/CAU and RAO/LAO angles.

Figure 13.

A CT cross section image shows the bone structure of the head clearly. The image shows that the bone between the upper zygomatic bone and lower frontal bone is relatively thin.

Figure 14.

Illustration of LAO/RAO angulation of the beam relative to the head phantom. When the beam projection angle is at about 55° LAO, it will go through the thin bone shown in Fig. 13 and go straight to the subterminal eye.