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Organ and effective dose reduction for region-of-interest (ROI) CBCT and fluoroscopy

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Abstract

In some medical-imaging procedures using CBCT and fluoroscopy, it may be needed to visualize only the center of the field-of-view with optimal quality. To reduce the dose to the patient as well as enable increased contrast in the region of interest (ROI) during CBCT and fluoroscopy procedures, a 0.7 mm thick Cu ROI attenuator with a circular aperture 12% of the FOV was used. The aim of this study was to quantify the dose-reduction benefit of ROI imaging during a typical CBCT and interventional fluoroscopy procedures in the head and torso. The Toshiba Infinix C-Arm System was modeled in BEAMnrc/EGSnrc with and without the ROI attenuator. Patient organ and effective doses were calculated in DOSXYZnrc/EGSnrc Monte-Carlo software for CBCT and interventional procedures. We first compared the entrance dose with and without the ROI attenuator on a 20 cm thick solid-water block. Then we simulated a CBCT scan and an interventional fluoroscopy procedure on the head and torso with and without an ROI attenuator. The results showed that the entrance-surface dose reduction in the solid water is about 85.7% outside the ROI opening and 10.5% in the ROI opening. The results showed a reduction in most organ doses of 45%–70% and in effective dose of 46%–66% compared to the dose in a CBCT scan and in an interventional procedure without the ROI attenuator. This work provides evidence of substantial reduction of organ and effective doses when using an ROI attenuator during CBCT and fluoroscopic procedures.

Keywords

ROI imaging; Monte Carlo; EGSnrc; dose reduction; CBCT; interventional fluoroscopy procedure

1. INTRODUCTION

Cone-beam CT (CBCT) and fluoroscopically-guided interventions (FGI) often involve high radiation dose to the patient's skin and internal organs. The International Commission on

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Radiological Protection (ICRP) has recently published a report on the effects of radiation in which it recognizes that some organs and tissue may be more sensitive to ionizing radiation than previously thought.¹ For example, the dose threshold for the formation of lens opacities was reduced from 5 Gy² in the case of acute irradiation of the eye lens to 0.5 Gy¹, and an absorbed-dose threshold to the brain of 0.5 Gy was determined as likely to produce cerebrovascular disease.¹

Not all FGI procedures require the highest image quality throughout the field of view (FOV) but only within a region of interest (ROI) where the interventional activity is occurring. Lower quality may be acceptable in the periphery of the image which is used primarily for reference. We have previously developed a ROI attenuator method to reduce dose in regions of low interest and preserve high image quality in the ROI.^{3,4} ROI imaging techniques were introduced because of increasing concern about patient radiation exposure during fluoroscopic procedures.³ This work focused on ROI fluoroscopy to reduce the dose administered to a patient during an interventional endovascular procedure under x-ray guidance. To reduce the dose outside the ROI, an x-ray attenuating filter with a central opening is placed in the beam. During x-ray imaging, the attenuator effectively lowers the dose in the peripheral region while allowing high quality imaging of the ROI. This work was extended to real-time equalization of ROI fluoroscopic images using binary masks,⁵ and a thorough evaluation of this work in a clinical setting has been performed.⁶

Although, measurements of dose reduction due to the ROI attenuator were carried out in terms of integral dose^{4, 7, 8, 9}, there have been no detailed studies of organ and effective dose reduction for CBCT and interventional fluoroscopic procedures with the ROI attenuator. For this work, we used EGSnrc Monte Carlo code to calculate the organ and effective dose reduction with a ROI attenuator in CBCT and interventional fluoroscopic procedures.

2. MATERIALS AND METHODS

2.1 Monte Carlo method for X-ray beam modeling

To generate the spectra used for CBCT and interventional fluoroscopic procedures with/without the ROI attenuator, the x-ray tube of the Toshiba Infinix C-Arm System was modeled by BEAMnrc/EGSnrc code. All parts of the tube were simulated according to the manufacturer's specifications. We used the XTUBE component module (CM) of the BEAMnrc code library to simulate the tube target. The SLABS CM was employed to simulate the beryllium (Be) window, inherent filtration and added filtration. The CIRCAPP CM was employed to simulate the ROI attenuator with different dimensions and materials. The JAWS CM was set up to simulate two pairs of lead collimators which can adjust the FOV. In all simulations, the photon energy cut-off (global PCUT) was set to 10 keV for range rejection.¹⁰ Material data were generated by the PEGS4 code developed at NRC.¹¹ A parallel rectangular mono energetic 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 SpekCalc spectrum generating software. 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 (model NE2507/3A, Nuclear Enterprises, Fairchild, NJ) in a solid water phantom at 80 kVp. Both PDD curves were normalized to their maximum value.

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, PHSP were used to run DOSXYZnrc user code in order to determine the relative dose deposited per simulated particle in the phantom. 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 and source type 2 (full phase-space source file) to simulate every exposure of the interventional procedures.

2.2 ROI attenuator and phantom geometry modeling

The ROI attenuator in the x-ray tube of the Toshiba Infinix C-Arm System in our laboratory was modeled in EGSnrc. The ROI attenuator is a rectangular sheet of copper with a thickness of 0.7 mm and a circular aperture which is 12% of the area of the FOV of the 30 × 30 cm detector at 120 cm SID.

To validate the reliability of our simulation, we compared the entrance dose distribution calculated with EGSnrc to that measured with GafchromicTM XR-QA2 film (Ashland, NJ, USA) for DA exposures on a solid water block phantom. The phantom's dimensions were 30 cm × 30 cm × 20 cm thick. The beam mag mode was 12 inch at 120 cm SID. The beam peak voltage was set to 80 kVp (HVL = 3.1 mm eq. Al), tube current was 80 mA, exposure time was 10 ms, frames/second was 15, scan time was 50 s and the 1.8 mm aluminum beam filter was used. The distance from source to phantom surface was 54 cm, which was the interventional reference point. The dose-response curve of the film was determined using a calibrated 0.6 cc Farmer type ionization chamber. We put the film at the same location at the entrance surface of the phantom and did the same DA exposure with and without the ROI attenuator. To get the dose distribution, the exposed films were digitized with a HP Photosmart 7510 flatbed scanner 24 hours after exposure.

For organ and effective dose calculation in our simulations of CBCT and interventional procedures, the Zubal CT torso + head phantom¹³ was used. 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.

2.3 Organ and effective dose calculation for CBCT scans

For the CBCT scans, we used the LCI-Middle protocol on the Toshiba Infinix system with a source to iso-center distance of 69 cm, a field size of 30×30 cm at 120 cm SID, a peak voltage of 120 kVp, a tube current of 4.56 mAs per frame, a rotational range of 203 degrees (from RAO 101° to LAO 102°) and 407 frames. Monte Carlo simulated CBCT scans were performed in the head and in the heart position of the thorax.

2.4 Organ and effective dose calculation for interventional fluoroscopy procedures

We also simulated a neuro and a cardiac interventional fluoroscopic procedure on our Toshiba Infinix C-Arm System using geometry and exposure parameters similar to clinical procedures. All of the projection geometry and exposure parameters for every x-ray pulse used in these procedures were saved from the imaging system digital CAN bus messages in a log file by the real-time skin-dose tracking system (DTS)^{14–21} we previously developed. After the procedures, we used Matlab code to read data from the log files and to automatically generate definition files in the format used by EGSnrc and grouped data with similar technique parameters to reduce calculation time. The efficiency and accuracy of this grouping method has been validated in previous studies.^{22,23,24}

In this study the effective dose was calculated using the tissue weighting factors according to ICRP 103 after we calculated individual organ doses. Although the dose to the eye lens does not contribute to the effective patient dose, it is considered individually because of the increasing concern for cataract formation. Recent studies have suggested that the dose threshold for cataracts is lower than previously believed or even that the effect is stochastic without a threshold.^{25,26,27}

3. RESULTS

3.1 Validation of the Monte Carlo model

Comparison of the SpekCalc simulated x-ray spectrum with the spectrum calculated using the EGSnrc/BEAMnrc is shown in Figure 1. 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 2 shows the comparison of the PDD curve produced by the EGSnrc/BEAMnrc simulation and experimental measurement with the 0.6 cc Farmer chamber. 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 EGSnrc/BEAMnrc simulation and measurement with the ionization chamber are 3.2 and 3.1 mm Al, respectively.

3.2 Surface dose distribution for solid water block phantom

Figure 3 shows the color-coded dose distribution calculated by EGSnrc on the surface of the solid water phantom after a single DA projection without (a) and with (b) the ROI attenuator. The ROI attenuator thickness and opening size of the FOV is the same as the ROI attenuator in our C-arm system (0.7 mm Cu and 12% FOV). The non-uniformity of dose distribution in the anode-cathode direction (horizontal) is due to the Heel effect.

Figure 4 shows the entrance surface dose profiles at the midline axis of the entrance field dose distribution calculated by EGSnrc. It shows the average surface dose reduction in the ROI opening is about 10.5% resulting from the reduced backscatter from the area outside the ROI. Also, the average relative surface dose reduction outside the ROI opening is about 85.7%. It also illustrates the line dose profiles obtained along the midline axis of the entrance field dose distribution with ROI attenuator simulated by EGSnrc and validated by Gafchromic film measurement. The result shows good agreement between Monte Carlo simulation and measurement in both the ROI and the periphery.

3.3 Organ dose and effective dose reduction in CBCT procedures

Figure 5 and Figure 6 showed a reduction in the dose to most organs of 45%–50% and in effective dose of about 46% compared to the dose in standard neuro and thoracic CBCT scans without the ROI attenuator.

3.4 Organ and effective dose calculation in interventional fluoroscopy procedures

Figure 7 shows the dose reduction effect of a ROI attenuator with 0.7 mm thickness and opening size of 12% FOV in a simulated neuro interventional procedure. In this procedure, most of the organ dose reductions were about 55%–60%. For example, the salivary glands dose decreased from 294 mGy to 123 mGy with the ROI attenuator added, resulting in a dose reduction of about 58%. The effective dose also decreased about 58% from 36.6 mGy to 15.9 mGy.

Figure 8 shows the dose reduction effect of a ROI attenuator with 0.7 mm thickness and opening size of 12% FOV in a simulated cardiac interventional procedure. In this procedure, the dose reductions for most of the radiosensitive organs were about 65%–70%. For example, the lung dose decreased from 55 mGy to 16 mGy with the ROI attenuator added, for a dose reduction of about 71%; the stomach dose decreased from 41 mGy to 17 mGy with the ROI attenuator added, for a dose reduction of about 59%. The effective dose decreased from 22.7 mGy to 7.8 mGy, for a reduction of about 66%.

4. DISCUSSIONS

It is important to minimize patient dose to minimize the radiation risk during CBCT scans and interventional procedures.²⁸ Dose management techniques include the use of intermittent fluoroscopy (short bursts of beam-on time)²⁹ and positioning the image receptor as close to the patient's body as possible while maximizing the distance from the x-ray tube.³⁰ Collimating the x-ray beam to include only the anatomic ROI can substantially decrease patient dose, but with a loss of visualization of the peripheral region. To maintain visualization over the entire FOV while gaining much of the dose reduction benefit of collimation, we developed a method of using an ROI attenuator to reduce dose in regions of lower interest and preserve high image quality in the region of interventional activity.

The neuro and the cardiac interventional fluoroscopic procedures in this study were simulated with similar geometry and exposure parameters to clinical procedures. However, there is a large variability between actual procedures due to differences in the complexity of the case and the experience of the interventionist, and thus the total dose distribution may

differ with individual clinical cases. Also, the dose reduction in our simulated interventional procedures will likely be overestimated since we applied the ROI attenuator for the whole procedure, while the interventionist would likely apply the attenuator selectively during a procedure when concentrating on the activity in a small region. However, since the most of the dose to the patient is given during the interventional activity after the target region has been localized, the dose reduction calculated in our simulated interventional procedures should not be a large overestimate. By using our grouping method for exposure events, the Monte-Carlo dose calculation time was greatly reduced while maintaining high accuracy. For instance, in the simulated neuro interventional procedure, the simulation time was reduced from several tens of days (estimated) if the dose was calculated for every exposure pulse to about 10 hours with EGSnrc by grouping and such calculations would likely be done after a procedure. We expect that different “rules” for grouping may be appropriate depending on the type of procedure in order to optimize the reduction of calculation time while maintaining accuracy.

5. CONCLUSIONS

In this work we quantitatively evaluated the potential organ and effective dose reductions of ROI imaging applied to CBCT and interventional fluoroscopic procedures. For a ROI attenuator made with 0.7 mm thick Cu and a circular aperture which was 12% of the FOV, the results of Monte-Carlo calculations showed a reduction in the dose to most organs of 45%–50% and in effective dose of about 46% compared to the dose in standard neuro and thoracic CBCT scans without the ROI attenuator; a reduction in dose for most radiosensitive organs of 55%–60% (65%–70%) and in effective dose of 58% (66%) compared to the dose in a simulated neuro (cardiac) interventional fluoroscopic procedure without the ROI attenuator was determined. In particular, the reduction in eye lens dose can be up to 80% compared to the dose in standard neuro CBCT without the ROI attenuator. This work demonstrates the effectiveness of ROI imaging in reducing patient radiation dose.

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Fig. 1. X-ray spectrum at 80 kVp calculated using BEAMnrc for simulation of the Toshiba Infinix beam compared with the spectrum generated by SpekCalc.

Fig. 2.
Comparison of the 80 kVp PDD curve simulated by EGS and that measured in solid water using a Farmer ionization chamber.

Fig. 3.

The color-coded dose distribution calculated by EGSnrc on the entrance surface of the solid water block for a DA exposure without (a) and with (b) the ROI attenuator. The ROI attenuator was a rectangular sheet of copper with a thickness of 0.7 mm and a circular aperture which was 12% of the FOV of the 30×30 cm detector at 120 cm SID.

Fig. 4. Line dose profiles calculated by EGSnrc along the midline axis of the entrance field dose distribution (Figure 4) with and without the ROI attenuator and line dose profile measured by Gafchromic film with the ROI attenuator.

Fig. 5.
Organ and effective dose comparison for a neuro CBCT scan with/without ROI attenuator.

Fig. 6.
Organ and effective dose comparison for a cardiac CBCT scan with/without ROI attenuator.

Fig. 7. Organ and effective dose comparison for a simulated neuro interventional procedure with and without a ROI attenuator.

Fig. 8.

Organ and effective dose comparison for a simulated cardiac interventional procedure with and without a ROI attenuator.