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Investigation of organ dose variation with adult head size and pediatric age for neuro-interventional projections

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Abstract

The purpose of this study was to evaluate the effect of patient head size on radiation dose to radiosensitive organs, such as the eye lens, brain and spinal cord in fluoroscopically guided neuro-interventional procedures and CBCT scans of the head. The Toshiba Infinix C-Arm System was modeled in BEAMnrc/EGSnrc Monte-Carlo code and patient organ and effective doses were calculated in DOSxynrc/EGSnrc for CBCT and interventional procedures. X-ray projections from different angles, CBCT scans, and neuro-interventional procedures were simulated on a computational head phantom for the range of head sizes in the adult population and for different pediatric ages. The difference of left-eye lens dose between the mean head size and the mean $\pm$ 1 standard deviation (SD) ranges from 20% to 300% for projection angles of 0° to 90° RAO. The differences for other organs do not vary as much and is only about 10% for the brain. For a LCI-High CBCT protocol, the difference between mean and mean $\pm$ 1 SD head size is about 100% for lens dose and only 10% for mean and peak brain dose; the difference between 20 and 3 year-old mean head size is an increase of about 200% for the eye lens dose and only 30% for mean and peak brain dose. Dose for all organs increases with decreasing head size for the same reference point air kerma. These results will allow size-specific dose estimates to be made using software such as our dose tracking system (DTS).

Keywords

head size; Monte Carlo; EGSnrc; organ dose; X-ray projection; CBCT

1. INTRODUCTION

Fluoroscopically-guided neuro-interventional procedures and CBCT scans of the head have increased in recent years, providing important benefits to public health. However, patients can receive relatively high doses to their organs in the head (e.g., eye lens and brain) in addition to receiving a high skin dose. The International Commission on Radiologic Protection (ICRP) has reviewed recent epidemiologic evidence suggesting that there are deterministic effects in some tissues and organs, for which threshold doses might be lower

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than previously considered. Recent studies have suggested that eye lenses may be more sensitive to ionizing radiation and the dose threshold for radiation-induced cataracts (500 mGy, ICRP 2011) is lower than previously believed or even that the effect may be stochastic without a threshold in some recent studies. Although uncertainty remains, medical practitioners should be made aware that the absorbed-dose threshold for cerebral-vascular circulatory disease may be as low as 500 mGy to the brain.¹ The spinal cord is known to be highly radiosensitive even when a small segment is irradiated.² For the eye lens, thresholds exist with lower values for children than those for adults. The ICRP has also stated that in the case of pediatric patients, low-dose irradiation (1–2 Gy) to the developing brain of children can cause long-term cognitive and behavioral defects. Since the head size in the population varies and there are differences (head size, bone thickness and bone density) between the pediatric and adult patient's head, we investigated the variation in dose distribution with head size and pediatric age. There are few research articles on the topic of patient doses in neuro imaging procedures, and the existing articles focus most often on the dose to the skin, the effective dose, or other dose indicators, but they rarely deal with lens dose and brain doses. For this work, we use EGSnrc Monte Carlo code to calculate the organ dose for these 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, the x-ray tube of the Toshiba Infinix C-Arm System was modeled by BEAMnrc code. All parts of the tube were simulated according to the manufacturer's specifications.³ We used the XTUBE component module (CM) of the BEAMnrc code library to simulate the tube target, with a target material of tungsten-rhenium (WRe) and an anode angle of 11 deg. The incident electron energy was simulated using a constant potential with no ripple. The SLABS CM was employed to simulate the beryllium (Be) Window, inherent filtration and additional filtration. Additional aluminum filtration was adjusted to match the half-value layer (HVL) with that measured for the beam. The JAWS CM was set to simulate two pairs of lead collimators, which can adjust the FOV.

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 2000 and the Russian Roulette (RR) was set outside the DBS field of interest. The anode bremsstrahlung cross-section enhancement was increased by a factor equal to 200.³ In all simulations, the photon energy cut-off (global PCUT) was set to 10 keV for range rejection.⁴ Material data were generated by the PEGS4 code developed at the National Research Council.⁵ The NIST data were used for all bremsstrahlung cross-section simulations. The EXACT boundary crossing algorithm (BCA) was used, which utilizes a single elastic scattering mode for electron transport as soon as they are within a distance from the boundary given by the EGSnrc input "skin depth for BCA."⁶ The PRESTA-II electron-step algorithm was employed to calculate lateral and longitudinal corrections. A parallel rectangular monoenergetic beam of 1×10^{10} electrons was incident on the target for the calculations and the results were scaled to the mAs used for the individual simulations.

2.2 Patient head phantom geometry modeling

The Zubal CT computational phantom⁷ was used in our Monte Carlo simulation. 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. Based on the Zubal phantom, we first modified the head phantom by voxel resizing and bone density modification to five sizes: the mean adult population head size, the mean plus and minus one standard deviation (SD) and the mean plus and minus two SD based on the head size information from Hans Delye et al⁸ and J. Lee et al⁹. To investigate the head difference between children and adults, head phantoms of 3 years, 9 years and 20 years old were also developed with different head size and skull bone thickness and density based on Hans Delye et al.⁸ Right and left lens dose, spinal cord average dose, average brain dose and peak brain dose were investigated in this study. The brain volume having greater than 95% peak brain dose was also calculated to better show the brain dose distribution and potential deterministic risk.

2.3 Neuro imaging procedures simulated in the study

For single X-ray projections from 0° to 90° RAO (right anterior oblique), we simulated the DA (digital acquisition) 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. The beam peak voltage was set to 80 kVp (HVL = 3.1 mm Al) and the 1.8 mm Al system beam filter was used. All organ doses were normalized to 1 Gy of air kerma at 54 cm from the source (15 cm tube side of isocenter).

For the CBCT scans, we simulated the LCI-High (low contrast image) 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 110 kVp and 4.2 mm Al HVL, an exposure of 4.56 mAs per frame, a rotational range of 216 degrees (from RAO 108° to LAO 108°) and 607 frames. The simulated CBCT scans were performed centered on the circle of Willis position of the head.

We also simulated two neuro-interventional fluoroscopic procedures on our Toshiba Infinix C-Arm System using geometry and exposure parameters from 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 Controller Area Network (CAN) bus messages in a log file by the real-time skin-dose tracking system (DTS)¹⁰ that was 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. We grouped data with similar technique parameters to reduce calculation time. The efficiency and accuracy of this grouping method has been demonstrated in previous studies.^{11–13}

3. RESULTS

3.1 Organ dose comparison in X-ray projections from different angles

Figure 1 shows for the right eye lens, the dose difference between the mean head size and the mean ± 1 SD is about 30% to 40% from 0° to 90° RAO projections. For the left eye lens,

the dose difference between the mean head size and the mean ± 1 SD is about 20% to 35% from 0° to 45° RAO and went up to 300% from 45° to 90° RAO projections. This is because the left eye lens was exposed to the primary beam when the angle was more than 60° RAO. Figure 2 shows for the brain, the difference between the mean head size and the mean ± 1 SD is about 10% to 14% from 0° to 90° RAO for the average brain dose and about only 1% to 3% from 0° to 90° RAO for the peak brain dose. Figure 3 shows for the spinal cord, the dose difference between the mean head size and the mean ± 1 SD is about 35% to 45% from 0° to 90° RAO and the absolute dose of spinal cord is relatively low. It is reasonable that the dose difference in brain and spinal cord is less than that for the eye lens from 0° to 90° RAO because the brain and the spinal cord are in the relative center position of the head.

3.2 Organ dose comparison in CBCT scans

Figure 4 shows the isodose lines (normalized to the peak dose in the mean head size phantom) in the LCI-High protocol for head phantoms of mean and mean ± 1 SD size. We can see the location of the 5%, 10% and 20% isodose lines were moved to the posterior side of the head when the size of the head is increased.

Figure 5 shows that for a LCI-High protocol CBCT scan, organ dose increased monotonically when the head size is reduced. We used the averaged lens dose of right and left eye since the dose in the two eye lenses were nearly the same for the CBCT scan. The lens dose for the mean head size is 54.2 mGy, and for mean + 1 SD and mean - 1 SD is 29.9 mGy and 138.4 mGy, respectively. For the peak and the mean brain dose, the difference between the mean head size and the mean ± 1 SD is about 10%. However, the difference is more obvious for the volume of 95% peak brain dose, which is 4.5 cm³, 2.1 cm³ and 11.4 cm³ for mean, mean + 1 SD and mean - 1 SD size, respectively.

Figure 6 shows that for a LCI-High protocol CBCT scan, organ dose decreased monotonically with increasing age. The lens dose for 20 yrs old head is 54.2 mGy and is about 200% higher for the 3 yrs head. For the brain, the difference for peak and mean brain dose for the 20 yrs head compared to the 9 yrs and 3 yrs old head is about 15% and 30%, respectively. The difference is more obvious for the volume of 95% peak brain dose (lower histogram), which is 103 cm³, 25 cm³ and 4.5 cm³ (10.9%, 2.3%, and 0.4% of the brain volume) for 3 yrs, 9 yrs and 20 yrs head size, respectively. The same CBCT exposure parameters were used for these dose comparisons between different age heads. These results will allow age specific dose estimates to be made using software such as our dose tracking system (DTS). In most cases, lower exposure factors will be used for the younger child because of their smaller size and the dose will not necessarily be higher than for the adult. The investigation of organ dose to young patients is important because of the increased sensitivity of children to radiation and the larger number of years of life during which to express any potential effects.

3.3 Organ dose comparison in interventional fluoroscopy procedures

Figure 7 shows that for an aneurysm stent procedure, organ dose increased monotonically when the head size is reduced. The left eye lens dose for the mean head size is 32.8 mGy, and for mean + 1 SD and mean - 1 SD is 15.9 mGy and 66.8 mGy, respectively. The right

eye lens dose for the mean head size is 37.2 mGy, and for mean + 1 SD and mean – 1 SD is 20.9 mGy and 72.6 mGy, respectively. For the peak and average brain doses, the difference between for the mean head size and the mean $\pm$ 1 SD is about 10%.

Figure 8 shows that for a thrombectomy procedure, organ dose again increased monotonically when the head size is reduced. The left eye lens dose for the mean head size is 30.1 mGy, and for mean + 1 SD and mean – 1 SD is 16.2 mGy and 47.1 mGy, respectively. The right eye lens dose for the mean head size is 47.1 mGy, and for mean + 1 SD and mean – 1 SD is 27.1 mGy and 188.2 mGy, respectively. This significant dose difference for the mean – 1 SD head size may be because the beam directly exposes the right eye lens at some gantry angles. For the peak and average brain doses, the difference between the mean head size and the mean $\pm$ 1 SD is about 15%.

4. CONCLUSIONS

In this work, we quantitatively evaluated the difference of organ dose to the eye lens, brain and spinal cord in different head sizes in the adult population and for different age pediatric heads for X-ray projections at different angles and CBCT scans. The left eye lens dose difference between the mean head size and the mean $\pm$ 1 SD is about 20% to 40% from 0° to 45° RAO and the difference is much greater and went up to 300% from 45° to 90° RAO. The dose for other organs varies less and is about 10% for the brain. For a LCI-High CBCT scan, the difference between mean and mean $\pm$ 1 SD head size is about 100% for lens dose and only 10% for mean and peak brain dose; the difference in dose between 20 yrs and 3 yrs old mean head size is about 200% for eye lens dose and only 30% for mean and peak brain dose. However, the difference in the volume of 95% peak brain dose was greater between them. For the interventional fluoroscopy procedures demonstrated in this report, the difference between mean and mean $\pm$ 1 SD head size is about 100% to 200% for lens dose and only 10% to 15% for mean and peak brain dose. This work demonstrates that, unless technique factors are adjusted for head size during neuro x-ray examinations, organ doses increase substantially with decreasing head size. The results of these calculations expand the dose information that can be provided by the dose tracking system (DTS) software.¹⁴

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Fig. 1.

Lens dose for single 80 kVp X-ray projections at RAO angles ranging from 0° to 90° for different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD). Figure (a) is for the right lens and figure (b) is for left eye lens. Notice the dose scale difference; for RAO angulations, the x-ray tube is closer to the left eye and it received the higher dose.

Fig. 2. Brain dose for single 80 kVp X-ray projections at RAO angles ranging from 0° to 90° for different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD). Figure (a) is for peak brain dose and figure (b) is for average brain dose.

Fig. 3.

Spinal cord dose for single 80 kVp X-ray projections for RAO angles ranging from 0° to 90° for different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD).

Fig. 4.

Isodose lines (normalized to the peak dose in the mean head size phantom) in a CBCT scan on head phantoms with mean and mean ± 1 SD size.

Fig. 5.

Organ dose distribution for a CBCT scan for different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD). The LCI-High protocol was used with the same technique parameters for all head sizes.

Fig. 6. Organ dose distribution for a CBCT scan of heads for different age patients (3 yrs, 9 yrs and 20 yrs).

Fig. 7. Organ dose distribution for an aneurysm stent procedure on different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD).

Fig. 8.

Organ dose distribution for a thrombectomy procedure on different head sizes (mean, mean $\pm$ 1 SD and mean $\pm$ 2 SD).