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Monte Carlo radiography simulation for assessment of absorbed radiation dose in femur bone marrow during X-ray radiography for constant mAs and AEC techniques

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ABSTRACT

***Background*:** The purpose of this study was to find the accurate absorbed dose in the femur bone marrow during the X-ray radiography for constant mAs and AEC techniques. ***Materials and Methods*:** The DOSXYZnrc was used to simulate radiation doses in two human femurs during diagnostic radiography. EGSnrc phantoms produced from actual CT images of human femurs were modified by adding seven micrometre layers of marrow tissues. The X-ray machine was simulated using BEAMnrc using 30 billions particles for different combinations of energies and filters. The resultant data was used to in DOSXYSnrc simulations to evaluate the absorbed dose in the human femur. ***Results*:** In the head of the femur, for 2.5 mm aluminium filtered 85 kVp X-ray set at 50 mAs, the absorbed dose in the marrow was found to be 1.360 mGy, ~ 36% of the absorbed dose in the cortical bone. It was also found that for the constant mAs technique, the radiation dose in the marrow over the studied energies and filter combination, ranges from 0.356 mGy to 2.403 mGy, with higher dose recorded for higher kVp settings. However, for the AEC technique, the dose is lower for higher kVp settings. For a typical setting, viz. 85 kVp, 6 mAs at 48 inches SID, the bone marrow absorbed dose was found to be 0.186 mGy for the constant mAs technique and 0.0308 mGy for the AEC technique. ***Conclusion*:** It was confirmed that the radiation dose is lower when the AEC exposure technique is used as opposed to using constant mAs technique. For the AEC technique, typical dose to the bone marrow was found to be ~ 0.05 mGy, decreasing with both kVp settings and beam filtration. For constant mAs technique, the typical dose to bone marrow is found to be higher, ~ 0.2 mGy, decreasing with the amount of filtration used but increasing with the kVp setting.

Keywords: *DOSXYZ simulation, bone marrow, dosimetry, X-ray.*

INTRODUCTION

Bone marrow produces the blood cells, i.e., the white blood cells, red blood cells and platelets. All of these components are sensitive to radiation. If the red blood cells are affected, the patient becomes anaemic, and requires transfusions, if the white blood cells are affected, the body will lose its defense against infections and if platelet cells are damage, the probability of internal bleeding will be increased [(1)]. To find

the absorbed dose to bone marrow, a method to convert CT numbers into elemental weights of human tissues was introduced by Schneider *et al.* These data were later used as input for Electron Gamma Monte Carlo shower codes, EGS4. Seventy one types of human tissues were considered for their functional relationships between tissue elements and CT numbers. Any missing data lying between the main points were derived through interpolation. The maximum errors predicted for carbon and oxygen weights were up to 14%. These errors are less than 5% for the rest of the elements [2]. In 2005, Verhaegen & Devic evaluated the inaccuracies in CT segmentations using phantom for energies ranging from 250 kVp to 15 MV. Their research concludes that inaccuracies in CT data used in simulations produces as high as 40% errors in radiation doses for 250 kVp X-ray, with lesser error for higher energy radiation. This amount of disparity implies that CT calibration with proper phantom is essential [3]. In 2005, a new model was introduced to provide a three-dimensional geometry for Monte Carlo simulations in bony tissues based on micro CT images. For energy interval between 50 to 200 keV, it was found that the absorbed fractions to red marrow diverge from those estimated using previous techniques of spongiosa transport [4]. In 2006, ICRP updated two digital phantoms which have already been recommended to use in the field of radiation protection fields. MAX or male adult and FAX or female adult voxel are the phantoms which have been updated with new organs and tissues data [5]. In 2007, Vanderstraeten *et al.* developed one of the most important researches about the human material compositions. They found a method to convert CT numbers to tissue parameters using a CT number calibration technique. The converted data were then utilized in a Monte Carlo Treatment Planning system: MCTP. Using these data, total amounts of evaluated errors were found to be ~ 5% [6]. In 2007, Bhatti et al measured the chromosome translocations in blood lymphocytes during the diagnostic procedures. Translocations were counted in 1800 metaphase cells and reported in term of cell equivalents, CE, per person. The results shows that mean dose to the red marrows is 1.9 cGy. A linear relationship between the dose to red marrow and translocations was also found, the slope of which is 0.15 excess translocations per 100 CE per cGy. For instant, there would be around 8 translocations per 100 CE for 5 cGy dose to red marrow [7]. Our earlier Monte Carlo simulation work on the absorbed dose in femur bone phantom during X-ray radiography was described elsewhere [8]. In the current work, the absorbed dose in marrow of the femur during radiography was calculated using CT information of actual human.

MATERIALA AND METHODS

In this study, the egsphant phantoms, i.e. the digital phantom used in the DOSXYZnrc simulations were constructed from real human femur CT data using CTCREATE [9]. Five tissues, listed in table 1, were defined to assist the conversion of the CT images to egspahnt phantom file (egsphant). In the first, the voxel size for the egsphant phantom was set to 0.28×0.18×0.3 cm^3. The phantom file was then modified by manually adding seven columns of data representing bone marrow at the location right after bone tissues. The thickness of each added layer was defined to be 1 μm. This modification was carried out to minimize the effect of voxel averaging of absorbed dose, enabling more accurate determination of maximum absorbed dose in the bone marrow.

The DOSXYZnrc simulation code was then used to estimate the absorbed dose in the bone marrow. The particle phase-space files needed

Table 1. Density data of various tissues in human femur used for the egsphant file [10], *[2].

Tissue	Density	
	Lower (g/cm^3)	Upper (g/cm^3)
Air: AIR700ICRU	0.001	0.044
Muscle	1.01	1.1
Spongy Bone	1.1	1.14
Cortical Bone	1.14	2.088
*Bone Marrow	1.03	1.03

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for this simulation were obtained from separate simulations for a Philips X-ray machine by the authors described elsewhere [11]. A total of 30 billion particles from the phase space files were used for this simulation using 600 particle recycle times. To evaluate possible errors due to the high number of particle recycling, the simulation was repeated ten times using different random number seeds. The simulations were carried out on a Debian Linux cluster, with 3 Intel cores i7 CPU (24 total number of cores) model number 2600, 3.40 GHz with 24 GB RAM. Two additional human femurs were simulated to find the bone marrow absorbed dose in the head and the body of femur using similar procedures. For these simulations, the voxel size of all egsphant phantoms was 0.5×0.5×0.5 cm^3. These egsphant phantoms were also modified to include the micrometer-thick bone marrow layers. The simulations for these phantoms were then carried out to determine the absorbed dose in bone marrow during X-ray radiography using both constant mAs and AEC techniques. For these simulations, three diagnostic X-ray energies, viz 102, 85 and 70 kVp with combinations of four different filters were used. The simulation results of radiation doses as a function of kVp values and filters for head and body of the femur were transformed to relative doses for both constant mAs and automatic exposure control (AEC) techniques to reflect clinical considerations.

RESULTS AND DISCUSSION

The depth dose curves for the femur phantom and modified femur phantom (phantom with marrows) are depicted in figure 1. It appears from the plot that the absorbed dose decreases in the muscle until 1.7cm depth, followed by a rapid increase of the dose due to increase absorption in the cortex bone. The dose falls again after ~2.2cm depth due to lower density spongy bone, specified to be ~1.12 g/ cm^3 while the density of cortex bone is ~1.27 g/ cm^3. Comparing the dose values of the phantoms with and without the additional layers of bone marrow reveals no significant disparity between the two, the maximum

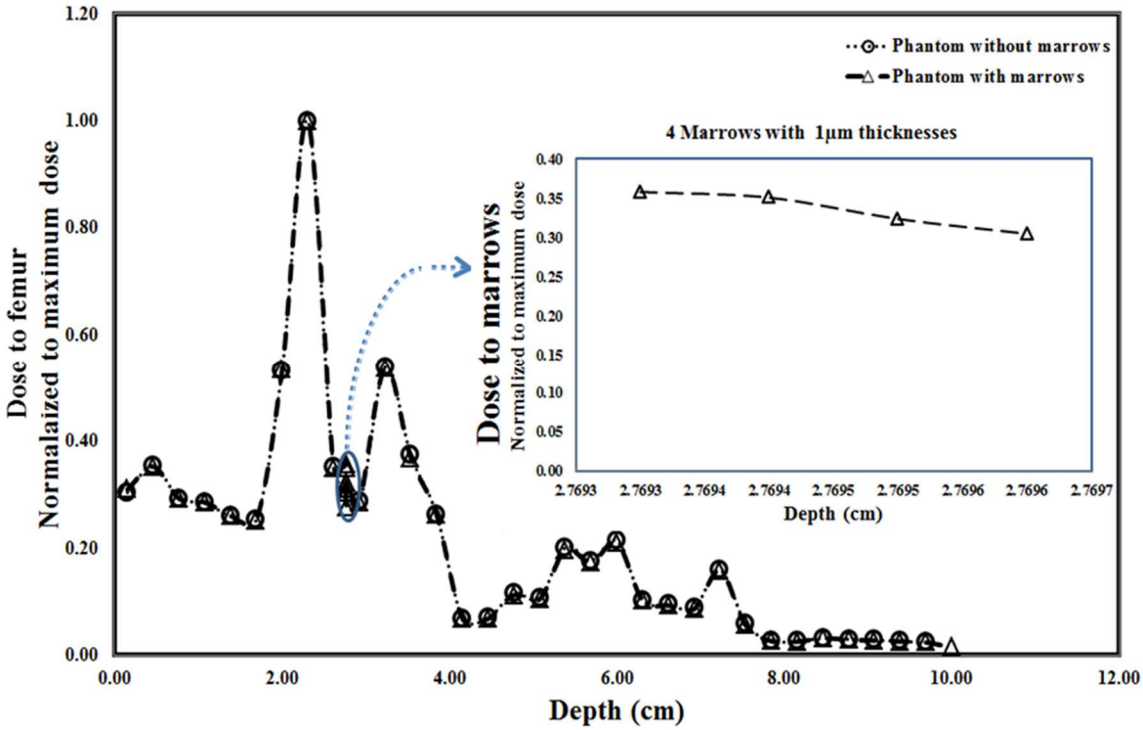

Figure1. Depth dose for a typical human femur from 0 to 10 cm along the Z axis for femur phantom and modified femur phantom included the data of bone marrows.

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disparity being 4.96%, observed at the depth of 7.54 cm. This provides a support that the data at the locations of marrows are reliable.

The dose plots for marrows are exploded for clarity, located at the top right side of figure 1. The femur surface dose found here, 1.317 mGy, lies within the interval of entrance dose values reported by Schandorf *et al.* 0.3 to 1.7 mGy table 2 [12].

Current work by using micrometer-dimension voxel in the Monte Carlo simulation. Thus, to our knowledge, it can be deduced that the results of this work contains the most accurate reported values for absorbed dose in marrow of the femur head during a diagnostic radiography. Due to dose averaging effect in voxels, the accuracy of the results in current work is also better than what have been reported using 200 μm thick layers of marrows [17].

The results for DOSXYZnrc simulations for automatic exposure control (AEC) technique are illustrated in figure 2(a), confirming higher marrow doses for lower kVp settings and softer X-ray beams. The lower kVp, however, results in lower radiation dose to marrow for constant current (mAs) technique (figure 2(b)). Holding constant mAs, the dose is confirmed to increase with kVp. To use the obtained results for the constant mAs technique under practical radiography conditions, the exposure settings must be renormalized for mAs settings, source to image distance (SID) and object to image distance (OID). For exposure settings of 85 kVp and 6 mAs at 48 inch (121.92 cm) SID, with OID of 9 cm and femur thickness of 12.5 cm, the calculated maximum absorbed dose in femur bone marrow, using the linear relation between dose and mAs and inverse square law, is 0.186 mGy. For the AEC technique in femur radiography, the typical exposure settings are 200 mA at 48" (121.92 cm) [18]. In this case the bone marrow absorbed dose for 10 ms exposure are 0.0308 mGy, 0.0484 mGy and 0.0698 mGy for 70 kVp, 85 kVp and 102 kVp respectively.

Table 2. The absorbed dose in the head of femur for 85 kVp X-rays, 50 mAs at 100 cm SSD.

Absorbed dose (mGy)	Femur surface dose	Maximum dose to bone	Maximum dose to marrows
	1.317 ± 0.017	3.753 ± 0.034	1.360 ± 0.096

CONCLUSION

To determine the absorbed dose in the femur bone marrow, Monte Carlo codes were used. In the head of the femur, the absorbed dose in the

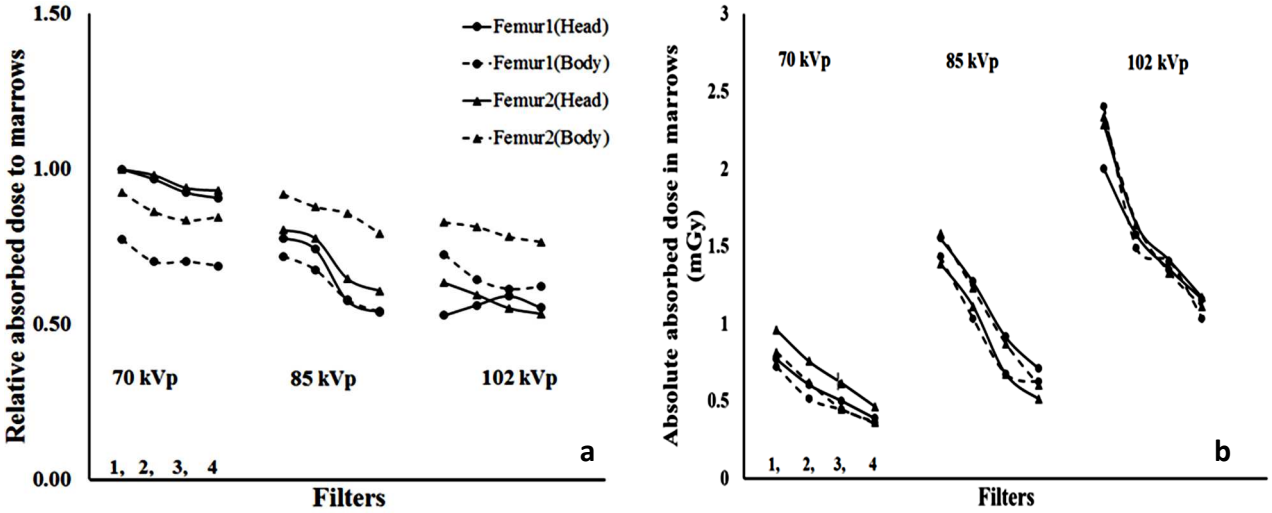

Figure 2. (a) The relative absorbed dose to bone marrow of femur head and body using automatic exposure control (AEC) technique and (b) the absolute absorbed dose to bone marrow using constant mAs technique. The filters are: Filter 1 (2.5 mmAl), Filter 2 (4.5 mmAl), Filter 3 (3.5 mmAl+0.1 mmCu) and Filter 4 (3.5 mmAl+0.2mmCu).

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bone marrow for 85 kVp, with 50 mAs at 100 SSD, was found to be 1.360 mGy, i.e., ~36% of maximum absorbed dose in the cortex bone of the femur. For the constant mAs technique, the dose to femur bone marrow ranges from 0.356 mGy to 2.403 mGy, with higher dose for higher kVp settings. The dose was also found to decrease with the amount of filtration used. For automatic exposure control (AEC), however, the relative dose was found to be lower for both higher kVp settings and increased filtration. When the constant mAs technique was applied for femur radiography, using settings of 85 kVp and 6 mAs at 121.92 cm SID, the maximum femur bone marrow absorbed dose was found to be ~0.186 mGy. With the AEC technique, the maximum bone marrow absorbed dose to femur for 10 ms was found to be 0.0308 mGy, 0.0484 mGy and 0.0698 mGy for 70 kVp, 85 kVp and 102 kVp respectively.

Conflict of interest: *Declared none*

REFERENCES

1. Deeley JOT and Moore JL (1989) Nuclear Lysate Sedimentation Measurements of Peripheral Blood Lymphocytes from Radiotherapy Patients. *International Journal of Radiation Biology,* ***56(6):****963-73.*
2. Schneider W, Bortfeld T, Schlegel W (2000) Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions. *Physics in Medicine and Biology,* ***45(2):****459.*
3. Verhaegen F and Devic S (2005) Sensitivity study for CT image use in Monte Carlo treatment planning. *Physics in Medicine and Biology,* ***50(5):****937.*
4. Shah AP, Rajon DA, Patton PW, Jokisch DW, Bolch WE (2005) Accounting for beta-particle energy loss to cortical bone via paired-image radiation transport (PIRT). *Med Phys,* ***32(5):****1354-66.*
5. Kramer R, Khoury HJ, Vieira JW, Lima VJ (2006) MAX06 and FAX06: update of two adult human phantoms for radiation protection dosimetry. *Phys Med Biol,* ***51 (14):****;3331-46.*
6. Vanderstraeten B, Chin PW, Fix M, Leal A, Mora G, Reynaert N, *et al.* (2007) Conversion of CT numbers into tissue parameters for Monte Carlo dose calculations: a multi-centre study. *Phys Med Biol,* ***52(3):*** *539-62.*
7. Bhatti P, Preston DL, Doody MM, Hauptmann M, Kampa D, Alexander BH, *et al.* (2007) Retrospective biodosimetry among United States radiologic technologists. *Radiat Res,* ***167(6):****727-34.*
8. Salehi Z and Yusoff AL (2013) The absorbed dose in femur exposed to diagnostic radiography. *Radiation Protection Dosimetry,* ***154(3):****396-9.*
9. Kawrakow I, rogers DW, walters B (2009) DOSXYZnrc Users Manual, NRCC Report PIRS-794. Ottaw: Ionizing Radiation Standards National Research Council of Canada; Available from: http://irs.inms.nrc.ca/software/beamnrc/documentation/pirs794/pirs794.pdf.
10. Zhou H, Keall PJ, Graves EE (2009) A bone composition model for Monte Carlo X-ray transport simulations. *Med Phys,* ***36(3):*** *1008-18.*
11. Salehi Z, Ya Ali NK, Yusoff AL (2012) X-ray spectra and quality parameters from monte carlo simulation and analytical filters. *Applied Radiation and Isotopes,* ***70 (11):****2586-9.*
12. Schandorf C and Tetteh GK (1998) Analysis of dose and dose distribution for patients undergoing selected X-ray diagnostic procedures in Ghana. *Radiation Protection Dosimetry,* ***76(4):****249-55.*
13. Ay MR, Shahriari M, Sarkar S, Ghafarian P(2004) Measurement of organ dose in abdomen-pelvis CT exam as a function of mA, KV and scanner type by Monte Carlo method[Original Research]. *Iranian Journal of Radiation Research,* ***1(4):****187-94.*
14. Sohaib SA, Peppercorn PD, Horrocks JA, Keene MH, Kenyon GS, Reznek RH (2001) The effect of decreasing mAs on image quality and patient dose in sinus CT. *Br J Radiol,* ***74(878):****157-61.*
15. Alzimami K, Sassi S, Alkhorayef M, Britten AJ, Spyrou NM. (2009) Optimisation of computed radiography systems for chest imaging. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers. *Detectors and Associated Equipment,* ***600(2):****513-8.*
16. Snyder WS, Ford MR, Warner GG (1970) Estimation of dose and dose commitment to bladder wall from a radionuclide present in urine. Oak Ridge National Laboratory 1970; ORNL-4584, pp. 206-208]. Available from: <http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=4362195>.
17. Kulkarni RN (1981) Monte Carlo calculation of the dose distributions across a plane bone-marrow interface during diagnostic X-ray examinations. *British Journal of Radiology,* ***54(646):****875-7.*
18. Long BW, Frank ED, Ehrlich RA (2005) Radiography Essentials for Limited Practice: *Elsevier Health Sciences.*

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