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Monte Carlo dosimetry of iodine contrast objects in a small animal microCT

M. Rodríguez-Villafuerte *, A. Martínez-Dávalos

Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, 01000 México D.F., Mexico

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ABSTRACT

Small animal microcomputed tomography (microCT) studies with iodine-based contrast media are commonly used in preclinical research. While the use of contrast media improves the quality of the images, it can also result in an increase in the absorbed dose to organs with high concentration of the contrast agent, which might cause radiation damage to the animal. In this work we present the results of a Monte Carlo investigation of a microCT dosimetry study using mouse-sized cylindrical water phantoms with iodine contrast insets for different X-ray spectra (Mo and W targets, 30 – 80 kVp), iodine concentrations (0, 5, 10 and 15 mg mL^{-1}) and contrast object sizes (3 and 10 mm diameter). Our results indicate an absorbed dose increase in the contrast-inset regions with respect to the absorbed dose distribution within a reference uniform water phantom. The calculated spatial absorbed dose distributions show large gradients due to beam hardening effects, and large absorbed dose enhancement as the mean energy of the beam and iodine concentration increase. We have found that absorbed doses in iodine contrast objects can increase by a factor of up to 12 for a realistic 80 kVp X-ray spectra and an iodine concentration of 15 mg mL^{-1}.

1. Introduction

Nowadays dedicated small animal microCT systems are being extensively used in a wide variety of applications. It is well known that good quality microCT studies require high spatial resolution, high contrast and low noise. This can be achieved by both reducing the detector size and increasing the total X-ray fluence rate, thus ensuring a reasonably high signal-to-noise ratio per detector element. This implies, however, that the better the image quality, the larger the absorbed dose imparted to the subject. Maintaining the absorbed dose well below a certain threshold is very important since the imaging protocol must have a negligible effect on the health of the animal [1]. Several methods can be applied to reduce the absorbed dose in microCT, which include lowering the X-ray tube current, decreasing the imaging time [2] or increasing the kVp. In these cases, and in order to maintain good image quality, the contrast can be enhanced using iodine-based contrast agents. In spite of the common practice of using contrast agents in small animal microCT studies, the absorbed dose to the animal in regions labeled with the contrast medium is still an unresolved issue.

In this work, a Monte Carlo simulation of radiation transport was carried out to calculate spatial absorbed dose distributions in mouse-sized cylindrical water phantoms with iodine-based contrast insets, assuming typical X-ray beam qualities to be as those used in small animal microCT studies. Several iodine concentrations (5, 10 and 15 mg mL^{-1}) and cylindrical inset diameters were considered. The results were compared with respect to a reference cylindrical phantom uniformly filled with water.

2. Materials and methods

2.1. Monte Carlo simulation

The PENELOPE Monte Carlo code [3] was used to simulate the transport of photons and electrons in a simple microCT cone beam geometry closely resembling a microCT prototype currently being built in our laboratory. Simulations were performed over a range of tube potentials (30–80 kVp) for X-ray tubes with Mo and W targets. Polychromatic X-rays beams were calculated [4,5] with the parameters shown in Table 1 (see also Fig. 1), and incorporated in the simulation assuming an isotropic point source in a cone beam geometry by limiting the angle of emission within a cone of 12° aperture towards the phantom. The geometry of the microCT considered a 20.5 cm source-to-object distance, 360° circular acquisition with a step angle of 3.6° (100 projections). Mouse-sized cylindrical water phantoms (30 mm ∅, 40 mm length) containing centered cylindrical insets (3 and 10 mm ∅, 40 mm length) filled with a mixture of water and different iodine concentrations were considered. Deposited energy in the phantom was calculated in cubic voxels of 0.25 mm length assuming 2×10^6 photon histories per projection and cut-off energies of 1 and 5 keV

* Corresponding author. Tel.: +52 55 5622 5052; fax: +52 55 5616 1535.
E-mail address: mercedes@fisica.unam.mx (M. Rodríguez-Villafuerte).

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Table 1
Parameters of polychromatic X-ray beams used in the simulation.

Label	Target	kVp	Filter (mm Al)	Additional filtration	E_{mean} (keV)	Iodine concentration (mg mL^{-1})
Mo30	Mo	30	0.5	20 μm Mo	18	0, 10
W40	W	40	1.0	–	24	0, 10
W50	W	50	2.0	–	31	0, 10
W80	W	80	0.7	0.1 mm Cu	46	0, 5, 10, 15

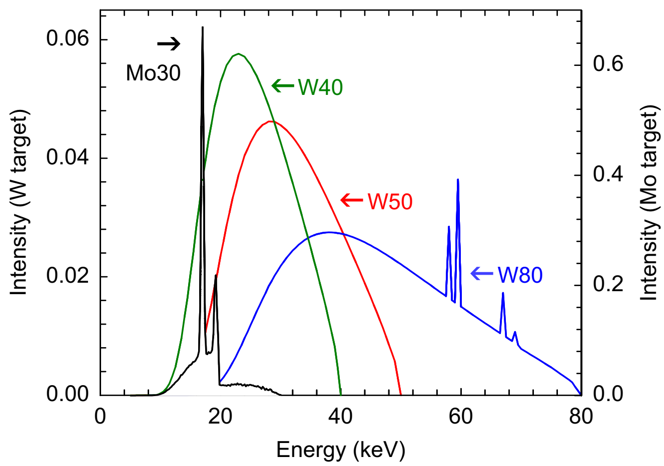

Fig. 1. Normalized energy spectra of X-ray beams used in simulation.

for electrons and photons, respectively. The absorbed dose was obtained as deposited energy per unit mass.

2.2. Effect of beam quality

A Monte Carlo simulation was carried out using the four X-ray beam qualities listed in Table 1, assuming the same photon fluence to be incident at isocenter and a constant iodine concentration of 10 mg mL^{-1}. Three-dimensional absorbed dose distributions were calculated and from these, 2D and 1D histograms were extracted.

2.3. Effect of iodine concentration

The W80 X-ray beam was of particular interest since it represents the beam quality used in a reported experiment carried out by Badea et al. [6] in a small animal microCT study with an iodine-based contrast medium. The importance of using this spectrum lies in the fact that very high fluxes can be achieved from a W anode with 70–80 kVp tube potentials, which in turn allow very short acquisition times [7]. Badea et al. [6] measured an exposure of 3.92×10^{-3} C kg^{-1} (labeled as X_B in Eq. (1)) during their experiment when using an X-ray tube operating at 80 kVp, 150 mA and 10 ms per projection; data acquisition covered a 189° circular arc with a step angle of 0.75° (252 projections).

The W80 simulation results were compared with values reported in Ref. [6] by normalizing the Monte Carlo calculations by a multiplicative factor $N_{MC\to Exp}$ given by

$$N_{MC\to Exp} = \frac{X_B}{X_{MC}} = \frac{3.92 \times 10^{-3}\,\mathrm{C\,kg^{-1}}}{X_{MC}} \quad (1)$$

where X_{MC} is the calculated Monte Carlo exposure at isocenter produced by the total number of photon histories sampled from the W80 X-ray spectrum in the absence of the phantom. The photon-fluence-per-exposure coefficients were obtained from Ref. [8].

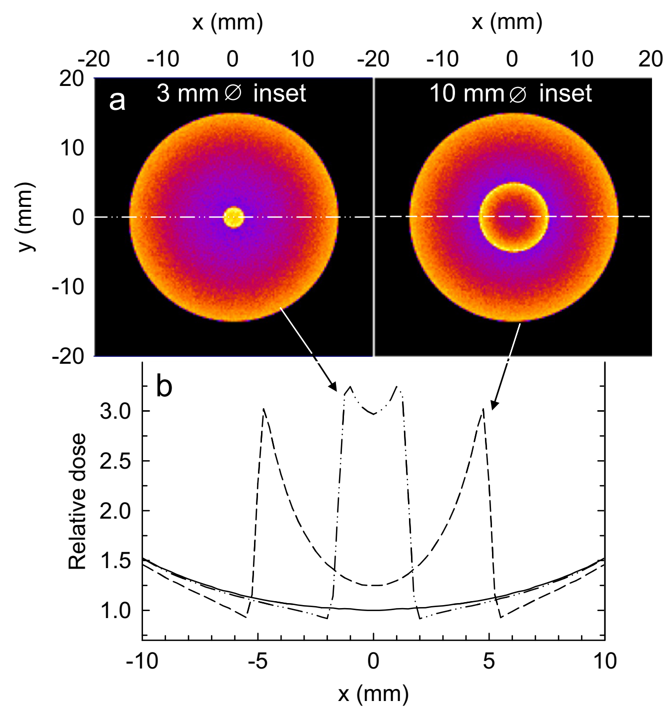

Fig. 2. (a) 2D spatial absorbed dose distributions and b) radial dose profiles across midplane of contrast phantom for Mo30 and 10 mg mL^{-1} iodine concentration. The continuous line in (b) represents calculations in a reference water phantom.

3. Results

3.1. Effect of beam quality

Two-dimensional absorbed dose distributions with their corresponding radial dose profiles in the midplane of the phantom were extracted. Absorbed dose values were normalized with respect to the absorbed dose at the center of a uniform water phantom. Only the data for the Mo30 beam are shown (Fig. 2), since the results for the other X-ray spectra present approximately the same features. It can be observed that the radial dose profiles display large values in the contrast-inset region with respect to the simulation of a uniform water phantom (continuous line in Fig. 2b). Also, the absorbed dose distributions have large gradients due to beam hardening effects. As would be expected, these gradients are a function of the X-ray beam quality—the smaller the mean energy of the beam, the larger the gradient. Absorbed doses in the phantom periphery remain approximately the same with or without the contrast inset.

Dose increase factors (DIFs), defined as radial dose profiles in the contrast insets normalized with respect to radial dose profiles in the same region of a uniform water phantom, were evaluated for all beam qualities. For a given X-ray beam quality, the DIFs cover a range of values due to beam hardening effects, with minima and maxima at the center and towards the periphery of the inset,