Evaluation of patient dose using a virtual CT scanner: Applications to 4DCT simulation and

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Evaluation of patient dose using a virtual CT scanner: Applications to 4DCT Simulation and Kilovoltage Cone-Beam Imaging

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Abstract. This work evaluates the effects of patient size on radiation dose from simulation imaging studies such as four-dimensional computed tomography (4DCT) and kilovoltage cone-beam computed tomography (kV-CBCT). 4DCT studies are scans that include temporal information, frequently incorporating highly over-sampled imaging series necessary for retrospective sorting as a function of respiratory phase. This type of imaging study can result in a significant dose increase to the patient due to the slower table speed as compared with a conventional axial or helical scan protocol. Kilovoltage cone-beam imaging is a relatively new imaging technique that requires an on-board kilovoltage x-ray tube and a flat-panel detector. Instead of porting individual reference fields, the kV tube and flat-panel detector are rotated about the patient producing a cone-beam CT data set (kV-CBCT). To perform these investigations, we used Monte Carlo simulation methods with detailed models of adult patients and virtual source models of multidetector computed tomography (MDCT) scanners. The GSF family of three-dimensional, voxelized patient models, were implemented as input files using the Monte Carlo code MCNPX. The adult patient models represent a range of patient sizes and have all radiosensitive organs previously identified and segmented. Simulated 4DCT scans of each voxelized patient model were performed using a multi-detector CT source model that includes scanner specific spectra, bow-tie filtration, and helical source path. Standard MCNPX tally functions were applied to each model to estimate absolute organ dose based upon an air-kerma normalization measurement for nominal scanner operating parameters.

1. Introduction and Background

Over the last few years the role of image guidance in radiation therapy has become an important component for accurately defining the location of the tumor volume relative to adjacent normal tissue structures. Conventional simulation techniques utilizing a diagnostic radiography and fluoroscopy machine have largely been replaced in favour of CT-based virtual simulation methods. A corresponding change has also taken place with respect to monitoring patient position during the course of radiotherapy. Although standard megavoltage port films are still used to check patient position on a weekly basis, kilo-voltage cone-beam CT (kV-CBCT) is slowly being adopted as a daily image guidance tool. Although diagnostic CT imaging studies typically represent some of the highest dose estimates to the general population, the radiotherapy community typically ignores this imaging dose given the relatively large scatter and leakage whole-body dose contributions due to a course of primary radiation therapy. There are several studies evaluating patient-specific dose from diagnostic CT scanning protocols using Monte Carlo simulation techniques and anthropomorphic or voxelized patient models (Caon 1999, Khursheed 2002, Schmidt and Kalender 2002, Tzedakis 2005, Castellano 2005, Salvado 2005, DeMarco 2007).

With respect to CT simulation, 4DCT scanning protocols attempt to account for the patient's respiratory motion by utilizing a low pitch scan (p=0.1) to produce a highly over-sampled CT data set. This raw CT data set can be reconstructed into separate image sequences at discrete points on the respiratory cycle. This type of highly over-sampled CT scan results in a dose increase that is inversely proportional to the table pitch; producing a 10-fold dose increase relative to a pitch=1.0 and normalized on a per mAs basis. Kilovoltage cone-beam imaging is a relatively new imaging technique that requires an on-board kilovoltage x-ray tube and a flat-panel detector. Instead of porting individual reference fields, the kV tube and flat-panel detector are rotated about the patient producing a cone-beam CT data set (kV-CBCT). Although the tube potential for kV-CBCT is similar to a conventional CT scanner ($\approx$120 kVp), the total number of photons incident upon the patient is based upon the number of projections and the mAs per projection. This is significant since patient dose is directly proportional to the total mAs exiting the tube. Islam et al. (2006) have previously evaluated dose in cylindrical phantoms from a kV-CBCT unit (Elekta Synergy XVI system). Wen et al. (2007) have measured patient surface dose from a Varian CBCT using TLD's and in-vivo dose with a Rando pelvic phantom. The Synergy system delivers 600 mAs per CBCT based upon 360 projections and 2 mAs per projection while the Varian system delivers 1320 mAs per CBCT based upon 660 projections and 2 mAs per projection. This study seeks to quantify the absolute organ dose from 4DCT and kV-

CBCT imaging protocols using Monte Carlo simulation methods to calculate the average organ dose in patient specific voxelized models.

2. Methods of Materials

2.1. MCNPX Monte Carlo Code

All simulations were performed using the MCNPX (MCNP eXtended v2.6.c) Monte Carlo code (Waters 2003). For this work, the simulation was operated in photon mode with a low-energy cutoff of 1 keV. The photon transport model creates electrons but assumes that they travel in the direction of the primary photon, and that the electron energy is deposited at the photon interaction site, creating a condition of charged particle equilibrium (CPE).

2.2. Voxelized Patient Models

MCNPX voxelized models were created based upon the GSF family of voxelized phantoms where individual organs have been segmented. (Petoussi-Henss et al 2002, Zankl et al 2002). Table 1 provides a description of the size and simulation characteristics for each adult voxelized model implemented in this study. The GSF data represents a three-dimensional matrix of voxels with each voxel assigned an integer corresponding to a specific body organ or tissue segmented from the original CT scans. Each GSF organ was assigned an organ specific elemental composition and mass density based upon the ICRU 44 organ composition tables (ICRU 1989) and implemented as a geometry structure using the MCNP lattice and the voxel dimensions described in Table 1a and 1b.

Table 1a and 1b – Gender, size and MCNPX simulation characteristics for the adult GSF models
(1a)

GSF Model	Age (yr)	Gender	Weight (kg)	Height (cm)
Irene	32	Female	51	163
Donna	40	Female	79	170
Helga	26	Female	81	170
Golem	38	Male	69	176
Frank	48	Male	95	174
Visible Human	?	Male	103	180

(1b)

GSF Model	in-plane matrix size	in-plane voxel size(mm)	# of slices	4DCT scan length (cm)
Irene	131x66	3.75	348	24.5
Donna	128x128	3.75	179	21.0
Helga	128x128	3.92	114	19.0
Golem	128x128	4.20	220	22.8
Frank	128x128	2.97	193	25.6
Visible Human	128x128	3.68	250	23.5

2.3. 4DCT Simulation Characteristics

The standard MCNPX source code was modified to allow the simulation of a multi-detector CT scanner used for 4DCT scan protocols. The 4DCT source model for this work (Siemens Sensation Open) includes scanner geometry (i.e. distance from focal spot to isocenter) and helical source path. Based upon specifications provided by the manufacturer, the scanner source model includes the CT bowtie filter and the scanner specific photon spectral distribution for 120 and 140 kVp. A simulated 4DCT thoracic scan protocol was performed for each GSF adult phantom model, using a scan length extending from 1 cm superior to the lung apex to 1 cm beyond the inferior base of the lungs. The scan protocol was based upon a nominal beam collimation of 24x1.2 mm and a scan pitch of 0.1. All scans were normalized on a tube current rotation time product (mAs) basis. To convert simulation calculated values (cGy per source particle) into absolute dose (cGy), the required normalization factor was calculated based upon an air scan measurement ($CTDI_{100}$ in air) and corresponding air simulation performed at the appropriate scan energy and collimation.

2.4. kV-CBCT Simulation Characteristics

A preliminary Monte Carlo based, kV cone beam model was tested by using the in-phantom measurements of Islam et al. as reference calibration measurements (Islam 2006). The authors measured the dose at depth in a 30 cm diameter water phantom for four different field sizes and a 120 kVp tube potential. The x-plane distance was kept constant at 26.0 cm and the longitudinal jaws were varied between 5 and 26 cm. The output spectrum was modeled using a standard 120 kVp spectrum with added filtration to match the half-value layer as measured from the Synergy system. The ratio of the measured dose at the center of the 30 cm phantom versus the Monte Carlo calculated dose represents the normalization factor.

2.5. Estimating Radiation Dose from Each Experiment

Based upon the MCNPX material index, the mean organ dose was computed by averaging the dose received by each voxel in a particular organ across all voxels assigned to the organ. Absorbed dose within a voxel was computed by a track-length estimate of energy fluence multiplied by the material-specific and energy dependent mass energy-absorption coefficient. This tally represents collision kerma as a function of organ composition and is equivalent to absorbed dose under conditions of charged-particle equilibrium (CPE). The assumption of CPE is reasonable almost everywhere in the model given the energy distribution of the incident photons. The mass energy-absorption coefficients were taken from the tables of Hubbel & Seltzer (Hubbell and Seltzer 1995). A total of 4 million photon histories were used for each simulation resulting in a 1σ standard deviation of less than 1% for each organ that falls within the primary scan volume. For this study all simulations were performed on a 1.70GHz laptop PC with 1 GB of RAM.

3. Results

Figure 1 illustrates the results of average lung dose (cGy) for each adult GSF voxel phantom model based upon the 4DCT scanning protocol. The results are plotted as a function of the scanner mAs setting which ranges between 40 and 120 mAs per tube rotation. For a pitch of 0.1 this translates into effective mAs settings of between 400 and 1200 mAs per tube rotation. For the Irene voxel model (open circle) the average lung dose ranges between 6 and 18 cGy. For the Visible Human voxel model (asterisk symbol) the average lung dose ranges between 3.5 and 10.5 cGy. The Irene and Visible Human models receive the highest and lowest average lung dose respectively from the 4DCT scan protocol with the other adult models falling between this upper and lower dose range. Figure 2 compares the average organ dose of the lung, thyroid, breast, and stomach for the Irene voxel model. The average dose to the lung and the breast are approximately equal as a function of the scanner mAs setting. The average thyroid ranges between 6.6 cGy and 19.8 cGy while the average stomach dose ranges between 3.3 cGy and 10.0 cGy. Figure 3 compares the average lung dose for the Irene voxel model as a function of tube potential. The dose increases approximately 45% as tube potential is increased from 120 kVp to 140 kVp.
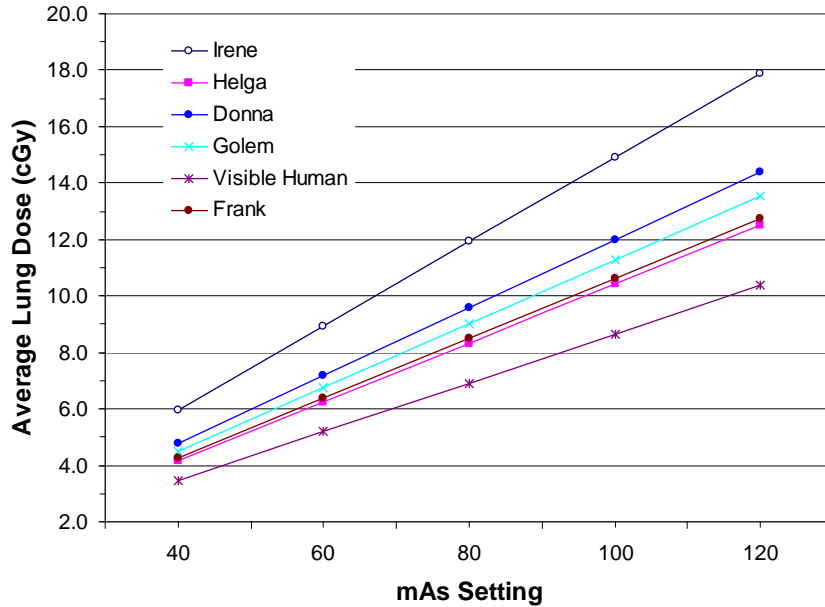
Figure 1 – Average lung dose calculated using a 4DCT Monte Carlo source model as a function of GSF phantom model. The simulated thorax protocol is based upon a 120 kVp tube potential, table pitch = 0.1 with the results plotted as a function of the scanner mAs setting.
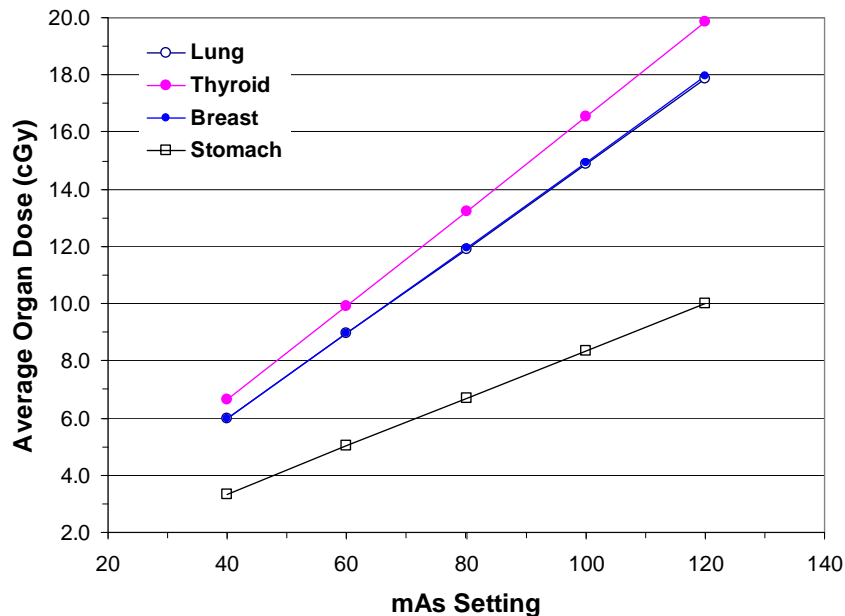

Figure 2 - Average organ dose calculated using a 4DCT Monte Carlo source model for the lung thyroid, breast, and stomach of the Irene voxel model.
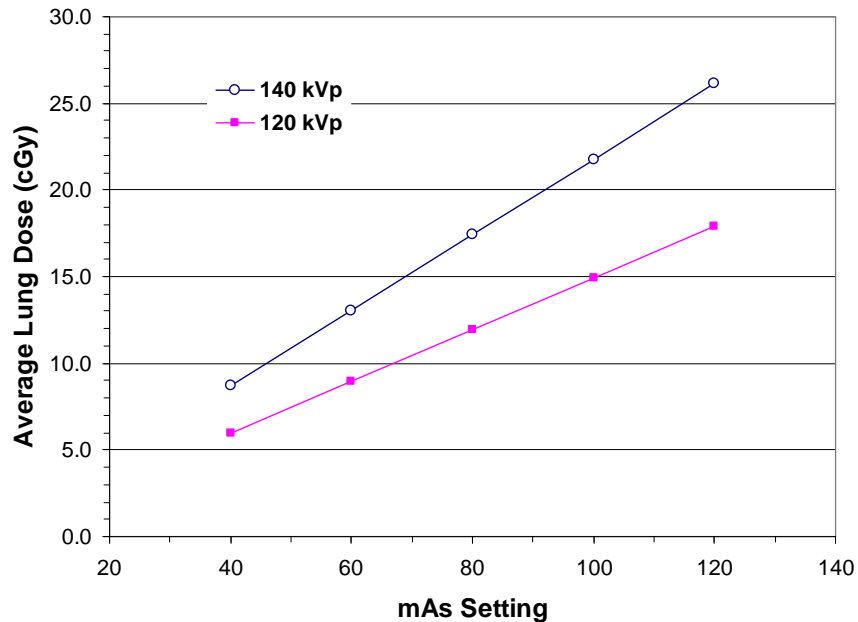
Figure 3 – A comparison of the average lung dose calculated using a 4DCT Monte Carlo source model for a tube potential of 120 and 140 kVp

Table 2 describes the average organ dose for the breast, lung, and heart from a kV-CBCT scan through the thorax of the Irene voxelized model. As the longitudinal jaws are increased the dose increases approximately 35% when averaged across all three anatomical locations.

Table 2 – Average organ dose (cGy) to the heart, breast, and lung of the Irene voxel model from a simulated kV-CBCT thorax scan. The imaging field of view represents the x- and y-field size in units of cm for the kV imaging device.

Imaging FOV	Average Heart Dose (cGy)	Average Breast Dose (cGy)	Average Lung Dose (cGy)
5x26	1.8	3.0	2.2
10x26	2.2	3.0	2.5
15x26	2.3	3.2	2.7
26x26	2.6	4.0	2.8

4. Discussion

This work confirms the relationship between patient size and organ dose demonstrated in our earlier work (DeMarco 2007). For the 4DCT scanning protocol, the average lung dose generally decreases in a predictable manner based upon patient size with the Irene voxel model receiving the highest dose

and the visible human model receiving the lowest dose. Figure 2 illustrates the average dose for four organs (lung, thyroid, breast, stomach) as a function of scanner mAs setting for the Irene adult model. The average lung and breast dose are approximately equal given that both organs are completely covered within the scan volume. For the Irene model the thyroid receives the highest dose while the stomach receives the lowest dose. Although not specifically addressed in this study, the change in individual organ dose is presumably a function of the amount of overlap for the organ in question relative to the scan volume and the thickness of the patient in the vicinity of the organ. Figure 3 illustrates the change in average lung dose for the Irene voxelized model as the tube potential is increased from 120 to 140 kVp. The change in kVp setting results in a dose increase of approximately 45% across the range of mAs settings studied. This dose increase is primarily due to the increased photon output from the CT target and a corresponding increase in the mean photon energy, resulting in a larger scatter dose component. The scanner mAs setting evaluated in this study ranges from 40 to 120 mAs. With respect to multi-detector CT scanners, this mAs setting can also be defined as effective mAs which is the ratio of the mAs and the table pitch. Based upon a table pitch of 0.1 the plotted effective mAs settings range between 400 and 1200 mAs. For actual scan conditions, the choice of mAs setting is important since the absorbed dose is directly proportional to this value and represents a trade-off between image quality and dose. The kV-CBCT simulation produces lower estimates of the average organ dose for a thorax scan through the Irene voxel model with the average lung dose ranging between 2.2 and 2.8 cGy per scan. The increase in dose as the longitudinal field size is increased is mainly due to an increased fraction of scattered photons throughout the scan volume. The difference in dose between a conventional CT scanner and a kV-CBCT system is presumably due to the difference in tube output (mAs) between the systems. A CT scanner delivers dose based upon mAs per single slice rotation while the output from the kV-CBCT system is based upon mAs per projection delivered across a much larger square or rectangular field size. Dose differences between the systems can also be attributed to filtration and beam hardening through the bow-tie filter. Although smaller on a per scan basis, the overall impact is presumably greater since a 4DCT scan protocol will typically be used once during the simulation process while the kV-CBCT scan can be used at the beginning of every treatment fraction. Varian OBI imaging protocols require twice the number of projections as the Elekta Synergy system (Wen et al. 2006) and therefore will produce twice the dose relative to the Elekta Synergy system.

5. Conclusion

This work demonstrates the ability to estimate average organ dose from 4DCT and kV-CBCT scan protocols. A 4DCT Monte Carlo based simulation model was used to provide estimates of average organ dose for patient-based models of different sizes, using a detailed model of an MDCT scanner. For a scanner mAs setting of 120 (mAs$_{eff}$ = 1200) the average lung dose ranges from 10 to 18 cGy across the range of patient models studied. The clinical implications associated with whole-body dose from a 4DCT scan are probably minimal assuming you limit the number of 4DCT scans and apply a judicious use of the scanner mA setting. A simple kV-CBCT simulation model predicts average organ doses that range between 1.8 to 4.0 cGy based upon a thorax imaging scan and 120 kVp tube potential. The average dose to the lung and breast increases by approximately 30% as the longitudinal image size is increased from 5.0 cm to 26.0 cm based upon a female voxelized model. This work demonstrates the application of Monte Carlo based dose prediction models and the ability to calculate imaging dose in patient specific voxelized phantoms.

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