THE PROFOUND EFFECTS OF PATIENT ARM POSITIONING ON ORGAN DOSES FROM CT PROCEDURES CALCULATED USING MONTE CARLO SIMULATIONS AND DEFORMABLE PHANTOMS

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The purpose of this study was to evaluate the organ dose differences caused by the arms-raised and arms-lowered postures for multidetector computed tomography procedures. Organ doses were calculated using computational phantoms and Monte Carlo simulations. The arm position in two previously developed adult male and female human phantoms was adjusted to represent 'raised' and 'lowered' postures using advanced BREP-based mesh surface geometries. Organ doses from routine computed tomography (CT) scan protocols, including the chest, abdomen–pelvis, and chest–abdomen–pelvis scans, were simulated at various tube voltages and reported in the unit of mGy per 100 mAs. The CT scanner model was based on previously tested work. The differences in organ dose per unit tube current between raised and lowered arm postures were studied. Furthermore, the differences due to the tube current modulation (TCM) for these two different postures and their impact on organ doses were also investigated. For a given scan parameter, a patient having lowered arms received smaller doses to organs located within the chest, abdomen or pelvis when compared with the patient having raised arms. As expected, this is caused by the attenuation of the primary X rays by the arms. However, the skin doses and bone surface doses in the patient having lowered arms were found to be 3.97–32.12 % larger than those in a patient having raised arms due to the fact that more skin and spongiosa were covered in the scan range when the arms are lowered. This study also found that dose differences become smaller with the increase in tube voltage for most of organs or tissues except the skin. For example, the liver dose differences decreased from –15.01 to –11.33 % whereas the skin dose differences increased from 21.53 to 25.24 % with tube voltage increased from 80 to 140 kVp. With TCM applied, the organ doses of all the listed organs in patient having lowered arms are larger due to the additional tube current necessary to overcome the presence of the arms while maintaining sufficient image quality. Arm position affects the dose to internal organs from CT scans by as much as 25.3 %. The presence of arms in the scan range results in a dose increase for the skin and bone surface, but a dose decrease for organs located in the torso. Considering the use of TCM, which is common in many clinics, the patient having lowered arms may receive 50 % higher radiation dose to most of the organs because of the increased tube current. The use of higher tube voltage might narrow such dose differences between patients of these two postures due to the greater penetration of higher-energy X rays. Therefore, when calculating or reporting patient doses from CT scans, it is prudent to select an appropriate phantom that accurately represents the patient posture.

INTRODUCTION

As an essential diagnostic tool, computed tomography (CT) has been increasing at an annual rate of >10 % for many years, driven largely by popularity and technological advances according to surveys performed in the USA^(1–3). A significant concern about patient radiation exposure and potential risk has been raised by a number of professional organisations^(3–6). It has been suggested that radiation dose to individual radiosensitive organs is a more appropriate measure of the risk than effective dose^(7, 8). In recent years, Monte Carlo simulations using anatomically accurate computational phantoms are widely used to estimate organ doses for CT procedures⁽⁹⁾. The flexibility in adjusting the computational phantom for various clinical conditions is attractive for research purposes.

Clinically, thoracoabdominal CT scans are typically performed in a situation when arms of a patient are raised above the head (so they are outside the scan

range). On the other hand, head or neck CT scans are performed in the arms-down posture, unless patients are unable to comply due to medical conditions such as trauma or mental diseases. Most computational phantoms used in CT dose calculations, however, either do not include arms^(9–11) or have the arms positioned on the sides of the trunk⁽¹²⁾, which is not common for CT scans performed anywhere along the thoracic region. The arm position may affect patient organ doses due to the different organs or tissues covered in the thoracoabdominal CT scan range. Previous studies by Brink et al. showed that the effective dose from a chest CT scan with tube current modulation (TCM) for patients who cannot raise their arms was 45 % higher compared with those who raised both arms⁽¹³⁾. However, results by Brink et al. were based on the CT dose software ImpACT, which used stylised phantoms that have poorly defined anatomy⁽¹⁴⁾. When compared against anatomically realistic voxel phantoms⁽¹⁵⁾, stylised phantoms have

been found to differ significantly in estimated organ doses for low-energy X rays^(10, 14, 16). Additionally, the stylised phantoms used in ImPACT software are not in an arms-raised posture but had the arms removed instead. Therefore, it is interesting to develop phantoms for studying organ dose from body CT examinations in both arms-raised and arms-lowered positions. This study aims to quantify the impact of the arm positions on patient organ doses during the CT scans.

MATERIALS AND METHODS

Development of RPI adult patient arms-raised phantoms

Zhang et al. at Rensselaer Polytechnic Institute (RPI) developed a set of voxel phantoms called RPI-AM and RPI-AF for organ dose simulation using the

Monte Carlo method⁽¹⁷⁾. There are 122 separate organs or tissues defined in RPI-AM and 121 organs or tissues defined in RPI-AF, with 28 different material compositions appropriately assigned to these organs or tissues. The tissue elemental compositions and densities were derived from ICRP Publication 89⁽¹⁸⁾ and ICRU Report 46⁽¹⁹⁾. The RPI-AM and RPI-AF have a standing posture with both arms placed on the body sides. For this study, a pair of BREP-based arms-raised phantoms for body CT dose calculations called RPI-AM-AR and RPI-AF-AR (where AR stands for arms raised) were developed by adjusting the arm position of the original phantoms using the Rhinoceros 4.0 software. Throughout the process of phantom modelling, most of the organs remain unchanged with the exception of the bones, muscles, blood vessel, and skin located in the arms. The modified phantoms retained the organ anatomical features defined by the ICRP-89

Figure 1. Original adult male and female phantoms and their revised counterparts (RPI-AF-AR and RPI-AM-AR) having arms raised to the overhead position to more realistically represent the clinical CT scan conditions.

reference values. These BREP-based phantoms, as shown in Figure 1, were converted to voxel-based geometry using an in-house voxelization tool. The finalised phantoms were used for Monte Carlo organ dose calculations.

CT scanner model

The CT scanner model used in this study was previously built to simulate the GE LightSpeed Pro 16 scanner (General Electric Healthcare Corporation, Waukesha, WI, USA). The Monte Carlo CT scanner model includes parameters that specify the source geometry, source movement, X-ray energy spectrum, bowtie filter, and beam shape. Computed tomography scanner parameters incorporated into the Monte Carlo simulations include: source-to-isocenter distance of 54 cm, beam fan angle of 55° and beam thickness at the isocenter of 20 mm. The CT scanner model has been previously validated through experimental methods^(20, 21). As shown in Figure 2, a total of 16 discrete X-ray beam sources were constructed to simulate one rotation of axial CT scan, which has been shown to closely match the effect of a continuously rotating source.

Monte Carlo organ dose simulation

All CT dose simulations were performed using the MCNPX code version 2.6.0⁽²²⁾. Since the X-ray energy is <140 keV in CT diagnostic imaging, it is assumed that the secondary electrons deposit their energy locally. In the MCNPX code, the F6 track length tally was employed to record the absorbed dose to organs and tissues in the male and female phantoms.

Figure 2. Illustration of 16 X-ray sources and bowtie filters in the CT scanner model to simulate a single axial CT scan.

The simulation results are reported by the F6 tally card in MCNPX, in the unit of MeV g^{-1} per source particle. To obtain the absorbed doses in the more practical unit of mGy per 100 mAs, the MCNPX results were adjusted for the measured X-ray power output from the scanner. Here, the authors used an empirical conversion factor (CF) to convert the tally output to absorbed dose in the unit of mGy per 100 mAs^(20, 21, 23).

$$(\text{CF})_{\text{E,NT}} = \frac{\left((\text{CTDI}_{100})_{\text{in-air, mGy per 100 mAs}}^{\text{Measured}} \right)_{\text{E,NT}}}{\left((\text{CTDI}_{100})_{\text{in-air, MeV/g} \times \text{source particle}}^{\text{Simulated}} \right)_{\text{E,NT}}} \quad (1)$$

where $\left((\text{CTDI}_{100})_{\text{in-air, mGy per 100 mAs}}^{\text{Measured}} \right)_{\text{E,NT}}$ is the measured air kerma $(\text{CTDI}_{100})_{\text{in-air}}$ values by using the ionisation chamber in air at the CT scanner isocentre for a single axial scan using 100 mAs and different beam energies and beam collimations, and $\left((\text{CTDI}_{100})_{\text{in-air, MeV/g} \times \text{source particle}}^{\text{Simulated}} \right)_{\text{E,NT}}$ is the corresponding air kerma values acquired by simulating the ionisation chamber in the MCNPX code under the same CT scan scenario. $(\text{CF})_{\text{E,NT}}$ is expressed in the unit of $(\text{mGy} \cdot \text{gram} \cdot \text{source particle}) / (\text{MeV} \cdot 100 \text{ mAs})$.

The bone surface consists of a 10- μm -thick layer of cells on all of the cortical and trabecular bone tissues, and since the vast majority of bone surface cells are located in the trabecular bone, the average absorbed dose to the spongiosa was used as a substitute for the dose to the bone surface⁽²⁴⁾. For dose to the red bone marrow (RBM), the ‘three correction factors’ method was adopted for both types of phantoms⁽¹⁴⁾. The absorbed dose for the RBM depends on the photon fluence in the spongiosa and the photon energy, as defined in the following equation:

$$D_{\text{RBM}} = E_{\text{spongiosa}} \cdot \varphi \cdot \left[\frac{\mu_{\text{en}}(E)}{\rho} \right]_{\text{RBM}} \cdot S(E_{\text{ph}}) \quad (2)$$

where $E_{\text{spongiosa}}$ is the energy deposited in the spongiosa, φ is the photon fluence, $[(\mu_{\text{en}})/\rho]_{\text{RBM}}$ is the mass absorption coefficient of RBM at X-ray energy of E and $S(E_{\text{ph}})$ is the dose enhancement factor for the given bone and incident photon energy⁽²⁵⁾. The F4 fluence tally together with a set of DE/DF card in MCNPX code was used to implement the dose calculation algorithm.

In this study, all voxel-based patient phantoms were placed at the isocentre of the CT scanner model. Three standard CT exam protocols in the thoracoabdominal region were considered: a chest scan, an abdomen–pelvis scan and a chest–abdomen–pelvis (CAP) scan. The anatomical landmarks used to determine the scan positions are summarised in Table 1.

To estimate radiation doses for a patient undergoing a CT scan with *z*-axis TCM, the scan range was deconstructed into the individual tube rotations or slices of the scans. Each scan slice was simulated independently, and the dose contribution from each slice was weighted by the effective mAs of that slice, with the total dose being the sum of the contributions from each slice in the scan range.

$$D'_{H,TCM} = \sum_{i=\text{starting slice}}^{\text{end slice}} D_i \times w_i \quad (3)$$

where D_i is the organ dose result (in the unit of mGy per 100 mAs) calculated from the slice-by-slice MC simulations for the i th slice in user-specified scan region and is the tube current weighting factor (the actual mAs in the i th image divided by 100 mAs). To investigate the dosimetric effect of tube voltage between these two postures, this process was repeated for 4 different tube voltages (i.e. 80, 100, 120 and 140 kVp) and used on all voxel-based patient phantoms in the MCNPX code.

Table 1. Definition of anatomical boundaries for CT examinations.

CTexam	Anatomic coverage
Chest	From the top of lungs through the bottom of lungs
Abdominal-pelvis	From top of liver to pubic symphysis
Chest–abdomen–pelvis	From top of lungs to pubic symphysis

Table 2. Organ dose comparison between arms-raised (AR) phantoms and arms-lowered phantoms for chest CT scans (120 kVp), with dose difference relative to arms-raised phantom.

Organ/tissue	Organ dose (mGy per 100 mAs)		Difference (%)	Organ dose (mGy per 100 mAs)		Difference (%)
	RPI-AM-AR	RPI-AM		RPI-AF-AR	RPI-AF	
Colon	0.68	0.67	−1.41	0.71	0.70	−2.18
Lungs	12.51	11.81	−5.56	12.27	11.42	−6.97
Stomach	5.86	5.63	−4.04	5.24	4.98	−5.02
Breast	12.91	11.72	−9.25	11.91	10.81	−9.30
Red bone marrow	3.81	3.91	2.69	3.62	3.69	2.00
Testis/ovary	0.18	0.18	1.19	0.52	0.51	−1.81
Urinary bladder	0.17	0.16	−2.22	0.20	0.20	−1.22
Oesophagus	6.46	6.41	−0.78	6.91	6.88	−0.40
Liver	4.19	3.79	−9.37	3.54	3.20	−9.41
Thyroid	4.17	4.27	2.21	3.78	3.87	2.33
Brain	0.45	0.48	4.96	0.45	0.46	2.80
Salivary glands	1.00	1.08	7.80	0.88	0.90	2.73
Skin	2.34	2.76	18.29	2.39	2.76	15.42
Bone surface	2.20	2.40	8.99	3.81	3.96	3.97

The specific number of source photons was variable in each simulation and was selected to ensure whether the calculated organ doses had an acceptable level of statistical uncertainty (relative errors of <5 % in most organs and <15 % for organs with very small volumes located at large distances from the primary beam).

RESULTS

Organ dose comparison of none TCM situation

The organ dose results for both phantom postures are reported in the unit of mGy per 100 mAs. Additionally, the difference between the two values is reported relative to the arms-raised posture by the difference equation defined in Equation (3):

$$\text{Difference (\%)} = \frac{D_{\text{arms lowered}} - D_{\text{arms raised}}}{D_{\text{arms raised}}} \times 100 \quad (4)$$

where $D_{\text{arms lowered}}$ is for organ dose derived from the phantoms with arms down, whereas $D_{\text{arms raised}}$ is for organ dose of phantoms with arms raised.

Table 2 lists the results for the chest CT scan with the tube voltage of 120 kVp, showing that for most organs or tissues that located in the chest, the radiation doses in phantom having lowered arms are smaller than that having raised arms. For the organs or tissues that are completely covered by the chest scan and are thus irradiated by the primary X ray, organ doses differed by −5.56 to −9.30 %, respectively, for the breast and the lung. In the case of the arms-lowered posture, the arms offer greater attenuation of

Table 3. Organ dose comparison between arms-raised (AR) phantoms and arms-lowered phantoms for abdomen–pelvis CT scan (120 kVp), with dose difference relative to arms-raised phantom.

Organ/tissue	Organ dose (mGy per 100 mAs)		Difference	Organ dose (mGy per 100 mAs)		Difference
	RPI-AM-AR	RPI-AM		RPI-AF-AR	RPI-AF	
Colon	11.26	10.79	−4.20	12.90	12.38	−4.02
Lungs	3.26	3.08	−5.59	3.17	2.96	−6.51
Stomach	9.32	8.90	−4.59	9.92	9.22	−7.08
Breast	0.78	0.71	−8.70	1.36	1.31	−3.71
Red bone marrow	3.98	3.96	−0.47	4.74	4.70	−0.89
Testis/ovary	2.51	2.41	−3.97	11.90	11.63	−2.28
Urinary bladder	7.43	7.57	1.96	8.77	8.97	2.30
Oesophagus	0.53	0.49	−8.06	0.67	0.63	−5.82
Liver	12.49	10.89	−12.79	12.76	11.15	−12.60
Thyroid	0.42	0.40	−5.25	0.41	0.40	−3.92
Brain	0.15	0.16	1.86	0.16	0.16	2.96
Salivary glands	0.26	0.27	2.69	0.24	0.24	1.69
Skin	2.67	3.50	31.35	2.62	3.46	32.12
Bone surface	2.19	2.74	24.82	4.62	5.09	10.08

the X-ray photons, leading to this difference. For the phantom having lowered arms, doses to the thyroid, the brain and the salivary glands were larger than those in the phantom having raised arms by a range from 2.21 to 7.80 %, likely due to increased scattering from the tissues in the arm. Finally, as the coverage of the arms (in the arm-lowered phantom) in the primary X ray increases, a greater level of dose to the skin and spongiosa is expected. Indeed, this study found that the skin doses and bone surface doses in the arms-lowered postures were 3.97 to 18.29 % greater than those of arms-raised phantoms.

A nearly identical trend is found for the abdomen–pelvis scan, as shown in Table 3. Once again, because of the X-ray attenuation by the arms, radiation doses to most organs such as the stomach, liver, and colon that are located at abdomen–pelvis region of arms-lowered phantoms were noticeably smaller than those for arms-raised phantoms, with the difference ranging from −4.02 to −12.79 % for both male and female phantoms. Due to the proportion of the skin and spongiosa covered in the scan range being different between the two kinds of phantom, the skin doses and bone surface doses of arms-lowered postures were observed to be larger than those of arms-raised phantoms with differences ranging from 10.08 to 32.12 %.

To investigate the dosimetric effects of tube voltage between these two postures, organ doses from CAP scans for both kinds of phantoms were simulated with tube voltages of 80, 100, 120 and 140 kVp, respectively. Dose differences are presented in Table 4. It can be seen that the dose differences decrease with increasing tube voltage for most of organs or tissues except the skin. For example, the liver dose differences decreased from −15.01 to −11.33 % as the tube voltage

Table 4. Organ dose differences of CAP scans with different tube voltages.

Organ/tissue	80 kVp (%)	100 kVp (%)	120 kVp (%)	140 kVp (%)
Colon	−5.07	−4.41	−4.14	−3.94
Lungs	−6.68	−5.84	−5.38	−5.11
Stomach	−4.82	−4.68	−4.46	−4.31
Breast	−11.01	−10.00	−9.24	−8.69
Red bone marrow	1.42	1.36	1.27	1.17
Testis	−5.73	−4.64	−3.80	−3.88
Urinary bladder	3.03	2.62	1.87	1.91
Oesophagus	0.43	−0.56	−1.07	−1.41
Liver	−15.01	−13.24	−12.12	−11.33
Thyroid	−0.31	0.53	1.49	0.76
Brain	6.40	4.68	4.01	4.50
Salivary glands	9.72	7.57	6.70	5.18
Skin	21.53	23.38	24.47	25.24
Bone surface	17.86	17.61	17.39	17.21

increased from 80 to 140 kVp. Higher tube voltages will produce X rays of a higher energy, which will be less attenuated, resulting in a smaller effect on the organ doses. The major exception is the skin dose, where the differences increase from 21.53 to 25.24 % with increasing tube voltage. This is due to the fact that the skin on the arms of the arms-lowered phantom is covered in the scan range and therefore contributes more to the whole skin dose with the increase in tube voltage. This would be also true of the

bone spongiosa in the arms, although the effect is somewhat offset by the spongiosa in the thoraco abdominal region. This is confirmed by the data in Table 4, and the dose differences for the bone surface and RBM decrease only slight as tube voltage increases.

Effect of TCM

The above-mentioned results are based on dose for a constant tube current of 100 mAs (i.e. in the unit of dose per 100 mAs). So, a direct comparison assumes that the scan parameters are kept the same for the two kinds of patient postures. Clinically, however, TCM is often used to automatically adjust the tube current according to the size and attenuation characteristics of the patient body region so a consistent image quality is achieved while minimising the radiation dose⁽²⁶⁾. When projecting through a part of the patient that is thicker (or denser), TCM uses a greater tube current output. Figure 3 demonstrates typical tube current values in z -axis (longitudinal modulation) for the two kinds of patient postures. Two sets of clinical TCM data were adopted from a paper by Brink⁽¹³⁾. In addition to longitudinal modulation, angular modulation is also widely used in clinical CT scans. Since the coronal length of human body is typically longer than the sagittal length of body, diagnostic X ray is usually attenuated more in lateral direction than it would be in frontal–dorsal direction.

To compensate this effect and to achieve consistent image quality, angular modulation (if turned on) is used in each rotation of X-ray tube to increase the tube current when the tube rotates to lateral positions and to decrease the tube current when the tube rotates to frontal–dorsal positions. Angular modulation works together with longitudinal modulation in clinical CT scans. However, only the average of tube current of a complete rotation is typically reported in the output of CT scans. The TCM data in this study are all average current of each rotation (Figure 3); thus, only longitudinal modulation is available for calculation. It has been shown that explicitly including angular modulation has minimal effect on calculated organ doses in most cases (reference UCLA paper).

Organ doses from CT scans involving TCM were calculated with the average tube current per rotation using Equation (3). Table 5 lists organ doses for the male phantoms with the two kinds of postures from different TCM protocols. It can be seen that the doses to organs in the phantom having lowered arms are larger than those of phantom having raised arms. The dose differences for most of the organs are $>50\%$, with the skin dose difference for the abdomen–pelvis scan reaching as high as 112.03 %. This is due to the fact that the tube current for patient having lowered arms is higher than that for phantom having raised arms, as depicted in Figure 3.

Figure 3. Typical mAs_{eff} values superimposed on two types of male phantom⁽¹³⁾: (a) arms-lowered male phantom and (b) arms-raised male phantom.

Table 5. Organ dose differences of different scan protocols with TCM.

Organ/tissue	Chest scan			Abdomen–pelvis scan			CAP scan		
	RPI-AM-AR	RPI-AM	Difference	RPI-AM-AR	RPI-AM	Difference	RPI-AM-AR	RPI-AM	Difference
Colon	1.18	2.12	79.30	19.44	29.94	53.97	20.01	30.96	54.71
Lungs	20.77	36.36	75.09	6.10	10.43	71.06	22.72	39.74	74.92
Stomach	9.85	17.80	80.68	16.85	29.74	76.44	20.86	37.41	79.38
Breast	21.88	39.48	80.44	1.43	2.30	60.59	22.68	40.72	79.58
Red bone marrow	7.55	12.46	65.11	7.20	10.89	51.11	13.71	21.49	56.72
Testis	0.32	0.57	80.34	4.84	6.89	42.28	5.05	7.26	43.70
Urinary bladder	0.29	0.51	76.20	14.22	20.73	45.75	14.40	21.03	46.06
Oesophagus	14.37	21.02	46.30	0.98	1.60	62.99	14.86	21.81	46.74
Liver	7.39	12.27	65.94	22.28	36.23	62.59	24.48	40.20	64.20
Thyroid	11.03	14.37	30.20	0.76	1.26	66.37	11.50	15.09	31.18
Brain	1.01	1.56	54.03	0.28	0.49	74.81	1.21	1.89	56.16
Salivary glands	2.37	3.57	50.38	0.47	0.84	77.90	2.70	4.12	52.76
Skin	4.59	8.78	91.41	4.84	10.26	112.03	8.61	17.07	98.22
Bone surface	4.42	7.65	73.10	3.99	7.71	93.41	7.81	14.17	81.41

CONCLUSION

Patients are generally asked to raise their arms when receiving CT scans of the thoracoabdominal region (i.e. chest scans, abdomen–pelvis). In some cases, however, the patient is unable to raise their arms due to medical conditions. This study investigated the impact of these two postures on organ doses. It is found that, for the same scan parameters, doses to organs located within the chest, abdomen, or pelvis regions of the phantom having lowered arms were noticeably smaller than those of phantom having raised arms, due to the attenuation of the primary CT X ray in the arms. The skin dose and bone surface dose for the arms-lowered postures were found to be larger than those of arms-raised patients, due to a greater proportion of the skin and spongiosa falling within the scan range for patient who could not raise their arms. The dose differences generally decrease with the increasing tube voltage for most organs or tissues, suggesting that the effect of arms on organ dose is relatively smaller under higher tube voltages. For CT scans with TCM, patients who could not raise their arms will subsequently receive higher radiation dose than patients whose arms are raised, with dose differences for the skin being as large as 100 %. This is due to the additional tube current necessary to penetrate the arms to produce the same image quality. Given the profound organ dose differences in phantoms having two arm locations as reported in this study, it is prudent to select an appropriate phantom according to the patient posture when calculating patient doses from CT scans in the future⁽²⁷⁾.

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