FETAL DOSES TO PREGNANT PATIENTS FROM CT WITH TUBE CURRENT MODULATION CALCULATED USING MONTE CARLO SIMULATIONS AND REALISTIC PHANTOMS

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To investigate the radiation dose to the fetus using retrospective tube current modulation (TCM) data selected from archived clinical records. This paper describes the calculation of fetal doses using retrospective TCM data and Monte Carlo (MC) simulations. Three TCM schemes were adopted for use with three pregnant patient phantoms. MC simulations were used to model CT scanners, TCM schemes and pregnant patients. Comparisons between organ doses from TCM schemes and those from non-TCM schemes show that these three TCM schemes reduced fetal doses by 14, 18 and 25 %, respectively. These organ doses were also compared with those from ImpACT calculation. It is found that the difference between the calculated fetal dose and the ImpACT reported dose is as high as 46 %. This work demonstrates methods to study organ doses from various TCM protocols and potential ways to improve the accuracy of CT dose calculation for pregnant patients.

INTRODUCTION

Radiation risk associated with routine or accidental patient exposure to X-ray computed tomography (CT) scans has become a headline topic in recent years⁽¹⁾. Recent research has focused on methods to reduce the CT dose, especially to radiosensitive populations such as children and pregnant women. When a CT scan is performed on a pregnant patient, the protocol needs to be designed carefully to ensure that the diagnostic benefits outweigh potential radiation risks⁽²⁾. Lazarus *et al.*⁽³⁾ recently documented and analysed the use of imaging for pregnant patients at one academic institution over 10 y (1997–2006), and finally concluded that there had been a significant increase in the application of ionising radiation imaging to pregnant patients. The increase in the CT use in pregnant patients was the largest and much greater than the other imaging modalities⁽³⁾. Felmlee *et al.*⁽⁴⁾ measured the fetal dose by using an adult anthropomorphic phantom and estimated the fetal dose based on the CT dose index. Hurwitz *et al.*⁽⁵⁾ also assessed the fetal dose by using physical measurements on an anthropomorphic phantom. Monte Carlo (MC) simulation-based methods have also been used to assess fetal doses, and many of them used the dose to the uterus to approximate the dose to the fetus. Tube current modulation (TCM) schemes and the fetus itself were not considered in these studies. More recently, a clinical-practice guideline was published for fluoroscopy and CT-based interventions during pregnancy⁽⁶⁾ to help

increase radiation awareness and guide radiation usage. To reduce radiation dose to the expectant mother and her fetus, it is now possible to employ a lower tube current without compromising image quality through automatic exposure control (AEC) that is based on the principle of TCM^(7–9). Such AEC systems are designed to adjust the tube current according to patient shape, size and X-ray attenuation characteristics. Existing AEC systems are generally based on two specific approaches: (1) longitudinal (or *z*-axis) AEC that modulates according to the patient body attenuation along the *z*-axis defined by a preliminary localiser radiograph and (2) ‘rotational’ (or ‘angular,’ or ‘*x*–*y* axis’) AEC that modulates during the rotational course to compensate for differences in attenuation between the lateral and anteroposterior projections^(8–10). The implementation of TCM differs among manufacturers and is very specific to the examination requirements and the patient. Several studies have investigated the impact of TCM on the dose, for different examinations. Angel *et al.*⁽¹¹⁾ assessed the effects of TCM for modern multidetector CT (MDCT) on breast doses using patient models developed from CT images. Brisse *et al.*⁽¹²⁾ assessed the impact of AEC on organ doses and effective doses for pediatric patients. Since manufacturers do not provide details about the TCM algorithms, assumptions about the modulation schemes were made by the authors when reconstructing organ doses from procedures. To date, the effects of TCM on pregnant patients have not been reported.

At Massachusetts General Hospital (MGH), Boston, MA, several CT examinations on pregnant patients were carried out using TCM. Right lower quadrant pain with suspected appendicitis was the reason for the majority (58%) of abdominal-pelvic CT examinations performed in pregnant patients. Trauma (16%) and nonspecific abdominal pain (13%) comprised the other common indications for abdominal-pelvic CT in pregnant patients^(13, 14). This paper describes a study to estimate the organ doses to pregnant patients using TCM data selected from archived clinical records for pregnant patients who underwent CT procedures at Massachusetts General Hospital. MC simulation techniques were used to model a CT scanner, the TCM schemes and the pregnant patient at different gestational stages.

METHODS AND MATERIALS

Patient phantoms

This study utilised a set of realistic computational phantoms of pregnant patients at the end of three gestational periods of 3, 6 and 9 months—designated the RPI-P3, RPI-P6 and RPI-P9 phantoms as illustrated in Figure 1—which have been previously developed⁽¹⁵⁾. Unlike partial-body CT images that contain limited number of organs and hampered by poor image quality⁽¹⁶⁾, the RPI-P phantoms were carefully adjusted by modifying organ volumes and masses of pregnant phantoms to agree with reference values recommended in the ICRP Publication 89⁽¹⁷⁾. Since the phantoms representing the mother are adjusted to agree with the ICRP Publication 89, the body habitus is considered to be ‘normal,’ representing a population average. Measurement of the cross-section images of the phantoms show that the maternal perimeters of the abdomen are 57, 100 and 109 cm for P3, P6 and P9 phantoms, respectively, which differ from the data set of the maternal perimeter provided by Angel *et al.*⁽¹⁶⁾ A total of 35 organs and tissues in the mother and fetus were included in these phantoms. The phantom geometries were designed with realistic representations of fetus that includes the fetal skeleton (except for the 3-month phantom), brain and soft tissue. For MC calculations, each phantom was voxelised at a resolution of $3 \times 3 \times 3$ mm, involving a total of about 25 million voxels⁽¹⁸⁾.

In this study, three TCM protocols were selected that were applied to patients at 15, 20 and 31 weeks of gestation, respectively. Although not an exact match of gestation time, the RPI-P3, P6 and P9 phantoms are the best matches to these three protocols.

MC simulations

All radiation transport and dose calculations were performed using the MCNPX MC code⁽¹⁹⁾. MCNPX

is a general-purpose MC radiation transport code that tracks all particles at all energies necessary for these simulations. In this study, the photon physics mode with the default energy cut-off was used. 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 to satisfy the condition of charged particle equilibrium (CPE)⁽²⁰⁾, which is a valid assumption in the energy range of diagnostic X rays. Under the conditions of CPE, the collision kerma is equal to the absorbed dose and is recorded using the type 6 (F6:p) tally of the MCNPX. In all simulations, the number of histories was selected to achieve a relative statistical uncertainty of $<5\%$ in most organs (or detectors), and $<10\%$ for organs with very small volumes or located at large distances from the primary beam.

MDCT scanner model

The two MDCT scanner models for the GE LightSpeed Pro 16 and GE LightSpeedTM 16 (General Electric Healthcare Corporation, Waukesha, WI) were considered in MCNPX simulations. In the MDCT scanner models, 16 stationary X-ray sources per rotation are uniformly positioned along the X-ray tube trajectory, which has previously been shown to be a valid representation of a single axial scan⁽²¹⁾. In this study, those sources were positioned on the helical trajectory to simulate the specific CT examination, with the total number of source positions dependent upon the scan length and pitch. The MDCT scanner model produces a good approximation of the X-ray energy spectrum, the effect of the bowtie filters, the beam shape and the source motion trajectory. The body bowtie filters were selected for this study and aluminum was selected as the bowtie filter material for all simulations. Simulations of the X-ray source with a CT dose index (CTDI) phantom were also performed for the purpose of validation⁽²¹⁾. In this study, the body CTDI phantom is used, 15 cm in length with a diameter of 32 cm, made of PMMA with a density of 1.19 g cm^{-3} . The MCNP simulation dose is calibrated to the true dose (per unit integrated tube current) by matching simulated CTDI values with measured CTDI values. The two scanner models used in this study were validated by the approach described in the previous study⁽²¹⁾.

Modeling TCM

Three typical sets of TCM data were selected for the abdominal scans of patients whose stage of pregnancy matches those of the RPI-P phantoms. For comparison, a conventional tube current (fixed tube current) without modulation scan was used to assess the

Figure 1. RPI pregnant female phantoms with 3-, 6- and 9-month pregnancy, respectively.

impact of TCM on the organ doses. The selection of conventional or fixed tube current is complex, depending on many factors including expected image quality, patient thickness, etc. Based upon clinical experience, the milliamperage of fixed tube current was set to the maximum current in each TCM scheme for each case, ensuring that the image quality would not be poorer at any point than under TCM, and also that the maximum difference between the dose from fixed tube current and that from the TCM scheme was obtained.

In this study, TCM in the longitudinal direction only was considered, as these were the schemes applied in clinically archived data for pregnant patients. The current at each position, or slab location, is based upon the actual patient anatomy at that position. A slab is the concept used by ImPACT CT Patient Dosimetry Calculator⁽²²⁾ to describe a scan's starting and ending positions. From the two slab locations corresponding to the starting and ending positions of the TCM scheme, a scan range (or exposure area) was established for the MIRD phantom used in ImPACT for comparison. Using the identified anatomical markers of the MIRD phantom, the corresponding scan range was determined for RPI-P phantoms to cover the similar anatomical area. The scan ranges for RPI-P phantoms are illustrated in Figure 2. The tube current at a particular longitudinal position is represented by $I(z)$, where z is the location-ray source position. The value of $I(z)$ was chosen from the current recorded in the archived CT data corresponding to the slab at that position. For implementation of the TCM schemes by using MCNPX codes modelling, the tube current was modulated in the X-ray plane as well as along the z -direction, such that the current changes along the length of the patient according to the shape of the patient phantom as shown in Figure 2. It should be remembered that the selected TCM

schemes in this study were not those that combined the modulation along the x - y axis (or along the projection angle) and the modulation along the z -axis (or along longitudinal direction)⁽²³⁾. The intensity value of each X-ray source was directly used as inputs to define the source distribution function in the source specification⁽¹⁹⁾. This is not the exactly fine match between the archived TCM scheme at MGH and the implemented TCM scheme in the MCNPX code, however, the implementation approach in this study is reasonably allowed to access the fetal doses.

The specifications of the three cases corresponding to three different TCM schemes are summarised in Table 1, while Figure 3 provides the visualisation of these data with the phantoms. Among the clinically archived TCM schemes reviewed, the three listed in Table 1 for 15-, 20- and 31-week pregnancies were found to closely match RPI-P3, -P6 and -P9 phantoms, respectively. Figure 3 illustrates the scan ranges for the RPI-P series phantom and the comparable scan range on the MIRD phantom. As the two types of phantoms have different anatomical geometry and organ positions, the scan ranges are somewhat different, but cover a similar anatomical area to reflect the same examination.

Dose calculations

The F6:p tally results in MCNPX are normalised per source history. To determine the absorbed dose from each CT scan procedure, the tally values in MeV gram^{-1} source particle⁻¹ were converted to the absorbed dose in mGy 100 mA s^{-1} by a conversion factor (CF). As described in a previous study⁽²⁴⁾, the CF represents the ratio of the measured exposure at isocentre per 100 mA s free-in-air to the

Figure 2. Three modulated tube current (MTC) profiles along the longitudinal direction (or z -axis) which indicates slab location, clinically for patients at 15, 20 and 31 weeks of gestation, respectively. Implemented in this study are MTC profile for the (a) 3-month pregnant patient, (b) 6-month pregnant patient and (c) 9-month pregnant patient.

Table 1. Simulation parameters of three cases for the three TCM schemes, respectively.

Case	Pregnancy (weeks)	Phantom	MDCT scanner	kV _p	Collimation (mm)	Pitch
1	15	RPI-P3	LightSpeed Pro16	140	20	0.9375
2	20	RPI-P6	LightSpeed Pro16	120	20	0.9375
3	31	RPI-P9	LightSpeed 16	140	20	0.9375

The tube rotation time was 0.5 s for all the three protocols.

simulated dose per photon. In this way, the absorbed dose to the organ or tissue (D_T) in mGy is given by

$$D_T = D_{\text{simulated}} \times CF \times \frac{\sum_i I_i}{(100 \text{ mA s})} \quad (1)$$

where $D_{\text{simulated}}$ is the tally result obtained directly from the MNCPIX output file and I_i is the tube current in each slab along the scan range. Since the multi-beam function in the MNCPIX code was used

to model the X-ray source along the entire scan trajectory, D_T is therefore the total dose to the organ or tissue from the entire scan and not the dose contributed by one specific slab or X-ray source individually.

RESULTS

CT source validation

In order to validate the MDCT scanner models used in this research, CTDI values were calculated from

Figure 3. Comparison of phantoms and CT scan range in two types of phantoms: ImPACT phantom (on the left) and RPI-P phantom (on the right). (a–c) Protocols 1, 2 and 3, individually.

simulations and compared with the measured values. The CTDI values were determined by taking the product of the normalised CTDI dose calculated by MCNPX and the kV_p -dependent $CF^{(21)}$. The kV_p -dependent CF s were calculated from single axial scans simulated free-in-air at the scanner isocentre for tube potentials of 80, 100, 120 and 140 kV_p using the 20-mm beam collimation with the body bowtie filter. For each simulation, the result was the

MC-calculated air kerma (in units of $MeV\ g^{-1}$ source particle $^{-1}$) that occurred in the simulated ion chamber. Using the appropriate CF s described above, the simulated CTDI values at the centre and at the 12:00 peripheral positions of the CTDI phantom were calculated and compared with the measured values as shown in Tables 2 and 3 for the LightSpeed Pro 16 and LightSpeed 16, respectively. It is found from Table 2 that the maximum

Table 2. Comparison of measured and simulated CTDI₁₀₀ results from a single axial scan in the CTDI body phantom using the LightSpeed Pro 16 MDCT scanner operated at each kV_p settings; all scans using 100 mA s.

kV _p	Position	Measured body CTDI ₁₀₀ (mGy 100 mA s ⁻¹)	Simulated body CTDI ₁₀₀ (mGy 100 mA s ⁻¹)	% Difference
80	Centre	1.2	1.06	-14.66
	Peripheral	3.3	2.83	-15.33
100	Centre	2.7	2.51	-6.79
	Peripheral	6.3	5.82	-7.71
120	Centre	4.6	4.57	-0.22
	Peripheral	9.2	9.59	4.43
140	Centre	6.8	6.60	-3.63
	Peripheral	13.1	13.62	4.15

Measurements were performed at MGH, Boston, MA. All scans used a 20-mm beam collimation and a body bowtie filter. The duration of the scan was 0.5 s with the tube current of 200 mA.

Table 3. Comparison of measured and simulated CTDI₁₀₀ results from a single axial scan in the CTDI body phantom using the LightSpeed scanner operated at each kV_p settings; all scans using 100 mA s⁽²⁰⁾.

kV _p	Position	Measured CTDI ₁₀₀ (mGy 100 mA s ⁻¹)	Simulated CTDI ₁₀₀ (mGy 100 mA s ⁻¹)	% Difference
80	Centre	1.34	1.30	-2.80
	Peripheral	3.45	3.43	-0.60
100	Centre	2.97	2.86	-3.77
	Peripheral	6.66	6.79	1.89
120	Centre	5.12	4.98	-2.78
	Peripheral	10.48	10.97	4.69
140	Centre	7.65	7.52	-1.76
	Peripheral	15.01	15.87	5.72

All scans used a 20-mm beam collimation and a body bowtie filter. The duration of the scan was 1 s with the tube current of 100 mA.

difference between measurements and simulations is around 15 %, occurring at 80 kV_p tube potential. For 120 and 140 kV_p, the difference between measurements and simulations are within 5 %. It is found from Table 3 that the difference between measurements and simulations are all within or around 5 % for all available tube voltages.

Fetal doses

Table 4 summarises the calculated fetal doses for each of the three cases. The fetal dose using the

TCM scheme is also compared with the dose calculated using a fixed tube current to analyse the TCM's effect on the dose. The milliamperere of fixed tube current was set to the maximum current in each TCM scheme, which was 155, 192 and 320 mA for cases 1, 2 and 3, respectively. As shown in Table 4, the total fetal doses from scans using these TCM schemes are 7.94, 7.81 and 20.92 mGy for cases 1, 2 and 3, respectively, compared with 9.27, 9.47 and 28.00 mGy when not applying TCM. The fetal doses from TCM are clearly smaller than those from non-TCM in all cases. Furthermore, it was found that the fetal dose increased with the size of the fetus, which is a finding that differs from the conclusions of a previous study by Angel *et al.*⁽¹⁶⁾ One possible cause of this discrepancy is the fact that, in this study, patient-specific TCM schemes were applied to different patient phantoms, not necessarily representing the same diagnostic purpose. Additionally, Damilakis *et al.*⁽²⁵⁾ and Dauer and coworkers⁽²⁶⁾ provided quantitative results of fetal doses for three different trimesters from other radiation-associated examinations. Damilakis *et al.*'s study showed that during the first, second and third trimesters, the fetus received 1.7, 2.7 and 4.9 mGy, respectively for X-ray absorptiometry scans of the posteroanterior lumbar spine. Dauer *et al.*'s study showed that the sentinel lymph node (SLN) technique using radioactive ^{99m}Tc-sulfur colloid delivered 0.206, 0.618 and 0.739 μ Gy MBq⁻¹ radiation doses, respectively, to the fetus during the first, second and third trimesters.

DISCUSSION

Comparison with data from ImPACT

The TCM schemes considered in this study were applied to actual pregnant patients who underwent CT examinations at MGH. As part of the routine procedure at MGH, CT scan doses are clinically archived using the ImPACT software⁽²²⁾. In ImPACT, the TCM schemes are represented using the different tube current values at the different slab location, as described previously. During clinical assessment in hospitals, the fetal dose is represented by the uterine dose when pregnant patients undergo examinations, even though the uterus model used in the ImPACT software does not represent a pregnant patient, and regardless of it being geometrically unrealistic. A comparison of the archived results with those obtained from MC calculations and realistic phantoms is summarised in Table 5. These results show that the ImPACT calculations consistently yielded larger dose estimates, by as much as 40–50 %, than those presented above. The main reason for the large difference lies in the phantoms used in these two types of calculations. The ImPACT calculations

Table 4. Results of doses to different fetus organs of the RPI-P3, P6 and P9 phantoms.

Organ	Organ dose (mGy)								
	Case 1			Case 2			Case 3		
	Non-TCM	TCM	Δ^a	Non-TCM	TCM	Δ^a	Non-TCM	TCM	Δ^a
Fetal soft tissue	9.41 (0.004)	8.06 (0.004)	14.28	8.34 (0.003)	6.88 (0.003)	17.49	24.22 (0.002)	18.10 (0.002)	25.27
Fetal skeleton	NA ^b	NA ^b	NA ^b	27.52 (0.006)	22.83 (0.005)	17.06	67.19 (0.003)	50.26 (0.003)	25.19
Fetal brain	8.56 (0.010)	7.31 (0.009)	14.60	6.55 (0.009)	5.32 (0.008)	18.86	17.06 (0.006)	12.66 (0.006)	25.78
Fetus total	9.27 (0.005)	7.94 (0.004)	14.33	9.47 (0.003)	7.81 (0.003)	17.52	28.00 (0.002)	20.92 (0.002)	25.29

Fetus total dose can also be called as fetal dose. The data in parenthesis are the relative statistical uncertainty from MC simulations. Δ , as the per cent dose reduction was calculated as the dose difference between non-TCM scheme and TCM scheme normalised by the dose from the non-TCM scheme.

^aPer cent dose reduction.

^bRPI-P3 does not contain fetal skeleton.

Table 5. Comparison of two sets of fetal doses from RPI phantoms and those from ImPACT calculations, individually.

Calculation	Fetal dose from MDCT scan using TCM		
	Case 1	Case 2	Case 3
RPI phantom (mGy)	7.94	7.81	20.92
ImPACT (mGy)	11.6	11.4	28.9
Difference (%)	46.1	46.0	38.1

The results in the row ‘Difference’ were calculated as the dose difference between the results from RPI phantoms and ImPACT normalised by RPI phantom results.

were based on the MIRD-5 stylised phantoms that represent non-pregnant individuals of much smaller body sizes, as illustrated in Figure 3⁽²⁷⁾. The difference in the calculated CT dose between stylised and anatomically realistic phantoms has been clearly established. The scan ranges were adjusted according to the anatomical features in the MIRD phantom (used in the ImPACT) and RPI phantoms, so the dose discrepancy primarily represents the impact of differing geometries and not of organs falling inside or outside of the scan range.

Dose reduction effects by TCM

TCM can reduce doses to many organs. According to the data presented in III.B., the fetal dose using non-TCM schemes is 5.6, 4.6 and 8.2 mGy 100 mA s⁻¹ for cases 1, 2 and 3, respectively, which are comparable with the dose values in the range of 7.3–14.3 mGy 100 mA s⁻¹ provided by Angel *et al.*⁽¹⁶⁾. The study performed in this research utilised the RPI phantoms⁽¹⁵⁾ with complete anatomical descriptions which are based on ICRP 89, so the doses provided

by Angel *et al.* may be more patient specific. Since the maximum current in the TCM schema was used in the non-TCM scheme, all the organs (except for the lens of the eye in case 2) received larger doses under the non-TCM CT scans. It can be seen from Table 4 that the TCM scheme for case 1 reduced the fetal dose by 14%, the TCM scheme for case 2 reduced fetal the dose by 18% and the TCM scheme for case 3 reduced the fetal dose by 25%.

Limitations of the study

The scope of this study is limited in several ways. All the TCM schemes used in this study were originally clinically used for patients with different gestations. These TCM schemes were applied to RPI-P phantoms which are good anatomical matches to the original patients, but it is likely that these modulation schemes are not optimised for RPI-P phantoms. Secondly, only three pregnant patient phantoms (RPI-P3, -P6, -P9) were developed and used in this study to represent the early, middle and late gestation stages, respectively. Three sets of clinically archived TCM scheme data were selected from the database to match the three gestation stages. Thirdly, only the longitudinal modulation of the tube current was considered in this study, although most recent modulation techniques will result in an even greater level of dose reduction by combining the angular modulation and longitudinal modulation^(11, 28). Given access to measurement data for the combined modulation techniques, the method of modelling TCM scheme described in this paper can be extended to modern techniques by modifying the X-ray source specification in the MC code. Additionally, this study assumed a maximum fixed tube current when making comparison with TCM schemes, although in most clinical practice, a fixed tube current may be

adjusted lower according to the patient size and the examination requirements.

CONCLUSIONS

This paper describes the assessment of fetal doses after CT examinations using MC methods. Three clinical retrospective TCM schemes were considered suitable for three pregnant patient phantoms representing 3, 6 and 9 months of gestation. Comparisons were made with fetal doses from CT procedures with constant tube current. It was found that the three TCM schemes can reduce fetal doses by 14, 18 and 25 %, respectively. This work also shows that the CT dose can and should be assessed for more realistic anatomical phantoms than those utilised by the IMPACT database, which is based on crude anatomical phantoms.

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