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Monte Carlo simulations to assess the effects of tube current modulation on breast dose for multidetector CT

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Abstract

Tube current modulation was designed to reduce radiation dose in CT imaging while maintaining overall image quality. This study aims to develop a method for evaluating the effects of tube current modulation (TCM) on organ dose in CT exams of actual patient anatomy. This method was validated by simulating a TCM and a fixed tube current chest CT exam on 30 voxelized patient models and estimating the radiation dose to each patient's glandular breast tissue. This new method for estimating organ dose was compared with other conventional estimates of dose reduction. Thirty detailed voxelized models of patient anatomy were created based on image data from female patients who had previously undergone clinically indicated CT scans including the chest area. As an indicator of patient size, the perimeter of the patient was measured on the image containing at least one nipple using a semi-automated technique. The breasts were contoured on each image set by a radiologist and glandular tissue was semi-automatically segmented from this region. Previously validated Monte Carlo models of two multidetector CT scanners were used, taking into account details about the source spectra, filtration, collimation and geometry of the scanner. TCM data were obtained from each patient's clinical scan and factored into the model to simulate the effects of TCM. For each patient model, two exams were simulated: a fixed tube current chest CT and a tube current modulated chest CT. X-ray photons were transported through the anatomy of the voxelized patient models, and radiation dose was tallied in the glandular breast tissue. The resulting doses from the tube current modulated simulations were compared to the results obtained from simulations performed using a fixed mA value. The average radiation dose to the glandular breast tissue from a fixed tube current scan across all patient models was 19 mGy. The average reduction in breast dose using the tube current modulated scan was 17%. Results were size dependent with smaller patients getting better dose reduction (up to 64% reduction) and larger patients getting a smaller reduction, and in some cases the dose actually increased when using tube current modulation (up to 41% increase). The results indicate that radiation dose to glandular breast tissue generally decreases with the use of tube current modulated CT acquisition, but that patient size (and in some cases patient positioning) may affect dose reduction.

1. Introduction

Due to the increased temporal resolution of multidetector CT (MDCT) scanners, chest imaging is one of the fastest growing CT applications (Adam 2006). Of particular concern is dose to radiosensitive organs such as the glandular tissue of the breasts (Hurwitz *et al* 2006, Mayo *et al* 2003). A recently released report from the International Commission on Radiological Protection (ICRP) estimates glandular breast tissue to be more radiosensitive than previously recognized, making it one of the most radiosensitive organs in the body (ICRP 2007). Previous studies have shown that breast cancer risk may exist for doses of less than 100 mGy (Preston *et al* 2002, 2007) or 500 mGy (Boice *et al* 1979), and the risk increases for younger patients, particularly for those under the age of 20 (Hill *et al* 2002, Preston *et al* 2002, 2007).

The majority of radiation dose estimates for chest CT are estimates of whole-body effective dose, which is a weighted sum of organ doses accounting for differences in organ radiosensitivity. However, it was recently suggested that dose to radiosensitive organs is a better measure for estimating patient risk than effective dose. (Brenner and Hall 2007, Martin 2007).

Some estimates do exist for estimation of organ dose for glandular breast tissue in chest CT exams (Parker *et al* 2005, ImPACT 2000, Hurwitz *et al* 2006). But most of these estimates do not have any mechanism to account for the effects of tube current modulation (TCM) on organ dose. TCM is a dose reduction technique used commonly in modern MDCT scanners (McCollough *et al* 2006, Kalra *et al* 2005a). The concept is to decrease the dose to the patient while maintaining desired image quality (Kalender *et al* 1999a). This may be accomplished by using angular (or x/y) modulation which reduces tube current (expressed in milli-Amperes or mA) for those projections in which the path length through the patient is shorter, resulting in a lower attenuation of the beam (typically PA or AP projections), and using conventional mA values for more attenuating projections (typically lateral projections) (Gies *et al* 1999, Kalender *et al* 1999b). Some tube current modulation algorithms use three-dimensional modulation which includes modulation along the z -axis or cranial–caudal direction of the patient (McCollough *et al* 2006, Kalra *et al* 2005a). Additional modulation in the z -direction is achieved by reducing the mA for regions having lesser density, such as the lungs, and increasing the mA for regions having a greater density such as the shoulders (Greess *et al* 2000). Three-dimensional modulation is considered the most comprehensive approach to CT dose reduction and is the most common method used for conventional TCM (McCollough *et al* 2006).

Although TCM is a common technique intended to reduce radiation dose, it is not known how the modulation affects the actual organ dose absorbed by the patient. Current studies reporting dose reduction from TCM generally use the reduction in the overall tube current–time product (mAs) of a TCM exam to compare with the mAs of a fixed tube current exam. Using these comparisons, average estimated dose savings in chest CT have been reported to be between 17 and 43% (Greess *et al* 2000, Mulkens *et al* 2005, Rizzo *et al* 2006, Tack *et al* 2003, Kalra *et al* 2005b). While these estimates do give an idea of the decrease in total tube current output (total mAs), they do not directly establish how radiation dose to sensitive organs is affected. To the best of our knowledge, only one study to date has looked at actual breast dose reduction from TCM. This study by Vollmar *et al* measured and simulated dose reduction by attaching simulated breasts to the anterior of a semi-anthropomorphic quality assurance (QA) phantom which was homogenous along the z -direction. They found that TCM reduced dose to the breasts of the phantom by approximately 10% (Vollmar and Kalender 2008).

The purpose of this study was to develop a method for estimating the organ dose reduction achieved by TCM in CT exams of actual patient anatomy. This will be accomplished by

simulating a TCM and a fixed tube current chest CT exam on 30 voxelized patient models and estimating the radiation dose to each patient's glandular breast tissue. This new method for estimating organ dose will be compared with other conventional estimates of dose reduction.

2. Methods and materials

The two virtual MDCT scanners used for this study were created based on previous work (Jarry *et al* 2003, DeMarco *et al* 2005, 2007). These simulated CT scanners accurately represent the specific CT models' spectra, filtration and geometry and were created within a Monte Carlo radiation transport code environment to allow for photon transport through a collection of voxelized patient models. These models are derived from actual female patient images, spanning a range of patient sizes. The simulated TCM CT exams use the accurate TCM schema obtained directly from each patient's scan information and, therefore, are based on each model's actual patient anatomy.

2.1. Patient images

Institutional Review Board (IRB) approval was obtained for this HIPAA compliant study. Thirty detailed voxelized models of female anatomy were created based on image data from patients who previously underwent clinically indicated thoracic CT exams. The patients ages ranged from 16 to 78 years. The cranial-caudal length of each voxelized patient model was dependent on the length of CT image data available. The average length of image data was 32 cm and all of the image sets included at least the patient anatomy from the thoracic inlet to the lung bases. As an indicator of patient size, the perimeter of the patient was measured on the image containing at least one nipple using a semi-automated technique. An example is illustrated in figure 1.

Images for nine of the patients in the cohort were originally acquired on a Sensation 16 MDCT (Siemens Medical Systems, Erlangen, Germany) and for the other 21 patients were acquired on a Siemens Sensation 64. All patient images were reconstructed with 2 mm or 3 mm thick contiguous images. All of the patients in the cohort had CT exams performed in the supine position using three-dimensional TCM (CareDose4D, Siemens Medical Solutions, Forchheim, Germany). This TCM algorithm can be utilized using different mAs adaptation settings for small and large patients. The Sensation 16 scanner's TCM algorithm was set to use 'weak' mAs adaptation for slim patients and 'average' mAs adaptation for larger patients. The Sensation 64 scanner's TCM algorithm was set to use 'average' mAs adaptation for slim and large patients. For each patient, the Quality Reference mAs[®] was recorded from the clinical scan. The Quality Reference mAs is a manufacturer-specified parameter used to select a desired image quality. It varied slightly between the patients with a minimum of 220 mAs and a maximum of 250 mAs. The patients were originally prescribed chest CT exams for diverse reasons and slight variations in the Quality Reference mAs were most likely due to differences in image quality requirements for individual protocols. The Quality Reference mAs does not require adjustment with patient size.

2.2. Patient models

To create voxelized models of each patient's anatomy from the image data, a radiologist contoured a region encompassing the glandular breast tissue and including some adipose tissue for each CT image set. The glandular tissue was semi-automatically segmented from that region using methods similar to those of Tran *et al* (2004). The voxels within the contoured glandular tissue were identified specifically as belonging to the glandular breast tissue group and were modeled as soft tissue (density = 1.06 g cm^{-3}). Each voxel outside the glandular breast tissue was modeled as one of six tissue types (lung, fat, water, muscle, bone or air) and subdivided into one of 17 density levels, depending on its CT number following the methods described in

DeMarco *et al* (1998). The process of creating voxelized models from the original patient images is summarized in figure 2. Voxelized models were created for each of the 30 patients whose image data were obtained; these patient models were used in the Monte Carlo simulations.

2.3. Monte Carlo simulation code

Monte Carlo methods were used to simulate CT scans by modeling the voxelized patients, scanner geometry and photon transport through the voxelized patients. All simulations used the MCNPX (MCNP eXtended v2.5.c) Monte Carlo code created at the Los Alamos National Laboratory (Waters 2002, 2003). For this study we used the photon transport mode which only tracks photon interactions and assumes electron energy is deposited at the photon interaction site, creating a condition of charged particle equilibrium (CPE). For this work, the assumption of CPE is reasonable given the energy distribution of the incident photons and the resulting range of secondary electrons. Simulations were operated with a low-energy cutoff of 1 keV using sufficient simulated particles to get a statistical variance of less than 1%.

2.4. MDCT source model

Two MDCT source models were created using modifications to the MCNPX source code as described by DeMarco *et al* and Jarry *et al* (Jarry *et al* 2003, DeMarco *et al* 2005, 2007). The CTs modeled were the Sensation 16 and Sensation 64 (Siemens Medical Systems, Erlangen, Germany). The CT source models simulate a helical source path with the photons emitted from a point source at the location of the x-ray tube anode. The MDCT models include the scanner-specific spectral distribution, beam filtration including the bowtie filter and beam collimation in the longitudinal direction as well as the ability to describe the source path geometry (e.g. helical path and pitch). The two scanner models used for this study were validated with CT Dose Index (CTDI) phantom measurements using methods similar to those used by Jarry *et al* (2003) and DeMarco *et al* (2005, 2007). Both scanners showed agreement between simulation and measurement to be within 10% in a CTDI phantom.

2.5. Modeling tube current modulation

The actual values of tube current for each projection were obtained from the raw projection data of each patient's actual clinical scan. The tube current values were represented by a value, I , that is a function of the tube angle and table position: $I(\Theta, z)$ where Θ represents the angle of the tube within the gantry and z is the table position. An example of the patient-specific tube current values is demonstrated in figure 3. All values of $I(\Theta, z)$ were divided by the maximum tube current to obtain normalized tube current values which were used in the TCM simulations as weighting factors at each (Θ, z) position along the source path. This allows for an accurate representation of the 3D tube current modulation for each patient.

2.6. Simulated CT scans

For each voxelized patient model, there were two scan protocols simulated: one using TCM and another using fixed mA, in which the mA value selected is derived from the Quality Reference mAs recorded during the clinical scan. The Quality Reference mAs[®] is a manufacturer-specified parameter used in exams employing TCM to select a desired image quality. It represents the effective mAs level that would have been used in a fixed tube current scan to get equivalent image quality for an average-size patient (McCollough *et al* 2006, Kalra *et al* 2005a).

The two simulated scan protocols for a given patient model used the same scan length, which varied from patient to patient and ranged from 277 to 391 mm. The length of patient represented by the image data was used as the scan length in the simulation. The simulated scans were run

on all 30 of the voxelized patient models. Helical scans of this nature would include extra irradiation directly before and after the image data in the z -direction due to z -axis over-ranging. Due to the limitation of image data available, z -axis over-ranging was not modeled in the simulations but is expected to have little effect on breast dose as there is a notable distance between breast tissue and the edge of the image volume in chest CT.

2.7. Dose calculations

The radiation dose to the glandular breast tissue was determined for the region defined by the voxels identified as glandular breast tissue as described in section 2.2. Absorbed dose within the contoured region was computed using the collision kerma. Collision kerma was calculated from the MCNP track-length estimate of energy fluence, and multiplied by the material-specific and energy-dependent mass energy-absorption coefficient. The calculation of organ dose per simulated source particle can be summarized as follows:

$$\text{organ dose per simulated source particle} = \frac{1}{n} \sum_{i=1}^n \left[\Psi(E) \left(\frac{\mu_{\text{en}}}{\rho} \right)_E \right]_i$$

where n is the number of simulated photons interacting with the tally region (i.e. the organ of interest), $\Psi(E)$ is the track length estimate of energy fluence for photon i with energy E and $\left(\frac{\mu_{\text{en}}}{\rho} \right)_E$ is the mass energy-absorption coefficient at energy E for the tissue in the organ. The mass energy-absorption coefficients were taken from the tables of Hubbel and Seltzer (1995).

To convert the organ dose per simulated source particle to organ dose per mAs, the organ dose values were multiplied by a normalization factor, which is scanner, kVp and collimation setting specific (Jarry *et al* 2003, DeMarco *et al* 2005). To convert from dose per mAs to absolute dose, the dose per mAs results were multiplied by the total tube current time product of the exam (i.e. mA multiplied by total scan time). For the tube current modulated simulations, the maximum tube current (I_{max}) was used in the conversion to absolute dose because the mAs weighting factors used in the simulation were designed to account for the tube current values relative to I_{max} .

2.8. Dose comparisons

To determine the amount of breast dose reduction from TCM as compared to a fixed tube current acquisition, the percent reduction in glandular breast dose was calculated as the difference in dose between the TCM and the fixed mA simulations, divided by the dose from the fixed mA simulation. These breast dose reductions were calculated for each patient and recorded along with patient perimeter so that the effect of patient size could be investigated as well. Linear regression analysis was used to investigate the trends of organ dose with patient perimeter.

3. Results

Table 1 summarizes acquisition/simulation parameters and also reports the measured patient perimeter, breast dose for the fixed tube current and TCM simulations and organ dose reduction for simulations using TCM relative to fixed tube current.

3.1. Glandular breast dose and dose reduction

The average glandular breast dose from a fixed tube current scan was 19 mGy with a range of 14–29 mGy. The average breast dose from a TCM scan was 15 mGy with a range of 8–20

mGy. The average dose reduction resulting from TCM was 17% with results ranging from an increase of 41% (reduction of -41%) to a decrease of 64%.

The results of glandular breast radiation dose from a fixed tube current scan as a function of patient size (perimeter) are shown in figure 4. This figure demonstrates that smaller patients receive higher radiation doses than larger patients when fixed tube current is not adjusted for patient size. Figure 5 shows the plot of breast dose from a TCM scan as a function of patient size. Figure 6 shows the reduction in breast dose when TCM is used as opposed to fixed tube current. Figure 6 demonstrates that larger women receive less of a decrease in breast dose from TCM than do smaller women. Note that for nine of the larger patients, there was actually an increase in breast radiation dose due to tube current modulation.

3.2. Comparison of methods to estimate dose reduction

The conventional method for estimating dose reduction in TCM CT studies is to find the total mAs used in a fixed tube current exam and compare that to the total mAs used in a TCM scan. This conventional method of estimating dose reduction was compared to the Monte Carlo-based glandular breast dose results from this study. Table 2 shows the percent dose reduction for both of these methods for all 30 patients' TCM CT exams. The conventional method underestimated the dose reduction by up to 26% with a mean underestimation of 9%. For eight of these patients, the dose reductions were overestimated by the conventional estimation method.

4. Discussion

This work demonstrates that Monte Carlo methods can be used to obtain detailed estimates of radiation dose to specific organs for patients undergoing TCM CT exams. These simulation methods were used to create detailed models of women of different size (perimeter) and whose glandular breast tissues were located in various positions (that is, some more medial and some more lateral) as naturally occurs in the supine position. Heterogeneity in this small patient population led to differences in radiation dose, using both fixed tube current and tube current modulation schemes.

The potential sources of uncertainty in the dose calculations involve the creation of the voxelized patient models, modeling of the CT scanners and the Monte Carlo simulations. The voxelized patient models may have uncertainty due to partial voluming in the voxelization of the CT images, variance in the tissue definitions and variance in the segmentation of the tally region. Since the tally region in this study, glandular breast tissue, is much larger than the voxel size, it is expected that the uncertainty in the voxelized patient models is negligible. The uncertainty of the CT scanner models is expected to be within 10% as determined by the validation methods described in section 2.4. The statistical variance in the Monte Carlo simulations was less than 1%.

The results, which were analyzed according to patient size, indicated that glandular breast dose decreases on average when using TCM as opposed to fixed tube current CT acquisition. But in some cases (particularly with larger women with a perimeter greater than 122 cm) the breast dose may actually increase as a result of using tube current modulation. This is because the TCM algorithm used in this study automatically adjusts for patient size. For some large women with fatty breasts, the radiation doses of fixed tube current acquisition were relatively low, thus counteracting some effects of the increase in dose from TCM in large patients. It should also be noted that larger patients who receive an increase in dose with TCM acquisition may also benefit from some improvement in image quality as compared to fixed tube current acquisition.

4.1. Comparison to the existing method of dose reduction estimation

The Monte Carlo simulations from this study were used to establish estimates of the reduction in breast dose when using TCM as opposed to fixed tube current acquisition. In the current literature, dose reduction has been predicted using the difference in total mAs between TCM and fixed tube current exams. Current estimates of dose reduction have ranged from 17 to 43% using this method (Greess *et al* 2000, Mulken *et al* 2005, Rizzo *et al* 2006, Tack *et al* 2003, Kalra *et al* 2005b). This can be compared to the estimated breast dose reduction for the 30 patients in this study which ranged from a dose reduction of 64% to an increase in dose of 41%. The conventional method is intended to estimate whole body dose reduction as opposed to organ dose reduction. Therefore, to further compare this study's results with the published estimates, the conventional method of predicting the dose reduction from the difference in total mAs was used for the 30 patients in this study and compared to the actual organ dose estimates. The conventional method of using total mAs reduction to predict patient dose reduction was found to be substantially inaccurate and would cause underestimations of the dose reduction from TCM of up to 26%. This result was consistent with the measurement results demonstrated in an anthropomorphic phantom by Kalender *et al* (1999b).

A study by Vollmer and Kalender estimated dose reduction from TCM chest CT to be approximately 10% for the breast region of a phantom (Vollmer and Kalender 2008). The results from the present study estimated the average breast dose reduction to be almost double that estimated by the Vollmer study. Some of this difference may be due to the fact that the phantom model used in the Vollmer study was fairly uniform in the z-axis direction, thus limiting longitudinal TCM. The phantom was also comprised of different material compositions than the human tissues used in the voxelized patient models of this study. However, it is difficult to speculate further on the cause of this discrepancy since the Vollmer study focused on a single patient model of a fixed size whereas this study investigated a range of patient models.

4.2. Confounding factors

This section investigates outlier data and interesting results for specific patient models to determine their underlying explanations. One of the patient models had a smaller than average size perimeter of 98.4 cm but received a lower breast dose for the fixed tube current simulation than would have been expected given the size-dependent data. The breast dose estimate for this same patient undergoing the TCM simulated CT was similar to other patients of similar size. This discrepancy was most likely due to a patient positioning problem during CT acquisition. As seen in figure 7, the patient's arms were not fully over her head during CT image acquisition. For the fixed tube current exam, the arms will attenuate some of the incident beam before it reaches the breast tissue and act as a dose shield thus decreasing breast dose. For the TCM exam, the arms would have increased the observed tissue density in that region and in turn the TCM algorithm would respond by increasing the tube current and thus equalizing out the dose to the breast tissue. Therefore, the estimated glandular breast dose for a TCM scan for this small patient was only 11% less than the dose from a fixed tube current exam and much less than the expected amount of dose reduction for a patient of that size. The positioning of the patient's arms is not the only positioning concern in TCM. Another patient positioning concern is incorrect centering of the patient in the scanner gantry which will cause over- or under-magnification of the topogram. The topogram is used to estimate patient size for TCM algorithms, thus causing unwarranted dose effects (Li 2007). Patient centering was not specifically investigated in this study.

Another interesting finding of this study was that the TCM schema for larger patients appears to have little or no longitudinal or z-axis modulation. This phenomenon is most likely due to the limits of the x-ray generator which 'cuts off' the tube current at the maximum limit. This

is demonstrated in figure 8, which shows the TCM scheme for a large patient (142 cm perimeter). In this specific implementation of TCM, the tube cut-off caused by larger patients may be mitigated by increasing the rotation time and/or decreasing the pitch for a given Quality Reference mAs.

4.3. Study limitations

One limitation to this study was that only two scanners were evaluated using the TCM algorithm specific to one manufacturer. The TCM algorithms and approaches that are used in the CT industry do vary from one manufacturer to another and this limits the generalization of these results. Another limitation was that although the patient population used in this study did provide some variation in size, it is not meant to be fully representative of the general population. A third limitation was that image quality was not considered directly here. There is no accepted quantitative metric of image quality for comparing CT exams with and without TCM. While the tube current value used for the fixed tube current simulation (the Quality Reference mAs) was intended to provide a condition that would yield approximately the same image quality as the tube current modulation scheme, we were unable to verify that image quality was comparable between the two acquisition techniques. A fourth limitation of this study was that the mAs for the fixed tube current simulations was not adjusted for patient size. For fixed tube current scanning, some imaging centers do adjust the tube current for patient size which was not taken into account in this study design. If this study were designed to account for patient size adjustments in the fixed tube current simulations, then the dose reduction results would have shown less variation with patient size.

5. Conclusion

Dose to glandular breast tissues is of great importance for CT scanning, especially in regions where the breast is irradiated directly such as thoracic CT scans (and cardiac CT scans). Tube current modulation schemes have been shown to reduce the dose to the glandular breast tissues for the majority of patients. For smaller patients, the breast dose reduction from TCM is more effective, most likely taking advantage of the fact that glandular tissues most often are located over a region of low attenuation—the lungs. Assuming that all patients would use a similar fixed tube current (i.e. no adjustment for patient size), some larger patients with perimeters greater than 122 cm actually receive an increase in dose when using TCM as compared to fixed tube current acquisition. Since the methods used in this study do not adjust tube current for patient size in fixed tube current imaging, the larger patients who receive an increase in dose with the use of TCM acquisition will also benefit from improved image quality. Therefore, the increase in dose for larger patients undergoing TCM acquisition may be entirely appropriate for the diagnostic task at hand.

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Figure 1.
Sagittal (left) and axial (right) images demonstrating location of patient perimeter measurement (perforated white line).

Figure 2. Generation of a voxelized model: (a) original patient image, (b) radiologist's contour of the breast region, (c) threshold image to identify glandular breast tissue and (d) the resulting voxelized model.

Figure 3.
Plot of tube current versus x -axis location of the TCM schema for a patient model with a perimeter of 125 cm. The background of the plots is a sagittal view of the patient.

Figure 4.

Breast dose versus patient perimeter for all 30 patient models in the fixed tube current simulations. Breast dose decreases linearly with an increase in patient perimeter ($R^2 = 0.76$).

Figure 5. Breast dose versus patient perimeter for all 30 patient models in the TCM simulations. Breast dose increases linearly with an increase in patient perimeter ($R^2 = 0.46$).

Figure 6. Percent dose reduction for the TCM simulations as compared to the fixed tube current simulations. Percent dose reduction decreases linearly with an increase in patient perimeter ($R^2 = 0.81$).

Figure 7. Three-dimensional image of CT data for a patient with her arms in the imaged volume. Arms are cut off by the edge of the field of view of the image reconstruction, but the remainder of the arms would have been in the gantry.

Figure 8.

Plot of mA versus z-axis location for TCM of a large patient model with a perimeter of 142 cm. The background of the plot is a sagittal view of the patient.

Summary of results for all 30 patient models. Breast dose is shown for the fixed tube current and TCM simulations. Percent breast dose reduction as compared to a fixed tube current scan is reported. A negative percent dose reduction denotes a larger breast dose when using TCM than when using fixed tube current scanning.

Patient perimeter (cm)	Scanner	Fixed tube current effective mAs ^d	Breast dose (mGy)		Percent dose reduction
			Fixed tube current	TCM	
81.3	S16	250	29	13	57
86.9	S64	250	23	8	64
88.4	S64	235	22	9	60
88.5	S64	235	21	12	41
89.3	S16	250	26	13	50
91.9	S16	250	24	14	43
92.3	S64	240	19	9	52
93.4	S64	235	22	8	62
98.4	S64	240	16	14	11
99.0	S16	230	21	15	27
100.5	S64	250	19	13	34
101.4	S16	230	22	19	14
101.5	S16	230	20	12	40
111.8	S16	250	20	18	10
114.1	S64	235	16	14	8
114.2	S16	220	18	12	34
115.3	S64	240	16	11	30
116.0	S64	235	18	15	15
118.5	S64	235	16	18	-12
121.5	S64	250	16	15	5
121.7	S64	250	17	15	10
122.5	S64	250	16	18	-12
124.3	S64	250	16	19	-15
124.9	S16	230	19	19	0
128.3	S64	250	14	20	-41
128.4	S64	250	16	18	-14

	Patient perimeter (cm)	Scanner	Fixed tube current effective mAs ^a	Breast dose (mGy)		Percent dose reduction
				Fixed tube current	TCM	
	131.9	S64	235	15	16	-8
	133.5	S64	235	14	17	-21
	135.0	S64	250	14	16	-15
	141.7	S64	235	14	16	-16
Mean	110.5		241	19	15	17
Minimum	81.3		220	14	8	-41
Maximum	141.7		250	29	20	64

^aFixed tube current effective mAs is the Quality Reference mAs.

Table 2

Comparison of dose reduction estimates from a method based on breast dose from Monte Carlo simulations of organ dose to a method based on reduction in total mAs.

Patient perimeter (cm)	mAs of fixed tube current	Mean mAs of 3D TCM	% Dose reduction			Underestimate of breast dose reduction by the total mAs method
			Based on Monte Carlo simulated organ dose	Based on total mAs reduction		
81.3	325	200	57	38		18
86.9	500	304	64	39		25
88.4	470	282	60	40		20
88.5	470	357	41	24		17
89.3	325	206	50	37		14
91.9	325	242	43	25		17
92.3	480	334	52	31		21
93.4	470	302	62	36		26
98.4	480	387	11	19		-9
99.0	460	378	27	18		9
100.5	500	352	34	30		5
101.4	460	365	14	21		-7
101.5	460	366	40	20		20
111.8	325	358	10	-10		20
114.1	470	494	8	-5		14
114.2	435	302	34	31		4
115.3	480	442	30	8		22
116.0	376	376	15	0		15
118.5	470	520	-12	-11		-1
121.5	400	410	5	-2		7
121.7	500	514	10	-3		13
122.5	500	559	-12	-12		0
124.3	500	540	-15	-8		-7
124.9	308	360	0	-17		17
128.3	400	539	-41	-35		-6
128.4	500	570	-14	-14		0

	% Dose reduction				Underestimate of breast dose reduction by the total mAs method
	Patient perimeter (cm)	mA of fixed tube current	Mean mA of 3D TCM	Based on Monte Carlo simulated organ dose	Based on total mAs reduction
	131.9	564	580	-8	-3
	133.5	470	560	-21	-19
	135.0	500	568	-15	-14
	141.7	470	577	-16	-23
Mean	110.5	446	411	17	8
Minimum	86.9	308	206	-41	-35
Maximum	141.7	564	580	64	40
					-5
					-1
					-1
					7
					9
					-9
					26