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## Dose to Radiosensitive Organs During Routine Chest CT: Effects of Tube Current Modulation

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### Abstract

**Objective**—The aims of this study were to estimate the dose to radiosensitive organs (glandular breast and lung) in patients of various sizes undergoing routine chest CT examinations with and without tube current modulation; to quantify the effect of tube current modulation on organ dose; and to investigate the relation between patient size and organ dose to breast and lung resulting from chest CT examinations.

**Materials and Methods**—Thirty voxelized models generated from images of patients were extended to include lung contours and were used to represent a cohort of women of various sizes. Monte Carlo simulation–based virtual MDCT scanners had been used in a previous study to estimate breast dose from simulations of a fixed-tube-current and a tube current–modulated chest CT examinations of each patient model. In this study, lung doses were estimated for each simulated examination, and the percentage organ dose reduction attributed to tube current modulation was correlated with patient size for both glandular breast and lung tissues.

**Results**—The average radiation dose to lung tissue from a chest CT scan obtained with fixed tube current was 23 mGy. The use of tube current modulation reduced the lung dose an average of 16%. Reductions in organ dose (up to 56% for lung) due to tube current modulation were more substantial among smaller patients than larger. For some larger patients, use of tube current modulation for chest CT resulted in an increase in organ dose to the lung as high as 33%. For chest CT, lung dose and breast dose estimates had similar correlations with patient size. On average the two organs receive approximately the same dose effects from tube current modulation.

**Conclusion**—The dose to radiosensitive organs during fixed-tube-current and tube current–modulated chest CT can be estimated on the basis of patient size. Organ dose generally decreases with the use of tube current–modulated acquisition, but patient size can directly affect the dose reduction achieved.

### Keywords

CT; Monte Carlo simulation; radiation dose; tube current modulation; voxelized patient model

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CT is unique from other imaging techniques in that 3D image acquisition of the entire thoracic region can be performed within a single breath-hold. As a result, chest CT is frequently used as a diagnostic tool. The news media have been giving increased attention to exposure of the general population to ionizing radiation during medical imaging, specifically CT [1]. For chest CT, the most radiosensitive organs are the lungs and glandular breast [2–4]. Risk of breast cancer may correlate with doses less than 100 mGy, and risk of lung cancer may correlate with doses as low as 100 mGy [5].

In discussion of individual risk during CT, organ dose is a better measure for estimating patient risk than is effective dose because effective dose is intended for estimating radiation exposure of entire populations, not for individual dose estimates [6,7]. Most existing methods for estimating radiation dose to the radiosensitive organs during chest CT are based on measurements or simulations of a single patient model or phantom with unrealistic anatomic features (e.g., breasts modeled as a homogeneous material located directly anterior to the thoracic region) [2,8–11]. It is not known how well these methods serve for estimation of organ doses in an actual patient population, which includes natural variations in patient size and breast composition.

The primary limitation of most previous tools used for estimation of organ dose during chest CT may be that those methods do not account for the effects of tube current modulation. Tube current modulation is an acquisition technique often used in CT scanners to decrease the overall dose to the patient while maintaining image quality [12,13]. Tube current modulation is accomplished by reducing the product of the tube current in milliamperes and the time in seconds for regions of lower attenuation, such as the lungs, and increasing the tube current–time product for regions of higher attenuation, such as the shoulders [14–16]. In more recent algorithms, tube current is modulated in three dimensions, accounting for the elliptic shape of a patient and for changes in attenuation, such as across the shoulder–lung interface [17,18]. The most common method of comparing the doses of specific CT acquisitions is to measure the CT dose index (CTDI), but CTDI is not defined, and cannot be measured, for tube current–modulated CT acquisition.

Many imaging centers use tube current–modulated CT acquisition to decrease radiation exposure to patients, but it is not known how the modulation affects dose absorption in the patient. Published estimates of dose reduction with tube current modulation are generally based on a comparison of the total tube current–time product of a modulated examination and the total tube current–time product of a fixed-tube-current examination. In those studies [19–22] the estimated dose savings of tube current modulation in chest CT have been between 17% and 43% for 3D modulation. These dose estimates do not directly establish how radiation dose to radiosensitive organs is affected by tube current–modulated acquisition. They simply are estimates of the decrease in tube current output. Vollmar and Kalender [23] estimated that the actual breast dose reduction from tube current modulation is 10%; they did not assess lung dose. Those investigators estimated breast dose by measuring and simulating breast dose reduction in a semianthropomorphic phantom that was homogeneous along the z-axis.

Using Monte Carlo simulation–based MDCT scanner models, we can overcome the limitations of previous dose estimation tools by incorporating a range of actual anatomic features of patients undergoing patient-specific tube current–modulated CT acquisition and by incorporating the actual scanner spectra, geometries, and tube current modulation schemes [24–26]. The purposes of this study were to extend previous work with detailed Monte Carlo simulations to estimate the radiation dose to radiosensitive lung tissue in patients of various sizes undergoing routine chest CT examinations with and without tube current modulation; to quantify the effect of tube current modulation on organ dose; and to investigate the relation between patient size and organ dose to the breast and lung during chest CT examinations.

## Materials and Methods

The simulations used in this study include previously validated virtual CT scanners that take into account details of the scanner, including helical source path, actual source spectra, filtration, and geometry [24–26]. The methods used to simulate tube current modulation were those reported previously [27]. Voxelized patient models based on CT images of actual women were extended to include lung contours for this study. Monte Carlo simulations of chest CT examinations were performed on these voxelized patient models. Radiation dose was estimated for the lung tissue of each patient model for both fixed-tube-current and tube current–modulated chest CT examinations and compared with similar, previously obtained estimates for breast tissue.

### Patient Cohort and Image Data

Thirty detailed voxelized models representing the anatomic features of women 16–89 years old were used [27]. These models were based on patient images from a cohort of 45 women who had undergone clinically indicated tube current–modulated CT of the thoracic region. All of the patient models were based on chest CT examinations performed with attenuation-based 3D tube current modulation (CareDose4D, Siemens Healthcare). The specific clinical indication for each examination was not available for the patient images, from which identifying information had been removed. The original tube current modulation scheme and reference tube current–time products were obtained for each examination. Fifteen of the 45 CT examinations were not used because of technical complications such as problems retrieving tube current modulation data from the scanner. For this HIPAA-compliant study, institutional review board approval was obtained for the use of the CT images, from which identifying information had been removed. Each voxelized patient model included at least the anatomic structures from the thoracic inlet to the lung bases. The perimeter (or circumference) of each patient at the skin–air boundary was included in this study as an indicator of patient size. The perimeter was measured on one transverse image with the techniques described in Angel et al. [27].

The simulated tube current–modulated examination of each patient model matched the acquisition protocol from the patient's original examination. Images of nine of the patient models were originally acquired with a 16-MDCT scanner (Sensation 16, Siemens Healthcare) at a nominal beam collimation of  $16 \times 0.75$  mm, 120 kVp, rotation time of 0.42–0.5 seconds, and pitch of 0.65–1.0. Images of the other 21 patient models were acquired with a 64-MDCT scanner (Sensation 64, Siemens Healthcare) at a nominal beam collimation of  $32 \times 0.6$  mm ( $n = 20$ ) or  $24 \times 1.2$  mm ( $n = 1$ ), 120 kVp, rotation time of 0.5 seconds, and pitch of 0.8–1.0. All patient images were reconstructed with a B30f reconstruction kernel and contiguous images with a thickness of 2 or 3 mm. The 16-MDCT scanner tube current modulation algorithm was set to the weak tube current–time product adaptation for slim patients and to the average tube current–time product adaptation for larger patients. The 64-MDCT scanner tube current modulation algorithm was set to the average tube current–time product adaptation for slim and large patients.

### Extension of Patient Models

Voxelized models of the anatomic features of each patient were obtained from previous work [27] and extended to include lung-tissue contours. The lung contours were semiautomatically segmented with a method in which thresholds were dynamically selected for edge detection [28]. The voxels within the contoured lungs were modeled as lung tissue [29] with density ranging from 0.048 to 0.65 g/cm<sup>3</sup> on the basis of the attenuation of the lung in the original image data. This process resulted in 30 voxelized models with both lung and breast tissue segmented. These models were used in the Monte Carlo CT simulations.

## MDCT Source Models

Monte Carlo simulations were used to simulate CT scans by means of modeling of the voxelized patients, scanner geometry, and photon transport through the voxelized patients according to a method described previously [27]. All simulations were made with MCNPX version 2.5.c software [30,31]. Two virtual MDCT scanners representing the Sensation 16 and Sensation 64 (Siemens Healthcare) models were obtained [24–26]. These virtual scanners include the x-ray spectrum, filtration, and geometry of the specific scanner model and were found to agree with physical measurement results from standardized dosimetric phantoms (CTDI phantoms) to within 10% [24–27].

## Modeling of Tube Current Modulation

For each patient, the actual tube current modulation values used in the patient's clinical scan were obtained from the raw projection data according to the method described previously [27]. This modulation scheme, which is illustrated in Figure 1, includes the table position, gantry angle, and tube current used for each projection as the tube rotates around and traverses the patient. The tube current values were used as weighting factors for each projection in the Monte Carlo simulations of a CT scan for the corresponding patient model. Using the exact tube current modulation schema allows accurate representation of the tube current modulation specific to each patient.

## Simulated Chest CT Scans

Two scan protocols were simulated for each voxelized patient model: the actual tube current–modulated scan and a fixed-tube-current scan [27]. With the exception of tube current, the simulated acquisition protocols (e.g., collimation, rotation time, pitch) were consistent between the two simulated examinations and matched those used for the actual patient's chest CT examination. A Monte Carlo simulation tally was used to calculate the average radiation dose, in milligrays, to the lung tissues [24,25,27,30–32].

The lung dose saving from tube current modulation was determined by calculation of the percentage reduction of lung dose between the tube current–modulated and fixed-tube-current acquisitions. This value was calculated for each patient and was recorded with patient perimeter for study of the effects of patient size on organ dose. To allow comparison of a peripheral organ to a large central organ, previous breast dose estimates [27] were presented alongside the lung dose estimates. Linear regression analysis was performed on both lung and breast dose to assess the correlation between organ dose and patient perimeter, and  $p$  was calculated to determine statistical significance. A value of  $p < 0.5$  indicated a significant difference.

## Results

Table 1 shows the patient perimeters and ages, previously reported breast dose estimates [27], and the lung dose results for the simulated scans performed on each patient model. The average lung dose at fixed-tube-current chest CT was 23 mGy (range, 14–34 mGy). The average lung dose at tube current–modulated chest CT was 18 mGy (range, 12–25 mGy). The average lung dose reduction from tube current modulation was 16% with a maximum dose decrease of 56% and a maximum dose increase (dose penalty) of 33%.

The results for organ dose as a function of patient size (perimeter) at fixed-tube-current chest CT are shown in Figure 2. The relation between patient perimeter and organ dose for fixed tube current chest CT can be represented as:  $DF_{\text{breast}} = (-0.20 \times \text{perimeter}) + 40.3$  and  $DF_{\text{lung}} = (-0.24 \times \text{perimeter}) + 49.5$ , where DF is the organ dose, in milligrays, for fixed-tube-current chest CT. The equations are based on linear regression analysis of the lung dose results from this study and previously acquired breast dose results [27]. These equations showed a

significant linear correlation between patient perimeter and breast dose ( $R^2 = 0.76$ ;  $p < 0.001$ ) and between patient perimeter and lung dose ( $R^2 = 0.77$ ;  $p < 0.001$ ) at fixed-tube-current chest CT.

The results for organ dose as a function of patient size for tube current–modulated chest CT are shown in Figure 3. The relation between patient perimeter and organ dose for tube current–modulated chest CT (DTCM) can be represented as  $DTCM_{\text{breast}} = (0.134 \times \text{perimeter}) - 0.196$  and  $DTCM_{\text{lung}} = (0.104 \times \text{perimeter}) + 6.60$ . Linear regression analysis for the tube current–modulated chest CT simulations showed a slope close to 0 with lower coefficients of determination but still showed significant linear correlation between patient perimeter and breast dose ( $R^2 = 0.46$ ;  $p < 0.001$ ) and between patient perimeter and lung dose ( $R^2 = 0.31$ ;  $p = 0.001$ ).

Figure 4 shows percentage decrease in organ dose as a function of patient size with use of tube current–modulated as opposed to fixed-tube-current acquisition for chest CT. In nine of the 30 patient models, tube current modulation caused an increase in organ dose compared with fixed-tube-current acquisition. An increase in organ dose is shown in Figure 4 by a negative percentage dose reduction value. This finding was true for patients with a perimeter greater than 122 cm. As expected, larger women receive less dose reduction from tube current modulation than do smaller women. The relation between patient perimeter and percent dose reduction (PDR) from tube current modulation can be represented for breast and lung as follows:  $PDR_{\text{breast}} = (-1.53 \times \text{perimeter}) + 186$  and  $PDR_{\text{lung}} = (-1.35 \times \text{perimeter}) + 165$ . Linear regression analysis of percent dose reduction showed significant linear correlation between patient perimeter and percent breast dose reduction ( $R^2 = 0.81$ ;  $p < 0.001$ ) and between patient perimeter and percent lung dose reduction ( $R^2 = 0.82$ ;  $p = 0.001$ ).

## Discussion

In this study, Monte Carlo simulation methods were used to obtain detailed estimates of radiation dose to the lungs of patients undergoing chest CT examinations with and without patient-specific tube current modulation. The patient models represented the actual anatomy of women and included a range of patient sizes. As in a previous study [27], we found that the radiation dose to organs in the scan volume can increase rather decrease with the use of tube current modulation. Patient perimeter can easily be measured in the clinic with a tape measure before an examination. Linear regression analysis showed that we can use linear equations to estimate organ dose on the basis of patient perimeter for fixed-tube-current and tube current–modulated acquisitions and to estimate percentage dose reduction attained with tube current modulation. We found not only that the glandular breast, which is considered a peripheral organ, and lung, which is considered a large medially situated organ, receive similar doses during chest CT, both with and without tube current modulation, but also that the dose reduction from tube current modulation is similar for the two organs, especially with respect to patient size.

The limitations of this study were similar to those in our previous study [27]. Specifically, the patient cohort is not necessarily an accurate representation of the general patient population. In addition, only two scanners were modeled, and only one specific tube current modulation algorithm was evaluated. Results of another study [33] suggest that organ dose estimates during fixed-tube-current examinations can be extrapolated for estimates of organ doses for other scanners through comparison of physical phantom measurements. In future work, we will investigate the robustness of that theory for tube current modulated CT acquisition.

Image quality was not directly measured in this study. However, the value used for the fixed-tube-current simulations was selected to provide a condition that would yield approximately

the same image quality for a standard-sized patient as would the tube current modulation scheme. Because in this condition, image quality is adjusted only for a standard-sized patient, there would be no adjustment for patient size in the fixed-tube-current simulations. To have the same image quality as CT of smaller patients, CT of larger patients must be performed with greater tube current. Therefore, although tube current modulation has been found to increase organ dose for larger patients, image quality also can be improved. Some imaging centers adjust fixed tube current settings for patient size. If patient size adjustments had been modeled in this study, the results might have shown less variation with patient size.

Glandular breast and lung are two of the most radiosensitive organs irradiated during routine thoracic CT. Tube current–modulated CT acquisition was found to reduce the radiation dose to these tissues, especially in smaller patients (perimeter < 122 cm). These radiation dose reductions depend on patient size and can result in organ dose reductions up to 64% in our patient population. Larger patients may not receive a decrease in dose with tube current modulation.

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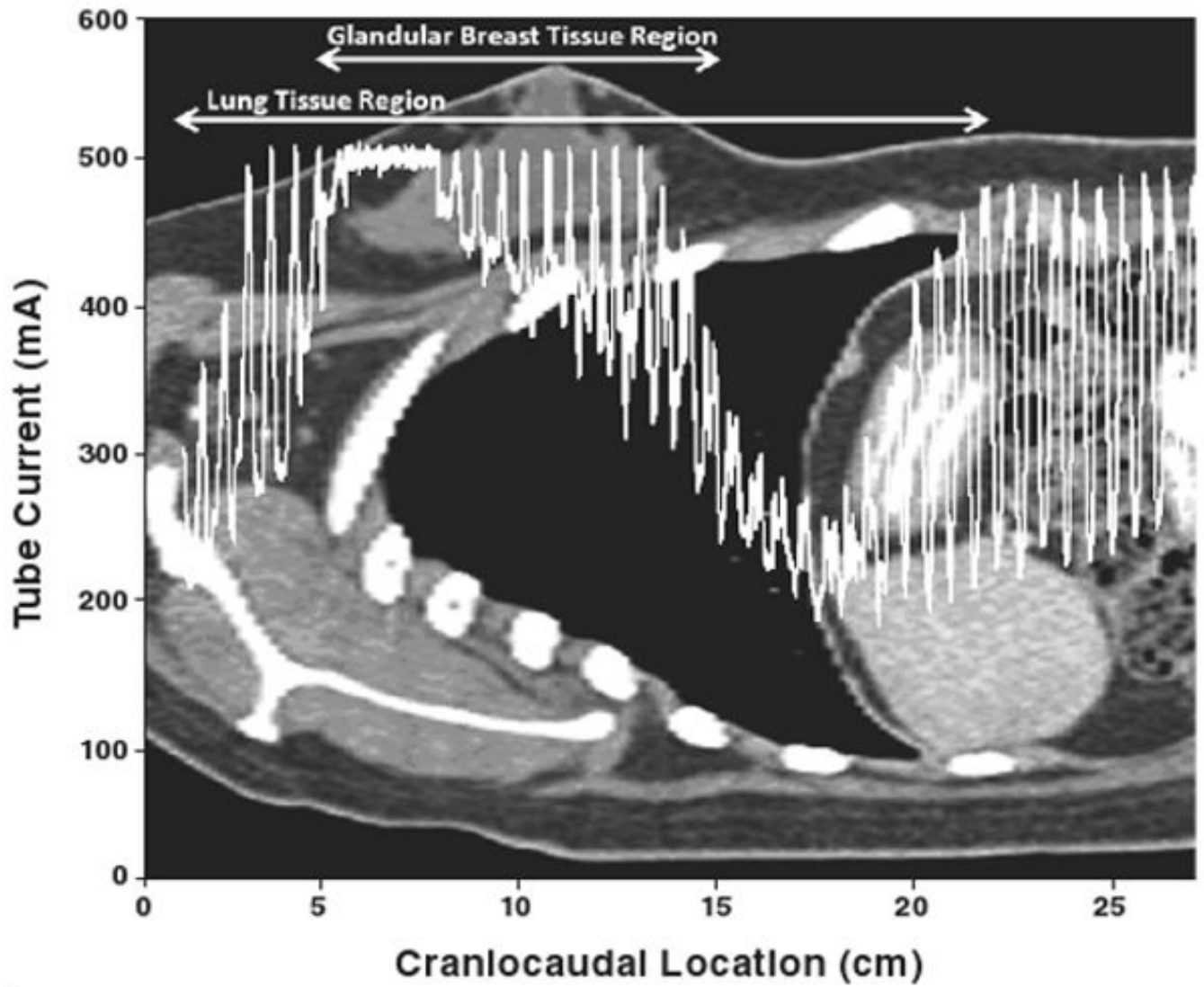
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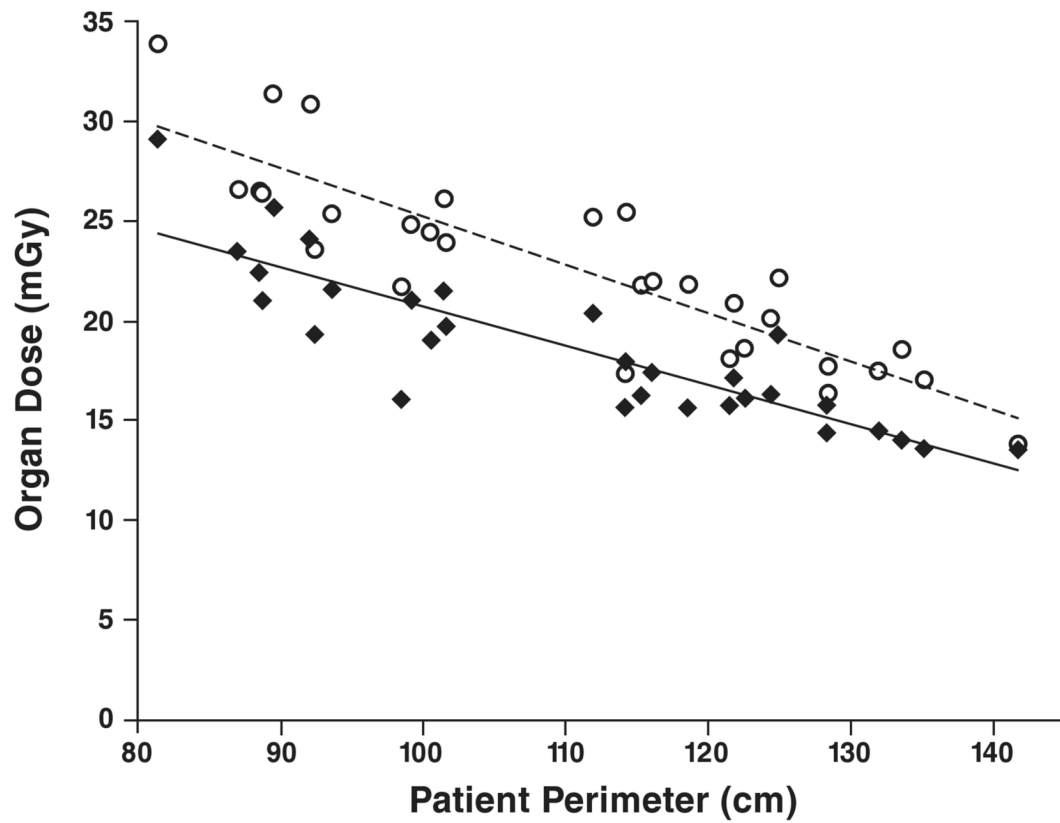
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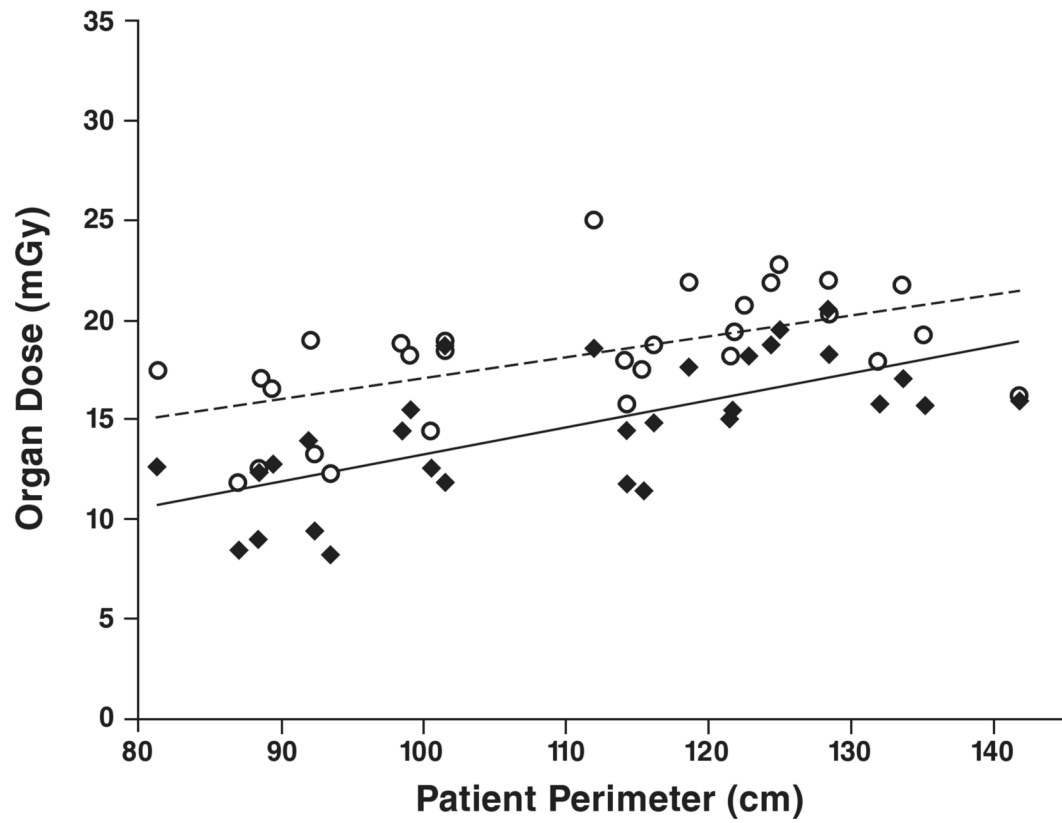




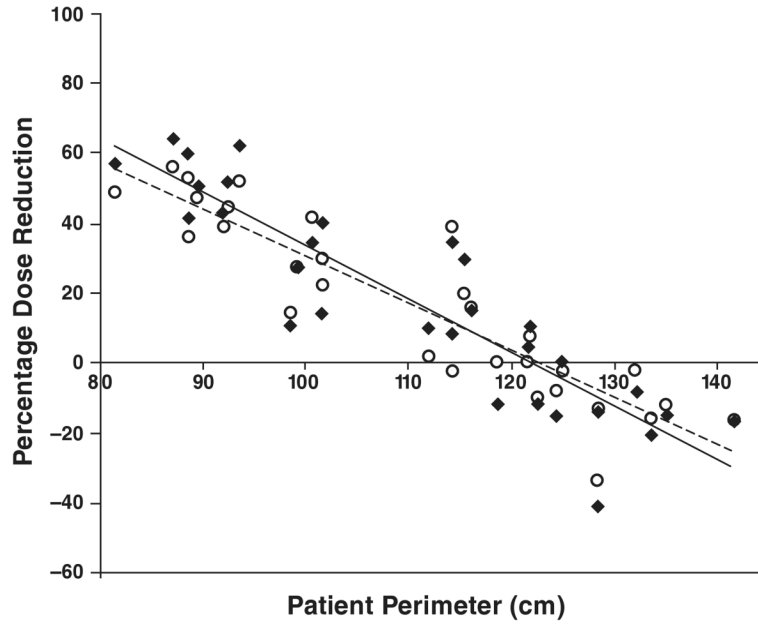
**Fig. 1.** 28-year-old woman undergoing tube current modulated chest CT. Plot shows patient's tube current modulation scheme overlaid on sagittal view of patient. Tube current versus table location is shown for patient model with perimeter of 101 cm.



**Fig. 2.** Graph of results for fixed-tube-current chest CT examination shows correlation between patient perimeter and radiation dose to glandular breast (*diamonds*) ( $R^2 = 0.76$ ) and lung (*circles*) ( $R^2 = 0.77$ ).



**Fig. 3.** Graph of results for tube current–modulated chest CT examination shows correlation between patient perimeter and radiation dose to glandular breast (*diamonds*) ( $R^2 = 0.46$ ) and lung (*circles*) ( $R^2 = 0.31$ ).



**Fig. 4.** Graph shows correlation between patient perimeter and percentage reduction or increase in dose to glandular breast ( $R^2 = 0.81$ ) and lung ( $R^2 = 0.82$ ) with use of tube current modulation as opposed to fixed tube current in chest CT. Negative percentage dose reduction value denotes increase in organ dose with use of tube current modulation as opposed to fixed tube current.

TABLE 1

Results of Simulated Scans

Patient Perimeter (cm)	Patient Age (y)	Breast Dose (mGy) <sup>fr</sup>			Lung Dose (mGy)		
		Fixed Tube Current	Tube Current Modulation	Percentage Dose Reduction	Fixed Tube Current	Tube Current Modulation	Percentage Dose Reduction
		81	63	29	13	57	34
87	57	23	8	64	27	12	56
88	35	22	9	60	26	12	53
89	64	21	12	41	26	17	36
89	67	26	13	50	31	16	47
92	41	24	14	43	31	19	39
92	16	19	9	52	24	13	44
93	89	22	8	62	25	12	52
98	71	16	14	11	22	19	14
99	61	21	15	27	25	18	27
100	52	19	13	34	24	14	42
101	28	22	19	14	24	19	22
101	78	20	12	40	26	18	30
112	62	20	18	10	25	25	2
114	75	16	14	8	17	18	-2
114	70	18	12	34	25	16	39
115	35	16	11	30	22	17	20
116	77	18	15	15	22	19	15
119	71	16	18	-12	22	22	0
121	44	16	15	5	18	18	0
122	56	17	15	10	21	19	8
123	49	16	18	-12	19	21	-10
124	31	16	19	-15	20	22	-8
125	70	19	19	0	22	23	-2
128	39	14	20	-41	16	22	-33
128	29	16	18	-14	18	20	-14
132	69	15	16	-8	17	18	-2

Patient Perimeter (cm)	Patient Age (y)	Breast Dose (mGy) <sup>a</sup>			Lung Dose (mGy)		
		Fixed Tube Current	Tube Current Modulation	Percentage Dose Reduction	Fixed Tube Current	Tube Current Modulation	Percentage Dose Reduction
134	62	14	17	-21	19	22	-16
135	55	14	16	-15	17	19	-12
142	62	14	16	-16	14	16	-16
111 (mean)	56	19	15	17	23	18	16
81 (minimum)	16	14	8	-41	14	12	-33
142 (maximum)	89	29	20	64	34	25	56

<sup>a</sup> Breast dose estimates from [27].