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Monte Carlo and Phantom Study of the Radiation Dose to the Body from Dedicated Computed Tomography of the Breast

Ioannis Sechopoulos, Ph.D.^{1,2}, Srinivasan Vedantham, Ph.D.¹, Sankararaman Suryanarayanan, Ph.D., M.B.A.¹, Carl J. D'Orsi, M.D.¹, and Andrew Karellas, Ph.D.^{1,2}

¹ Emory University School of Medicine, Department of Radiology and Winship Cancer Institute, 1701 Uppergate Drive, Suite 5018, Atlanta, GA 30322

² Georgia Institute of Technology, Wallace H. Coulter Department of Biomedical Engineering, 313 Ferst Drive Atlanta, GA 30332

Abstract

Purpose—To prospectively determine the radiation dose absorbed by the organs and tissues of the body during a dedicated computed tomography of the breast (DBCT) study using Monte Carlo methods and a phantom.

Materials and Methods—Using the Geant4 Monte Carlo toolkit, the Cristy anthropomorphic phantom and the geometry of a prototype DBCT was simulated. The simulation was used to track x-rays emitted from the source until their complete absorption or exit from the simulation limits. The interactions of the x-rays with the 65 different volumes representing organs, bones and other tissues of the anthropomorphic phantom that resulted in energy deposition were recorded. These data were used to compute the radiation dose to the organs and tissues during a complete DBCT acquisition relative to the average glandular dose to the imaged breast (ROD, relative organ dose), using the x-ray spectra proposed for DBCT imaging. The effectiveness of a lead shield for reducing the dose to the organs was investigated.

Results—The maximum ROD among the organs was for the ipsilateral lung with a maximum of 3.25%, followed by the heart and the thymus. Of the skeletal tissues, the sternum received the highest dose with a maximum ROD to the bone marrow of 2.24%, and to the bone surface of 7.74%. The maximum ROD to the uterus, representative of that of an early-stage fetus, was 0.026%. These maxima occurred for the highest energy x-ray spectrum (80 kVp) analyzed. A lead shield does not protect substantially the organs that receive the highest dose from DBCT.

Discussion—Although the dose to the organs from DBCT is substantially higher than that from planar mammography, they are comparable or considerably lower than those reached by other radiographic procedures and much lower than other CT examinations.

Advances in Knowledge

1. Our study, based on Monte Carlo methods and an anthropomorphic phantom, found that although the radiation dose received by the organs and tissues of the body outside the primary x-ray field from DBCT is considerably higher than that

Corresponding Author: Andrew Karellas, Ph.D., Tel: (404)712-2411, Fax: (404)712-5813, E-mail: akarell@emory.edu.

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from planar mammography, it is still low (less than 8% of the average glandular dose to the imaged breast), and comparable to other radiographic applications.

2. The inclusion of a 1 mm lead sheet inside the table top between the patient and the x-ray source does not substantially lower the dose to the higher-exposed organs, but it does decrease the dose to the uterus (by up to a factor of twenty).
3. The dose deposited in the uterus, representative of that deposited in an early-stage fetus, is low (less than 0.03% of the average glandular dose to the imaged breast).

Implications for Patient Care

1. Our study results provide information on the radiation dose to the organs of the body from dedicated breast computed tomography.
2. In regards to using this procedure for women in early stages of pregnancy, we found low dose levels absorbed by the uterus during DBCT imaging.

INTRODUCTION

Dedicated breast computed tomography (DBCT) is being investigated as an alternative or an adjunct to planar mammography (1–10). Planar mammography, both screen-film and digital, suffers from the problem of tissue superposition, where normal tissue may mask a lesion, lowering detectability and increasing recalls (11). DBCT results in a fully reconstructed 3D volume of the imaged breast, avoiding the problem of tissue superposition. Currently, at least one manufacturer is developing DBCT systems that are aimed to be used for diagnostic purposes. Since the breast is uncompressed during DBCT acquisition, to maintain the dose to the breast comparable to that from a two-view planar mammography acquisition, preliminary DBCT imaging studies are being performed with tungsten targets with kVp settings in the 49–80 kVp range (12–16); considerably higher energies than those used in planar mammography. Several studies on the glandular dose to the breast from these high energy x-ray spectra in DBCT have been reported (1,2,7,9,17,18), but the effect that these higher energies have on the dose to the other organs of the body outside the primary x-ray field has not been investigated. Previous studies have found that the organs of the body receive low dose from planar mammography (19,20), but the dose to the organs from DBCT could be substantially higher due to the higher x-ray energy and different projection geometry used.

If DBCT is to be introduced in the clinical environment, as either an alternative to planar mammography for screening for breast cancer, or as an adjunct to mammography for a subset of patients (high-risk groups, diagnostic stage, etc.), the radiation dose to the organs and tissues of the body from DBCT acquisition must be well understood. In addition, the dose to the fetus must be studied to know if DBCT is an option for physicians attempting to diagnose a finding in the breast of a pregnant patient. Thus, the purpose of our study was to prospectively determine the radiation dose absorbed by the organs and tissues of the body during a DBCT study using Monte Carlo methods and a phantom.

MATERIALS AND METHODS

A C++ computer program, that interfaces with the Geant4 toolkit for Monte Carlo simulations (21,22), similar to that used by Sechopoulos et al (20) to study planar mammography was implemented and used by one of the authors (I.S., with 5 years of experience in medical physics) to compute the radiation dose deposited in various organs and tissues of the body during DBCT acquisition. In a similar fashion to that work, the Monte Carlo program was implemented to

simulate the Cristy mathematical anthropomorphic phantom (23), developed by Cristy and Eckerman (24) at the Oak Ridge National Laboratory (ORNL). To simulate the conditions present during DBCT acquisition, the geometrical description of both breasts, and the positioning of the x-ray source and detector had to be modified from the descriptions of Cristy and Eckerman and Sechopoulos et al, which used an upright patient with breast compression for both standard mammographic views.

Monte Carlo simulation

In our simulations, the x-ray focal spot, approximated as a point source, was placed 86 cm away from the detector surface, which was located 40 cm from the iso-center of the imaged breast (17). With varying projection angle, both the x-ray source and the detector were rotated about the isocenter of the breast, maintaining constant both the source-to-imager distance (SID) and the breast isocenter-to-imager distance (IID) throughout the DBCT acquisition. During the simulation, monochromatic x-rays were emitted from the x-ray point source towards random points on the simulated detector surface, so as to result in a uniform x-ray field completely congruent with the detector limits. All x-rays were tracked from their emission until either their complete absorption in the detector or in the body or until their exit from the simulation limits. During their tracking, all x-ray interactions in the body that resulted in energy deposition were recorded, along with the location of the interaction. For each organ, the dose was found by dividing the total energy deposited in the volume of the organ by its mass. To be able to obtain results for different x-ray spectra, the simulation was performed by tracking 40 million monochromatic x-rays of energies varying from 17 keV to 80 keV in 1 keV steps, interpolating these results to 0.5 keV resolution, and then combining these monochromatic results with the relative number of photons in each spectrum as reported by Cranley et al (25). The x-ray spectra used consisted of a tungsten target, with a 0.5 mm beryllium window and 0.3 mm added filtration of copper, with kVp settings of 40 kVp to 80 kVp, in 10 kVp steps. After simulating all 64 energies, the x-ray source and detector were rotated around the isocenter of the breast by 10 degrees, and the process was repeated. Simulations were performed from a total of 35 positions, covering an entire revolution around the imaged breast. The results from these 35 positions were later interpolated and summed (I.S.) to obtain dose results from the equivalent of 500 projections from an entire 360° revolution (17). Due to the asymmetric location of some organs of the body, all simulations were performed for both breasts. This resulted in a total of 4,480 simulations of 40 million x-rays each. To be able to perform this complete computation in a feasible time frame, a high performance computer cluster consisting of 64 dual-processor nodes was used.

The dose deposited in each organ was normalized by the average glandular dose deposited in the imaged breast, to obtain the relative organ dose (ROD) as previously defined (20). The computation of the average glandular dose to the breast was performed using the methodology described by Boone (26) with the suggestion of Wilkinson and Heggie (27). The dose to the red bone marrow and to the bone surfaces was measured separately, using the three-parameter mass-energy absorption coefficient ratio method (MEAC) (28–31) for the red bone marrow dose, and the homogeneous bone approximation (HBA) (31) for the bone surfaces, as suggested by Sechopoulos et al (20).

To determine the suitability of using 40 million photons per energy level to obtain acceptable precision, the simulation of the 0° projection of the left breast was repeated five times and the coefficient of variation ($COV = 100\sigma/\mu$) of the results computed (I.S.).

Anthropomorphic phantom

The modified version of the Cristy phantom (23) that was used to represent the patient was based on the simulations of Sechopoulos et al (20). Slight modifications had to be introduced

(I.S.) in the anthropomorphic phantom to better recreate the geometry during DBCT imaging. The DBCT acquisition geometry simulated consisted of the patient lying prone on a table with the imaged breast pendant through a hole (32). Therefore, the breasts were represented as portions of ellipsoids of equal volume but different shape. The imaged breast was implemented to reflect a pendant breast, having a longer chest-wall to nipple distance (CND) and smaller diameter along the chest wall than the contralateral breast. The latter was implemented as slightly compressed by the body against the table (Figure 1). The head and neck of the phantom were rotated towards the contralateral side, as shown in Figure 2 of the publication by Boone et al (32). The imaged breast was specified as having a diameter at the chest wall of 12.4 cm and a CND of 8 cm. The contralateral breast had a diameter at the chest wall of 15.0 cm and a CND of 5.2 cm. These dimensions were chosen to obtain breast volumes similar to the mean breast volumes found in mammography studies (33). The composition of the breasts was specified as a homogeneous mixture of 50% adipose and 50% glandular tissue, as reported by Hammerstein et al (34). The organs, bones, skin sections and other volumes included in the anthropomorphic phantom were the same as those simulated by Sechopoulos et al (20) (Table 1).

Dose reduction effectiveness of lead shield

In a prototype DBCT system, the patient would lie prone on a table with an aperture through which the imaged breast would be suspended for imaging. This geometry lends itself to including a lead shield in the table top to help protect the body from scattered x-rays. As suggested elsewhere (20), the effectiveness of such a shield was studied by including a 1 mm thick “virtual” shield in the Monte Carlo simulation. This “virtual” shield did not affect the x-rays’ energy or direction, but tagged each x-ray that traveled through it and a second tally of dose deposition was recorded in which the x-rays that went through the invisible shield were ignored. This “virtual” shield was placed between the body and the rotating x-ray source, was large enough to cover the whole body, and included a 30 cm diameter hole for the pendant imaged breast. This algorithm assumes that all x-rays that enter the shield are absorbed in it, an approximation that was made valid by specifying that the lead shield was 1mm thick, which results in an absorption of approximately 94% of 80 keV x-rays and more than 98% of x-rays of energy of 70 keV or less.

Effective Dose

With the ROD values found, the effective dose from a complete dual DBCT study was computed (I.S.) using both the 1990 ICRP recommended tissue weighting factors (35) and the recently approved 2007 ICRP recommended tissue weighting factors (36).

Validation

The simulation was modified (I.S.) to closely resemble the geometry studied by Boone (7) in his investigation of glandular dose to the breast from DBCT. The major modification involved changing the definition of the shape of the imaged breast to a cylinder. The glandular dose from the 0° projection was computed and compared to that reported by Boone (7).

RESULTS

Validation

The glandular dose to the breast computed from the simulations in our validation study was found to be within 8.0 % of that reported by Boone.

ROD

The ROD variation with projection angle (Fig. 2) (0° is defined as when the x-ray source is exactly above the breast, and the x-ray source rotates counter-clockwise facing the patient with increasing angle) is different for different organs, due to the position of the organs with respect to the x-ray source. The distributions chosen (Fig. 2) are representative of the ones found for the rest of the organs. The suitability of the angular interpolation can also be clearly seen.

The organs that receive the highest dose from DBCT are the heart, lung and thymus, with maximum ROD values of 1.5% to 3.2% (Table 2). The ribs and sternum's bone marrow (ROD: 1.6%–2.2%) and bone surfaces (ROD: 5.6%–7.7%) receive the highest dose (Table 2) of the skeletal tissues. The dose to the uterus, representative of an early-stage fetus, is several orders of magnitude lower than the glandular dose to the imaged breast, resulting in a maximum ROD of 0.026% for the highest energy x-ray spectrum (Table 2).

The COV of the ROD results for the x-ray spectra with the lowest and highest number of x-rays (40 kVp and 80 kVp) was found to be less than 3% and 1% for all the organs and tissues (Table 2), except for the ROD of the contralateral adrenal, which presented a COV of 5.3% and 2.1%, respectively. The inclusion of the lead shield did not protect substantially the organs with relatively high ROD. Only some of the organs with relatively low ROD were protected. More importantly, the dose to the uterus was reduced by the presence of the shield by a factor of four for the higher kVp spectra and up to by a factor of twenty for the lowest kVp spectra.

Effective Dose

The effective dose per unit glandular dose to the breast was found to range from 0.053 mSv/mGy (mrem/mrad) for the 40 kVp spectrum to 0.059 mSv/mGy (mrem/mrad) for the 80 kVp spectrum using the 1990 tissue weighting factors. With the revised tissue weighting factors, these values increase to 0.124 mSv/mGy (mrem/mrad) and 0.130 mSv/mGy (mrem/mrad).

DISCUSSION

Our results show that the dose to the organs and tissues of the body, except the skin of the imaged breast, increases considerably with increasing kVp setting. In addition, the higher energy spectra used in dedicated breast computed tomography imaging result in higher dose to the organs and tissues of the body compared to those resulting from planar mammography (20). For the 80 kVp spectra, the heart, ipsilateral lung and thymus receive a dose of approximately 100–140 μ Gy from a DBCT acquisition that deposits 4.5 mGy in the imaged breast. This dose level for the lungs is approximately thirty times higher than that from planar mammography (approx. 4.8 μ Gy) (Table 3) (20). In addition, the computed lung dose level is comparable to that of a chest radiograph (200 μ Gy) (37), and one or two orders of magnitude less than that of a chest CT scan (2.5 to 9.0 mGy for low-dose scan, approx. 20 mGy for standard CT) (38,39). The highest doses to the bones are that of the ribs and sternum, which receive approximately 70 μ Gy to 100 μ Gy to the red bone marrow and approximately 250 μ Gy to 350 μ Gy to the bone surface from a similar DBCT study. It is important to note that the dose to the bone tissues are upper limit estimates, due to the known overestimation of the dose to the bone tissues by the methodology used in our study (31).

The dose to the uterus, representative of that to the fetus in the first trimester, was found to be low, in the range of 0.2 μ Gy to 1.2 μ Gy from a 4.5 mGy DBCT acquisition, depending on the x-ray spectrum used. Although there is a wide variability in estimates of damage or increase of risk to the fetus from different levels of x-ray radiation, all studies seem to suggest that damage to the fetus or increase in risk of damage to the fetus is possible at several orders of magnitude above the levels found in our study (40).

Even though these radiation levels to the fetus are minimal, it was found that the presence of the 1 mm lead shield decreased these levels substantially, introducing the possibility of lowering the dose to the fetus further. Aside from the protection to the uterus/fetus, which is of particular interest, the presence of the lead shield did not contribute substantially to the protection of the body. This indicates that the majority of the exposure to the internal organs of the body that had the higher ROD values comes from x-rays that scatter in the breast and enter the body through the tissue connecting the breast to the trunk.

The computation of the effective dose during DBCT imaging shows that the dose to the organs outside the primary x-ray field is low, but not negligible. Using the 1990 recommended tissue factors the dose to the other organs increase the effective dose by between 6% and 18%, depending on the x-ray spectrum used. Using the revised factors, due to the increased radiosensitivity assigned to the breast, the importance of the dose to the other organs decreases, with a maximum contribution of approximately 8%. More importantly, the effective dose from DBCT is only slightly higher than that from planar mammography (19,20), but approximately one order of magnitude lower than that from chest CT (39).

The accuracy of the results of our study depend on Geant4's predictions on dosimetry, total and individual linear attenuation coefficients in soft tissue, and x-ray scatter, characteristics which have been extensively validated for both DBCT (18,41) and for planar and tomosynthesis imaging of the breast (42–45).

The main limitation in our study is the use of a mathematical phantom with simplified organ distribution and shapes. The error introduced by the use of this simplified geometry can be estimated to result in both under- and over-estimates in the order of 15% to 40% (46). This error, though substantial, still allows assessment of the importance of the dose to the organs and other tissues outside the primary x-ray field received from DBCT imaging. It must be pointed out that Monte Carlo dosimetry data like those reported here should not be used as an exact measure of the dose received by each individual patient, but rather as a guideline to be considered by the scientists and physicians concerned with this new imaging technique (27). Other sources of error that are not considered in our study but that we estimate to not be substantial are possible additional x-rays incident on the breast and the body from x-ray tube leakage and back-scatter from the housing of the DBCT system.

In summary, using the implementation of a modified anthropomorphic phantom and of a simplified DBCT system, in conjunction with a well-established Monte Carlo toolkit, the radiation dose received by 65 different volumes of the body from the DBCT acquisition was computed. At a dose to the breast equivalent to that from a standard two view mammogram, the dose levels to the other tissues of the body were found to be more than an order of magnitude higher, but were comparable to other common radiographic applications.

Practical Application

Our study results have shown that although the dose levels are substantially higher than those of planar mammography, they are comparable or considerably lower than those reached by other radiographic procedures and much lower than other CT examinations. These results provide needed information when considering adopting DBCT as one more tool for screening or diagnosing breast cancer. In addition, we found low dose levels to the uterus during DBCT imaging if this procedure is used for women in early stages of pregnancy.

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Fig 1.
(a) Top and (b) front view of the DBCT simulation.

Fig 2.

Variation of dose deposition in different organs (dark) with projection angle during a DBCT imaging of the left breast. The symbols in the graph represent the Monte Carlo results, while the lines are the result of the interpolation to obtain the data for 500 projections. The 0° degree projection is when the x-ray source is directly above the breast, and the x-ray source moves counter-clockwise (when looking at the patient) with increasing angle.

TABLE 1

Tissue volumes of the modified Cristy phantom as implemented for our study. The mass of each volume is per unit and is exclusive of contents.

	Name	Mass (g)
Organs	Adrenal	5.1
	Brain	1,407.6
	Breast	601.6
	Colon (ascending)	71.6
	Colon (transverse)	95.2
	Colon (descending)	70.4
	Colon (sigmoid)	55.4
	Esophagus	34.3
	Eye	6.6
	Eye Lens	0.2
	Gall Bladder	9.1
	Heart	242.7
	Kidney	125.2
	Liver	1,425.5
	Lung (left)	266.1
	Lung (right)	305.4
	Ovary	5.4
	Pancreas	64.9
	Small Intestine	830.4
	Spleen	125.6
	Stomach	116.5
	Thymus	28.0
	Thyroid	12.1
	Urinary Bladder	35.5
	Uterus/Fetus	78.2
Skeleton	Arm Bone (lower section) ²	173.6
	Arm Bone (middle section) ²	145.1
	Arm Bone (upper section) ²	193.0
	Clavicle	29.2
	Cranium	711.5
	Facial Skeleton	92.8
	Leg Bone (lower section) ²	484.6
	Leg Bone (middle section) ²	588.6
	Leg Bone (upper section) ²	396.1
	Pelvis	644.0
	Rib Cage	725.8
	Scapulae	104.8
Soft Tissue	Spine	1,059.1
	Sternum	58.1
	Head	2,108.1
	Leg	7,033.0
Skin	Neck	561.8
	Trunk	24,892.2
	Breast	54.5
	Head	205.1
	Leg	514.5
	Neck	47.8
	Trunk	1,068.2

¹ Note: Sections as defined in the description of the Cristy phantom (23)

TABLE 2

Ratio of dose to the different tissues per unit dose to the imaged breast (ROD). The tissues that received doses below 0.10% of that of the imaged breast are not included. Where two values are included, they represent the dose ratio when the (left/right) breast, is being imaged, if only one value is shown, the doses during the imaging of either breast were equivalent. The dose ratio to the uterus, which is representative of that to the fetus during early pregnancy, is also included. The first half value layers of the x-ray spectra used are shown.

Tissue Type	Volume	40 kVp 2.51 mm Al	50 kVp 3.45 mm Al	60 kVp 4.29 mm Al	70 kVp 5.04 mm Al	80 kVp 5.81 mm Al
Organs	Adrenal (CL)	0.01%/0.01%	0.03%/0.03%	0.05%/0.06%	0.08%/0.10%	0.11%/0.13%
	Adrenal (IL)	0.04%/0.06%	0.10%/0.14%	0.16%/0.23%	0.23%/0.31%	0.29%/0.39%
	Breast (CL)	0.57%	0.72%	0.83%	0.91%	0.97%
	Colon (transverse)	0.02%	0.04%	0.06%	0.08%	0.10%
	Esophagus	0.09%/0.07%	0.21%/0.16%	0.34%/0.27%	0.46%/0.37%	0.57%/0.46%
	Gall Bladder	0.03%/0.06%	0.07%/0.13%	0.11%/0.20%	0.15%/0.27%	0.19%/0.34%
	Heart	1.06%/0.44%	1.75%/0.79%	2.32%/1.11%	2.74%/1.37%	3.08%/1.58%
	Kidney (IL)	0.01%	0.03%	0.06%	0.09%	0.12%
	Liver	0.05%/0.23%	0.10%/0.44%	0.15%/0.63%	0.20%/0.79%	0.24%/0.92%
	Lung (CL)	0.05%/0.04%	0.11%/0.09%	0.19%/0.16%	0.26%/0.22%	0.32%/0.28%
	Lung (IL)	1.14%/1.32%	1.79%/2.03%	2.29%/2.57%	2.65%/2.95%	2.93%/3.25%
	Pancreas	0.07%/0.03%	0.18%/0.08%	0.29%/0.13%	0.40%/0.19%	0.50%/0.25%
	Spleen	0.07%/0.00%	0.16%/0.02%	0.27%/0.03%	0.36%/0.05%	0.44%/0.07%
	Stomach	0.26%/0.03%	0.47%/0.07%	0.66%/0.11%	0.82%/0.14%	0.95%/0.18%
	Thymus	0.73%	1.27%	1.72%	2.07%	2.35%
	Thyroid	0.04%	0.08%	0.12%	0.15%	0.19%
	Uterus/Fetus ¹	0.005%	0.010%	0.015%	0.021%	0.026%
	Arm Bone (middle section, IL)	0.11%	0.22%	0.33%	0.43%	0.52%
	Arm Bone (upper section, IL)	0.10%	0.20%	0.29%	0.38%	0.46%
Bone Marrow	Clavicle (CL)	0.03%	0.06%	0.09%	0.12%	0.15%
	Clavicle (IL)	0.22%	0.40%	0.56%	0.69%	0.81%
	Rib Cage	0.74%	1.04%	1.28%	1.45%	1.59%
	Scapulae (IL)	0.02%	0.05%	0.08%	0.12%	0.15%
	Spine (trunk section)	0.01%/0.01%	0.03%/0.03%	0.06%/0.07%	0.09%/0.10%	0.12%/0.14%
Bone Surface	Sternum	0.85%	1.30%	1.69%	1.99%	2.24%
	Arm Bone (lower section, IL)	0.06%	0.10%	0.14%	0.17%	0.20%
	Arm Bone (middle section, IL)	0.47%	0.87%	1.22%	1.50%	1.72%
	Arm Bone (upper section, IL)	0.43%	0.77%	1.07%	1.30%	1.49%
	Clavicle (CL)	0.14%	0.24%	0.34%	0.42%	0.50%
	Clavicle (IL)	0.92%	1.57%	2.11%	2.50%	2.80%
	Cranium	0.04%	0.07%	0.09%	0.10%	0.11%
	Facial Skeleton	0.05%	0.07%	0.10%	0.12%	0.13%
	Rib Cage	3.06%	4.14%	4.86%	5.30%	5.56%
	Scapulae (IL)	0.08%	0.20%	0.32%	0.43%	0.52%
	Spine (head section)	0.02%	0.04%	0.07%	0.10%	0.13%
	Spine (neck section)	0.03%	0.07%	0.12%	0.18%	0.23%
	Spine (trunk section)	0.04%/0.05%	0.11%/0.14%	0.21%/0.25%	0.31%/0.37%	0.41%/0.48%
	Sternum	3.52%	5.16%	6.37%	7.18%	7.74%
	Breast (CL)	0.95%	1.08%	1.17%	1.23%	1.27%
	Breast (IL)	128.93%	118.82%	114.00%	111.35%	109.63%
	Head	0.09%	0.09%	0.10%	0.11%	0.11%
	Neck	0.05%	0.07%	0.10%	0.12%	0.14%
	Trunk	0.50%	0.57%	0.61%	0.65%	0.67%
Skin						

¹ Note: Fetus in the first trimester. CL = Contralateral, IL = Ipsilateral

Dose comparison for some tissues resulting from different x-ray spectrum in planar mammography and dedicated breast computed tomography, assuming a total glandular dose to the breasts of 4.5 mGy. The planar mammography data were taken from Table 4 of Sechopoulos et al (20), which assumes glandular dose levels of 2 mGy from CC view and 2.5 mGy from MLO view. All values are in μ Gy.

TABLE 3

	Volume	Mo/Mo 25 kVp	Planar		DBCT	
			Mo/Rh 30 kVp	Rh/Rh 35 kVp	W 50 kVp	W 80 kVp
Organs	Heart	0.6	1.4	2.9	57	105
	Lung	0.7	2.2	4.8	86	139
	Thymus	0.7	1.8	3.8	57	106
Bone Marrow	Uterus/Fetus ¹	<0.003	<0.003	<0.03	0.44	1.17
	Rib Cage	4.4	6.2	8.4	47	72
	Sternum	10.6	13.6	18.0	59	101
Bone Surface	Rib Cage	17.4	25.3	35.4	186	250
	Sternum	43.0	56.8	74.7	232	348

¹Note: Fetus in the first trimester.