Evaluation of the absorbed dose to the breast using radiochromic film in a dedicated CT mammotomography system employing a quasi-monochromatic x-ray beam

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Purpose: A dual modality SPECT-CT prototype system dedicated to uncompressed breast imaging (mammotomography) has been developed. The computed tomography subsystem incorporates an ultrathick K-edge filtration technique producing a quasi-monochromatic x-ray cone beam that optimizes the dose efficiency of the system for lesion imaging in an uncompressed breast. Here, the absorbed dose in various geometric phantoms and in an uncompressed and pendant cadaveric breast using a normal tomographic cone beam imaging protocol is characterized using both thermoluminescent dosimeter (TLD) measurements and ionization chamber-calibrated radiochromic film.

Methods: Initially, two geometric phantoms and an anthropomorphic breast phantom are filled in turn with oil and water to simulate the dose to objects that mimic various breast shapes having effective density bounds of 100% fatty and glandular breast compositions, respectively. Ultimately, an excised human cadaver breast is tomographically scanned using the normal tomographic imaging protocol, and the dose to the breast tissue is evaluated and compared to the earlier phantom-based measurements.

Results: Measured trends in dose distribution across all breast geometric and anthropomorphic phantom volumes indicate lower doses in the medial breast and more proximal to the chest wall, with consequently higher doses near the lateral peripheries and nipple regions. Measured doses to the oil-filled phantoms are consistently lower across all volume shapes due to the reduced mass energy-absorption coefficient of oil relative to water. The mean measured dose to the breast cadaver, composed of adipose and glandular tissues, was measured to be 4.2 mGy compared to a mean whole-breast dose of 3.8 and 4.5 mGy for the oil- and water-filled anthropomorphic breast phantoms, respectively.

Conclusions: Assuming rotational symmetry due to the tomographic acquisition exposures, these results characterize the 3D dose distributions in an uncompressed human breast tissue volume for this dedicated breast imaging device and illustrate advantages of using the novel ultrathick K-edge filtered beam to minimize the dose to the breast during fully-3D imaging. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3574875]

Key words: dosimetry, computed tomography, breast imaging, radiochromic, thermoluminescent detectors, mammotomography

I. INTRODUCTION

A few research groups, including ours, have developed prototype devices dedicated to breast cancer imaging using cone beam computed tomography (breast CT or mammotomography).¹ One advantage of these tomographic devices over dual view mammography, the current standard of care for breast cancer screening, is the potential for separating and improving contrast between tissues with similar attenuation coefficients in reconstructed images of the breast volume. By improving visibility of small lesions that may otherwise remain occluded in conventional 2D planar imaging using mammography, fully-3D volumetric imaging using a dedicated CT system may improve the diagnostic accuracy of breast imaging, increase the effectiveness of breast cancer screening, and consequently have a beneficial impact on patient outcomes.

Since breast CT acquires many hundreds of individual 2D projection images, the cumulative dose absorbed by the breast during a tomographic scan is of paramount importance to imaging system design.² Guidelines from the American College of Radiology (ACR) require that the average absorbed dose from dual view mammography to a 4.2-cm-thick compressed breast consisting of 50-50% adipose–glandular tissue not exceed 6 mGy.³ Lacking an equivalent standard for uncompressed breast imaging since the technology is still in its infancy, investigators likewise aim to confine the cumulative absorbed dose for a breast CT scan to that around dual view mammography as a starting point in system development and optimization.

Dosimetry for mammography has been performed using both empirical and simulation-based measurements,⁴⁻⁸ whereas dosimetry for breast CT has generally been estimated using a combination of measurements in air, computer-modeling of x-ray tube spectra incident on the breast, and 3D Monte Carlo simulations.⁹⁻¹¹ An initial Monte-Carlo-based dosimetry study demonstrated the ability of breast CT to successfully image the uncompressed breast at doses equivalent to that of mammography.¹⁰ Two subsequent studies generated dose conversion factors specifically for breast CT as a function of various imaging techniques and breast compositions.^{9,11} In addition to generating the conversion factors estimating the cumulative absolute dose to simulated uncompressed breasts, the studies also simulated the spatial dose distribution for breast CT at different beam energies and tube potentials. One study,¹¹ using mean beam energies of 20–40 keV in the simulated breast CT system, similar to those employed in the practical breast CT system described in this study, showed that the resulting dose profiles across the breast phantom were highly nonuniform, with dose absorbed at the periphery of the phantom being far higher than the dose in the center. Not surprisingly, dose profiles across the phantom were shown to become more uniform as the simulated mean beam energy increased

above approximately 60 keV. In the study using tungsten tube potentials from 80 to 120 kVp, a more uniform dose profile for breast CT was demonstrated at these higher tube potentials.⁹ A recent study¹² employed embedded TLDs to study the dose distribution in a 14 cm diameter PMMA half-ellipsoid phantom. By varying tungsten target x-ray tube potentials from 60 to 80 kVp, the dose was seen to increase appreciably toward the periphery both radially (near the skin) and toward the anterior breast. However, a follow-up study by the same investigators using radiochromic film and the same imaging system at 80 kVp indicated a reduction in dose toward the nipple.¹³

The breast CT imaging system described in this work was developed as part of a novel prototype dual modality SPECT-CT system for uncompressed breast imaging. One of the key design features of the CT subsystem was the development of the quasi-monochromatic x-ray beam^{2,14-16} which has a peak dose efficiency (SNR^2/dose) for 5 mm lesions between 30 and 40 keV and is approximately three times greater than the peak dose efficiency of polychromatic beams^{2,14,15} for the same purpose. This system is being used in ongoing studies to image human subjects with encouraging results.^{2,16,17} When previously compared against digital mammography in a phantom-based observer study, our CT subsystem demonstrated statistically significant improved ability to visualize small (<5 mm) spherical “lesions” in low-contrast media containing structured background material at doses comparable to that of dual view mammography.¹⁸ In that observer study, the dose imparted to the breast from the CT acquisition was estimated using the previously defined dose conversion factors⁹ since no experimental validation of the absolute dose estimates was available at the time.

In contrast to previous simulation studies, this current study empirically quantifies the dose imparted to a pendant uncompressed cadaveric breast and illustrates the 2D spatial dose distribution obtained using our dedicated 3D breast CT imaging system. Storage phosphors, or computed radiography (CR) plates, could also potentially provide a 2D dose distribution, but they have been generally used in high energy radiation therapy situations, unlike the diagnostic energy range detailed in this study.^{19,20} In addition, although storage phosphor plates come in a variety of sizes, they cannot be submerged in any type of liquid since the liquid would render the plate unreadable in the CR plate readout device.

The absorbed dose to the uncompressed breast is characterized in this study using a tomographic cone beam imaging protocol in conjunction with calibrated TLDs and ionization chamber-calibrated radiochromic film. Initially, two separate absorptive scatter media are employed in breast phantom volumes to characterize the variation in absorbed dose for what would be the expected boundary conditions of 100% fatty or 100% glandular breast tissue composition, although it is acknowledged that no such extreme compositions actually exist in the breast.²¹ Three different phantom shapes

are tested to observe variations in absorbed breast dose as a function of the geometry (i.e., shape and effective radius) of the breast phantoms and x-ray cone beam intersecting it. Ultimately, an excised breast cadaver is scanned using the dedicated breast CT imaging system and the results are compared to the geometric phantom studies as well as the results of previous simulation studies. As far as we are aware, this is the first study to investigate the absorbed dose to geometric volumes of various shapes using TLDs, radiochromic film, and in media that mimic boundary value characteristics of breast tissues. This is also the first empirical study undertaken of the 3D dose distribution inside a breast tissue volume, and particularly using a dedicated 3D breast imaging system in conjunction with radiochromic film.

II. MATERIALS AND METHODS

II.A. Dedicated breast CT imaging subsystem

The SPECT and CT subsystems (Fig. 1) are secured to a common rotation stage capable of 360° azimuthal rotations around the vertical chest to nipple axis of the pendant breast. The CT subsystem employs a rotating tungsten target cone beam x-ray source (model Rad-94, 0.4 mm focal spot size, 14° anode angle, Varian Medical Systems, Salt Lake City, UT) and a CsI:TI based amorphous silicon digital x-ray detector (model Paxscan 2520, Varian Medical Systems, Salt Lake City, UT) with a grid size of 1920×1536 and 127 μm pixel pitch. A cerium ($Z = 58$, $\rho = 6.77 \text{ g/cm}^3$, K-edge = 40.4 keV, Santoku America, Inc., Tolleson, AZ) 100th value attenuating filter (0.0508 cm, evaluated at 60 kVp) is used to yield a mean x-ray beam energy of approximately 36 keV and a FWHM of 15% (Refs. 14 and 22) (Fig. 1). These nonconventional beam characteristics have been previously exploited to optimize the dose efficiency of the system for lesion imaging in the uncompressed breast.¹⁵ A 60 cm source-to-image distance (SID) is employed, with a magnification of 1.57 for an object placed at the system's isocenter, nominally located 38 cm from the x-ray source. The integrated CT subsystem is restricted to simple circular motion about a vertical axis at a nominal 3° fixed source-detector axis tilt with respect to the horizontal. The typical tomographic data acquisition protocol

consists of an x-ray exposure technique (60 kVp, 100 mA, 25 ms) and 255 projection images collected about the breast, with 15 projection images (between 5% and 6% of total exposures) used for initial system calibration and other technical reasons prior to tomographic scanning. Additional details of the prototype compact dual modality breast imaging system are described elsewhere.¹⁶

II.B. Radiochromic film preparation and readout

The radiochromic XQRA film (GafChromic™, International Specialty Products, Wayne, NJ) used in the experiment undergoes solid-state polymerization in real time in reaction to incident radiation.²³ The polymerization creates a dye-complex darker in color compared to unexposed portions of the film and is subsequently digitized after a 24-h period needed to allow stabilization to occur. The polymerization in the film yields an absorption spectrum at a maximum at 635 nm,²⁴ which is most sensitively detected with optical digitization using red light.

Exposed XRQA films were digitized using reflection densitometry^{25,26} on a flatbed scanner (Expression 10000XL, Epson America, Long Beach, CA). The scanner employed a xenon gas fluorescent source light and a linear charged coupled device (CCD) array²⁷ for film readout. The 155 scanner's source light illuminates only during previewing and scanning; so, to "warm-up" the scanner, ten blank scans were performed in succession and then discarded. Warming up the scanner provided a more stable light source and more consistent optical density (OD) readings.²⁸ The films were placed on the scanner in an area of high source-light uniformity, which corresponds to the center of the scanner. Each exposed film was scanned five times²⁸ at a resolution of 72 pixels/in. (0.4 mm pixels), with no color corrections, and image files were saved in uncompressed format. All films were digitized using 48-bit color depth with RGB file format (16-bit per color channel) and the red (R) channel was extracted for analysis in MATLAB (R2007a, Mathworks Inc., Natick, MA).²⁹ The final image consisted of an average of the five scans smoothed with a 3×3 pixel kernel. The films were scanned prior to being exposed to ionizing

Fig. 1. (Left) Photograph of the prototype integrated SPECT-CT system dedicated to breast cancer imaging seen below the Pb-shielded patient bed. The SPECT system gamma camera is visible in the center of the image. The x-ray source and detector are nominally tilted from the horizontal. The combined system rotates around a common vertical axis of rotation, with the CT subsystem restricted to purely circular orbits in this prototype. (Right) Breast-incident energy spectrum of the unconventional, ultrathick K-edge Ce-filtered beam at 60 kVp.

radiation and then carefully realigned on the scanner for postexposure scans (realignment error was measured to be ~ 1 mm). Once irradiated, the films darkened such that their OD increased approximately quadratically with exposure.^{23,30} A net OD (OD_{net}) was calculated as the log transformation of the ratio of pre-exposed (I_{pre}) and post-exposed (I_{post}) scanner light intensity value,³¹

$$OD_{\text{net}} = OD_{\text{post}} - OD_{\text{pre}} = \log_{10} \left(\frac{I_0}{I_{\text{post}}} \right) - \log_{10} \left(\frac{I_0}{I_{\text{pre}}} \right) \\ = \log_{10} \left(\frac{I_{\text{pre}}}{I_{\text{post}}} \right),$$

where I_0 was the measured light intensity of the flat field scan performed at the same time of the pre-exposure and postexposure film scans.

II.C. TLD preparation and readout

All LiF:MgTi TLDs used in the experiment ($3 \times 3 \times 1$ mm³ Harshaw TLD-100 chips, Thermo Eberline, LLC, Franklin, MA) were first tested for batch uniformity by being exposed to a cumulative exposure of 1R. Chips that deviated more than 2 standard deviations from the batch mean were discarded. The TLDs were annealed using a TLD-annealing furnace (168-300, Radiation Products Design, Inc., Albertville, MN), and read using a TLD reader (Harshaw 5500, Thermo Fisher Scientific, Inc., Waltham, MA) with WINREMS software. Nitrogen gas was introduced during the readout cycle to reduce non-radiation-induced signals.³²

II.D. Dosimeter calibrations

The TLDs and XRQA film were cross-calibrated with a 6 cm³ ionization chamber (Mammochamber, Model 10 $\times$ 5-6M-3, RadCal, Monrovia, CA). The ion chamber was calibrated by the University of Wisconsin's Accredited Dosimetry Calibration Laboratory. Separate sets of dosimeters including one piece of film, two TLDs, and the ion chamber were exposed in air to four separate exposure levels with the quasi-monochromatic x-ray beam of the dedicated breast CT,

ranging from 659.5 mR to 1.915 R. The dosimeters were located approximately 38 cm from the x-ray focal spot (on the tomographic system's isocenter) and localized along a vertical line near the center of the x-ray cone beam field of view in order to eliminate variations associated with the heel effect due to the tube's orientation. Orthogonal lasers were used to locate the vertical axis of the system. One set of TLDs and one section of film were set aside elsewhere in the laboratory for background measurements. TLD and film responses were plotted as a function of the absorbed dose converted from the ion chamber measurement. Absorbed dose was calculated by multiplying the ion chamber exposure reading (IC) by the energy dependent water and oil f -factors [$f(E_{\text{material}})$], 0.88 and 0.58 cGy/R, respectively, at 36 keV] and Wisconsin's provided calibration factor ($W_{\text{calibfactor}}$) for 60 kVp:

$$D_{\text{absorbed}} = IC \times f(E_{\text{material}}) \times W_{\text{calibfactor}}$$

Dosimeter calibration plots were fit using least-squares regression techniques. The various measurements and appropriate least-squares fits to the data can be used to calibrate one set of measurements from the other. In this case, the TLD and exposure meter measurements are considered the gold standard to which the XRQA film is calibrated and evaluated.

II.E. Dose measurements of the phantom volumes using radiochromic film

Three phantom volumes were used to measure the absorbed dose using our CT system: two geometric phantoms composed of polyurethane shells in the shapes of a cylinder and a cone, and an anthropomorphically shaped breast phantom made of polyester terephthalate, modified with glycol (Fig. 2). The phantom containers were each 1–2 mm thick and photon absorption through each of the phantom's shells was considered negligible due to both the low molecular weight plastics composing the materials and the x-ray beam filtration method that produced a substantially pre-hardened quasi-monochromatic x-ray beam incident on the thin material.

The regular cylindrical phantom presents a constant cross section of absorbing material to the divergent x-ray cone

FIG. 2. (Upper row) Photographs of the scanned (left) cylindrical, (middle) conical and (right) anthropomorphic breast phantoms, respectively. A representation of the approximate position of the x-ray cone beam emanating from the x-ray tube is superimposed over each setup. (Lower row) Radiochromic films of the same cross-sectional shapes showing dimensions of the films for the tested phantoms.

beam and mimics the setup often used in Monte Carlo dose simulation studies. The conical shaped phantom more closely mimics the shape of a pendant breast, decreasing in radius from chest wall to nipple, but it does so in a linear, uniform fashion. From previous studies, it has been observed that approximately 15% of subjects indeed have this conically shaped pendant breast.³³ The anthropomorphic breast shape is then a natural progression from the prior geometric shapes and represents a 60% prevalent clinical geometric pendant breast shape, dimension, and volume.³³

Cross-sectional templates of the phantom volumes, cut from the radiochromic film, are shown in Fig. 2 with their associated dimensions. Given these dimensions, the conical phantom then simulates a large diameter breast at the upper edge of the cone, tapering to a smaller diameter toward the nipple. Due to the asymmetric 3D shape of the anthropomorphic breast phantom, separate templates of each axis (in sagittal and transverse orientations) were created by photographing the water-filled phantom from orthogonal perspectives. The orthogonal short axis film section was sliced vertically through its centers to enable interlacing it with an unsliced film. For each of the variously shaped phantoms, a single sheet of the film was attached with adhesive tape at several points to the inside surface of the phantom, ensuring minimal movement of the film during filling of the volumes with water or oil, and subsequent scanning. The phantoms were positioned as close to the isocenter of the cone beam CT imaging system as possible (Fig. 2) and scanned using the tomographic imaging protocol described previously. This enabled the absolute dose profiles to be measured across the 2D central plane of each of the 3D breast phantom volumes. The phantoms were initially filled with 1000 ml of water ($\rho = 1.0 \text{ g/cm}^3$) and scanned. The water was subsequently replaced by 1000 ml of mineral oil ($\rho = 0.84 \text{ g/cm}^3$) and the tomographic exposure process repeated using unexposed XRQA film. To ensure adequate exposure of the XRQA film using the low flux CT scanning technique, each film dosimeter was exposed to three consecutive full tomographic scans under each experimental setup and the dosimeter responses were scaled to represent a single scan measurement.

II.F. Validation of radiochromic film dose measurements using TLDs

Results from the XRQA film measurements in the conical breast phantom were validated with dose measurements acquired using TLDs. Thirty seven TLDs (18 pairs and 1 single TLD, with pairs being used to ensure greater accuracy in the “point dose” measurements) were located on a regular array across the triangular template of the conical phantom (Fig. 3), to measure the dose to the breast at varying distances from the breast surface to the center of the breast, and at different anterior distances from the “chest wall” toward the decreasing diameter at the nipple. The rows of TLD pairs were vertically spaced at intervals of 2.5 cm and were also spaced regularly in the horizontal direction. Each pair of TLDs was vacuum sealed and secured to a 5 mm thin acrylic sheet placed inside the conical phantom (Fig. 3). The acrylic sheet and TLDs were then additionally vacuum sealed to isolate the TLDs from liquid contamination and to further secure them in place to the sheet surface. The entire TLD validation experiment was repeated twice separated by a number of days from the first experiment (in case of local background differences) using identically located pairs of TLDs on the sheet. The measured TLD values were averaged from four TLD measurements (2 separate TLD runs with pairs of TLDs located at each point, in each run). For comparison, the film measurements were obtained 255 from ROI of the same size as the TLDs and were located at their corresponding positions in the image.

II.G. Measurements of dose to an uncompressed breast using 3D breast CT

A cadaver breast was used to investigate the dose to uncompressed human breast tissue using the tomographic protocol used with the breast CT system. The breast, obtained from a 48-yr old woman who died of causes other than breast cancer, was secured inside the same plastic anthropomorphic breast phantom holder that was used in the geometric dose experiments (see Fig. 4).

The breast was cut in half along the medial–transverse breast dimension from posterior to anterior breast. A sheet of

FIG. 3. Photographs of the pairs of TLDs (left) individually attached and (middle) subsequently vacuum sealed to the acrylic template. (Right) Contrast-enhanced photograph of the template in the plastic cone prior to the addition of water. Note, the uppermost row of TLD pairs was not immersed in water, leaving 14 of the 19 TLD pairs in the field of view of the x-ray beam.

FIG. 4. (Top) Photograph of the sheet of radiochromic film inserted into the oil-filled cadaveric breast volume. (Bottom) Reconstructed tomographic images of the cadaver breast, without additional oil, in the (bottom, left) transverse and (bottom, right) coronal orientations. Note the predominantly adipose composition of the breast tissue and the apparent absence of air pockets within the cadaveric breast volume.

radiochromic film, cut to the contoured template of the breast phantom cross section, was inserted between the two cut sections of breast tissue. The phantom was then suspended into the FOV of the CT system. Due to the lack of an attached chest wall, the excised breast volume tended to sag in the middle of the phantom and so 175 ml of mineral oil was added to ensure a continuum of near-tissue equivalent medium above the chest wall of the suspended breast (Fig. 4, top). Prior to the study, the cadaver breast was maintained frozen at a temperature of -40°C , but was allowed to thaw to room temperature for the duration of the experiments. The composition of the breast tissue was not rigorously investigated by pathology, but upon visual inspection while slicing the breast in half, the tissue appeared to be predominantly adipose. Tomographic images of the breast (Fig. 4, bottom row), acquired prior to the addition of oil, substantiate this observation. Additionally, very few small air pockets were apparent within the breast tissue volume.

Similar to the experiments using the geometric phantoms, three full tomographic scans using the developed imaging protocol were performed on the suspended cadaver breast to expose the radiochromic film. The entire experimental protocol was subsequently repeated using a new sheet of XRQA film inserted into an incision cut orthogonally into the suspended breast along the medial–sagittal dimension.

III. RESULTS AND DISCUSSION

III.A. Dosimeter calibration

The quasi-quadratic fits obtained for the calibration of the ionization chamber to the radiochromic film measurements in both water and oil ($R^2 = 0.99$) and the fitting function for the radiochromic film in the cadaver breast ($R^2 = 0.99$) are

depicted in Fig. 5, which also shows the linear fitting functions for both TLD calibration runs in water ($R^2 = 0.99$). A separate calibration curve was created for the cadaver experiment because a different batch of XRQA film was required. A separate calibration curve was therefore created for the cadaver breast exposures in order to provide a proper means for dosimetry comparison between oil and water phantom and cadaver breast exposures. Both oil and cadaver breast calibration curves were developed using similar exposure levels and the same f -factor for oil. In spite of the similar exposure and calculation conditions, the curve developed for the cadaver breast experiment demonstrated a slight difference in response than the oil curve; this response difference was attributed to the use of a different batch of XRQA film, a difference in response which has been previously documented for a similar radiochromic film.³⁴

The derived fitting functions were used to calibrate the radiochromic film and TLDs measured *in situ* for the three phantoms and the cadaver breast. The shapes of these curves are consistent with the known characteristics of the dose-response of these types of dosimeters.

III.B. Dose measurements

III.B.1. TLD validation of the radiochromic film results

A comparison plot of TLD point dose measurements in the conical water-filled phantom compared to dose measurements extracted from regions of interest (ROIs) on the co-registered radiochromic film image is shown in Fig. 6. Only 14 of the original 19 TLD pair locations were immersed in the water that filled the phantom (see Fig. 3). TLD dose figures range from 2.5 to 5.2 mGy with a mean dose of

FIG. 5. (Top) Close up photograph of the calibration setup with the indicated ion chamber, radiochromic film, and TLDs arranged in a vertical line, thus avoiding the heel effect of the tube spectrum. (Bottom, left) Generated TLD charge for water for both calibration runs. (Bottom, right) Calibration curves for absorbed dose as a function of radiochromic film optical density for water (dashed line, square markers), oil (black line, closed round markers), and cadaver breast (dashed line, open round markers).

3.7 ± 0.9 mGy; the equivalent figures for the radiochromic film are 3.8 ± 0.7 mGy.

The results for TLDs and radiochromic film therefore track each other very well, with most results within 10% of each other. The greatest discrepancies between the dosimeter measurements, however, are located toward the periphery of the triangular template. These differences can potentially be attributed to slight inaccuracies during image registration, proximity to the water–air interface at that location, and differences in angular dependence (anisotropy) of response between the film and TLDs. While the calibration of the TLDs and the film was performed using a normal incidence x-ray exposure technique in air, the angular dependence of the responses was not explicitly characterized in this study.

The overall close agreement between TLD and radiochromic film measurements, moreover, serves to validate the film measurements that are reported throughout this work.

III.B.2. Cylindrical phantom

Figure 7 shows grayscale images of the absorbed dose to the cylindrical breast phantom in water and oil, measured using the radiochromic film; also shown are horizontal (#1–3) and vertical (#4) profiles that illustrate the variation in dose at different distances from the chest wall of the phantom to the “nipple.”

The horizontal profiles are drawn at approximate distances of 0.5, 4, and 7 cm from the chest wall, respectively. The chest wall is defined as the top plane of the x-ray cone beam.

FIG. 6. (Left) Reconstructed maximum intensity projection image of the TLD pairs numbered for clarity. (Right) The average and standard deviation of the point doses measured from the TLDs in water compared to the dose at equivalent ROI locations in the radiochromic film. Standard deviations for the radiochromic film were determined as the variation from the mean of the ROI on the film.

FIG. 7. (Left) Grayscale images (lighter color indicates areas of lower absorbed dose and darker color indicate areas of higher absorbed dose) of the exposed radiochromic film in the cylindrical phantom containing water and oil, with (right) horizontal (#1–3) and vertical (#4) profiles at the indicated locations. The approximate location of the central x-ray is marked by an “X” on the image of the film in water; the location of the central x-ray was similar for the film in oil. Note, the measured dose in water (mimicking 100% glandular tissue) is consistently higher than that of the oil (mimicking 100% fatty tissue). Also note the greater asymmetry in the water-based film compared to that of the oil-based phantom.

The profiles indicate that there is a consistency in the deposited dose from chest-to-nipple despite the gradient of the cone beam incident on the cylindrical phantom (cf., Fig. 2) and also that the measured dose in water is consistently greater than that of the equivalent profile in oil for all positions. The mean measured dose to the radiochromic film within the water-filled cylindrical phantom for a single tomographic scan was measured to be 5.4 ± 0.4 mGy, ranging from 3.4 to 7.1 mGy. The equivalent measurement for oil had a mean dose of 3.5 ± 0.3 mGy with a range between 2.5 and 4.5 mGy.

The horizontal dose profiles show a prominent cupping effect at the center of the cylinder for both water- and oil-filled phantoms. The marked cupping effect is similar to the cupping effects seen in others' simulation studies employing cylindrical phantoms at beam energies close to the mean beam energy of our breast CT system.¹¹ The cupping effect is not as prominent in the oil-filled phantom compared to the water-filled phantom. This is in part due to the shorter mean free photon path length or, equivalently, the greater probability for photon absorption in water than oil due to the greater mass energy-absorption coefficient of water compared to oil at 36 keV.

For the water phantom, peak dose levels at the periphery of the rectangular film are approximately 13% and 34% greater than at the center of the phantom for the left and right peripheries, respectively (profiles #1 and #2 in Fig. 7). The horizontal asymmetry seen in the profiles may be due to an uncentered cylinder that received a higher fluence while the CT system was on one side of the phantom. For oil, the dose profile is relatively flat from one periphery to the center of the cylinder, but is approximately 20% higher than the center toward the other side. Given that the system obtains routine

CT data with a full 360° scan, these sorts of asymmetries are expected to be minimal and appear to be impacted more due to the greater density of the water-filled phantom than any misalignment of the phantom in the exposure field. Other factors potentially affecting the horizontal asymmetry were additionally interrogated. The measured variation in flat field light exposure across the calibrated radiochromic film scanner was approximately 1%–2%, which may contribute to the observed bias, especially if the phantom was initially located off-center. Some of the asymmetry may also be caused by the 15 calibration images occurring at one specific azimuthal location of the cylinder relative to the x-ray source during the scan; however, the effect of the proportionally small number of calibration exposures (5%–6% of the total number of exposures are for calibration) cannot explain the magnitude of the elevated dose levels. Thus, careful centering of the patient's breast would be recommended given the close geometrical configuration of this compact system and especially if the subject is suspected of having very dense breasts.

The vertical dose profile (profile #4 in Fig. 7) for the water-filled phantoms from chest wall to nipple demonstrates an approximate 5%–10% change between maximum and minimum absorbed dose values. The greater uniformity in vertical dose profile may be due to the constant diameter of the cylinder relative to the divergent cone beam. If positioned exactly at isocenter, the constant diameter equalizes the path length of the x-rays incident on the cylinder, and so photons tend to deposit the energy in a likewise consistent manner. There is a slight peak in the absorbed dose profile approximately where the central x-ray of the beam is located (~4 cm from the chest wall in this instance). This may be explained by two factors: the greater photon fluence (less

FIG. 8. (Left) Grayscale images of the absorbed dose in the water- and oil-filled conical phantom as measured by the radiochromic film, with (right) accompanying horizontal (#1–3) and vertical (#4) profiles. Note the pronounced concave dose profile across the thickest section (profile #1, chest wall) of the cone becoming less pronounced (profile #2) and turning convex as the effective diameter of the conical volume decreases near the nipple (profile #3). Note also that the mean dose level increases closer to the nipple (profile #4). The $>50\%$ increase in dose between the chest wall and nipple is evidence of the influence that the breast diameter has on absorbed dose.

divergence) along the central ray of the beam, progressively reducing toward the superior and inferior peripheries of the beam and given the peaked 3D scatter-to-primary distribution in the center of cylinder,³⁵ more scattered photons contributing to the dose in this symmetric cylindrical phantom. The greater decrease in dose levels toward the upper edge of the cylinder may be attributable to the proximity of the edge to the air interface where the lack of chest-wall scatter-in decreases the overall dose to the volume, especially when compared to the middle of the cylinder.

III.B.3. Conical phantom

The cone shaped phantom more closely resembles the characteristic shape of a pendant breast, with a tapering of the effective diameter of the phantom from the wider chest wall to the narrower nipple area. As mentioned earlier, approximately 15% of pendant breasts from MRI scanned subjects have been characterized to have this geometry.³³ This dramatic tapering has an evident affect on the dose distributions, seen in the profiles in Fig. 8.

There is a pronounced concavity in the water dose profile at the thickest section of the phantom (profile #1 in Fig. 8) with an approximate 50% difference between the peak periphery measured dose (~ 6 mGy) and the center of the phantom (~ 4 mGy). At this posterior level, the diameter of the cone is approximately 15 cm wide, slightly wider than the cylindrical phantom altogether. The peak peripheral dose in the equivalent oil dose profile is more uniform with only approximately 17% greater dose at the edges than that of the central section of the phantom (~ 2.9 mGy vs 2.5 mGy). In contrast

to the cylindrical phantom, the dose profile for both the oil- and water-filled conical phantom is more symmetrical about the vertical axis of rotation, partially due to more accurate centering of the phantom. Horizontal dose profiles progressively flatten closer to the nipple (see profile #2, Fig. 8, generated at a 9.25 cm diameter, and 5 cm from the chest wall), due to the decrease in effective phantom diameter. As the breast diameter further decreases, the cumulative absorbed dose in the center of the breast, aggregated over the tomographic scan, increasingly approaches that of the entrance dose. Indeed, the convex appearance of profile #3 (see Fig. 8, generated at a diameter of approximately 3 cm and 10 cm from the chest wall) indicates that very close to the nipple, the center of the phantom cumulatively absorbs more dose than the peripheral “skin.”

The increasing nature of profile #4 in going from the chest wall toward the nipple more closely illustrates the increasing overall dose with decreasing phantom diameter. The skin (edge) dose remains relatively constant (~ 6 mGy) as the breast diameter reduces (not shown in Fig. 8), but the dose along the medial phantom increases from 4 mGy at the chest wall to approximately 6.5 mGy by the nipple region (see profile #4 in Fig. 8). The mean cumulative dose measured in the 2D conical cross section of the water-filled conical phantom is 5.3 ± 0.6 mGy, and that of the oil-filled phantom is 3.1 ± 0.3 mGy.

III.B.4. Anthropomorphic breast phantom

Figure 9 illustrates grayscale images of the dose measured in the more clinically relevant anthropomorphic breast

FIG. 9. (Left) Grayscale images of the absorbed dose in the water- and oil-filled anthropomorphic phantom measured by the radiochromic film with (right) accompanying horizontal (#1–3) and vertical (#4) profiles. Similar to the responses observed in the conical phantom, the horizontal dose profiles progressively flatten, and the mean dose level increases approaching the nipple. The vertical dose profile (#4) indicates a 28% increase in dose along the center of the breast from the chest wall toward the nipple. The dose profile for water is again consistently higher than that of the oil, but the difference is less pronounced compared to the geometric phantoms.

phantom, based on shape, size, and density content. The mean dose measured in the water-filled phantom was 4.5 ± 0.4 mGy and that of the oil-filled volume is 3.8 ± 0.2 mGy. Similar to the results of the conical phantom, the results in Fig. 9 also illustrate an increase in mean dose levels closer to the nipple. Evident in the profiles is the cupping close to the chest wall of the breast (profile #1 is generated at a breast diameter of 13.4 cm and a distance of 0.5 cm from the chest wall) and the gradual flattening of the profile as the nipple is approached. However, the anthropomorphic breast does not taper near the nipple as sharply as the cone (the breast diameter for profile #3 is 6 cm, at an approximate distance of 7 cm from the chest wall) and so the convex-shaped profile that was present close to the nipple in the conical phantom is not evident in the anthropomorphic breast phantom.

Furthermore, breast dose measured in the oil-filled anthropomorphic phantom is consistently higher than for the other oil-filled geometric phantoms, and the reverse is true for the breast dose measured in water, making the point-wise differences between water and oil (glandular and adipose) smaller. All measurement procedures, radiochromic film immersion in the fluids, calibration and characterization procedures were identical to the earlier measurements. Thus, the greater similarity in the cumulative mean dose levels for both oil and water implies that the breast geometry may play a larger role in overall absorbed dose than material content alone. However, further investigation of this result is warranted.

Histograms of dose values from the radiochromic films (Fig. 10, left) acquired across the 2D cross sections of both the oil- and water-filled anthropomorphic breast phantoms show a broader spectrum of dose values for the water-filled

phantom. There is a slight skew toward the higher dose levels in water, whereas dose in the oil-filled phantom is more tightly distributed about the mean.

An illustration of the variation in dose normalized to the dose at the center of the thickest section of the breast (Fig. 10, right) highlights the spatial trends seen in the dose profiles, where the periphery of the breast receives, between 30% and 40%, more dose than the central volume of the breast. Asymmetry is evident in the dose profile close to the chest wall of the breast phantom with the peak peripheral dose being between 20% and 30% greater than the mean dose in the center of the phantom. This trend in increased peripheral dose to the skin corroborates previous simulated and measured dosimetry experiments for breast CT (Refs. 11 and 12) and is otherwise consistent with depth-dose expectations.

III.B.5. Cadaveric breast tissue

Grayscale images of the orthogonally positioned radiochromic films irradiated inside the cadaver breast volume are shown in Fig. 11. The locations of horizontal dose profiles across various planes of the radiochromic films are indicated on the images. Generally good agreement exists in the absolute dose measurements and in the shape of the dose profile across the films. There is less of an asymmetrical increase toward one side in the films. Similar to the earlier phantom measurements, the mean dose along the vertical profile is approximately 17% greater at the nipple than at the posterior breast.

The overall mean doses measured for the cadaver tissue, not including the oil-filled regions, were 4.3 ± 0.3 mGy and

FIG. 10. (Left) Area normalized histogram of dose measurements for the anthropomorphic breast volume filled with water (black) and oil (gray). The histograms illustrate the broader distribution of dose in the denser water medium compared to the less dense oil medium. (Right) Percentage increase in dose normalized to the lowest dose in the center of the thickest part of the anthropomorphic breast for water (top) and oil (bottom).

4.2 ± 0.3 mGy in the medial–lateral (transverse) and superior–inferior (sagittal) directions, respectively. The measured dose ranges from 3.3 to 5.1 mGy across both cadaver film orientations (see Fig. 12). These breast tissue dose measurements are between the mean doses of 3.8 and 4.5 mGy measured for the oil- and water-filled phantoms, respectively. It should be noted that this cadaveric breast tissue did not contain blood, which has a high iron content and overall density of ~ 1.05 g/cm³, which, in these measurements, would have raised the mean density of the interrogated tissue. The result of the increased mean breast density containing blood would most likely be to yield a higher mean absorbed dose in these measurements, though the dose profile trend would be expected to remain similar to those reported here.

Figure 12 shows histograms of the dose values measured solely in the cadaver tissue for both the medial–lateral and superior–inferior dimensions, outside of the oil-filled regions. These show close agreement in terms of shape and distribution of measured dose in the cadaver breast across both film orientations. Figure 12 also contains images that indicate the mean measured dose in various indicated regions of interest in the cadaver breast template. Comparisons of these dose levels are reported relative to the minimum measured dose level in the thickest section of the breast volume (containing oil).

Figure 13 illustrates a composite histogram of the dose distribution of the cadaver breast tissue, averaged across the orthogonal views, and those of the oil- and water-filled

FIG. 11. Grayscale images of the absorbed dose in the cadaver breast for the medial–lateral and superior–inferior films. The accompanying dose profiles indicate good agreement for the templates across dose profiles as the nipple is approached. The approximate outline of the oil back-filled region is marked with a dashed line. An X indicates the approximate location of the central x-ray.

FIG. 12. (Left) Area normalized histogram of dose measurements for the cadaver breast in the medial-lateral (black) and superior/inferior orientations (gray). The histogram is scaled to the same scale as that in Fig. 10. (Right) Percentage increase in dose, normalized to the lowest dose in the center of the thickest part of the cadaver breast volume, for the medial-lateral (top) and superior-inferior films (bottom).

anthropomorphic phantoms. The histogram indicates that the dose distribution in the cadaver breast tissue, composed primarily of adipose and glandular tissues among others is, as expected, located between the dose distributions of the oil and water-filled anthropomorphic phantom data. This result validates the previous anthropomorphic data using the boundary materials of oil and water to simulate lower and upper material composition bounds.

Table 1 summarizes the measured dose levels across all of the various setups used in the study. The values for water-filled (W) and oil-filled (O) geometric and anthropomorphic phantoms are listed, and the value listed for the cadaver breast is averaged across both medial-lateral and superior-inferior film orientations.

The ACR upper limits for absorbed dose from dual view mammography, 6 mGy, were developed for a breast composition having a perceived 50-50% glandular-adipose tissue

composition. The maximum absorbed radiation dose in this study was measured in equivalent 100% glandular material.

The radiochromic dosimetry technique described in this study may potentially be applied to a variety of breast imaging applications, including mammography, tomosynthesis, and even nuclear emission imaging techniques in phantoms containing radiotracers, although considerably longer exposure times or greater activity concentrations may be warranted in order to get enough signal near the operating range of the film. Other issues when employing radiochromic film include the necessity for the film measurements to be validated by additional measurement techniques, such as TLDs. In addition, the type of radiochromic film used here has a response dependence on x-ray energy that requires recalibration, if the x-ray tube potential is changed.³⁶ Another issue may be the 24-h minimum waiting period for the film to stabilize, that may inhibit its use in certain applications requiring a fast response time.

A potential limitation of this study relates to assumptions made in order to calculate the dose within the cadaveric

FIG. 13. Histogram composed of the (black) water- and (light gray) oil-filled anthropomorphic breast phantom dose distribution (previously shown in Fig. 9) along with the dose distribution of the averaged orthogonal cadaver breast tissue measurements (dashed line).

TABLE I. Mean, SD, and change (Δ) in absorbed dose from chest wall to nipple (as measured along each profile #4) for the various investigated dedicated breast CT setups. The ACR limiting value for mammographic screening of a 4.5 cm compressed 50-50% glandular-adipose breast is included for comparison.

		Δ Dose from chest wall to nipple (%)		
		Mean (mGy)	$\pm$ SD (mGy)	
Phantoms	Cylinder	(W)	5.4	0.4
		(O)	3.5	0.3
	Cone	(W)	5.6	0.3
		(O)	3.1	0.3
	Anthro pomorphic	(W)	4.5	0.4
		(O)	3.8	0.2
Cadaver	Breast	4.3	0.3	28
Mammography	Breast	<6	—	—

breast specimen. The fact that the film within the cadaveric breast absorbed more radiation than the oil, in spite of similar calibration curves used to calculate their respective absorbed dose values, may not be fully explained in the absence of a more thorough analysis of the breast tissue composition. However, even with a full understanding of the breast tissue composition, a more complete understanding of the absorbed dose in the breast tissue may not be fully realized due to the complexity of the effects of radiation scatter and absorption within a heterogeneous medium. In fact, the results of this work demonstrate the possibility that even small percentages of glandular tissue within a breast may have a nonlinear proportionality in absorbed dose to that of adipose tissue and cause increased dose level for the breast as a whole.

IV. CONCLUSIONS

In this study, the radiation dose absorbed by an uncompressed and pendant cadaveric breast when scanned using a dedicated 3D breast CT imaging system was measured using calibrated radiochromic film. The radiation dose deposited during scans of various geometric phantoms that contain oil and water, serving as equivalent 100% fatty and glandular breast tissue, were additionally measured using radiochromic film. This radiochromic film technique produced high resolution 2D dose distributions in both the cadaver and the geometric and breast shaped phantoms. The phantom-based measurements, while validating the absorbed dose measured in the cadaveric tissue, were further cross validated using TLDs, a reference standard in dosimetry. By assuming rotational symmetry in the breast and the phantom shapes, the 2D dose distribution can be extended to represent a 3D dose distribution throughout the volume.

The dedicated breast CT doses measured in anthropomorphic water- and oil-based phantoms are comparable to those typical of dual view planar mammography, with an average dose in oil (simulating 100% fatty tissue) of 3.8 mGy and the average dose in water (simulating 100% glandular tissue) of 4.5 mGy. The absorbed dose in the cadaveric breast tissue averaged across orthogonal orientations of the radiochromic film and measured at approximately 4.2 mGy is located between these two bounds. As mentioned previously, breast tissue containing blood would be further expected to have a higher overall absorbed dose, though the profile trends would most likely remain consistent with measured results. Previous dose measurements calculated via Monte Carlo simulation^{10,18,37} are supported by the measurements presented and evaluated herein.

The results of this dosimetry study, particularly those involving the cadaveric breast, combined with the results of the previously referenced contrast detail observer-based study using the same imaging technique, indicate that the dedicated breast CT system described in this work is capable of tomographically imaging the uncompressed breast using less than the maximum allowable dose for dual view screening mammography. This result further suggests that this dedicated breast CT imaging technique may be useful in the

breast imaging domain, where a low absorbed radiation dose to the breast would likely be a prerequisite.

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