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The potential role of dedicated 3D breast CT as a diagnostic tool: Review and early clinical examples

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Abstract

Mammography is the gold standard in routine screening for the detection of breast cancer in the general population. However limitations in sensitivity, particularly in dense breasts, has motivated the development of alternative imaging techniques such as digital breast tomosynthesis, whole breast ultrasound, breast specific gamma imaging, and more recently dedicated breast computed tomography or “breast CT”. Virtually all diagnostic work-ups of asymptomatic nonpalpable findings arise from screening mammography. In most cases, diagnostic mammography and ultrasound are sufficient for diagnosis, with magnetic resonance imaging (MRI) playing an occasional role. Digital breast tomosynthesis, a limited-angle tomographic technique, is increasingly being used for screening. Dedicated breast CT has full three-dimensional (3D) capability with near-isotropic resolution, which could potentially improve diagnostic accuracy. In current dedicated breast CT clinical prototypes, 300-500 low-dose projections are acquired in a circular trajectory around the breast using a flat panel detector, followed by image reconstruction to provide the 3D breast volume. The average glandular dose to the breast from breast CT can range from as little as a two-view screening mammogram to approximately that of a diagnostic mammography examination. Breast CT displays 3D images of the internal structures of the breast; therefore, evaluation of suspicious features like microcalcifications, masses, and asymmetries can be made in multiple anatomical planes from a single scan. The potential role of breast CT for diagnostic imaging is illustrated here through clinical examples such as imaging soft tissue abnormalities and microcalcifications. The potential for breast CT to serve as an imaging tool for extent of disease evaluation and for monitoring neoadjuvant chemotherapy response is also illustrated.

Keywords

Breast; Mammography; Cone beam computed tomography, Breast CT

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1. Introduction

Mammography has been the “gold-standard” for detection of nonpalpable breast cancer for more than 30 years and plays a key role in the diagnostic work-up of positive findings from screening. It is now an established fact that mammography contributes significantly to reducing mortality (1). However, the sensitivity of mammography is limited due to overlapping structures that may obscure suspicious lesions, particularly in the dense breast. Tissue overlap may also generate false positive findings. Several states now require that supplemental screening is made available for women with dense breasts. Adjunctive screening of women with dense breasts using whole breast ultrasound has been shown to detect additional cancers (2-4). However, this is achieved at the cost of an increased number of false positives and longer exam duration (2-4). Contrast-enhanced breast magnetic resonance imaging (MRI) is recommended for women at high-risk for breast cancer. The sensitivity of breast MRI is the highest of any imaging modality but the need for contrast injection, low specificity, and high cost, make it practical only for screening selected high-risk groups (5). Breast specific gamma imaging (BSGI) offers potentially high sensitivity for cancer detection particularly in dense breasts and for women at high-risk (6). The disadvantages of this approach include concerns about radiation dose and issues pertaining to radiopharmaceutical injection that makes this approach practical only at facilities that can handle radioactivity. Extension of the planar digital mammography to a tomographic approach has led to digital breast tomosynthesis which is an approach that enables limited-angle tomographic imaging of the breast. This can overcome some of the challenges associated with tissue superimposition (7-9). Studies have shown reduced recall rate (10), improved diagnostic accuracy (11, 12) and higher cancer detection rate (13), when two-view digital breast tomosynthesis is combined with two-view digital mammography.

Virtually all diagnostic work-ups of asymptomatic nonpalpable findings are prompted from screening mammography at this time. Mammography and ultrasound are used extensively for the diagnostic work-up of suspicious findings, with breast MRI playing an occasional role. However, breast MRI has been a valuable imaging tool for evaluating the extent of disease and for detecting ipsilateral or contralateral occult disease after recent diagnosis of breast cancer (14, 15). In most cases, the diagnostic work-up includes additional mammographic views such as spot compression and magnification views and may also include ultrasound for diagnosis. Spot compression and magnification views improve contrast and tomosynthesis reduces tissue overlap, allowing for more accurate diagnoses. Since the initial finding usually originates from the mammogram, it is natural that the radiologist would like the benefit of visualizing this finding with better contrast and in three-dimensional (3D) detail that demonstrates its relationship to the surrounding anatomy. Dedicated breast CT is capable of providing increased contrast and fully 3D anatomic information that has the potential to reduce the need for other techniques or modalities during diagnostic work-ups.

2. Challenges in current practice

Breast compression

Mammography and tomosynthesis both require physical compression of the breast for reasons that are well understood. Compression is important for good contrast as it reduces x-ray scatter and radiation dose, and to some degree it spatially extends the tissue outwards for improved visualization. Mammography and tomosynthesis images are both valuable tools for the detection and diagnosis of cancer, but breast compression results in a varying degree of discomfort to some patients undergoing the imaging exam. The breast exhibits anatomic variation as a complex three dimensional structure, and this 3D interrelationship among tissues can be useful for surgical planning. Dedicated breast CT is capable of imaging the breast without compression and can provide higher resolution 3D images compared to these existing modalities.

Superimposed breast parenchyma

Mammography is at a substantial disadvantage because the superimposition of breast tissues, both normal and abnormal, can cause problems in detecting abnormalities especially when abnormal tissue mimics normal tissue and vice versa. This commonly results in both false-negative and false-positive mammograms. Approximately 25% of recalls from screening mammography is attributed to tissue superposition (16). Tomosynthesis reduces this effect to a great extent, and the combination of mammography with tomosynthesis is already demonstrating effectiveness in circumventing some of the limitations of mammography (10, 12, 13). Prior work (17) showed that the background parenchymal structure, often referred to as anatomical noise, can be characterized by a power-law process of the form $kf^{-\beta}$, where k is the amplitude (18), f is the spatial frequency, and β is the power-law exponent. Higher values of β are associated with reduction in detection of soft tissue abnormalities and $\beta \approx 3$ for digital mammography (17). A recent study comparing β for the same group of subjects undergoing digital mammography, digital breast tomosynthesis and dedicated breast CT observed that $\beta \approx 3$ for digital mammography and digital breast tomosynthesis, whereas $\beta \approx 1.8$ for dedicated breast CT (19). A subsequent study observed that $\beta \approx 1.6$ for breast CT (20). These studies suggest that detection of soft tissue abnormalities is likely to be improved with breast CT compared to digital mammography and digital breast tomosynthesis. However, large-scale clinical studies demonstrating improved detection of soft tissue abnormalities with dedicated breast CT compared to digital mammography and digital breast tomosynthesis are yet to be reported.

Imaging the Dense Breast

An estimated 40% or more of the population of women undergoing screening mammography have heterogeneously dense or extremely dense breast tissue, especially women younger than 50 years of age and women on hormone replacement therapy (21-24). Several studies have demonstrated a relationship between mammographic density and breast cancer risk (25, 26). In the study by Kolb *et al.*, mammography detected 98% of cancers in women with fatty breasts, but only 48% of cancers were detected in women with dense breasts (2). Mammography is clearly challenged with dense breast tissue, but digital mammography has been shown to have improved sensitivity over the screen-film approach

for women with dense breasts (21). Whole breast ultrasound and digital breast tomosynthesis are being increasingly used as adjunctive screening modalities in the setting of dense breasts.

3. Dedicated breast CT

Why now?

Imaging of the breast with CT in a manner similar to conventional body and head imaging has long been of interest. However, the use of conventional CT scanners requires x-ray projections through the entire thorax. This is clearly undesirable in most situations where only the breast needs to be imaged. Dedicated computed tomography of the breast with the patient in the prone oblique position and the x-ray beam scanning only the breast has been explored since the early days of body CT (27). Early CT technology lacked the spatial resolution and dose efficiency to meet the requirements of breast imaging, but in recent years, technological advances in x-ray detectors, x-ray sources and image reconstruction algorithms have enabled the development of dedicated cone beam CT systems (28-30). In a typical approach to dedicated breast CT, a full 360 degree rotation scan of the pendant breast is performed with the subject in the prone position using cone beam geometry. The experimental system that was used in this work (Koning Corp, West Henrietta, NY, USA) operates at a fixed tube potential of 49 kVp and at adjustable tube current of 50 - 200 mA depending on the breast density and size. The nominal focal spot size is 0.3 mm and the source-to-center of rotation distance is 65 cm. The flat panel detector is an amorphous silicon photodiode with CsI:Tl scintillator (PaxScan® 4030CB, Varian Medical Systems, Salt Lake City, UT) with a pixel pitch of 0.194 mm in the full resolution mode. During breast CT image acquisition, the detector is operated in the binned mode by combining 2×2 adjacent pixels, thus forming a 0.388 mm pixel. At the center of rotation that coincides approximately with the center of the breast, the effective voxel size is 0.274 mm (30). Full resolution without combining adjacent pixels for a nominal voxel size of 0.137 mm at the center of rotation is possible in principle. However, current capability of flat panel detectors with respect to data transfer rates would result in longer scan duration. The current scan time is 10 seconds; but, with improvements in detector technology such as fast signal readout and data transfer, and with more powerful x-ray sources, shorter scan times are realistic.

Studies in recent years using breast CT prototypes (Fig 1) have demonstrated reasonably good coverage of the breast from the chest-wall to the nipple (see Fig 2) and sufficient spatial and contrast resolution to depict soft tissue abnormalities (see Fig 3) and most calcifications (29, 30). At this time, calcifications are not as well defined with breast CT compared to digital mammography, but this is an area of active investigation (see Figs 4 and 5). Acquisition at a smaller pixel size is technically feasible with new generation of detectors but currently software based finer sampling during reconstruction to 0.155 mm voxels is used to aid in visualization of microcalcifications. In comparison, digital mammography provides pixel size in the range of 0.05 to 0.1 mm, depending on the vendor. The compromise in spatial resolution compared to mammography is partly compensated by the ability to display calcifications in true 3D detail with reference to other calcifications and to the surrounding tissues. For example, in Fig 5 the coarse benign calcifications can be clearly

separated from the segmental malignant calcifications, which upon biopsy was pathology proven to be high-grade DCIS with focal invasive ductal carcinoma.

4. The developing role of breast CT

Fully 3D imaging for visualization of anatomy

The use of vigorous breast compression to the extent of causing substantial discomfort to some patients is a practice unique to mammography, which has been the primary breast imaging modality for more than 30 years. If an ideal breast imaging modality were to be designed de novo, it would likely not employ breast compression and it would be capable of 3D imaging to eliminate the tissue overlap that is inherent to planar imaging such as mammography, and also the partial overlap that is inherent to tomosynthesis. In particular, tissue overlap is a challenge in detecting and diagnosing abnormalities, specifically soft tissue lesions, in the presence of dense fibroglandular tissue. Currently, breast MRI and the recently available automated whole breast ultrasound are modalities used in breast imaging that do not employ breast compression and can provide 3D images. Several other modalities such as ultrasound tomography (31), optical tomography (32) and nuclear medicine techniques (33, 34) are under development which could also facilitate 3D imaging of the breast without using physical compression. However, compared to these modalities breast CT can provide for higher spatial resolution.

Breast CT and Breast Tomosynthesis: Similarities and differences

In digital breast tomosynthesis, a limited number of projections (typically from 9 to 25) are acquired over an arc spanning about 11 to 60 degrees. These projections are mathematically reconstructed in planes or “slices” of 1 mm nominal thickness and parallel to the detector to provide a quasi-tomographic view of the breast. There is no question about the ability of modern digital breast tomosynthesis systems to reduce the tissue superposition observed with mammography, but the tomographic information provided by this modality is limited compared to 3D breast CT. The ability of a tomographic system to separate the slices is referred to as slice sensitivity profile (SSP). In digital breast tomosynthesis, SSP worsens with increasing object diameter and improves when the arc span is increased, whereas breast CT provides a constant SSP (35). That study (35) also showed that for the 15 degree arc span used by a digital breast tomosynthesis system, the effective slice thickness is 8 mm even for a very small object, and was 0.5 mm for a breast CT system with voxel pitch of 0.23 mm .

Unlike breast CT, which generates images at any desired plane with near isotropic resolution, the resolution in breast tomosynthesis is highly asymmetric and out-of-slice artifacts are common. In tomosynthesis, the pixel size in each reconstructed slice is approximately 0.1 mm and is in the range of pixel sizes used in digital mammography (0.05 to 0.1 mm). In comparison, for the specific breast CT clinical prototype system used in this study, the system can provide isotropic voxels ranging from 0.155 mm to 0.273 mm on each side. Thus, digital breast tomosynthesis provides higher spatial resolution within each slice but inferior slice separation, when compared to breast CT.

In tomosynthesis the breast is imaged in the compressed state similar to mammography. The standard positioning of the patient to obtain craniocaudal (CC) and mediolateral oblique (MLO) views of the breast are also used with tomosynthesis. Since the positioning of the patient is similar to mammography, there is minimal need for additional training of the technologists. In comparison, physical compression of the breast is not needed for breast CT, thus alleviating the discomfort associated with breast compression. Additional training of the technologists and care in positioning may be needed so that the patient is positioned with a slight oblique rotation to improve inclusion of breast tissue in the axillary region. Breast CT involves prone imaging similar to MRI but only requires one image acquisition sweep of 10-17 seconds, depending on the prototype system. With current technology, the image acquisition duration is slightly longer than that for each digital breast tomosynthesis acquisition.

Tomosynthesis and digital mammography may be combined into one unit which allows acquiring tomosynthesis images alone, digital mammograms alone or a combination of the two. This combination of multiple acquisition modes in one unit can be very advantageous for efficient use of space and for convenience. Breast CT on the other hand requires a dedicated table that currently needs space similar to a standard stereotactic biopsy table. Breast CT with upright positioning of the subject in a manner similar to mammography and breast tomosynthesis and a vertical gantry is possible (36), and may be available in the future.

Role of breast CT compared to breast MRI

Dedicated breast CT is a part of a continuum of developments in breast imaging. At this time, clinical experience with breast CT is very limited, and experience with breast CT studies using injected contrast is even less. Advantages of breast CT compared to MRI include the image acquisition time in breast CT being substantially shorter; 10 seconds for a complete scan compared to about 4 to 8 minutes per sequence in MRI, resulting in approximately 40 minutes for an entire MRI exam. Breast CT may not replace breast MRI in the diagnostic setting but it does have the potential to serve as an alternative where access to MRI is limited. It may also be invaluable as an alternative to MRI if a patient has contraindications, such as implanted devices or metallic fragments in the head and neck. Patients with claustrophobia and physical limitations that prohibit positioning the subject within the bore of the MRI may also be suitable for imaging with breast CT.

Visualization and patient comfort

Mammography requires a minimum of two views with vigorous physical compression of the breast which can be extremely uncomfortable and may even discourage some women from returning for future screening or even for diagnostic examinations. Breast CT does not require breast compression and current technology only requires one 10-second sweep of the uncompressed breast, after which the image can be reconstructed and viewed in any plane; therefore, the image can be manipulated from different angles without reimaging the patient. In diagnostic mammography, it is frequently necessary to image the patient multiple times for asymmetries, partially obscured masses and calcifications using spot compression, magnification and other additional views to confirm a lesion and to determine its exact

location. In breast CT, the nearly infinite viewing options arising from its intrinsic isotropic 3D nature and the display protocol, provides the capability to detect asymmetries, masses and calcifications in any desired plane from the initial acquisition. The breast CT field of view includes the breast from the chest wall to the nipple. In mammography, the mediolateral oblique (MLO) view allows for imaging the axilla. For example in Fig 2, the MLO view (Fig 2B) shows the axillary region which also contained pathology verified benign lymph nodes. In breast CT, the position of the x-ray focal spot relative to the patient support table and the need for gantry rotation could pose a challenge in imaging the entire axilla. Posterior breast coverage can be improved with careful optimization of the imaging system geometry (36). Breast CT can also image the lower axillary region in many patients. For example in Fig 2C-2E, the lowest lymph node in the axillary tail of the breast is fully visualized and additional lymph nodes higher in the axillary tail are partly visualized. This suggests that in some women, good coverage of the axillary region can be achieved.

The 3D reconstructed images are available for viewing in three orthogonal planes: axial, sagittal and coronal, or in any other oblique plane. The axial image corresponds to the mammographic CC view. The sagittal view corresponds to a 90 degree lateral mammographic view. CT views can be reconstructed to correspond to the angled mammographic MLO view, if needed. The breast CT coronal view is a useful view not available with mammography or tomosynthesis. The coronal view is also known as the “surgeons view” because it most closely corresponds to the view of the surgeon during surgery. The ability to view the breast in any desired orientation can also be useful for surgical planning.

The need for supplemental imaging

Sensitivity of mammography decreases with increasing breast density (37). The study (37) recommended that all mammography reports should routinely include a statement about breast density. In the United States, several states have passed legislation requiring radiologists to inform patients in writing of their breast density. This awareness has already led to a demand for supplemental imaging. It is generally accepted that women at high-risk because of strong family history, genetic mutations or previously diagnosed high-risk pathology resulting in an estimated lifetime risk above 20% are offered screening MRI in addition to screening mammography. Women with dense breasts are not consistently offered supplemental screening, but this is likely to change with these new legislations (4, 38). At present, whole breast ultrasound and digital breast tomosynthesis are the imaging tools of choice for such supplemental screening. The major challenges associated with whole breast ultrasound are related to operator dependence and length of time required to perform the examination as well as the increase in false positive findings.

Breast CT has the potential to play an important role in the setting of dense breasts and intermediate lifetime risk of breast cancer. Unlike breast ultrasound, breast CT has more similarities to the mammographic image and can be interpreted on the same image processing and display platform as body CT. Breast CT is inherently less operator dependent than whole breast ultrasound and findings can be clearly localized in 3D, illustrating an

abnormality in any desired plane. Breast CT also offers the capability to biopsy an abnormality using the modality on which it was detected.

An additional issue with breast density is that it is considered an additional risk factor for breast cancer. Breast density is currently assessed using the American College of Radiology (ACR) guidelines based on the interpreting radiologist's assignment of the visualized breast density into one of 4 categories from the distribution of density seen on the 2D mammogram. While moderate to good agreement between radiologists using this scale has been reported (39), the availability of 3D information with breast CT makes it feasible to obtain an accurate quantitative estimate of breast density (22, 23).

Contrast enhanced imaging of the breast

As with any other organ or structure in the body, intravenously injected contrast can provide enhancement of suspicious features that are not apparent in the absence of contrast material. Preliminary studies have shown that x-ray contrast enhancement can potentially reveal lesions in the breast that are not detectable with mammography (40, 41). Contrast-enhanced MRI is known to reveal tumors that were not detected on mammography (5) and increasingly the evidence suggests that iodinated contrast agents used with x-ray imaging also concentrate in the neovascularity due to tumor associated angiogenesis (27, 40-42). In a study of 1625 patients using an early breast CT prototype, contrast-enhanced breast CT was shown to detect 94% of the cancers, compared to 77% for mammography (27). Digital subtraction angiography of the breast was shown to provide differentiation between benign and malignant breasts in a small study of 23 women (42). In more recent studies, Jong *et al.* investigated the use of intravenous contrast enhancement of breast lesions using single-energy digital mammography (41). Lewin *et al.* conducted a study using dual-energy for contrast enhanced digital mammography (40). Recent clinical studies have demonstrated the feasibility of contrast enhanced digital mammography as a diagnostic work-up tool (43). Dual-energy contrast-enhanced digital mammography is now available for routine clinical use in the USA, Canada and Europe.

In a recent study, contrast-enhanced breast CT has been shown to be a promising method to detect abnormalities and to differentiate between benign and malignant lesions in the breast (44). Initial clinical experience with contrast-enhanced breast CT imaging using a cone-beam CT system showed improved conspicuity of malignant lesions including DCIS (44). Our experience is similar and also shows increased conspicuity of benign masses in dense breasts (see fibroadenoma in Fig 6).

Contrast-enhanced MRI is the established standard for evaluating extent of disease and multi-centricity, following a diagnosis of cancer. It has also been shown to be a valuable tool for monitoring response to neoadjuvant chemotherapy (45). Key factors attributed to the superior performance of MRI for evaluating extent of disease and monitoring response to chemotherapy are the contrast uptake and the availability of 3-D image data for estimating tumor volume (45). Since dedicated breast CT also provides 3-D image data at a much higher resolution, it is quite conceivable that breast CT could play an important role in such imaging tasks. Figures 7 and 8 show the potential of breast CT for evaluating extent of disease and for monitoring chemotherapy response, respectively. The scan time with breast

CT is 10 seconds and a bilateral contrast-enhanced breast CT exam can be completed in a few minutes depending on the number of post-contrast scans. In comparison, a breast MRI exam typically lasts about 40 minutes. Positioning of the patient for breast CT exam is similar to that with breast MRI and breast CT can be beneficial for patients with claustrophobia. Current breast CT systems image one breast at a time and require repositioning of the patient for bilateral exams. However, a bilateral contrast-enhanced breast CT exam can be completed with a single administration of contrast media (44). The capital and operational costs with breast CT are expected to be much lower than MRI. However, there is a radiation-associated risk with breast CT and is addressed below. Access to breast MRI due to location, scheduling, and priority for other studies, can be a challenge at many institutions even when MRI is available. Although the complete replacement of breast MRI with contrast-enhanced CT is highly unlikely, the use of breast CT where breast MRI is contraindicated or unavailable due to aforementioned reasons would be of clinical value. Contrast-enhanced breast CT may also match or even surpass breast MRI for evaluating extent of disease and for detecting occult multifocal, multicentric, or contralateral lesions, following breast cancer diagnosis, but this has to be investigated.

5. Initial experience with breast CT

Selected cases from clinical feasibility studies aimed at investigating the role of breast CT as an imaging tool in diagnostic work up and for clinical management following diagnosis of breast cancer are presented. All presented cases were accrued under HIPAA-compliant protocols that were approved by the Research Subjects Review Boards of our institutions. Figures 3 through 6 are provided to illustrate the potential of breast CT as a diagnostic tool. These cases were selected to show the ability of breast CT to visualize soft tissue abnormalities (Fig 3), microcalcifications (Figures 4 and 5) and the added value of contrast-enhancement (Fig 6). In Figure 3, dedicated breast CT shows a spiculated mass that was proven at pathology to be an invasive ductal carcinoma and could be observed as a small focal asymmetry in the MLO mammogram. In Figure 4, a small cluster of calcifications (high-grade DCIS) is visualized on both breast CT and in the mammograms. In Figure 5, extensive microcalcifications and numerous benign coarse calcifications are observed in the mammograms. Breast CT illustrates that the benign calcifications are clearly separated from the segmental distribution of calcifications that were malignant and confirmed by pathology as high-grade DCIS with focal invasive ductal carcinoma. In Figure 6, a palpable mass is not visualized on the mammograms but is well delineated on breast CT due to the lack of tissue overlap. Addition of intravenous iodinated contrast displayed the benign characteristics of the mass which was pathology-confirmed to be a fibroadenoma.

The potential of contrast-enhanced breast CT to serve as an imaging tool for extent of disease evaluation following diagnosis of breast cancer is illustrated in Figure 7. Additionally, it provides a qualitative comparison with breast MRI. Mammograms show a partially obscured spiculated mass (index lesion, arrows) in an extremely dense breast. The index lesion (arrow 1) is visualized with both breast CT and MRI, but the irregular margins are better visualized with breast CT. An additional enhancing focus (arrow 2) is also observed with both breast CT and MRI. However the resolution is substantially better in breast CT images compared to MRI. Breast CT showed extensive nodular enhancement in

the surrounding tissue and suggested that the entire upper outer quadrant of the breast was involved with the tumor. Histopathology following mastectomy correlated with these CT findings.

Breast CT can potentially be a valuable tool to assess response to neoadjuvant therapy. Figure 8 shows one case from a small recent study using non contrast breast CT for monitoring response to neoadjuvant chemotherapy. A 54 year old woman presented with a greater than 4 cm mass in the 11-12 o'clock location of the left breast and underwent neoadjuvant chemotherapy treatment. The mammogram could not depict the extent of disease due to the dense breast parenchyma in this premenopausal woman. The initial breast CT scan was performed prior to the start of therapy and a second breast CT scan was performed midway through the treatment, three months later. The third breast CT scan was performed upon completion of chemotherapy. Volume calculations were obtained and are displayed on a bar graph. Substantial tumor shrinkage based on volume measurements can be observed at midpoint of treatment and accounted for the majority of the response. Breast CT provided superior resolution over the full extent of tumor in this patient with dense breast and a known large tumor.

6. Radiation dose

Data on the average glandular dose (AGD) in breast CT for various breast sizes and composition have been reported (46-48). For a pendant breast of 50/50 glandular/fat composition with a diameter of 14 cm that is approximately equivalent to a 5 cm thick compressed breast in mammography, the AGD from breast CT varied from 5 to 15 mGy, depending on the choice of kVp, filtration and mAs (46, 47). In mammography, the AGD to the breast for the CC-view is approximately 1.6 to 2.5 mGy, and the AGD to the breast for the MLO view is slightly higher. In tomosynthesis, the AGD is approximately 8% higher than the AGD from mammography (49). The low end of the reported range for AGD from breast CT is approximately similar to a 2-view screening mammography exam (46) and is slightly lower than that from a combined tomosynthesis-mammography 2-view screening exam (49). For subjects undergoing diagnostic mammography more than two views may be required to render a diagnosis (48). In one study (48) that analyzed the radiation dose for 133 subjects who underwent diagnostic mammography and breast CT, the median AGD from breast CT was equivalent to 4-5 mammography views and the diagnostic mammography exam on average had 4.53 views. Studies have also shown that the dose distribution is more uniform in breast CT compared to mammography (47, 50). Substantial dose reduction in breast CT appears feasible with further optimization in x-ray detectors and image reconstruction techniques.

7. Summary

Dedicated breast CT is currently investigational in the US and Canada but is approved for use in the European Union*. Dedicated breast CT has the potential to be superior to conventional mammography in visualization and diagnostic evaluation of abnormalities,

*Note: The Koning breast CT has received CE Mark approval in Europe.

particularly soft tissue abnormalities, even in dense breasts. It may be valuable as an adjunctive diagnostic tool to be used after conventional mammography. Lesion visualization is improved with cone beam breast CT over mammography due to elimination of superimposed glandular tissue. Contrast enhanced breast CT further improves lesion visualization and could be useful for extent of disease evaluation. The radiation dose from breast CT is similar to, and is within the range of, conventional diagnostic mammography. Given all the potential roles in breast imaging including adjunctive screening and diagnostic evaluation, guiding biopsies, extent of disease evaluation, and monitoring response to neoadjuvant therapy, breast CT could become an important imaging tool.

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Fig 1.
Schematic representation of breast CT and subject positioning.

Fig 2.

An example demonstrating coverage of the axillary aspect with dedicated breast CT compared to mammography. (A) CC view does not show the lymph nodes in the axillary tail. (B) MLO view shows multiple lymph nodes (arrows) in the axillary tail. Pathology following ultrasound guided biopsy indicated a benign diagnosis suggestive of dermatopathic lymphadenopathy. (C) Surface rendering of the skin shows the axillary extent imaged with breast CT. (D) The lower lymph node (arrow 1) is visualized in its entirety, where the lymph nodes higher in the axillary tail (arrow 2) are partly visualized. (E) 4-view display showing the lymph nodes.

Fig.3.

Bilateral screening mammograms (A: CC view; B: MLO view) show a small focal asymmetry in the MLO view of the right breast (indicated by circle in B). Histopathology from ultrasound-guided core biopsy indicated a 7 mm invasive ductal carcinoma. In C, the 4-view display (top-left: axial, top-right: sagittal; bottom-left: coronal; bottom-right: 3-D volume rendering) from dedicated breast CT shows a spiculated mass.

Fig 4.

A small cluster of calcifications in the right breast is observed at approximately 3:00 location (A: CC view; B: ML view). Corresponding magnified mammographic views are shown in C and D, respectively. The 4-view display (maximum intensity projection, MIP) from dedicated breast CT (E) clearly shows the calcification cluster (top-left: axial MIP of 3 mm slab; top-right: sagittal MIP; bottom-left: coronal MIP; bottom right: 3-D MIP). In F, zoomed-in axial MIP (3 mm slab) of the calcification cluster is shown. Histopathology from core biopsy showed high-grade DCIS.

Fig 5.

Extensive microcalcifications measuring at least 6 cm in diameter are observed on mammograms (A: CC view; B: ML view) in a 73 year old asymptomatic woman and there are also numerous benign coarse calcifications. The 4-view MIP (6.2 mm slab) display from dedicated breast CT (C) illustrates clearly the segmental distribution of the calcifications, which on biopsy revealed pathology indicating high-grade DCIS with focal invasive ductal carcinoma. The benign calcifications are also well imaged and are clearly separate from the segmental malignant calcifications.

Fig 6.

A 45 year old woman with heterogeneously dense breast had a palpable mass in the left breast. Palpable mass indicated with a marker (arrows) on the skin in mammograms (A: CC view; B: ML view). Palpable mass is not visualized on the mammograms but is well delineated in breast CT because of lack of tissue overlap (C: 4-view display). The addition of contrast further displays the benign characteristics of the mass, which was confirmed on ultrasound guided biopsy, with pathology indicating benign fibroadenoma (D: pre (left) and post (right) contrast sagittal views; E: pre (left) and post (right) contrast axial views).

Fig 7.

A 43 year old woman with extremely dense breast had a palpable mass in the right breast. Mammography showed a partially obscured spiculated mass at the 12:00 location (A: CC view; B: MLO view). Contrast-enhanced MRI (C) for extent of disease evaluation showed an enhancing mass (index lesion, arrow 1) with irregular margins measuring $1.9 \times 1.5 \times 1.7$ cm and a 0.7 cm enhancing focus (arrow 2) located 2 cm posterior to the index lesion. The contrast-enhanced dedicated breast CT (D: pre (left) and post (right) contrast axial MIP (2 mm slab); E: 4-view post contrast MIP (3 mm slab)) shows the irregular mass (index lesion, arrow 1 in D and E) very clearly and also the smaller focus (arrow 2). Extensive nodular enhancement in the surrounding tissue are observed with both MRI and breast CT, however the resolution is much sharper on the breast CT. Breast CT suggested that the entire upper outer quadrant of the breast was involved with tumor and this correlated with histopathology following mastectomy.

Fig 8.

A 54 year old woman presented with a greater than 4 cm malignant mass in the 11-12 o'clock location of the left breast. Mammograms showed dense breast parenchyma in this premenopausal woman. The patient underwent neoadjuvant chemotherapy. Non-contrast dedicated breast CT scans were obtained (A) prior to start of chemotherapy, (B) midway (3 months after start) through therapy, and (C) upon completion of therapy. The tumor volume was calculated from each scan and the bar graph is shown (D). Excellent response to chemotherapy can be observed in the breast CT images and tumor volume measurements demonstrate that most of the reduction occurred by the midpoint of treatment.