

A study on phase sensitive imaging for breast tomosynthesis applications

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SUBMISSION: 17/7/2019 | ACCEPTANCE: 29/11/2019

ABSTRACT

Purpose: To examine the potential advantages of phase sensitive imaging in breast tomosynthesis (BT) for more accurate and early detection of breast cancer.

Material and Methods: An in-house phantom with a 5 cm radius and a 3 cm thickness of paraffin wax with embedded spheres, fibers and clusters of CaCO₃, simulating breast malignancies, was used. BT images were acquired with an in-line phase contrast mode using synchrotron radiation at 20 keV. Fifteen projections were obtained with an object to detector distance of 150 cm, acquisition arc of 15° and mean glandular dose (MGD) of 2.3 mGy. Attenuation based BT images of the same phantom were acquired with the use of a commercial imaging system. In this case,

15 projections were obtained at 28 kVp, 35 mAs with MGD 1.4 mGy, within an acquisition arc of 15°.

Results: In both experiments filtered back projection reconstruction algorithms were utilised, resulting in BT planes of 1 mm distance. The reconstructed planes of the two experiments were compared visually and quantitatively. The edges of the main mammographic structures appeared to be sharper in the case of phase contrast imaging, which made their detectability easier. Line profiles and contrast to noise ratio values confirmed the superiority of phase contrast BT over conventional BT imaging.

Conclusions: Tomosynthesis phase contrast imaging is a promising technique for the detection of small abnormalities in breast screening.



KEY WORDS

Breast Tomosynthesis; Phase contrast imaging; Breast modeling; X-ray imaging Phantoms



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1. Introduction

While mammography is the most widespread screening tool for breast cancer, breast tomosynthesis (BT) is gaining ground in every day clinical practice. The problems caused by dense breast tissue, overlapping structures and thus structured noise in 2D mammography are significantly reduced in reconstructed tomosynthesis slices [1].

In BT imaging the x-ray source moves in a limited angle arc, providing a series of digital projection images of the breast [2-4]. These projections are then reconstructed into a stack of slices illustrating pseudo-3D structural information of the breast. The inherent disadvantage of conventional mammography to present superimposed structures in a single 2D image is resolved in BT [5]. BT may also result in greater accuracy for the size, shape and location of breast abnormalities and in more distinct illustration of abnormalities within dense breast tissue [6]. Tomosynthesis becomes a useful tool in the detection and depth localisation of breast abnormalities with dose levels not higher than those of conventional mammography [7]. Studies have shown that BT can also be beneficial in the characterisation of lesions particularly in dense breasts [8, 9] and has the potential to reduce the recall rate [10].

Recently phase contrast has been introduced as a promising x-ray imaging modality for the breast [11]. Conventional mammography and BT are imaging techniques based on the attenuation of the x-rays. Phase contrast (phase sensitive) imaging is a technique sensitive not only to attenuation but also to x-ray phase shift arising at the boundaries of different refractive materials [12, 13]. Tissues composed of low Z-elements, such as breast masses, produce low absorption contrast but considerable phase contrast, resulting in significant edge enhancement of structures [14-16]. It is worth mentioning that phase shift coefficients of tissues are greater than attenuation coefficients by two to three orders of magnitude, for x-rays in the diagnostic energy range. Additionally, phase shift coefficient diminishes less than attenuation coefficient as energy increases; thus, the potential application of phase contrast imaging with higher energies and lower delivered doses (an unrealistic approach in case of conventional mammography) is possible [17]. Among the different techniques under investigation nowadays for phase sensitive imaging, the in-line set up (free space

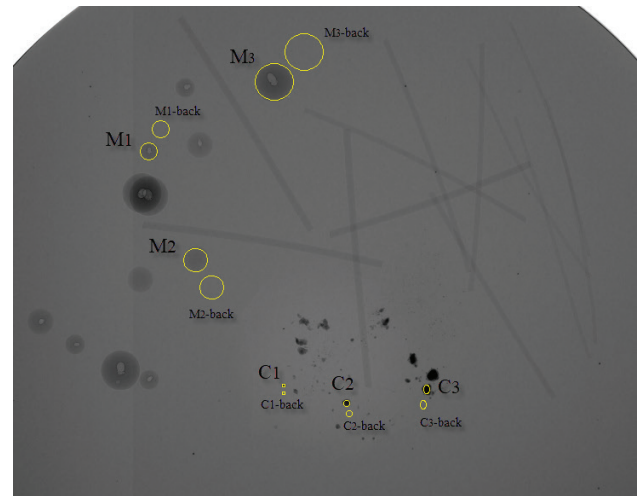


Fig. 1. ROIs under evaluation for the nylon spheres (M1, M2, M3) and for the specs of CaCO₃ (C1, C2, C3).

propagation imaging) is the most manageable and tested one. This approach does not require the use of any optics and grating elements in the imaging set-up between the sample and the detector, in order to perform wave splitting or any kind of image reconstruction [18-20].

In this study the potential advantages of BT combined with phase contrast imaging over conventional BT imaging were analysed. A relative comparison of BT slices generated by a commercial imaging system and by an in-line phase contrast set up with the use of synchrotron radiation was performed. For this comparison an in-house phantom was used, where the detectability and visualisation of structures simulating breast malignancies was evaluated.

2. Material and Methods

2.1. The Hardware Phantom

An in-house designed and made hardware phantom was used for the needs of the experiments. The phantom was made of paraffin wax (C₂₅H₅₂, density: 0.93 g/cm³, the real part of the refractive index decrement $\delta_{(20\text{keV})} = 5.53 \cdot 10^{-7}$) mimicking a homogeneous background of 50% glandular-50% adipose tissue. It had a cylindrical form of 5 cm radius and 3 cm thickness inside which were embedded three different types of structures representing breast abnormalities: four groups of nylon spheres of 4.8 mm, 3.2 mm and 2.4 mm simulating masses, nylon fibers with sizes of 0.9 mm, 0.7 mm and 0.5 mm, and CaCO₃ powder simulating microcalcifications (μCs). During the solidification process four layers

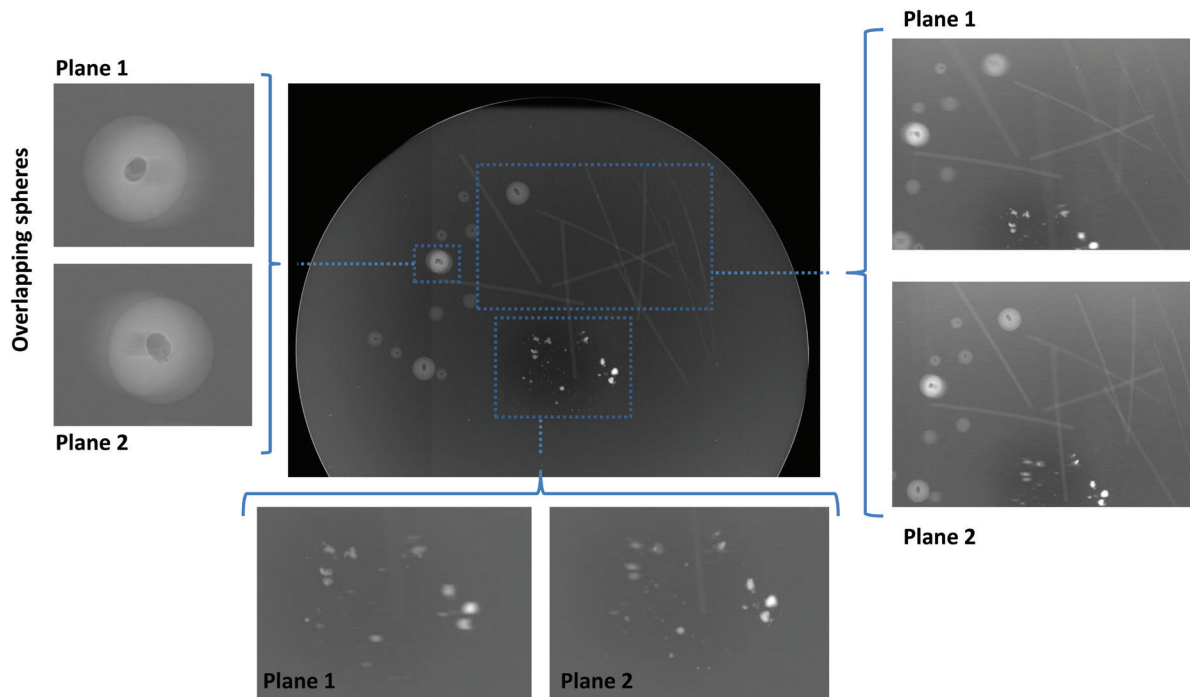


Fig. 2. Cropped phase contrast images illustrating spheres, fibers and CaCO₃ specs at two different in focus BT planes.

of the abovementioned structures were embedded. The aim of this arrangement was to produce areas with overlapping structures in order to facilitate a BT investigation. The phantom was tested in previous studies for phase contrast applications [21].

2.2. The Phase sensitive BT system

The experiment for phase sensitive imaging was performed at the Elettra Synchrotron at Trieste, using the SYNchrotron Radiation for MEDical Physics (SYRMEP) beamline, especially designed for research in medical diagnostic radiology. The optics were based on a double-crystal Si (111) monochromator working in the energy range of 18-35 keV. The detector was a Teledyne Dalsa Time Delay Integration (TDI) Charge-Coupled Device (CCD) camera with a pixel size of 54 μm . The x-ray beam provided at 20 m from the source was a laminar section with maximum area 120 x 4 mm². In order to acquire BT projections, the phantom was placed on a metal plate at 22.4 m from the source, moving vertically at each scan and able to rotate 360°. The object to detector distance (ODD) was 150 cm in a free space propagation set up. The energy of the monochromatic x-ray beam was 20 keV.

Projection images of 4400x2200 were produced within

an acquisition arc of 15° with 1° increment, resulting in 15 projections. Also a 2D image with the same acquisition parameters was obtained as a reference image for this experiment. The incident air kerma (K) was calculated in advance in order to acquire an MGD in the dose range of the European guidelines for quality assurance in breast cancer screening and diagnosing. For the calculations, the following equation was used:

$$MGD = K \times g \times c \times s \times t_{(g)} \quad (\text{Equation 1})$$

where g , c , and $t_{(g)}$ are conversion parameters depending on the breast thickness, the glandularity, the incident spectra and the angles of the acquisition arc respectively [22-25]. K was measured at the upper surface of the breast and was equal to 0.4 R resulting in 3.45 mGy Entrance Surface Exposure (ESE). In our study, where the base material of the phantom was paraffin wax, the equivalent breast thickness was calculated and found to be 2 cm. According to Equation 1 the total MGD in this case was 2.3 mGy.

2.3. The Commercial BT system

In order to acquire attenuation based BT images, an

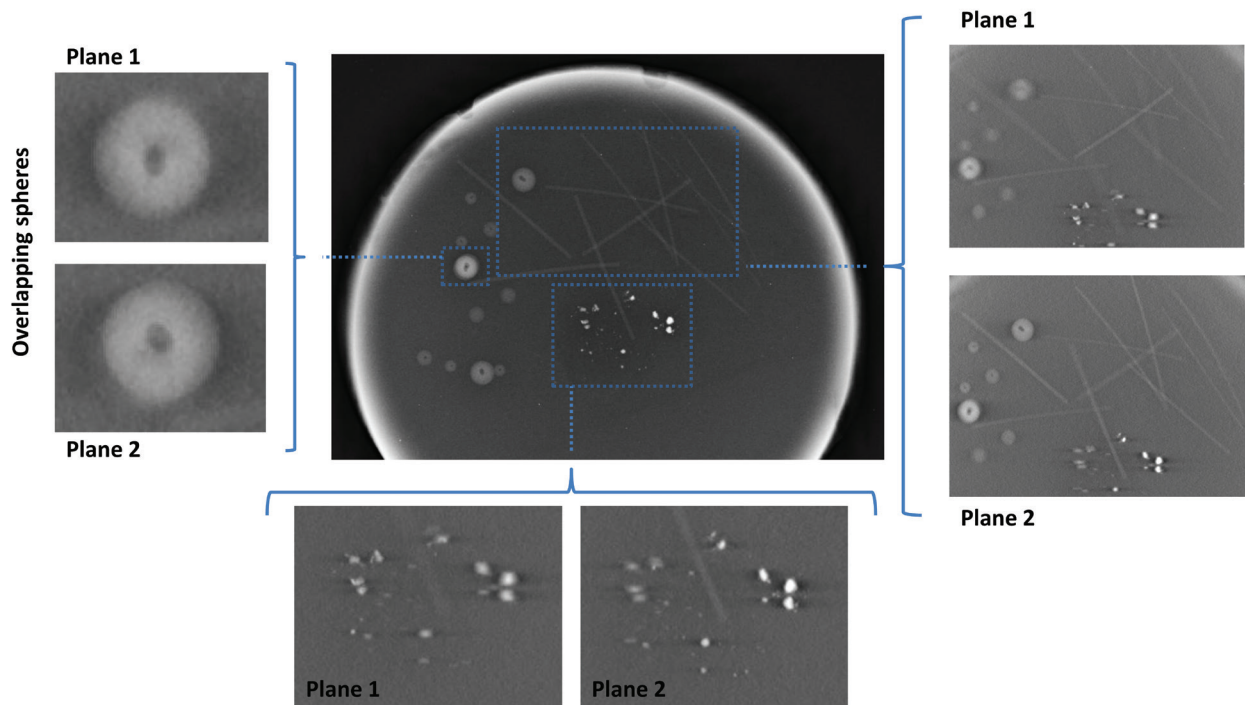


Fig. 3. Cropped attenuation based images illustrating spheres, fibers and CaCO_3 specs at two different in focus BT planes.

experiment using the same phantom was carried out at the University Hospital of Patras with the use of a commercial system (Selenia Dimensions, Hologic) [26]. The imaging system had a flat panel amorphous selenium detector with an image receptor size of 24×29 cm (3328×4096) and pixel size of $70 \mu\text{m}$. The x-ray tube had a Tungsten anode with 0.3 mm focal spot size. The projections were taken with an automatic exposure control (AEC) mode where the system selects filter, kVp and mAs. In our case an Al filter of 0.7 mm, 28 kVp and 35 mAs was used. Fifteen projections in 15° acquisition arc were obtained with an OOD of 5.8 cm and a source to detector distance of 70 cm. Also a 2D image with the same acquisition parameters was obtained as a reference image, alike in the previous experiment. The isocenter of this imaging system was in the detector that rotated making small moves. The ESE was derived from the imaging system and was equal to 2.45 mGy. The total MGD was calculated with the same Equation 1 and found to be 1.4 mGy.

2.4. Image processing and reconstruction

Before reconstruction, a flat-field correction was performed to the projection images acquired with the

in-line phase contrast BT set up. Additional processing was performed using MATLAB 2013 in order to correct the small vertical movements of the phantom during the BT acquisition arcs. For the reconstruction process an in-house platform was used [27] performing filtered back-projection. All the images were pre-filtered with the use of ramp filter. A pseudo-3D representation of the phantom was produced from the reconstructed axial planes at every 1 mm of the total volume. Windowing methods were used in order to obtain the best image quality regarding the visualisation of the structures inside the phantom. There was no extra filtration or any other post processing of the images before visual comparison.

2.5. Evaluation metrics for comparison

The reconstructed phase sensitive and attenuation images were compared visually and quantitatively. For visual assessment, five investigators familiar with medical imaging from our research group were involved. For the quantitative analysis evaluation metrics were used. In this study the Contrast to Noise Ratio (CNR) was calculated [28, 29] for the main mammographic findings (Nylon spheres and CaCO_3 specs) according to Equation 2,

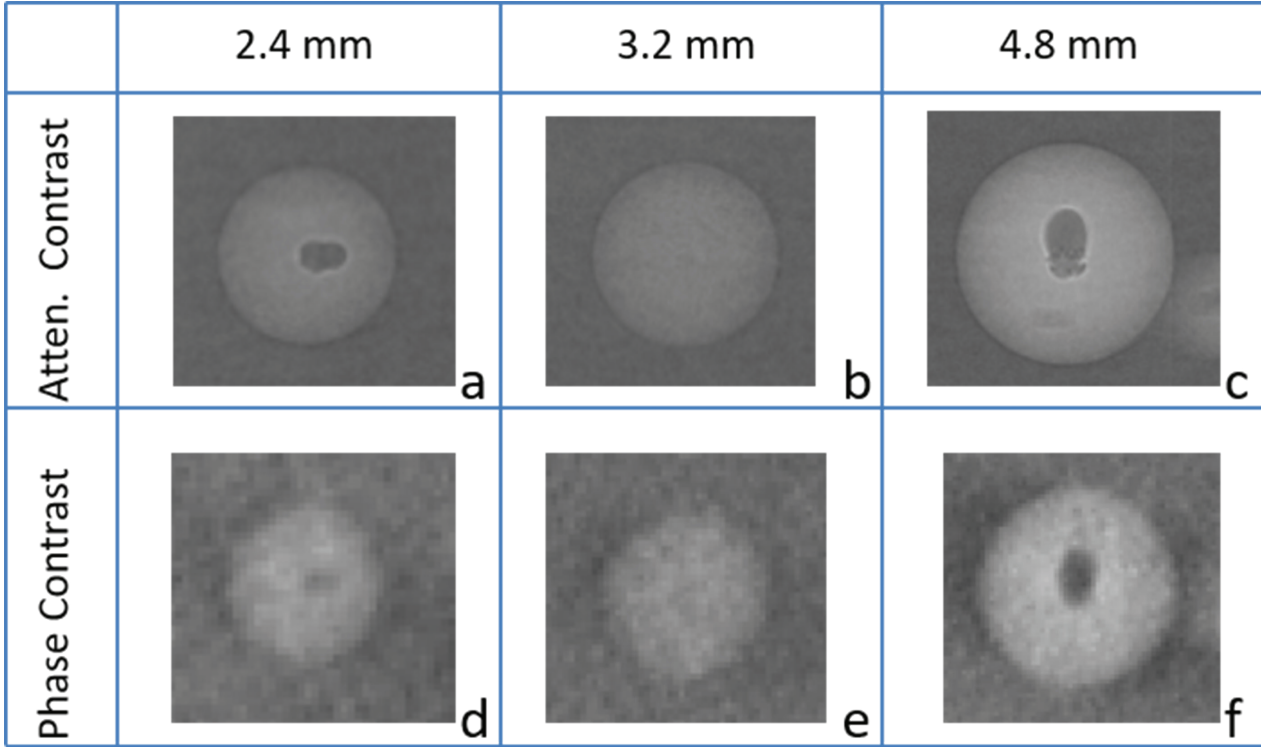


Fig. 4. Cropped images of spheres in focus with different sizes from phase contrast BT planes (a, b, c) and from attenuation contrast BT planes (d, e, f).

$$CNR = \frac{I_o - I_B}{\sqrt{\frac{\sigma_o^2 + \sigma_B^2}{2}}} \times \sqrt{\alpha_o / \alpha_p}$$

(Equation 2)

where I_o and I_B are the average intensity values of the object and background over a region of interest (ROI), σ_o and σ_B are the standard deviation values of the object and background ROI and α_o and α_p are the areas of the object and a pixel respectively.

The ROIs used were circular with altered sizes according to the size of each object under investigation (Fig. 1). M and C denote the ROIs for spheres and $CaCO_3$ specs respectively. For each structure under evaluation a background ROI was used, of the same size with the object's ROI. The background ROIs were placed in the neighbourhood of each object, where no details appeared.

$$FOM = \frac{CNR^2}{MGD}$$

(Equation 3)

Since the two experiments were performed with different doses and CNR values were depending on the radiation dose, a figure of merit (FOM) was introduced. In order to allow the comparison of CNR between the two experiments FOM values were calculated, where

the CNR^2 was normalised to the MGD according to Equation 3 [30].

3. Results

The reconstructed BT planes for phase sensitive and attenuation imaging were compared visually and quantitatively in means of CNR, FOM and line profiles. As we sliced through the reconstructed volume of 30 planes, different structures appeared in focus. In Fig. 2 a 2D image acquired with the in-line phase contrast set up is illustrated. Cropped images of spheres, fibers and $CaCO_3$ specs from areas of the phantom defined with dashed lines are demonstrated. Those images were cropped from 2 different planes (plane 1 and plane 2) out of the 30 that were reconstructed. Fig. 3 illustrates the same areas with Fig. 2, but attenuation based BT reconstructed planes acquired with the commercial imaging system were used.

In Fig. 4, which is dedicated to the low contrast features of the phantom, nylon spheres simulating breast masses with different diameters are illustrated. In the first row (Fig. 4a, b, c) cropped images of spheres with increasing diameter sizes of 2.4 mm, 3.2 mm and

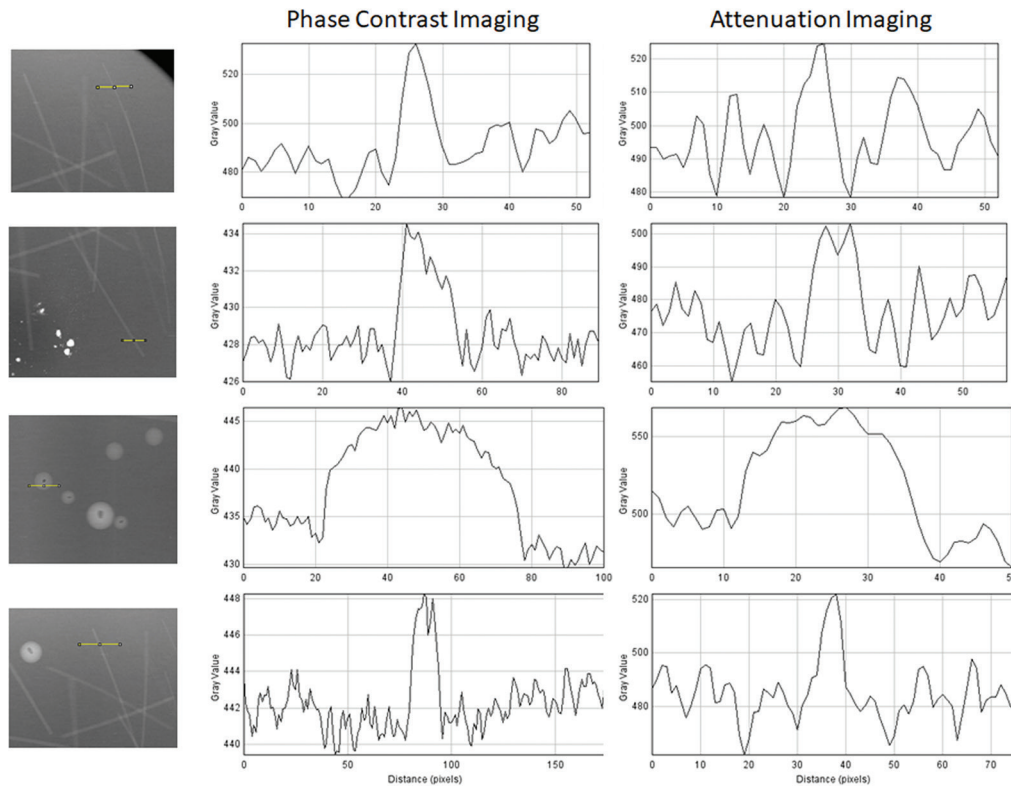


Fig. 5. Line profiles taken across fibers and one sphere from phase contrast and attenuation BT planes.

4.8 mm from phase contrast in-focus BT planes are presented. Whereas in the second row (Fig. 4d, e, f) the same spheres are presented, appearing in-focus in attenuation contrast BT planes.

In Fig. 5, line profiles for fibers and for one sphere in both imaging cases are highlighted. The first column from the left shows cropped images of the areas where the line profiles denoted with yellow lines were obtained. In the middle and third column are the line profiles obtained across phase sensitive reconstructed planes and attenuation based reconstructed planes respectively.

In Table 1 the calculated values of CNR and FOM according to Equations 2 & 3 for three nylon spheres and three CaCO₃ specs for the two different imaging modalities are listed. The ROIs used for those calculations are presented in Fig. 1.

4. Discussion

This study investigated the potential enhancement of image quality in the case of phase sensitive BT imaging over conventional BT. Experiments were performed with a commercial BT system for attenuation imaging

Table 1. Calculated values of CNR and FOM for the spheres (M1, M2, M3) and for CaCO₃ specs (C1, C2, C3)

	Phase Sensitive Imaging		Attenuation Imaging	
	CNR	FOM	CNR	FOM
M1	6.32	17.39	4.23	12.75
M2	7.59	25.04	4.75	16.15
M3	7.27	23.00	5.12	18.74
C1	14.70	93.95	11.03	86.87
C2	12.81	71.30	8.36	62.59
C3	10.59	48.73	6.31	28.48

and an in-line phase contrast BT set up with synchrotron radiation for phase sensitive imaging. An in-house phantom tested in previous experiments was used in both experiments with low and high contrast features mimicking breast abnormalities embedded into the base material.

Both BT cases managed to resolve areas with overlapping structures, providing better localisation and characterisation of those features. This can be seen

in areas of the phantom with spheres and fibers (**Fig. 2** and **Fig. 3** on the right). This is evident in the example of two superimposed spheres that in both BT modalities appeared in-focus in two separate reconstructed planes (**Fig. 2** and **Fig. 3** on the left). This advantage of in depth localisation of features that BT provides might be helpful in biopsy guidance and breast operation planning.

The detectability of the mammographic findings of the phantom from the two imaging modalities was evaluated visually and quantitatively. Visual assessments of the reconstructed slices showed superiority in the case of phase contrast BT. The nylon spheres mimicking masses with different diameters appeared in the phase sensitive images with sharper edges compared to those of conventional ones (**Fig. 4**). As seen in **Fig. 4d-f**, for attenuation contrast images the decrease in the size of the spheres resulted in inferior detectability of those features. Especially the sphere of 2.4 mm diameter (**Fig. 4d**) is not easily distinguished among the homogeneous background. In phase contrast images, the spheres appear sharper with more intense edge enhancement and even the smallest one is clearly depicted (**Fig. 4a**). The same stands for the fibers. However, for the CaCO_3 specs visually identified differences were not significant between the two modalities.

The diagnostic approach to breast calcifications is to analyse the morphology, distribution and sometimes change over time. The form or morphology of calcifications is the most important factor in deciding whether they are typically benign or of suspicious morphology according to Bi-RADS 2013 [31]. Also masses can be categorised according to their margins and shape. The superiority of phase sensitive BT in visualising stronger edge enhancement might be critical for the characterisation of breast abnormalities.

The results of visual assessments come in agreement with the quantitative analysis. Line profiles taken across three fibers and one sphere (**Fig. 5**) indicated superiority of phase contrast BT over conventional BT in the detectability of these features. Line profiles of

this modality clearly show the position of the fibers and the sphere inside the phantom. This clear appearance of a structure over the background, in the case of phase sensitive BT images, is due to the edge-enhancement effect. This outcome could provide ancillary information for digital segmentation applications and for computer-aided detection. Moreover, conventional BT planes suffer from background noise (quantum noise) and one of the reasons could be the lower dose level used.

The improved image quality of phase contrast BT over conventional BT is confirmed by the CNR and FOM values presented in **Table 1**. Low and high contrast features exhibited higher FOM values in phase sensitive BT. This is an important result for breast imaging, since the enhanced contrast of low contrast features as well as the clear visualisation of CaCO_3 specs is desired. As expected, high contrast features demonstrated significantly higher values of CNR and FOM compared to low contrast features in both imaging cases. For the nylon spheres, and as their diameter increased from M1 to M3, the FOM values increased. The opposite stands for the CaCO_3 specs, where the increase of their size from C1 to C3 resulted in decreased FOM values. This could be a result of the smaller ROI size that for specs varied from 12 to 104 pixels, whereas for spheres varied from 911 to 4250 pixels.

Synchrotron radiation performance has been found to be advantageous for phase sensitive imaging; however its use is limited for research. Therefore, in the future, alternative types of phase contrast imaging that could be applicable in clinical settings should also be studied and evaluated. **R**

Conflict of interest

The authors declared no conflicts of interest.

Acknowledgements

Funding: This research has been co-financed by the Greek State Scholarship Foundation (I.K.Y.) through the Operational Program “Education and Lifelong Learning”.

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Daskalaki A, Messaris G, Pallikarakis N. A study on phase sensitive imaging for breast tomosynthesis applications. *Hell J Radiol* 2019; 4(4): 18-26.