Contrast detail phantoms for X-ray phase-contrast mammography and tomography

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Abstract. Primary goal of this study is to investigate the visibility of low-contrast details of different size on images obtained at conventional mammography unit, and at a monochromatic synchrotron radiation source, in absorption based and phase contrast imaging setups. For this purpose, three physical phantoms made of paraffin as a bulk material were used. They embedded various low contrast features. Single projection images were acquired with the GE Senographe mammography unit and at the beamline ID17, ESRF, Grenoble. Comparison of images showed that images obtained in a phase contrast mode have more visible details than the images acquired either in absorption mode at the synchrotron or at the conventional x-ray mammography unit. Analysis for δ and μ suggests that paraffin may be a suitable material for the manufacturing of tissue-mimicking phantoms dedicated to phase contrast applications. Results will be exploited in the development of a dedicated phantom for phase contrast imaging.

Keywords. Phase contrast, breast phantoms, phantom materials.

1 Introduction

Phase-contrast (PhC) mammography and tomography are emerging alternative approaches to the absorption based mammography, digital breast tomosynthesis and breast computed tomography. Indeed, x-ray PhC imaging is a technique that is based not only on x-ray attenuation but also on the x-ray phase change related to diffraction and refraction effects during x-ray propagation in the tissue. The advancement in the development and the clinical implementation of this imaging technique is related to the development of new physical phantoms which correctly reflect the phase change characteristics of real breast tissues.

Nowadays, physical phantoms dedicated for testing the performance of x-ray breast imaging techniques are mostly suitable for absorption imaging. These physical phantoms reflect the photon absorbing and scattering properties of

the various breast tissues, rather than their phase contrast properties. The analysis of tissue simulating materials used for breast imaging showed that the commonly used PMMA substitute exhibited δ greater than the fibroglandular tissue by ˜12% [1]. Although several materials exhibited δ between that of adipose and fibroglandular tissue, there was an energy mismatch in terms of equivalent fibroglandular weight fraction between δ and μ for these materials. These results as well as the lack of up-to-date proper physical phantoms, cause the investigators to use tissue breast samples with and without breast cancers.
The aim of this investigation is related to the design and fabrication of suitable phantoms for x-ray breast imaging in absorption and phase-contrast modes, and to their test in a series of imaging studies with coherent monochromatic x-rays and with an incoherent polychromatic source.

2 Materials and Methods

2.1. Phantoms. Three physical phantoms that differ in their complexity were manufactured and used for the experimental work: (a) a homogeneous paraffin phantom of size 60mm × 40mm × 25mm with three water spheres placed at different heights, (b) a phantom with 12 nylon wires with diameters between 0.08 mm and 0.4 mm embedded in a paraffin slab of size 60mm x 60mm x 20mm, and (c) a paraffin phantom (60 mm x 60 mm x 28 mm) filled with water spheres. Photos of these phantoms are shown in fig 1.

(a) (b) (c) (d)

Fig. 1. Photographs and sketches of the physical phantoms used in the experimental work: (a) arrangements of the nylon fibers with diameters ranging from 0.08 mm to 0.40 mm; (b) phantom with nylon fibers embedded into a paraffin mixture; (c) water spheres embedded within a paraffin slab.

2.2. X-ray imaging systems. Images of the physical phantoms were acquired with a GE Senographe SD digital mammography unit featuring a detector with a pixel size of 0.1 mm × 0.1 mm and fully automatic exposure. The tube voltage was 28 kV (Mo/Rh), the source to detector distance was

660 mm, while the incident exposure depended from the phantom thickness (adjusted automatically). The three phantoms were also imaged at the ID17 ESRF [2]. The distance between the accumulation-ring source and the detector was about 155 m. The imaging protocol included acquisition of two images of each sample: one in PhC mode and one in absorption mode. To obtain a PhC image, the sample was placed approximately 11 meters far from the detector. To obtain pure attenuation type of images, the sample was moved as close as possible to the detector. Due to geometry limitations (mechanical construction of the sample carrying platform and the detector holder) the minimum distance was 17 cm. Changing the sample location, while keeping the detector position fixed with respect to the one of the source guaranteed the same x-ray beam properties, while obtaining the two different type of images.
At ESRF, the detector was a high resolution, fast readout low noise 'FReLoN' CCD camera with 2048 x 2048 pixels and pixel size of 47 µm x 47 µm.

3 Results & Discussion

Images of the paraffin phantom (fig. 1f) with the three water spheres acquired with the three different setups are shown in fig 2a-c, along with corresponding normalized intensity profiles (fig 2e-f), taken across the images of the central sphere.

It can be observed that the images acquired with the dedicated mammography unit and the one acquired at the ID17 in absorption mode are similar in their visual appearance. The evaluation of the corresponding profiles that were taken across the middle sphere, however, shows signal enhancement at the edges of these spheres in the case of the synchrotron beam (SR) beam (fig 2b) compared to the conventional radiographic image (fig 2a). This is expected, since the use of SR beams results in sharper edges of the features on the images [3] mainly due to the slit geometry that results in scatter rejection as well as elimination of the soft x-rays that are present in the polychromatic spectrum of the conventional mammography unit. The image acquired in a PhC mode (fig 2c) shows much more details which were not visible in images acquired in absorption mode.

The water spheres in PhC images are characterized by improved contrast and visualization due to the edge enhancement as a consequence of the fringes around the details. At the same time, the small air bubbles are very well visualized in this PhC mode, while in contrary, they fail to be visualized on images acquired in absorption mode. This is well seen in the normalized intensity profiles, integrated vertically over four lines from the corresponding digital images. The visibility of object edge, calculated from these two profiles, as $V_{edge} = (S_{max}-S_{min})/(S_{max}+S_{min})$ [4], with S_{max} and S_{min} denoting the maximum and the minimum signal intensities, respectively, observed in the region of the sphere border was 12% in PhC mode, while in the absorption mode, calculated only for the SR setup, this value was 2%.

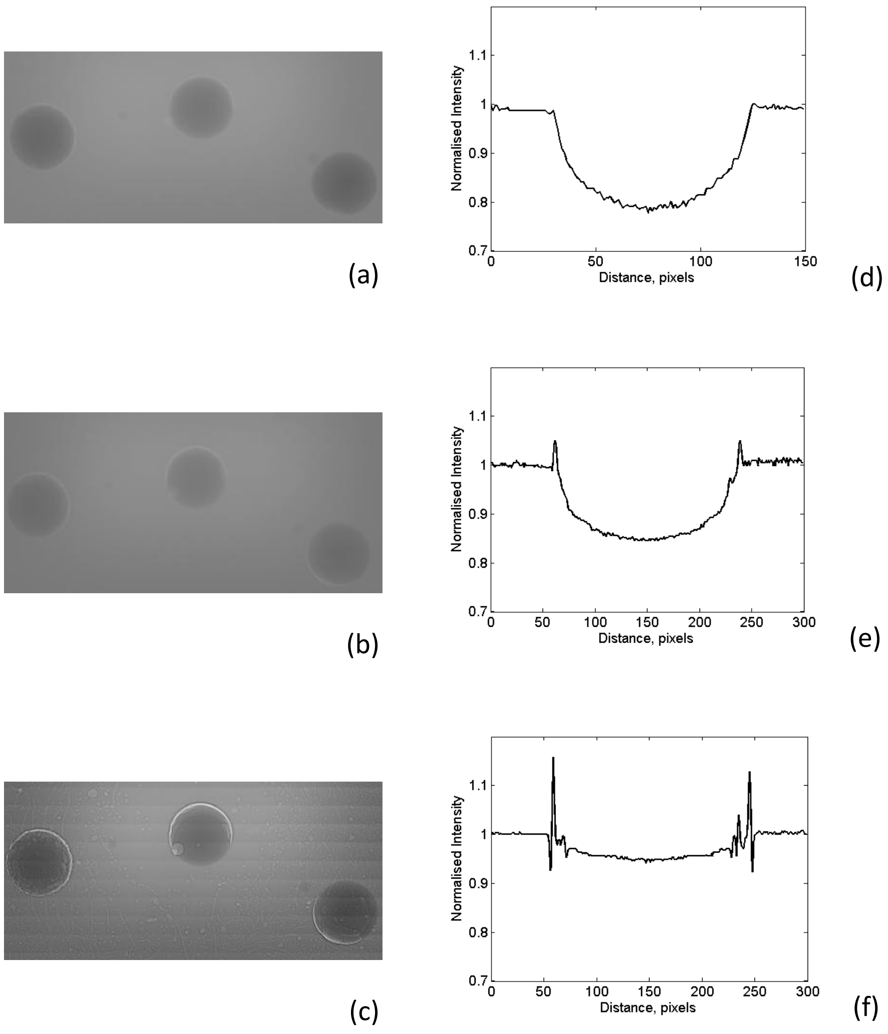


Fig. 2. 2D images (a, b, c) and corresponding line profiles (d, e, f) (taken across the middle sphere) of the paraffin slab with the three water-based spheres. The images were acquired with (a) a GE Senographe unit at 28 kV, and (b, c) at the ESRF beamline ID17 at 25 keV.

The benefits of the PhC effects are obviously in enhancing the borders between the different tissues. That is why a specific figure of merit is introduced (the edge contrast) and used to quantify the impact. For the used phantoms such enhancement is expected. In reality, the transition from a healthy to malignant tissues is smoother and such a significant improvement would probably not be observed. This needs to be confirmed in practice and it is planned as a part of the currently running Maxima project [5]. For microcalcifications though, the PhC effect is expected to improve the detectability significantly.

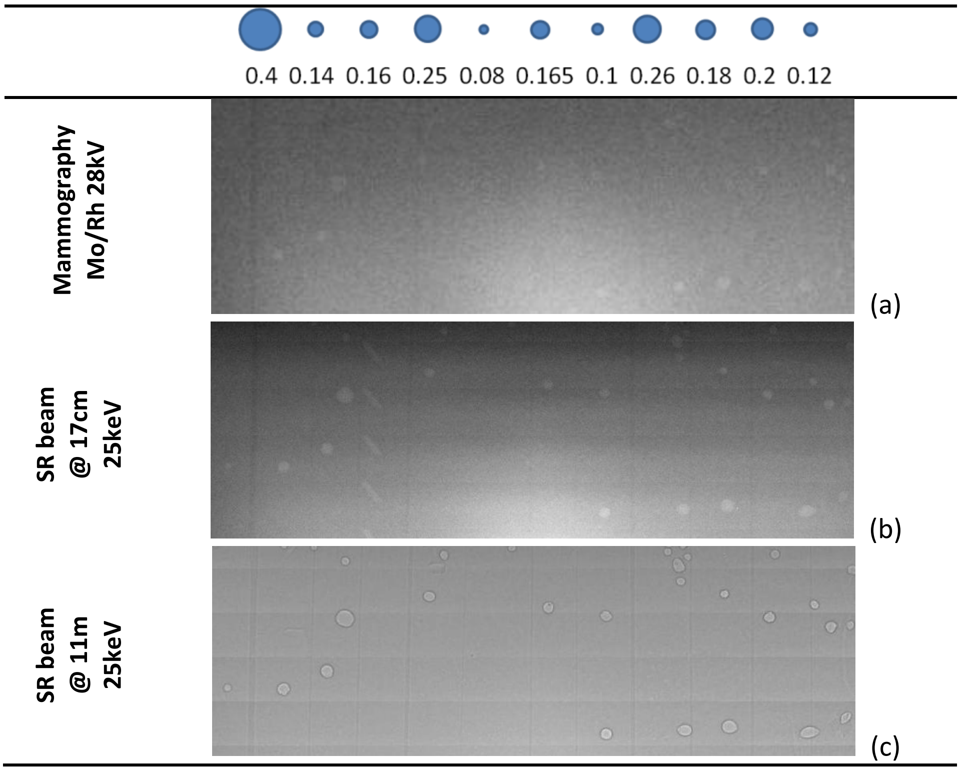


Fig. 3. Projection images of the paraffin phantom with the nylon wires acquired with (a) polychromatic 28 kVp Mo/Rh, and monochromatic 25 keV in (b) absorption and (c) PhC modes.

Regions of interest from the radiographic images acquired from the paraffin phantom with the twelve nylon wires (fig1-a, b) are shown in fig 3a-c. It can be observed that the visible nylon wires on the radiograph obtained from the conventional mammography system were these with a diameter between 0.25 mm and 0.4 mm (fig 3a). The image obtained at absorption mode on the

SR facility shows improved visualization of these nylon wires as well as some other nylon wires were visible (fig 3b). Specifically, nylon fibers with diameters greater than 0.2 mm were well visualized. The nylon fibers with a diameter between 0.16 mm and 0.2mm were slightly visible, while these with a diameter smaller than 0.16 mm were not visually depicted. The image, acquired in a PhC mode (fig 3c) is characterized with great nylon wire contrast improvement compared to the previous two images. All nylon wires were very well visualized. It should be noted that the incident dose was approximately equivalent in all cases. The quantitative analysis in terms of a comparison of profiles taken across the image confirms that the use of PhC setup results in higher image quality compared to the absorption setup realized either at SR facility or at conventional mammography units.

Figure 4 shows the comparison of 2D images obtained in absorption and PhC modes for the heterogeneous paraffin phantom shown in fig 2e. The visibility of the features, i.e. the water based spheres in the paraffin phantom and especially the edges are much improved in a PhC mode (fig 4c) compared to the images acquired in the absorption mode, which demonstrate similar visual appearance.

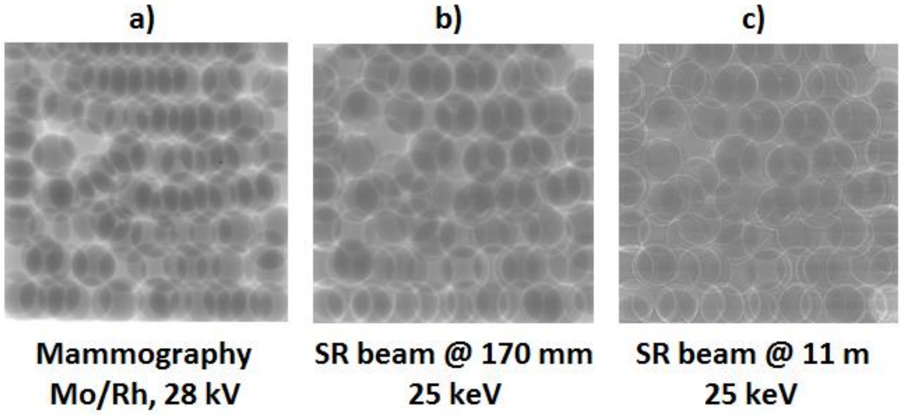
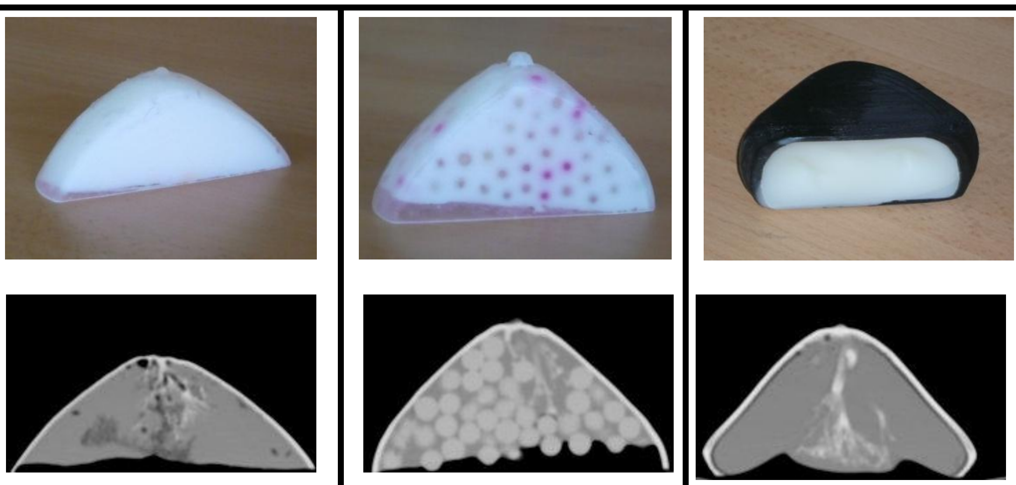


Fig. 4. Projection images of the paraffin phantom with the nylon wires acquired with (a) polychromatic 28 kVp Mo/Rh, and monochromatic 25 keV in (b) absorption and (c) PhC modes.

The design of this phantom included paraffin container filled with water spheres. The combination used in this phantom may be suitable for preparing physical phantoms dedicated to phase contrast studies.

Linear attenuation coefficient and refractive index decrement of paraffin-wax have been evaluated to be close to the corresponding coefficients of the adipose tissues for monoenergetic beam of 25keV. The values for μ and δ are

0.3 cm^{-1} and $3.55x10^{-7}$, respectively. Besides, the paraffin is handled more easily compared to other materials like the epoxy resin with fewer defects that may be introduced during their manufacturing. Paraffin wax has an elemental composition of 15%H and 85%C, while the density is 0.93 g/cm^3. It can be used successfully to mimic the adipose in a physical phantom dedicated for phase contrast effects in future studies.



(a) (b) (c)

Fig. 5. In-house developed breast phantoms (upper row) and their tomograms shown in the second row.

Development of a dedicated phantom for further research in this field is necessary. We are currently investigating the most appropriate materials to be used for the production of such a phantom. Amongst them are also epoxy resins, polylactide, leaf lard, as well as a mixture of epoxy and silver particles. Preliminary phantoms have been already developed (basic material is from lard-fig 5a,b and paraffin-fig 5c) and scanned at CT facility (fig 5, second row).

Further development and optimisation of such phantoms will include the use of modelling and simulation. These approaches will accelerate the process of development of a suitable physical phantom for phase contrast imaging.

4 Conclusions

This paper presented a comparative study of images from ad-hoc phantoms obtained at conventional mammography unit and at SR facility in both, absorption and PhC mode. Comparison of 2D images showed that images obtained in a PhC mode depicts much more details than the images acquired in absorption mode at the synchrotron and the conventional x-ray mammography unit. Results will be exploited in the development of a dedicated phantom for phase contrast studies as well as for setting a future experimental setup for phase contrast tomosynthesis.

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