Breast Computed Tomography with the PICASSO Detector: A Feasibility Study

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Abstract

The SYRMEP (Synchrotron Radiation for Medical Physics) collaboration has performed, for the first time in the world, a clinical program of mammography with synchrotron radiation. This program provided excellent results, although utilizing a commercial screen-film system as a detector. The PICASSO (Phase Imaging for Clinical Application with Silicon detector and Synchrotron radiation) project has developed a detector prototype capable of fully exploiting the peculiar characteristics of the synchrotron source, utilizing silicon microstrip sensors illuminated in the edge-on geometry and operated in single-photon counting. In this paper the potential of the PICASSO detector in breast-CT was evaluated by means of custom phantoms. Very encouraging results have been obtained with severe dose constrains as far as both spatial and contrast resolution are concerned. Moreover, the capability of detecting phase contrast effects was demonstrated, albeit with a higher delivered dose.

Key words: Silicon microstrip detector, Synchrotron Radiation, Mammography, Breast Computed Tomography

1. Introduction

The SYRMEP (Synchrotron Radiation for Medical Physics) collaboration has performed a clinical program of Mammography with Synchrotron Radiation (MSR) for the first time in the world. In these last years, a clinical series of patients underwent examinations of phase-contrast MSR at the SYRMEP beamline of the Synchrotron Radiation (SR) facility Elettra in Trieste. The SR beam at SYRMEP is particularly suited to mammography since it is monochromatic (in the energy range from 8.5 to 35 keV), laminar (with a cross section of 4 x 210 mm^2), high-flux (in the order of 10^8 photons/mm^2/s at 17 keV), and, moreover, it allows phase-contrast x-ray imaging [1].

The clinical program utilized a conventional screen-film system to collect MSR images [2]. In fact, the Ethics Committee recommended the use of a commercially available image receptor for clinical mammography, but digital detectors possessing adequately high spatial resolution (pixel size not larger than 50 μm) and sufficient field of view were not commercially available at the outset of the study. Thus, a conventional screen-film system was utilized due to its high intrinsic spatial resolution, which is mandatory to reveal phase-contrast effects [3].

This program provided excellent results, showing that MSR outperformed a state-of-the-art conventional mammographic system in the patient series. However, the utilization of a custom digital detector, capable of fully exploiting the peculiar characteristics of the SR source, could further improve MSR. Therefore, the PICASSO (Phase Imaging for Clinical Application with Silicon detector and Synchrotron radiation) project, funded by the Italian National Institute of Nuclear Physics (INFN), has developed a detector prototype based on silicon microstrip sensors illuminated in the edge-on geometry and operated in single-photon counting. The prototype meets the requirements for clinical MSR as far as spatial resolution, contrast resolution, efficiency and acquisition speed are concerned, showing outstanding results on phantom studies in planar imaging [4, 5, 6].

Moreover, since the patient support allows rotation around the breast axis, the PICASSO detector could be utilized, in principle, to perform 3D imaging techniques, such as breast-CT (Computed Tomography) or tomosynthesis. As a matter of fact, due to the laminar nature of the SR beam, the acquisition of a full breast in CT is impractical. However, breast-CT could be utilized as complementary to planar MSR, focusing on a limited number of slices which correspond to questionable or suspicious abnormalities in the planar mammographic image. In this paper a feasibility study is presented, where the potential of the PICASSO detector in breast-CT is evaluated by means of custom phantoms.

2. Material and Methods

2.1. The PICASSO detector

The PICASSO detector is based on 50-μm-pitched silicon microstrip sensors, arranged in the edge-on configuration, i.e. with the photons reaching the sensor on the thin side, parallel to the strips (Fig. 1). This geometry matches the laminar cross section of the beam providing a pixel array, where the aperture

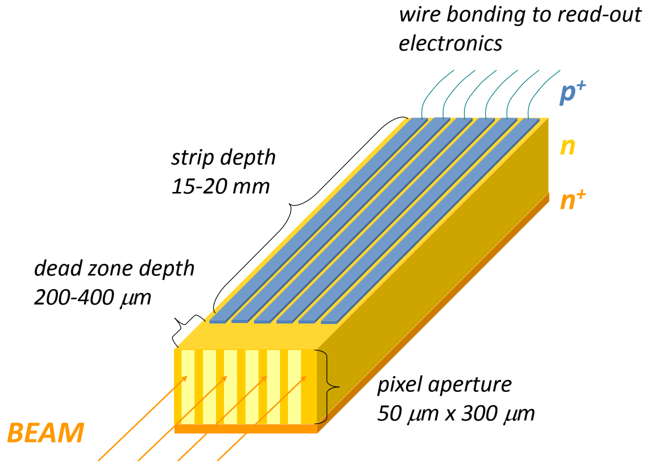

Figure 1: A sketch depicting the edge-on geometry of the PICASSO detector.

of each pixel is determined by the strip pitch (in width) and the sensor thickness (in height). Moreover, edge-on geometry assures high detection efficiency, since photons can be absorbed in the whole detector depth (15-20 mm). As a matter of fact, an undepleted entrance window cannot be avoided, in order to limit dark current. This "dead zone", where the impinging photons may interact without being detected, is only approximately 0.2 mm deep in the PICASSO prototype, and therefore does not spoil the efficiency, which is of the order of 80% in the range from 19 to 21 keV [5].

The final detector assembly will comprise 4 identical layers 210 mm wide, arranged in two couples deployed along the beam propagation direction. Each layer results from the juxtaposition of two silicon microstrip sensors produced by Hamamatsu (Hamamatsu Photonics, K.K., Hamamatsu City, Japan), one 90 mm x 15 mm x 0.3 mm and the other 120 mm x 20 mm x 0.3 mm (width x depth x height). Thus, each layer layer is around 210 mm in width, for a total of 4200 pixels. The prototype utilized in this study consists of two such layers, held one on top of the other by a high-precision mechanical system, with a spacing of 0.3 mm between them. However, the images presented have been acquired by illuminating only part of one layer, namely the 120-mm-wide sensor of the bottom layer. As a consequence, CT images consist of a single slice.

The read-out electronics is operated in single-photon counting and is based on the Mythen-II ASIC developed by the Paul Scherrer Institut (PSI) detector group [7]. The ASIC has been designed for the Mythen detector, which is widely used for SR powder diffraction experiments [8]. When applied to the PICASSO detector at the SYRMEP beamline, it proved capable of handling more than 1M incident photons per pixel per second, thus fulfilling the flux requirements for mammography. Moreover, Mythen-II features a 6-bit threshold trim DAC, which is fundamental to equalize the channel sensitivity, thus preserving the excellent contrast resolution provided by single-photon counting. All the data herein presented have been acquired with a control system based on custom control boards and on a VME I/O standard. However, a more compact PICASSO Control System (PCS) is being developed in collaboration with the PSI detector group. The new PCS distributes the bias voltage as well as the control signals and communicates with a PC via a client/server architecture based on TCP/IP.

2.2. Custom Phantoms and CT methods

Three phantoms have been designed and manufactured in order to perform the feasibility study. To first approximation, all of them could reasonably reproduce an uncompressed breast as far as size and x-ray absorption are concerned. The first, which will be referred to as T86-CR (contrast resolution) was obtained drilling 12 holes of 5 mm in diameter and 5 mm deep on a 70-mm-diameter, 10-mm-thick PMMA disc and filling the 12 wells with different mixtures of water and alcohol. The linear attenuation coefficient of PMMA lies in between those of water and alcohol (at 26 keV, they can be quoted as 0.434 cm^{-1}, 0.475 cm^{-1}, and 0.295 cm^{-1}, respectively). Thus, adequate mixtures were prepared in order to obtain tiny differences in contrast with respect to PMMA.

The second phantom, which will be referred to as T86-SR (spatial resolution), consisted in a 70-mm-diameter, 10-mm-thick PMMA disc, where 7 groups of 5 holes had been drilled, each group respectively with a diameter of 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, and 1.5 mm. The air-filled holes represent high-contrast details with respect to the PMMA background, and their visibility can be used to measure the capabilities of the detector on small-sized details.

The third phantom will be referred to as T86-B (breast phantom), since its shape approximately reproduces that of an uncompressed breast. It was obtained by filling a cup with a bottom diameter of 80 mm and a top diameter of 120 mm by means of glycerol. Quartz microspheres were included to mimic microcalcifications, while 3 Polyoxymethylene plastic cylinders (Delrin by DuPont, Wilmington, Delaware, US) 5 mm, 7 mm, and 10 mm in diameter were added to simulate masses. In fact, Delrin versus glycerol yields approximately the same contrast of a breast-tumor mass on a glandular tissue background.

All the images have been acquired utilizing the tomographic set-up of the SYRMEP beamline [9]. Since the beam is parallel and monochromatic, CT was performed spanning an angular interval of 180°. CT slices were then reconstructed by means of standard back-projection algorithms. In all cases, the dose was considered a relevant issue, and the images were acquired seeking the best compromise between delivered dose and image quality. Such conciliation often required acquiring the single projections with a low statistics and then re-binning the raw images prior to reconstruction, in order to increase the signal-to-noise ratio. Since this study is based on phantoms, all the dose values quoted refer to air entrance dose: however, it is worth noticing that the absorbed dose and the mean glandular dose, which are relevant parameters in mammography and breast-CT, are only a fraction of the absorbed dose quoted herein.

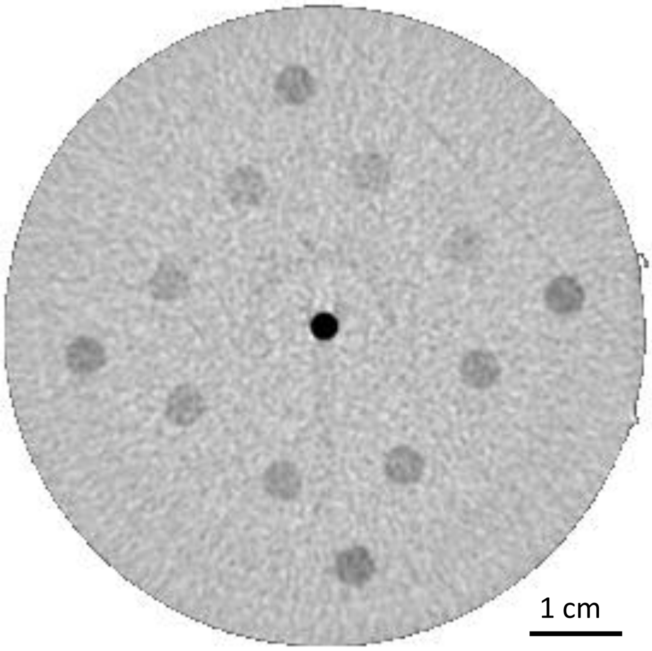

Figure 2: CT image of the T86-CR phantom, acquired at 26.6 keV delivering an air entrance dose of 10.4 mGy. The black circle in the centre corresponds to an empty borehole.

3. Results

A slice of the T86-CR phantom is shown in Fig. 2. The image has been obtained by applying filtered back-projection to a dataset of 360 projections acquired at 26.6 keV with an angular step of 0.5°. Prior to reconstruction, in order to increase the signal-to-noise ratio, each projection has been re-binned by a factor of 6, i.e. 6 consecutive pixels 0.05 mm wide were averaged to yield a pixel virtually 0.3 mm wide. This allowed us to keep the air entrance dose at the practical value of 10.4 mGy. All the details are clearly visible.

In Fig. 3, a detail of the T86-SR phantom is shown, which includes the two groups of 0.5-mm-diameter and 0.7-mm-diameter holes, acquired at 26.4 keV. Moving from Fig. 3a to Fig. 3e, the number of projections utilized to span the 180° angular interval is reduced. The air entrance dose *per projection* was kept at a constant value of 0.065 mGy. The total air entrance dose is simply the product between the dose per projection and the number of projections: thus, reducing the number of projections reduced the dose accordingly. More in detail, Fig. 3a was acquired with 360 projections (0.5° angular step) and 24 mGy air entrance dose, Fig. 3b with 180 projections (1° angular step) and 12 mGy, Fig. 3c with 90 projections (2° angular step) and 5.8 mGy, Fig. 3d with 45 projections (4° angular step) and 2.9 mGy, and Fig. 3e with 30 projections (6° angular step) and 1.9 mGy. In all cases, prior to reconstruction, in order to increase the signal-to-noise ratio, each projection has been re-binned by a factor of 4, to yield a pixel virtually 0.2 mm wide. The visibility of the holes clearly diminishes when reducing the number of projections: the 0.7-mm-diameter holes are anyway visible even with only 30 projections in Fig. 3e, while the 0.5-mm-diameter holes are barely visible in the 45 projections image and nearly vanish in the 30 projections.

Fig. 4 depicts a detail of the T86-B phantom including the 10 mm Delrin cylinder in the glycerol background, acquired at 26.6 keV, with a object-to-detector distance of respectively 205 mm (Fig. 4a) and 970 mm (Fig. 4b). In these conditions, the image in Fig. 4a is dominated by absorption, while Fig 4b highlights phase-contrast effects. In both cases, 180 projections (1° angular step) were acquired and no re-binning was performed, since a high spatial resolution is needed in order to preserve phase-contrast effects. The air entrance dose was of the order of 100 mGy. Noticeably, the Delrin cylinder is not visible in the absorption image (Fig. 4a), while it can be clearly identified in the phase-contrast image (Fig. 4b) thanks to the edge-enhancement effect.

4. Discussion

The three custom phantoms were designed to explore the contrast resolution, the spatial resolution and the overall performance of the PICASSO detector for applications in breast-CT. Since the breast is one of the most radiosensitive organs, the delivered dose is fundamental, and a compromise between dose and image quality must be achieved. We performed this feasibility study at approximately 26.5 keV, an energy which delivered the maximum figure of merit in previous studies [10].

The T86-CR (contrast resolution) phantom highlighted the possibility of detecting rather small contrast differences delivering a very sensible air entrance dose in the order of 10 mGy. In the T86-SR (spatial resolution phantom) the dose was further reduced showing that high contrast details 0.7 and 0.5 mm in diameter can be detected with an air entrance dose of only 3 mGy. In both cases, the PICASSO detector proved capable of providing an excellent uniformity in the acquisition of the single projections and of the whole dataset, uniformity which is essential to avoid artifacts in the CT reconstruction.

The T86-B phantom, which was designed to mimic the very subtle difference in contrast between healthy glandular and breast cancer tissues, highlighted the importance that phase effects can play in breast-CT. In fact, the Delrin cylinder simulating a tumor mass was not visible in absorption, and it could be identified due to the edge-enhancement effect in phase contrast. The detection of phase contrast effects was possible thanks to the high spatial resolution of the PICASSO detector, which is consistent with the 50-μm-pitched silicon microstrip sensors [6]. The air entrance dose delivered in this case (of the order of 100 mGy) was remarkably higher than in the previous cases, because no re-binning was performed in order to preserve the maximum spatial resolution. However, this high value is partially due also to the composition of the breast phantom, which simulated glandular tissue and thus resulted more absorbing than a real breast (which is modeled with 50% glandular and 50% adipose tissue).

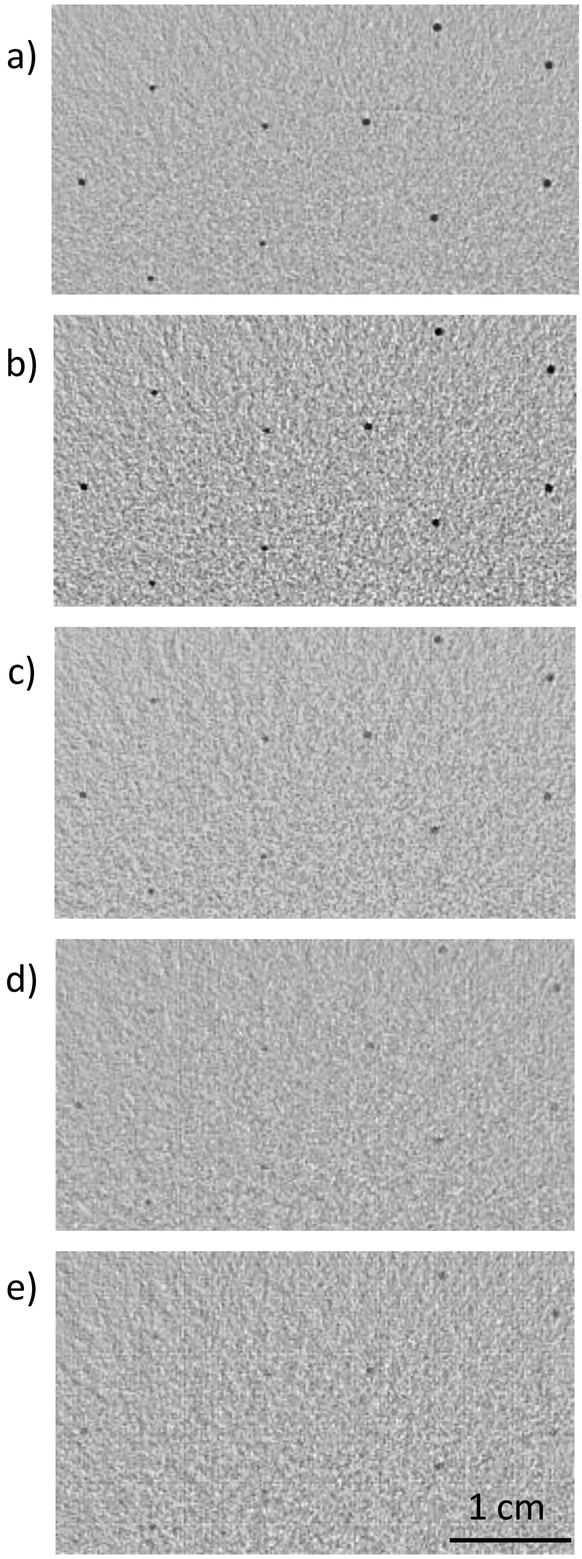

Figure 3: Detail of the T86-SR phantom, including the two groups of 0.5-mm-diameter and 0.7-mm-diameter holes. Moving from Fig. 3a to Fig. 3e, the number of projections was respectively 360, 180, 90, 45, and 30. In all cases, the air entrance dose was 0.065 mGy per projection: thus, the total air entrance dose was 24, 12, 5.8, 2.9, and 1.9 mGy, respectively.

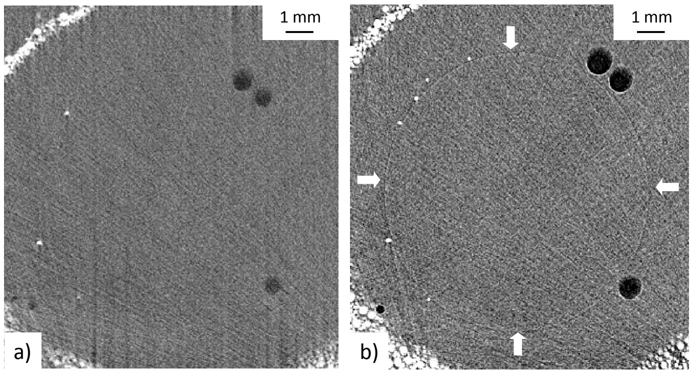

Figure 4: Detail of the T86-B phantom depicting the 10 mm Delrin cylinder in the glycerol background. The Delrin cylinder is not visible in the absorption image (4a), while it can be clearly identified (arrows) in the phase-contrast image (4b) thanks to the edge-enhancement effect. The white specks are quartz microspheres which mimic microcalcifications, while the black circles are air bubbles.

5. Conclusions

The feasibility study presented herein aimed at exploring the potential of the PICASSO detector in breast-CT, a technique which could be utilized at the SYMREP beamline as complementary to planar mammography, focusing on a limited number of slices which correspond to questionable or suspicious abnormalities in MSR. Very encouraging results have been obtained as far as both spatial and contrast resolution are concerned. Moreover, the capability of detecting phase contrast effects was demonstrated, albeit with a dose of about 100 mGy, which is about 4 times higher of that reported in the first Breast-CT clinical experience [11]. However, this result is partially due to the limitations of our phantom and further study is needed to optimize the dose in phase contrast CT images. Overall, PICASSO demonstrated remarkable imaging performances in CT of large objects with high spatial resolution and severe dose constraints, paving the way for significant applications in medical and multidisciplinary research.

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