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Design, Construction, and Initial Results of a Prototype Multi-Contrast X-Ray Breast Imaging System

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Abstract

By integrating a grating-based interferometer with a clinical full field digital mammography (FFDM) system, a prototype multi-contrast (absorption, phase, and dark field) x-ray breast imaging system was developed in this work. Unlike previous benchtop-based multi-contrast x-ray imaging systems that usually have relatively long source-to-detector distance and vibration isolators or dampers for the interferometer, the FFDM hardware platform is subject to mechanical vibration and the constraint of compact system geometry. Current grating fabrication technology also imposes additional constraints on the design of the grating interferometer. Based on these technical constraints and the x-ray beam properties of the FFDM system, three gratings were designed and integrated with the FFDM system. When installing the gratings, no additional vibration damping device was used in order to test the robustness of multi-contrast imaging system against mechanical vibration. The measured visibility of the diffraction fringes was $23 \pm 3\%$, and two images acquired 60 minutes apart demonstrated good system reproducibility with no visible signal drift. Preliminary results generated from the prototype system demonstrate the multi-contrast imaging capability of the system. The three contrast mechanisms provide mutually complementary information of the phantom object. This prototype system provides a much needed platform for evaluating the true clinical utility of the multi-contrast x-ray imaging method for the diagnosis of breast cancer.

1. INTRODUCTION

Due to its compatibility with medical-grade x-ray tubes and detectors, grating-based x-ray phase contrast imaging is considered a promising and viable approach to supplement conventional medical x-ray imaging for improved lesion detectability and soft tissue differentiability.¹⁻³ The grating-based method also provides x-ray dark field images, along with the phase contrast and conventional absorption contrast images, from the same data acquisition process with perfect co-registration. This multi-contrast imaging capability is particularly attractive for breast cancer imaging, due to the high sensitivity of the dark field mechanism to microcalcifications, and the improved soft tissue contrast sensitivity provided by the phase contrast mechanism.

In principle, any conventional medical x-ray imaging system can be modified to become a multi-contrast imaging system: the only major hardware modification is the introduction of a

so-called Talbot-Lau interferometer, which is composed of an x-ray diffraction grating G1, a source-splitting grating GO, and an analyzer grating G2. In practice, the construction of a clinically-compatible multi-contrast imaging system is subject to a series of technical constraints. For the specific purpose of breast cancer imaging, these constraints often include the limited source-to-detector distance, mechanical vibration and instability of the hardware system, unique spectra and beam filtration tailored specifically for mammographic imaging, etc. Previous research on multi-contrast x-ray breast imaging was predominantly synchrotron- and benchtop-based.⁴⁻⁶ Although they have generated many promising results, these system are quite idealized (relatively long x-ray free propagation distance, low system vibration, etc.), compared with a true clinically-compatible system. Consequentially, to what extent these research findings are directly applicable to clinical breast cancer imaging remains questionable, due to lack of the complete consideration of the constraints and technical considerations encountered in a true clinical setting.⁷

The purpose of this work was to develop a multi-contrast x-ray breast imaging prototype based on a clinical full field digital mammography (FFDM) system. This prototype system offers an opportunity to evaluate the true clinical utility of multi-contrast x-ray breast imaging through human subject studies, which is unlikely to be accomplished by using benchtop systems. In this paper, the design and construction of this prototype system are described, and preliminary phantom results generated by the system are presented.

2. SYSTEM DESIGN

The FFDM system used in this work (Senographe 2000D, GE Healthcare) features a dual track (molybdenum/rhodium) rotating anode (9000 RPM max) x-ray tube with 0.15 mm×0.3 mm nominal focal spot, 0.03 mm molybdenum/0.025 mm rhodium interchangeable beam filter, a 5 kW high frequency generator with an output range of 22-49 kV and 4-500 mAs, a 19 cm ×23 cm flat panel digital detector (CsI on top of amorphous silicon) with 100 μ m pixel size and 14 bit depth, a C-arm gantry that houses the tube and detector, and other peripheral equipments such as the image acquisition workstation. The C-arm gantry can rotate $\pm 180^\circ$, but the source-to-detector distance (SDD) is fixed at 66 cm, which is significantly shorter than majority of the benchtop-based multi-contrast systems reported in literature.

The small SDD imposes one of the major challenges for the grating design, since the required pitch of each grating is approximately proportional to SDD. Meanwhile, the finite precision of the current microfabrication technology determines that, the pitch can not be arbitrarily reduced without suffering structural collapse or nonuniform metal filling. Therefore, the design of the grating interferometer was primarily constrained by the 66 cm SDD and the existing commercial grating fabrication technology. Specifically, the limiting aspect ratio (structure height divided by structure width) of the current fabrication technology is about 50, and the smallest grating structure is about 1 μ m.

Based on these technical considerations and constraints, a set of three gratings were designed. Table 1 summarizes the major specifications of the three gratings, while Table 2 summarizes the overall system geometry. The maximal grating aspect ratio is 41.7, which is

within the limit of 50. Similarly, the smallest width of the grating structure is $2.4\ \mu\text{m} \times 50\% = 1.2\ \mu\text{m}$, which is above the minimal threshold of $1\ \mu\text{m}$. The gratings were fabricated by Microworks GmbH (Karlsruhe, Germany). Figure 1 shows photos and radiographic images of the fabricated gratings. The relative variations in the pixel value of the radiographs were 0.6% for G0, 0.2% for G1, and 5% for G2, which were within the expected fabrication tolerance of 10%.

3. SYSTEM CONSTRUCTION

Following acceptance testing, the fabricated gratings were integrated into the FFD system to construct the prototype multi-contrast breast imaging system. Since the three gratings need to be aligned to be mutually collinear, at least two of the three gratings must be equipped with fine-tuning mechanisms along the roll, yaw, and pitch rotation axes. We ended up by fixing the orientation of the source grating G0, and align the other two gratings towards the orientation of G0. Kinematic rectangular optic mounts were used to provide pitch and roll adjustments for G1 and G2, with each optic mount was fixed on a goniometer that providing yaw adjustment. In addition, the G1 grating assembly also contains a linear translation stage that provides fine adjustment for the distance between G1 and G2, which directly impacts the visibility of the diffraction pattern.

To install the G1 and G2 gratings into the designated positions in the gantry, T-slotted aluminum extrusions were bolted to the detector enclosure to form an “H” shape (left image in Figure 2), allowing each component of the grating interferometer to be easily fixed in place using t-slot connectors.

The installation of the source grating G0 was quite straightforward: it was directly attached to the exit window of the beam collimator assembly using a thin (2 mm) sheet of acrylic. No translation or rotation stage was attached to G0. Once all three gratings were installed in the gantry, the orientations of G1 and G2 were adjusted until the modulation amplitude of the morié pattern captured by the detector reached the maximum. Figure 3 shows a post-alignment morié pattern; the modulation amplitude (i.e. fringe visibility) was $23 \pm 3\%$. In order to test the system stability, the morié pattern was re-captured 60 minutes later; no visible drift/shift of the fringe was observed. The relative root mean square error (rRMSE) between these two images is only 3.2%, indicating good reproducibility.

4. PRELIMINARY IMAGING RESULTS

Figure 4 shows first batch of imaging results from the constructed prototype system. The image acquisition used 36 kVp, 90 mAs, Rh target, and Rh filter. The test phantom contains three layers of PMMA spheres and packing foams, which have very low x-ray absorption contrast but were clearly depicted in the dark field and phase contrast images. Additional results in Figure 5 further demonstrated the capability of the prototype system to generate three sets of images that provided mutually-complementary information, all from the same image acquisition process. Note that all images were acquired without bolting the gantry to the floor of the building to demonstrate the system robustness against possible mechanical vibration.

5. CONCLUSION

By integrating a tri-grating based Talbot-Lau interferometer with a commercial FFDM system, a prototype multi-contrast x-ray breast imaging system was developed. The system utilizes both the particle and wave nature of x-rays for imaging purpose, and it provides two extra sets of images (phase contrast and dark field contrast) in addition to conventional absorption contrast images, all from the same image acquisition process. Even with a very compact system geometry, satisfactory fringe visibility was achieved, and the system was found to be insensitive to the mechanical vibration of the free-standing FFDM gantry. This prototype system provides a much needed platform to directly evaluate the potential clinical utility of multi-contrast x-ray breast imaging via future human subject study.

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Figure 1.

Photographs and micrographs of the three gratings are shown in the top and middle rows, respectively. The bottom row depicts radiographs of the three gratings used to characterize the uniformity of the gratings. Units of the color bars in the bottom row are the detector output numbers.

Figure 2.
Photos of the constructed prototype system.

Figure 3.

(a) and (b) are two moiré patterns measured 60 minutes apart to demonstrate the system's stability, (c) shows experimentally measured fringe visibility map of the prototype system.

Figure 4.
First phantom results generated from the prototype system.

Figure 5. Additional results produced by the prototype system. Top row: multi-contrast images of cotton swabs; Bottom row: multi-contrast images of a murine lung specimen.

Table 1.

Grating Specifications

	Grating		
	G0	G1	G2
Pitch (μm)	20.7	4.3	2.4
Duty Cycle (%)	58	50	50
Depth (μm)	60	11.2	50
Aspect Ratio	5.0	5.2	41.7
Material	Au	Ni	Au
Diameter (cm)	3	10	5

Table 2.

System Dimensions

	<u>Distance</u>
Source to G0	19 cm
Source to Object	58 cm
G0 to G1	41 cm
G1 to G2	5 cm
Source to Detector	66 cm