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Advantages of magnification in digital phase-contrast mammography using a practical X-ray tube

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Abstract

Phase-contrast imaging with a practical cone-beam X-ray tube has been realized for clinical use in digital mammography using computed radiography (CR). To perform phase-contrast imaging, the X-ray detector must be distanced from an object so that the phase-contrast image achieves magnification; in a mammography unit dedicated to phase-contrast imaging, the magnification ratio is 1.75. When using an X-ray tube with a 0.1-mm focal spot, it appears that the penumbra in magnification blurs both projected images and the phase contrast, which generates an edge effect. However, where the sampling pitch of the CR plate is 43.75 μm, the blur stretches the width of the phase contrast so that unit pixels in the detector can capture it. Note that the width of an ideal phase contrast using an X-ray point source results in a phase contrast too narrow for detection with CR. In addition to phase contrast improving image quality, a re-scaling effect increases image sharpness in magnification. Further, image noise induced by magnification can be reduced during printing to photothermographic dry film by demagnifying the digital output image to the original image size. After demagnification by 1/1.75 from 43.75 μm in image acquisition, a 25-μm pixel size of the output image is obtained so that the spatial resolution matches that of conventional screen-film mammography. In this paper, such technical advantages of magnification in digital phase-contrast mammography are reviewed, and the image quality of phase-contrast images is discussed in light of diagnostic requirements in detecting breast cancer.

Keywords: Phase contrast; Magnification; Breast cancer; Digital mammography

1. Introduction

In the X-ray diagnosis of breast cancer, conventional screen-film (SF) mammography has long been the "gold standard." However, an alternative has been developed whose image quality equals or surpasses that of SF mammography: phase-contrast imaging. This paper presents the technical challenge of realizing phase-contrast imaging in practical digital mammography, but also presents the technical rewards of phase-contrast imaging's digital magnification with a practical X-ray tube in clinical applications.

2. Background to this study

Using monochromatic X-rays obtained from an X-ray tube after reflection from crystal monochromators, it has been shown that the refraction of X-ray increases the contrast of image boundaries [1,2], i.e. an edge effect appears due to phase contrast. Burattini et al. studied the phase-contrast imaging of breast specimens and of a lizard with monochromatic X-rays from synchrotron radiation (SR) using crystal monochromators [3]. Since that seminal study, many studies have been made of the mammographic application of phase-contrast imaging using monochromatic X-rays from SR [4–6]. In contrast, Wilkins et al. described phase-contrast imaging in an in-line configuration with polychromatic X-rays of a high degree of lateral coherence from a micro-focus X-ray tube, showing clear images of small fish due to edge effect [7]. Fitzgerald reviewed phase-contrast imaging techniques reported up to 2000, and stated that phase-contrast imaging is useful in the mammographic detection of breast cancer [8]. However, he also questioned the clinical application of the techniques he had reviewed because of the huge scale of SR facilities and because of the weakness of X-rays from micro-focus X-ray tubes designed for non-destructive testing.

A molybdenum-anode X-ray tube with a 0.1-mm focal spot is widely used for magnification mammography in medical

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facilities. For full-field mammography, the distance from the focal spot to an object is usually 0.65 m. Wu and Liu reported difficulty in obtaining high enough a lateral coherence of X-rays from such an X-ray tube in a practical mammographic configuration [9], while Gao et al. posited a high degree of coherence as a prerequisite to phase-contrast imaging [10]. Additionally, in order to perform phase-contrast imaging in an in-line configuration, the X-ray detector must be separated from the object so that phase-contrast imaging using cone-beam X-rays achieves magnification. The penumbra in magnification using an X-ray tube of a fixed-sized focal spot appears to blur the projected images [10].

Ishisaka et al. presented a new method of analyzing edge effect in phase-contrast imaging with incoherent X-rays from conventional, practical X-ray tubes [11]. Their theoretical analysis resulted in the development of phase-contrast mammography (PCM), in which a conventional mammography X-ray tube with a 0.1-mm focal spot is used [12,13]. Digital PCM systems are now used in many medical facilities in Japan and other countries [14,15].

3. A digital phase-contrast system

We have designed a digital PCM system consisting of a mammography unit, a computed radiography (CR) unit, and a photothermographic dry printer. As shown in Fig. 1, the mammography unit for phase-contrast imaging has a nominal 0.1-mm focal spot in a configuration of 0.65 m for the distance, R_1, from the focal spot to the object holder and 0.49 m for the distance, R_2, from the object holder to a storage phosphor plate holder with no anti-scatter X-ray grid. Because the phase-contrast imaging is set at 1.75 × magnification with the source-image distance (SID) of 1.14 m for full-field mammography, the storage phosphor plate used is 14 × 17 in. in size. After phase-contrast imaging, the storage phosphor plate is scanned in the CR unit by a laser spot at a sampling pitch of 43.75 μm. After image processing, the size of the acquired image is reduced 1/1.75 times to obtain object size when printed on a dry printer and where the pixel size is 25 μm in the printed dry film images.

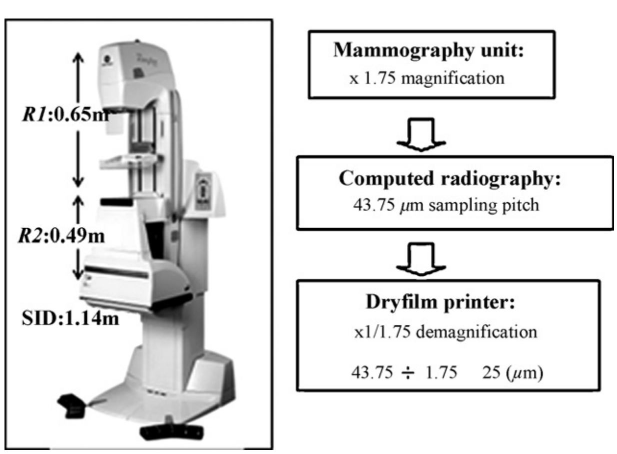

Fig. 1. Left: mammography unit dedicated to phase-contrast imaging. Right: schematic diagram of a digital PCM system.

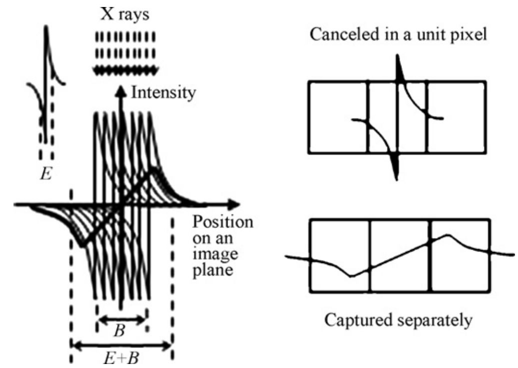

Fig. 2. Phase contrast with X-rays from a point source cannot be captured by a single unit pixel, but extended phase contrast derived from blur can be captured by a digital X-ray detector consisting of a plurality of unit pixels.

4. Phase contrast obtained with incoherent X-rays and phase contrast captured with a digital acquisition system

As reported by Ishisaka et al., the phase contrast obtained with incoherent X-rays can be simulated in ray optics, where the wave nature of X-rays is not considered because the incoherent X-rays are presumed not to interfere [13]. Phase contrast with half-width, E, shown in Fig. 2, is represented as obtained with X-rays from an ideal X-ray point source. On an image plane with blur owing to the penumbra in magnification, individual phase contrasts with half width, E, overlap each other in the range of the blur, B, and thus the half width of the phase contrast is stretched to a new half width, $E+B$ [11].

The phase contrast obtained with X-rays from an ideal X-ray point source is strong and sharp due to refraction because the X-rays are coherent. For example, the half-width, E, is simulated to be 26 μm using X-rays of 18 keV [11], when $R_1 = 1$ m and $R_2 = 0.5$ m. In this case, as shown in Fig. 2 on the right, the peak and the trough of phase contrast cancel each other out within a unit pixel of 50 or 100 μm, which are used in digital X-ray acquisition devices for medical imaging. When B is 50 μm, then $E+B$ is 76 μm. Consequently, the peak and the trough can be captured efficiently, for example, by 50-μm unit pixels, as illustrated on the right in Fig. 2, although the phase contrast is decreased by blur.

5. Image sharpness with re-scaling and edge effect

Shaw et al. reported a re-scaling effect in magnification mammography in which sharpness increases with the magnification ratio and in which blur occurs due to the penumbra [16]. Because phase-contrast mammography employs magnification, image sharpness is improved through both re-scaling and edge effect.

On the left in Fig. 3, X-ray signal profiles of object edges in images of an 8.5-mm diameter plastic fiber are presented for contact imaging and for digital PCM with 1.75× magnification. The corresponding X-ray images are shown above the profile graph. Edge effect is clearly observed in the PCM image, which draws upon both absorption contrast and phase contrast, but not in the contact image, in which only absorption contrast is used. The image sharpness of the fiber's edge is evaluated in terms of