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Diffraction Enhanced X-ray Imaging

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DISCLAIMER

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SUMMARY. Diffraction enhanced imaging (DEI) is a new x-ray radiographic imaging modality using synchrotron x-rays which produces images of thick absorbing objects that are almost completely free of scatter. They show dramatically improved contrast over standard imaging applied to the same phantoms. The contrast is based not only on attenuation but also the refraction and diffraction properties of the sample. The diffraction component and the apparent absorption component (absorption plus extinction contrast) can each be determined independently. This imaging method may improve the image quality for medical applications such as mammography.

KEY WORDS: synchrotron, mammography, diffraction enhanced imaging, DEI

INTRODUCTION

Normal medical x-ray radiography uses an area beam which, after traversing and interacting with the subject, is detected by an area detector. The interaction of x-rays with the subject is complex, involving absorption, refraction [1-2] and scattering. The scattering includes small angle scattering [3] (scattering angles less than mradians) which carries information about the subject's structure on the length scale up to microns. This information is lost in normal radiography because of its small angle nature. X-ray diffraction of perfect crystals, with its narrow reflection angular width (on the order of a few microradians) and peak reflectivity of close to unity (for Bragg diffraction), provides a mechanism for rejecting or accepting small angle scattering, thus providing additional information about the subject.

An imaging method called Diffraction Enhanced Imaging (DEI) has been reported [4] which utilizes a perfect crystal analyzer and centers around the concept of taking digital images at different analyzer positions and combining them to produce apparent absorption and refraction images of the object. It was demonstrated in experiments at the National Synchrotron Light Source that one can separate the refraction effects from the absorption by taking images at two positions on either side of the rocking curve. Objects which have different small angle scattering characteristics from their surroundings can be enhanced by taking images at suitable analyzer positions [5]. These experiments were done with standard mammography phantoms which, although suggesting the potential applicability of DEI to mammography, do not directly prove this due to anticipated differences between the phantom tumor simulation and real tumors. A new set of experiments was performed at the Advanced Photon Source (APS) to study the tissue characterization capability of DEI with biological phantoms consisting of imbedded tumors. This paper reports the preliminary results obtained in that experiment. A more detailed analysis of the results is in preparation and will be submitted for publication soon.

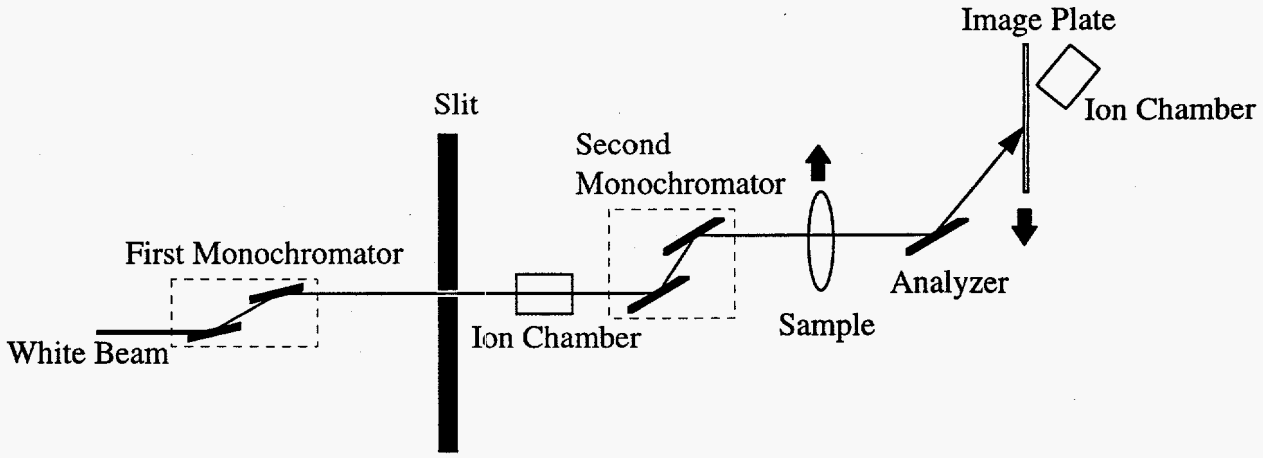

Fig.1. The setup of the experiment with an analyzer crystal

EXPERIMENTAL METHOD

The experiment was performed at the Synchrotron Radiation Instrumentation Collaborative Access Team (SRICAT) sector 1-BM-B (a bending magnet beamline) of the APS. The experimental setup is shown in Fig.1. Perfect silicon crystals in Bragg geometry were used for producing the monochromatic beam and as the analyzer. The first double-crystal monochromator was the beamline monochromator located upstream of the experimental hutch in the beamline. The [111] reflection was used for this monochromator to pre-monochromize the white beam to 18 keV and to deliver the beam into the experimental hutch. The second monochromator crystals were set to the [333] reflection. Because of the dispersion mismatch between the two monochromators and the vertical divergence of the incident beam, the tuning curve of the second monochromator unit with respect to the first monochromator was much wider than the Darwin width of the [333] reflection. Thus the beam intensity on the sample was stable against relative changes of angle between the two monochromators (which was hard to avoid in this prototype set-up due to vibrations).

The analyzer, also [333], was non-dispersive with respect to the second monochromator. The analyzer was mounted on a tangent arm with 1 meter arm length driven by a linear translator of 0.1 micrometer resolution. This provides an angular resolution of 0.1 microradians which is sufficient to tune the analyzer to any location on the analyzer rocking curve which has a FWHM of around 5 microradians for 18 keV x-rays. The tangent arm was mounted on the same optical table as the second monochromator to minimize intensity modulation due to relative angle changes between them caused by vibrations. The beam intensity at the APS was strong enough to provide a surface dose on the order of a few mGy to the sample at a sample scan speed of about 10 mm/s.

Various phantoms and biological samples were imaged. The biological samples studied included a mouse with an implanted tumor and beef tissue with an implanted subcutaneous dog tumor. Each biological sample was preserved in formalin, sealed in a plastic bag and compressed between two Lucite plates. Additional Lucite plates were added during the imaging to make the absorbing thickness on the order of 30-40 mm.

For each sample, a "normal" radiograph with the monochromatic beam at 18 keV was taken by moving the analyzer out of the beam and scanning the image plate and sample through the fan beam in the same direction and at the same speed. DEI tissue characterization studies were performed in several ways: a) With the analyzer tuned to various positions on the rocking curve, the entire phantom and the image plate were translated in opposite directions at the same speed through the fan beam; b) Multi-scans: with the analyzer tuned to each of a series of predefined

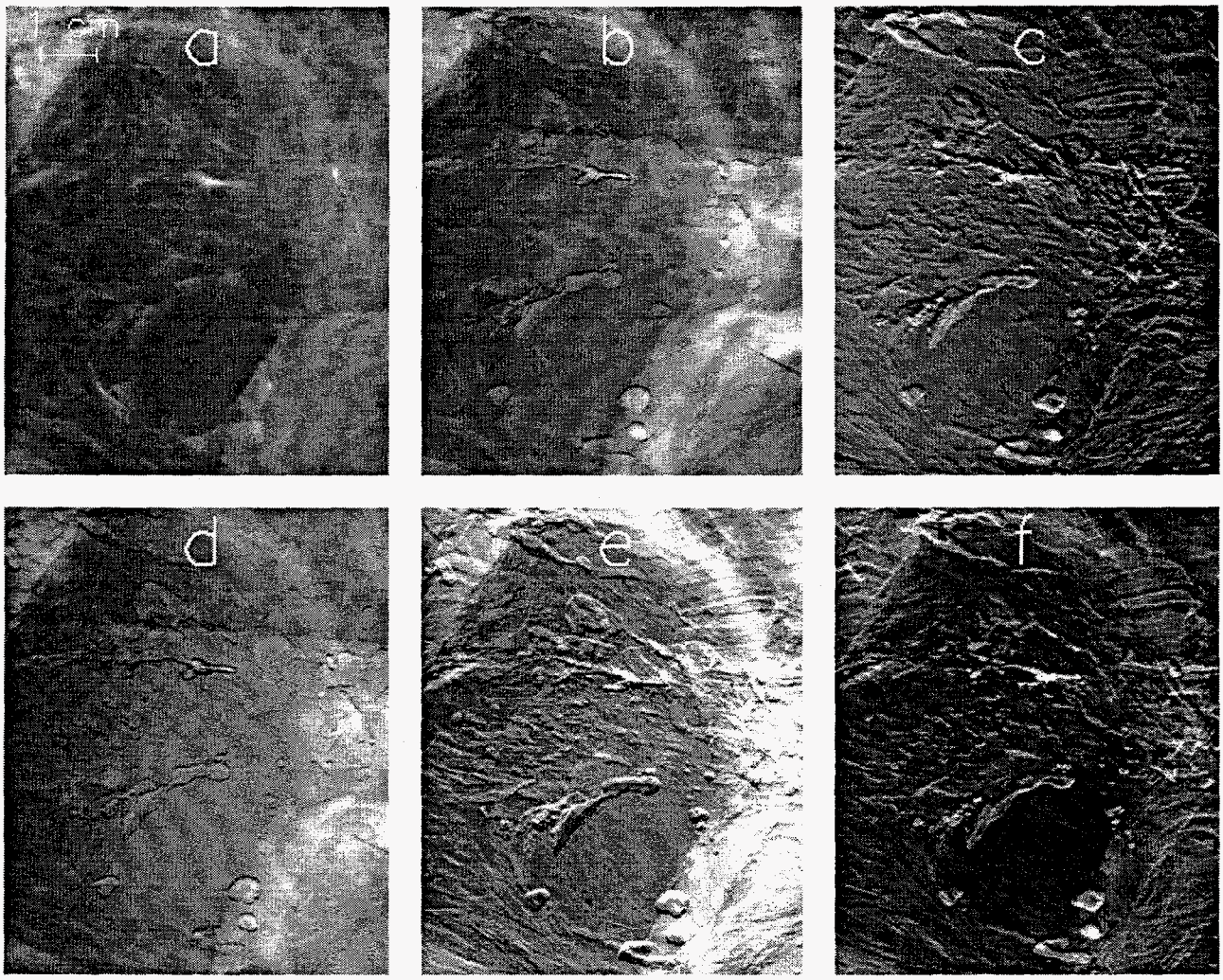

Fig. 2. Images of beef with an imbedded dog tumor. **a**. "Normal" radiograph taken with the analyzer removed. **b**. Apparent absorption image represented by sum of the images taken with the analyzer at $\pm$ 1.5 microradians. **c**. Refraction image represented by the difference of the $\pm$ 1.5 micro-radians images. **d**. Image taken with the analyzer at the peak of the rocking curve. **e**. Image with the analyzer at -3 microradians. **f**. Image with the analyzer at +3 microradians.

positions on the rocking curve, a short scan of a region of sample was performed as in a). The image plate was repositioned after each scan so that images did not overlap on the image plate; c) Rocking curves through a line on the phantom were obtained by fixing the phantom in the fan beam and performing a series of exposures with incrementing analyzer position and image plate vertical position.

RESULTS AND ANALYSIS

The images of the beef with the imbedded dog tumor are shown in Fig.2. Fig.2a shows a "normal" radiograph. The tumor is the roughly circular object with about 2 cm diameter close to the bottom of the image. Fig.2b and Fig.2c show the apparent absorption and refraction images, respectively. These images are derived from images taken at $\pm$ 1.5 microradians on each side of the analyzer rocking curve. It is clear from the refraction image that the tumor has been "implanted" in the beef. The refraction image shows the "crater" formed when the tumor was pushed into the tissue. The crater is not present in the "normal" radiograph. This clearly demonstrates DEI's ability to enhance edges of features in biological objects. Since DEI is not sensitive to refraction when the analyzer is

on top of the peak, the apparent absorption image (Fig.2b) is comparable to the image taken with the analyzer at the peak of the rocking curve (Fig.2d). Fig.2e and 2f show images taken farther out on the wings of the analyzer rocking curve at ± 3 micro-radians. It appears that the dog tumor may have a lack of small angle scattering and a lack of complex refraction at large analyzer rocking curve angles due to smoother morphology of the tumor as compared to beef tissue. There is a reversal in the contrast of the tumor relative to the beef when the analyzer angle is changed from the peak (Fig.2d) to +3 (Fig.2f) micro-radians. This is due to the different relative small angle scattering distributions of the tumor and the beef, and suggests that the tumor can be selectively highlighted. This indicates that DEI may be sensitive to the extinction and refraction contrast in cancerous tissue. In all cases, it is clear that new information is obtained by the DEI technique and that DEI at different analyzer positions on the rocking curve can enhance different features of the sample.

DISCUSSION

The consequence of the two sources of contrast (refraction and extinction contrast) is of importance to mammography and medical imaging in general. These contrast sources are largely energy independent effects as opposed to absorption. Conventional radiography depends on the absorption of x-rays by an object to create the radiograph, thus a compromise must be made between the contrast, signal to noise ratio and the absorbed dose. Refraction and scattering is expected to remain the same as the imaging energy is increased. This raises the possibility of successfully applying this technique at higher x-ray energies. This will be the focus of further investigation.

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