Tissue Visualization Using X-Ray Dark-Field Imaging towards Pathological Goal

Masami Ando¹, Yoshinori Chikaura², Tokiko Endo³, Rajiv Gupta⁴, Qingkai Huo¹, Kazuyuki Hyodo⁵, Shu Ichihara¹, Kensaku Mori⁶, Yuki Nakao¹, Norihiko Ohura¹, Naoki Sunaguchi², Hiroshi Sugiyama³, Yoshifumi Suzuki⁸, Yanlin Wu⁹, Tetsuya Yuasa¹⁰, Zhang Xiaowei⁵

¹ Research for Science and Technology, Tokyo University of Science, Yamasaki 2461, Noda, Chiba 278-8510, Japan, 2 Research Center for Synchrotron Light Applications, Kyushu University, Kasuga Koen 6-1, Fukuoka 816-8580, Japan, 3 Department of Advanced Diagnosis, Nagoya Medical Center, San-no-maru 4-1-1, Nakaku, Nagoya 460-0001, Japan, 4 Dept. of Radiology, Massachusetts General Hospital, Boston, MA 01778 USA, 5 Photon Factory, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan, 6 Graduate School of Information Science, Nagoya University, Furo-cho, Nagoya, 464-8603 Japan, 7 Department of Plastic Surgery, Medical School, Kyorin University, Shinkawa, Mitaka, Tokyo 181-0001, Japan, 8 Graduate School of Engineering, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan, 9 School of Accelerator Science, Graduate University for Science, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan, 10 Faculty of Engineering, Yamagata University, Yonezawa, Yamagata 992-8510, Japan

E-mail: msm-ando@rs.noda.tus.ac.jp

Abstract. In XDFI (x-ray dark-field imaging) LAA (Laue-case angle analyzer) simultaneously provides two x-ray images; one corresponds to a FD forward diffracted beam and a separate D diffracted beam. When this is applied to biomedical specimens x-ray images are very high contrast and very high spatial resolution. We constructed XDFI system at the vertical wiggler beamline BL-14C in KEK Photon Factory and performed imaging experiment of breast tissues and an excised human femoral artery. In this paper, we discuss a tissue visualization and pathological goal using 2D, 3D-CT and 2.5D image (tomoynthesis) with XDFI.

1. Introduction

Currently, a variety of imaging techniques have been developed such as phase-contrast imaging [1], DEI (diffraction enhanced imaging) [2], XDFI (x-ray dark-field imaging) [3] and grating-based imaging [4,5]. In this paper is mainly described the technique of XDFI. The idea of XDFI has a relationship to a pioneering one created by Ingal and Beliaevskaya [6] and by Chapman [7]. In the XDFI imaging the x-ray optics comprises MC (Bragg type monochromator-collimator) and LAA (Laue angle analyzer); Two beams, one \( I_{FD}(w) \) towards the direction of the forward diffraction FD and the other \( I_{D}(w) \) corresponding to the diffracted direction D are thus obtained.
2. Experimental: Optics of X-ray Dark-Field Imaging

The XDFI optics is shown in Fig. 1 that comprises asymmetric-cut MC (monochromator-collimator), LAA (Laue angle analyzer) and 2 imaging CCD’s. Dark-field image FD under the condition of \( I_{FD}(w)|_{w=0} = \cos^2(\pi H/\Lambda) = 0 \) and bright-field image D under the condition of \( I_{D}(w)|_{w=0} = \sin^2(\pi H/\Lambda) = 1 \), where \( H \) is thickness of LAA and \( \Lambda \) the pendelloesung fringe periodicity that is a function of x-ray energy \( E \) and it is inverse proportional to \( E^2 \). Fig. 1 shows a sketch of XDFI optics. \( I_{FD}(w) + I_{D}(w) = 1 \) holds for all \( w \) if photo-electron process of absorption can be neglected.

We have chosen the asymmetric factor \( b = \sin(\Theta_B - \alpha)/\sin(\Theta_B + \alpha) = 0.05 \), where \( \Theta_B \) is 10.6° for 440 diffraction at 35keV; the angle of divergence of the beam incident onto specimen \( S \) in Fig. 1 becomes 0.28 μrad.

We would like to emphasize that our system can thus provide FD and D image simultaneously by a single shot without significant intensity loss. XDFI which is very weak refraction-based signal from soft tissue can be imaged because illumination intensity has been completely suppressed.

An experiment was performed at beamline BL14C [8] with a vertical polarization of radiation. This means that the plane of incidence that comprises the incident x-rays and the diffracted x-rays is horizontal by that means since the rotation of crystal and sample is vertical handling of x-ray optical component and sample is relatively very easy.

By introducing a polynomial approximation of the two rocking curves high precision refraction angle for each picture element has been obtained. Thus the intensities of both FD and D beams that have been modulated according to their corresponding rocking curves are separately acquired by two CCD cameras. If the object displays no absorption characteristics, estimation of the refraction angle in the slice of interest from the measured intensities using the corresponding rocking curves can be determined.

In fact, since the beam is subject to absorption in the object, the intensity of the outgoing beam from the object is reduced by \( \exp\left(-\int L \mu dl\right) \), where \( L \) and \( \mu \) are the beam path in the object and the linear absorption coefficient of the beam in the object, respectively. This leads to intensity suppression of both FD and D beams such that a shift of the estimated angular deviation from the genuine refraction angle \( \theta_0 \) may occur, as shown in Fig. 2.

We estimated refractive angles using polynomial approximation [9]. Firstly, using the polynomial of degree \( n \) the rocking curves are given as

\[
I_{FD}(\theta) = \sum_{k=0}^{n} a_k^{FD} \theta^k, \quad \text{and} \quad I_{D}(\theta) = \sum_{k=0}^{n} a_k^{D} \theta^k.
\]

where \( I_{FD}(\theta) \) and \( I_{D}(\theta) \) corresponds to the forward diffraction and the diffraction component of measured intensity, respectively. \( F \) and \( D \) mean the forward diffraction and the diffraction component.
respectively. \( \theta \) is the rocking angle of the analyser crystal relating to the refraction angle from object. \( a_k^F \) and \( a_k^D \), fitting parameters for the forward diffraction and the diffraction rocking angles, respectively, are estimated from the measured rocking curves using the least squares method. Here, we use only the monotone regions because in order to estimate \( \theta \) there must be a one-to-one correspondence. Without absorption properties in the object, we observe \( I_{obs}^{FD}(\theta_0) \) and \( I_{obs}^{D}(\theta_0) \). However, actually, we observe \( I_{obs}^{FD}(\theta_0 + \Delta \alpha^F) \) and \( I_{obs}^{D}(\theta_0 - \Delta \alpha^D) \) due to absorption (Fig. 2), where \( \Delta \alpha^F \) and \( \Delta \alpha^D \) are the shifts from the refraction angle \( \theta_0 \) to be estimated. Since both beams are subject to the same absorption at each pixel corresponding to each element in the object, the followings hold:

\[
I_{obs}^{FD} = I^{FD}(\theta_0) \exp\left(-\int_L \mu k dl\right), \quad \text{and} \quad I_{obs}^{D} = I^{D}(\theta_0) \exp\left(-\int_L \mu k dl\right)
\]

Using the equations (1) and (2), we obtain

\[
\sum_{k=0}^{n} \left( \frac{a_k^{FD}}{I_{obs}^{FD}} - \frac{a_k^{D}}{I_{obs}^{D}} \right) \theta_0^k = 0
\]

We solve the algebraic equation using the Newton method to obtain the refraction angle \( \theta_0 \). Here, we select 6 as the optimal degree for the polynomial in a sense of AIC (Akaike’s Information Criterion).

The estimated refraction angles are employed as projections to reconstruct a refraction-contrast CT image. Following Chapman et al [2], Maksimenko et al [10], Dilmanian et al [11], and Huang et al [12] Sunaguchi et al [13] recently derived another direct reconstruction algorithm for DFI-CT to obtain refractive-index fields from the ray equation which is a fundamental equation in optics. The algorithm was different from the Huang’s one, not only in derivation process but also in data manipulation method.

3. Result and Discussion
As an example to show how XDFI can reveal breast soft tissue of DCIS (ductal carcinoma in situ) see Fig.3 and Fig. 4. TS (tomosynthesis) [14] in the left and a 2D projection of 3D reconstructed image in the right are shown in Fig. 3. Furthermore a 3D image of the milk duct is shown in the left of Fig. 4. This view was constructed from the right of Fig. 3. Thus an endoscopic view [15] was also made in the right.

In Fig. 5 is shown 3D reconstructed CT image of LCIS (lobular carcinoma in situ) that has inclusion of both healthy cells and terminal duct lobular units enlarged and deformed by proliferating cancer.
cells. This is a world first achieved x-ray image. The middle of Fig. 6 shows image of a coronal view of a femoral artery excised from a patient with diabetes; 1 and 2 shows its cross sectioned view, left and right, respectively. Black and dark parts probably correspond to calcification rich part. This may help surgeon to figure out an appropriate place for by-pass operation.

Fig. 5. 3D reconstruction of lobular carcinoma in situ (LCIS). The numerous spherical clusters represent terminal duct lobular units enlarged and deformed by proliferating cancer cells. The view has size of 20mm x 15mm.

Fig. 6. Reconstructed 3D image of a femoral artery of a patient with diabetes. The number 1 and 2 in the coronal view in the middle corresponds to cross sectioned view at both sides. The view has size of 5mm x 15mm.

4. Future Directions
Principle and 2D, 2.5D and 3D images of XDFI have been shown. The current spatial resolution is approximately vertically 5μm and horizontally 10μm. This was achieved by LAA whose thickness is 190μm and this can be improved down to at least 2-3μm and hopefully 1μm in a nearest future by thinning LAA down to less than 100μm. We could reach the level competitive to the spatial resolution

Acknowledgement
This work is supported in part by a Grant-in-Aid for Scientific Research (No. 22591353, 23602002) from the MEXT in Japan, and in part by a Grant-in-Aid for Clinical Research from the National Hospital Organization. The experiment was performed under the approval of the PAB at KEK under No. 2008S2-002, 2011G-672 for use of the Photon Factory.

References
[1] Snigirev, A. et al, I., Rev. Sci. Instrum., 66, 5486-5492, 1995.
[2] Chapman, D. et al., Phys. Med. Biol., 42, 2015-2025, 1997.
[3] Ando, M., et al, Jpn. J. Appl. Phys., 41, L1016-L1018, 2002.
[4] Momose, A., et al., Jpn. J. Appl. Phys., 42, L866–L868, 2003.
[5] Pfeiffer, F., Weitkamp, T., Bunk, O., David, C., Nat. Phys., 2, 258–261, 2006.
[6] Ingal, V.N., & Beliaevskaya, E.A., J., Phys. D: Appl. Phys., 28, 2314-2317, 1995.
[7] Chapman, D. et al., Rev. Sci. Instrum., 67, 3360, published on CD-ROM, 1996.
[8] Ando, M., et al, Nucl. Instr. & Meth., A264-1, 144-148, 1986.
[9] Sunaguchi, et al, Appl. Phys. Lett., 36, 153701-153701-3, 2010.
[10] Maksimenko, A., et al, Appl. Phys. Lett., 86, 124105-124105-3, 2005.
[11] Dilmanian, F.A. et al., Phys. Med. Biol., 45, 933-946, 2000.
[12] Huang, Z.F. et al., Appl. Phys. Lett., 89, 041124-041124-3, 2006
[13] Sunaguchi, N., Yuasa, T., Huo, Q., Ando, M., Optics Lett., 36, 391-393, 2011.
[14] Sunaguchi N, et al, Appl. Phys. Lett., 99, 103704-104704-3, 2011.
[15] Mori, K., et al, IEICE Trans. Inf. System, 79-D, 809-819, 1996.