Refraction-Contrast Computed Tomography Using X-Ray Dark Field Imaging Optics: Singe-Shot Acquisition of Angular Deviation from Forward-Diffraction and Diffraction Waves

In order to visualize the inside of biological soft tissues with high contrast and low radiation dose, a refraction-contrast computed tomography (CT) system is under development using X-ray dark field imaging (DFI) optics with a Laue-case analyzer (LA). If an X-ray beam containing internal information of a sample is incident upon LA, the beam will subsequently split into a forwardly diffracted beam and a separate diffracted beam. Refraction components from a sample can be deduced from these two beams acquired simultaneously at a single shot by fitting the rocking curves with polynomial functions. In order to demonstrate its efficacy, a sample with DCIS (Ductal Carcinoma In Situ) removed from a breast cancer patient was imaged.

X-ray imaging based on the phase-shift term δ produces much greater contrast in the case of biological soft tissues and soft materials consisting of low-Z elements than imaging based on the absorption term β, where $n = 1 - \delta - i\beta$ is the complex refractive index. So far, various imaging schemes based on the phase-shift term δ have been developed. However, they need multiple exposures in order to extract phase-related information. Especially, diffraction enhanced imaging (DEI), which is the world's most widespread method in biomedical applications [1], needs at least two time exposures at a single data point in order to detect the angular deviation from the incident beam to the refraction beam. In this research, we developed a phase-sensitive imaging system to obtain the angular deviation at a single shot using dark field imaging (DFI) optics [2] with a thin Laue-case analyzer (LA). The beam that passes through a sample is separated into two beams by DFI optics: one in a forward-diffraction (FD) direction and the other in a diffraction (D) one. These are called the dark-field image and the bright-field image, respectively. By using these two beams acquired simultaneously by two CCD cameras, the DFI system extracts an angular deviation due to refraction using a proposed data-processing method to fit the rocking curves with polynomial functions.

In addition, the imaging system is extended to a CT mode based on refraction-contrast [3]. The DFI-CT imaging system is constructed at the vertical wiggler beamline BL-14C. It is composed of an Si (440) asymmetrical Bragg-case monochromator-collimator (MC), an Si (440) symmetrical LA, and two CCD cameras (Fig. 1). The rocking axes of the MC and LA and the rotational axis of the object that is inserted between MC and LA are aligned parallel to each other. The angular positions of the MC and LA are fixed after being adjusted. The monochromatic synchrotron X-ray beam at 34.8 keV is expanded to a square parallel beam by an asymmetrical Bragg-case MC to cover the full object width. The beam impinging on the object is refracted and absorbed by the object. In this study, we demonstrated its efficacy using a sample with ductal carcinoma in situ (DCIS) removed from a breast cancer patient.

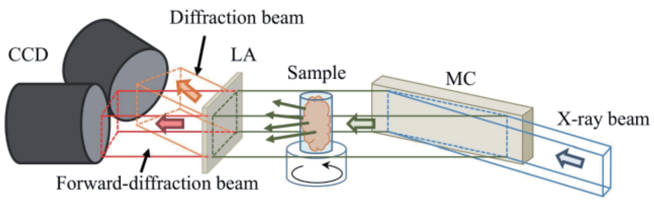

Figure 1
Schematic of DFI-CT imaging system

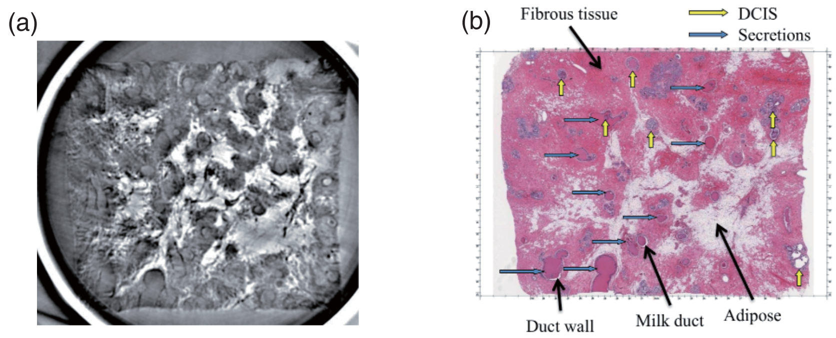

Figure 2
(a) DFI-CT image, (b) The corresponding histological section stained with hematoxylin and eosin (HE). Views of fibrous tissue, adipose, milk duct, duct wall and duct secretions in (a) are in good agreement with those in (b) pathological view.

The sample, of size 2.5 × 2.1 × 4.5 cm^3, was placed in an acrylic cylinder filled with alcohol. The number of projections acquired was 900. Figure 2 (a) shows a representative image of a 3-D DFI-CT image, representing the distribution of δ. In conventional X-ray CT based on absorption, the DCIS itself, except for calcification which sometimes occurs in secretions or necrotic material, is hardly depicted. After the CT experiments were completed, the entire tissue sample was serially sectioned and stained with hematoxylin and eosin (HE) for further histology and CT correlation studies (Fig. 2 (b)). Adipose tissue (fat) appears as white geographic areas in refraction-contrast X-ray CT (Fig. 2 (a)) and histological section (Fig. 2 (b)). Fibrous tissue corresponds to gray areas in refraction-contrast X-ray CT and red areas in stained histologic sections. The overall configuration of fibrous and adipose tissues closely matches between the refraction-contrast X-ray CT and the histologic section. In both images, milk ducts and duct walls are similarly depicted as shown in Fig. 2. In addition, ductal carcinoma in situ (DCIS) shown by yellow arrows and secretions shown by blue arrows is also recognized as well-defined round areas of various sizes with or without homogeneous secretory material in both images.

REFERENCES

[1] S. Ichihara, M. Ando, A. Maksimenko, T. Yuasa, H. Sugiyama, E. Hashimoto, K. Yamasaki, K. Mori, Y. Arai and T. Endo, *Virchows Arch.* **452** (2008) 41.
[2] M. Ando, A. Maksimenko, H. Sugiyama, W. Pattanasiriwisawa, K. Hyodo and C. Uyama, *Jpn. J. Appl. Phys.* **41** (2002) L1016.
[3] N. Sunaguchi, T. Yuasa, Q. Huo, S. Ichihara and M. Ando, *Appl. Phys. Lett.* **97** (2010) 153701.

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