Refractive-index based tomosynthesis using dark-field imaging optics

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Abstract. Tomosynthesis (TS) is a pseudo-3-dimensional image reconstruction method to recover depth-resolved information using restricted number of projections. In this research, refraction index based TS imaging using dark-field imaging (DFI) optics is proposed and biomedical soft tissues were imaged in low dose exposure. By a single exposure of an object, two projected images are obtained from a Laue-case analyzer of DFI. Calculating the both images refraction component is deduced, while two exposures are needed in DEI (diffraction enhanced imaging). Thus the measurement time and the radiation dose in DFI are half of DEI. In addition, the proposed reconstruction algorithm, derived from the quantitative relationship in measurement process, allows high contrast tomographic imaging in spite of one order smaller number of projections for CT (computed tomography). To demonstrate the proposed imaging protocol efficacy, an ex-vivo excised tissue of human lung were imaged using a system constructed at the vertical wiggler beamline at PF-BL14C at KEK. TS image is successfully delineated high quality soft tissue structures comparable to CT.

1. Introduction
Tomosynthesis (TS) is a pseudo-3-dimensional image reconstruction method intended to remove superimposition effects and recover depth-resolved information using restricted projections. Interest in TS has increased due to fast read-out solid state flat panel detectors and the advances in data processing, even though the basic principle was devised in the 1930’s [1]. TS reconstructs images from a limited number of projections and projection angle. Compared to CT, TS can acquire 3-dimensional information at less radiation dose without compromising longitudinal plane image quality but does exhibit lower image quality axially [2]. TS in current clinical use is based on absorption
effects similar to radiography and x-ray CT. Conventional x-ray imaging forms images based on $\beta$ in $n = 1 - \delta + i\beta$, where $n$, $\delta$, and $\beta$ are the refractive index, phase shift and absorption terms, respectively. Unfortunately, conventional x-ray imaging cannot produce sufficient soft tissue contrast because of low Z elements such as H, C, N, and O. For low Z elements $\delta$ is approximately 1000 times larger than $\beta$ in the x-ray energy regions ranging from 10 to 100 keV. Therefore, soft tissue imaging based on $\delta$ is more advantageous. We have proposed two forms of refraction-contrast TS for soft tissue imaging. The first uses DEI (Diffraction Enhanced Imaging) methods [3]. DEI using a Bragg-case analyzer acquires angular deviation information from incident directional x-rays due to refraction. Diffracted intensities include both absorption and refraction components as a result of the analyzer crystal rocking curve [4]. However, for DEI, two measurements are required for each data point in order to obtain angular deviations leading to radiation dose increase, and not suitable for in vivo imaging.

The other method is TS using DFI (dark-field imaging) with a thin Laue-case analyzer [5, 6]. Generally, incident beams impinging on a Laue-case analyzer near the Bragg angle is split into two beams, a forwardly diffracted and a diffracted beam. DFI uses a crystal such that the intensity of forwardly diffracted waves diminishes at the Bragg angle [7]. DFI optics under the above condition and without an object present interrupts the forwardly diffracted intensity. With an object in the incident beam, DFI optics at high contrast measures only refracted x-rays subsequently incident on the analyzer at angles not satisfying the DFI condition. DFI-TS employs the shift-and-add method (SAA) widely used in clinical medicine. We imaged some biological samples to demonstrate its efficacy. DFI-TS applied SAA to the projections acquired by DFI to inseparable refraction and absorption information. If only refraction information is collected, soft tissues at higher contrast can be visualized.

This paper proposes a data-acquisition protocol for refraction-contrast TS for soft tissue imaging outperforming conventional refraction-contrast TS. We then consider a pseudo-3-dimensional reconstruction algorithm effective for projections acquired by DFI optics.

2. Dark-field imaging optics

Figure 1 shows a schematic of the proposed imaging system. The beam monochromated, collimated, and enlarged by the asymmetrical Bragg-case crystal impinges on the object. The symmetrical Laue-case crystal analyzer under DFI conditions set downstream of the object splits the transmitted beam into the two beams in forwardly diffracted and diffracted directions. Both beams are separately and simultaneously detected by the two distinct CCD cameras. While conventional DFI-TS forms a pseudo-3-dimensional image from only forwardly diffracted images, the proposed method removes absorption effects from intensities including both absorption and refraction information with the help of distinct forward diffraction and diffraction rocking curves.

![Figure 1. Schematic of tomosynthesis imaging system using dark-field imaging optics.](image-url)

**Figure 1.** Schematic of tomosynthesis imaging system using dark-field imaging optics.
3. Tomosynthesis reconstruction

As representative TS reconstruction methods used in clinical medicine, SAA and the Filtered Back Projection (FBP) methods are well known [1]. The former emphasizes information in a cross-section of interest against that of other cross-sections using the imaging system geometrical relationships, and the latter estimates pixel values in a cross-section of interest based on quantitative relationships between the quantities observed and to be estimated or as a line integral from the incident beam with respect to the distribution of physical quantities to be estimated from the cross-section of interest, analogous to CT. Originally, TS is a reconstruction from incomplete sets of projections, not as mathematically rigid as CT. Therefore, the method selected is motivated by which method is regarded as more important - the geometrical relationship or the quantitative relationship.

DFI optics collects a set of projection images, assigning a set of projections with respect to angular deviations. If one regards the geometrical relationship of the imaging system as important, one should select SAA. Here, we note that SAA can be implemented by backprojection in the case of parallel incident beam geometry like the proposed imaging method [8]. Therefore, one can obtain a pseudo-3-dimensional image by applying SAA, or the backprojection method, to the angular deviation projections. On the other hand, if one regards the quantitative relationship in the measurement process as important, one selects FBP. In order to apply FBP, one must make clear the quantitative relationship between physical quantities observed and to estimate the cross-section of interest. The measurement process for angular deviations is represented as

$$\Delta \alpha(x) = \int_{-\infty}^{\infty} \frac{\partial}{\partial x} \delta(x, z) dz,$$

where the $xz$-coordinate system is shown in figure 2, and the incident beam propagates toward the positive $z$-axis: $\delta(x, z)$ and $\Delta \alpha(x)$ are phase shift distributions and angular deviations at beam position $x$, respectively. Equation (1) implies that the angular deviation is equal to the Radon transform of the derivative of phase shift distributions with respect to $x.$ Fourier transforming equation (1) with respect to $x,$

$$\int_{-\infty}^{\infty} \Delta \alpha(x) \exp(-2\pi i \xi x) dx = \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} \frac{\partial}{\partial x} \delta(x, z) dz \right] \exp(-2\pi i \xi x) dx$$

$$= 2\pi \rho \int_{-\infty}^{\infty} \delta(x, z) dz \exp(-2\pi i \rho x).$$

Thus,

$$\int_{-\infty}^{\infty} \delta(x, z) dz = \Delta \alpha(x) \otimes F^{-1} \left( \frac{1}{2\pi \rho} \right).$$

(3)

where $\otimes$ means convolution and $F^{-1}( \cdot )$ means the inverse Fourier transform. It is well known that $F^{-1}(1/i\pi \rho) = \text{sgn}(x) = 1$ $(x>0),$ $0$ $(x=0),$ $-1(x<0).$ Equation (3) shows that the Radon transform of the phase shift term can be obtained as the convolution between the angular deviation and function $\text{sgn}(x).$ Therefore, one can obtain a reconstruction image relative to the phase shift term by applying FBP to the convolution. On the other hand, from equation (1), SAA to backprojecting the angular deviation directly produces a reconstruction image relative to the derivative phase shift term.

![Figure 2. Schematic diagram of imaging geometry based on refraction.](image)
4. Imaging experiment

A complex internal structured sample is most desirable to be able to confirm the efficacy of TS reconstruction algorithm. We selected and imaged a honey-comb lung tissue sample excised from a 65-year-old man with end-stage lung associated with collagen vascular disease. In this stage, the dense fibrosis causes the destruction of normal alveolar architecture and formation of cystic spaces resulting in so called honey-comb fibrosis. The sample was cut into a quadrangular-prism shaped block measuring $16 \times 16 \times 23 \text{ mm}^3$. The sample was rotated around the vertical axis from $-45^\circ$ to $45^\circ$ at $1^\circ$ rotational steps, a total of 91 directions. Figure 3(a) and (b) show TS images at a representative cross-section selected from 3-dimentional data set reconstructed with FBP and SAA, respectively. Figure 3(c) shows a histological image stained with hematoxylin and eosion at almost the same cross-section as TS images. White areas on figure 3(c) show the d ilated air spaces. Arrows 1 and 2 shows small arteries identified in thickened alveolar septa with fibrosis and the remaining alveoli, respectively. These structures were delineated in both TS images as identical positions. However, figure 3 (b) was delineated edge component only, while figure 3(a) depicts the inner structure by high contrast. Such image formation is understood by the derivation of methods, that is, FBP and SAA were based on equation (1) and (3), respectively. Thus, from the viewpoint of morphological imaging, FBP is better than SAA. The result suggests that for refraction-contrast TS the quantitative relationship in the measurement process should be regarded as more important than the imaging system geometrical relationship.

![Figure 3](image1.jpg)

**Figure 3.** Comparison between TS images and a comparable histological image. (a) TS image with FBP, (b) a TS image with SAA, and (c) histological image. Arrows 1 and 2 show small arteries identified in the septum and remaining alveoli.

5. Conclusion

A TS system for soft tissue using DFI optics was proposed. It produced images in no way inferior to refraction-contrast CT images from the viewpoint of morphological imaging in spite of utilizing one tenth the number of projections of refraction-contrast CT imaging. Future work will consist in applying the imaging protocol to breast tissue in establishing low radiation dose and high sensitivity mammographic imaging.

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