CT dose reduction factors in the thousands using X-ray phase contrast

In X-ray imaging and computed tomography (CT), photon shot noise (Poisson noise) can be reduced by increasing radiation dose, but dose must be minimized for use with animals or humans or for high throughput applications.

Phase contrast imaging techniques can enhance image contrast by an order of magnitude or more using phase shifts (i.e., refraction) of X-rays. Propagation-based imaging (PBI) is the simplest phase contrast technique, whereby Fresnel diffraction fringes arise at the interfaces of an object upon propagation of the X-ray beam downstream from the object. This effect simultaneously enhances image contrast and spatial resolution. To recover information about an object from such images, Paganin *et al.* [1] developed a noise-robust algorithm for homogenous samples (TIE-Hom). Beltran *et al.* [2] and Croton *et al.* [3] extended TIE-Hom for multi-material samples. This approach has been shown to improve the signal-to-noise ratio (SNR) by up to 200-fold over conventional CT with minimal loss of spatial resolution [2,4]. These algorithms essentially smooth away the Fresnel fringes, whilst simultaneously reducing noise. A more complete description behind this huge gain in SNR has recently been suggested by Gureyev *et al.* [5] based on the quantum nature of image noise and the evolution of spatial Fourier spectra upon free-space propagation. The present article explores how such gains can be traded for massive reductions in radiation exposure, as reported by Kitchen *et al.* [4].

Experimental data was acquired in hutch 3 of SPring-8 **BL20B2** with a beam energy of 24 keV. The dose (air kerma) rate to the sample was fixed at 13.5±0.1 mGy/s. Twelve separate CT datasets of a newborn rabbit thorax were acquired to investigate the dependence of image quality on: (1) sample-to-detector propagation distance; (2) exposure time, and; (3) the effect of applying the TIE-Hom algorithm.

CT datasets were acquired at sample-to-detector distances of 0.16 m, 1.0 m and 2.0 m, and using four different exposure times of 1 ms, 10 ms, 100 ms, and 300 ms per projection at each distance. The shortest distance of 0.16 m was the closest we could safely position the detector to minimize phase contrast. A total of 1801 projections were recorded for each 180° CT scan. This gave a dose range from 24.3±0.1 mGy (1 ms exposures) to 7.29±0.01 Gy (300 ms exposures). We note that the lower dose is comparable to clinical CT scanners, but with much higher spatial resolution.

Figure 1 shows a reconstructed slice through the lungs at the smallest and largest propagation distances, and the effect of applying TIE-Hom phase retrieval algorithm. Figure 2 shows close-up images with absorption contrast at 0.16 m in (a) and with phase retrieval from a phase contrast dataset recorded at a distance of 2 m in (b), both at the lowest radiation exposure. With absorption contrast, the lungs are barely visible against the noise. Conversely, with phase retrieval the lungs are revealed with such high contrast and resolution that individual alveoli are readily visible.

Figure 3 shows the gain in SNR for phase retrieved CT, relative to that of the absorption CT, at each propagation distance as a function of exposure time. We discovered an unexpected effect that the SNR gain is consistently highest at the shortest exposure times, leading to large potential for dose reduction [4].

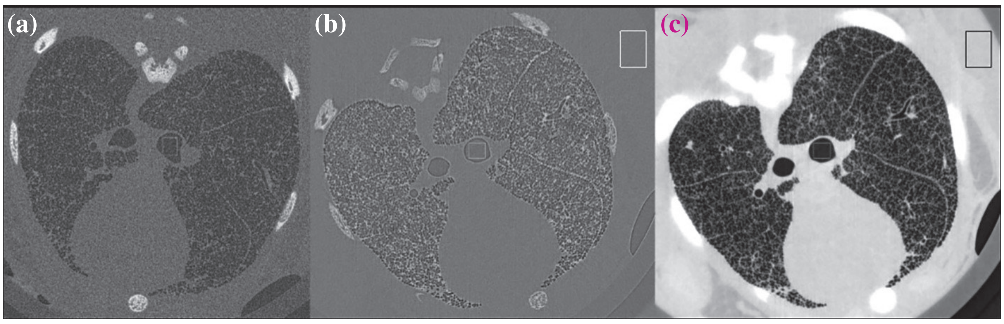

Fig. 1. CT reconstruction of rabbit kitten lungs. **(a)** Absorption contrast CT reconstruction at a sample-to-detector distance of 0.16 m. **(b)** Phase contrast CT at 2 m; **(c)** and with phase retrieval (TIE-Hom) at 2 m. Dark areas represent air-filled airways and bones appear bright. Black and white boxes indicate regions of interest for SNR analysis. The exposure time was 10 ms per projection for all images. Image dimensions: (a) 18.4 mm×18.5 mm; (b) and (c) 20.7 mm×18.5 mm.

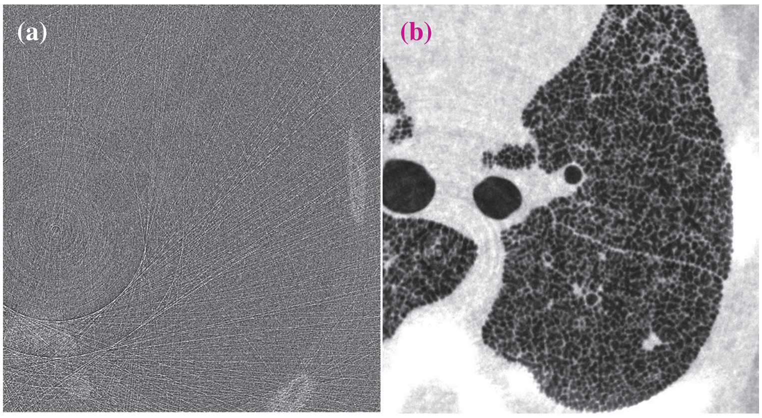

Fig. 2. High resolution lung CT reconstructions from absorption contrast data **(a)** and phase retrieved data (**(b)** 2 m propagation) at the lowest dose of 24.3±0.1 mGy (1 ms per projection). Voxel size = 15.3 μm. Small black circular objects are cross-sections through individual alveoli (~160 μm diameter). Image dimensions: 10 mm×11 mm.

The dose was reduced by a maximum of 300-fold in the experiment due to detector limitations. The SNR of the 1 ms phase retrieved data was still larger than the absorption contrast SNR at 300 ms by factors of 1.28±0.02; 5.16±0.05; and 9.6±0.2 at 0.16 m, 1.0 m and 2.0 m, respectively. From our noise analysis equations derived in [4] we can estimate the remaining dose reduction factor as the square of these numbers. This gives the expected dose reduction factors at 0.16 m, 1.0 m and 2.0 m of $300 \times 1.28^2 = 490 \pm 20$; $300 \times 5.16^2 = 7{,}990 \pm 30$; and $300 \times 9.6^2 = 27{,}600 \pm 30$, respectively. Our model for noise analysis shows that the dose reduction factors can potentially be in the hundreds of thousands, as discussed in [4].

The ability to improve CT image quality by factors in the tens to hundreds, or to reduce radiation exposure by factors in the hundreds to thousands, would have a dramatic impact on high-throughput low-dose imaging for clinical diagnostics and industrial non-destructive testing applications. Using less radiation will enable higher throughput imaging with fewer motion artifacts and be safer for human imaging or for longitudinal preclinical studies. The demonstrated dose reduction also lowers the requirements for brightness of micro-focus X-ray sources that can be used for medical phase-contrast X-ray imaging, thus potentially opening the way for the introduction of this method into routine clinical practice.

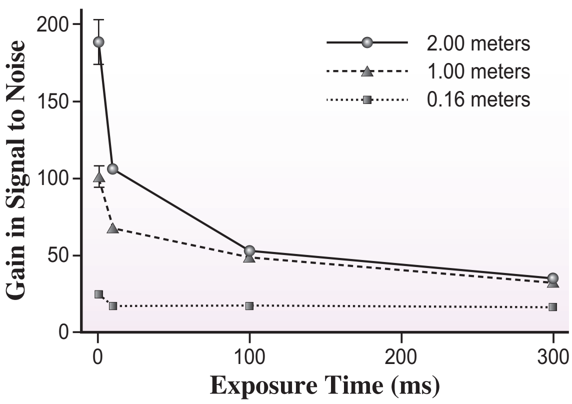

Fig. 3. Plots of the gain in SNR with phase retrieval CT as a function of exposure time.

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