Phase-contrast and dark-field imaging for biomedical applications

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The development of highly coherent X-ray sources from third-generation synchrotrons to today's diffraction-limited storage rings and X-ray free-electron lasers has significantly expanded the capabilities of X-ray imaging. Phase-contrast imaging utilizes the refraction of X-rays rather than their attenuation, offering greatly enhanced sensitivity to soft biological tissues, where traditional absorption contrast falls short. The dark-field imaging method, on the other hand, accesses small-angle scattering and can reveal sub-resolution microstructures, such as the alveolar architecture of lung tissue or microcalcifications in breast tissue.

This tutorial introduces the physical principles underlying both contrast mechanisms, starting with the complex refractive index and explaining how absorption, phase shift, and scattering contribute to three complementary imaging channels. The focus is primarily on imaging at the micrometer scale, specifically micro-CT. We will then survey the main experimental methods used, categorizing them into two groups: optics-free techniques and optics-based methods. The optics-free approach includes pure propagation-based imaging. The optics-based methods are more diverse, employing gratings, apertures, and related wavefront markers. We will discuss the strengths, limitations, and dose considerations associated with each.

Finally, we highlight representative biomedical applications, ranging from high-resolution imaging of soft tissues and biomaterials to preclinical studies, and outline the current challenges in achieving quantitative and dose-efficient imaging.