X-ray dark-field imaging using a grating interferometer

Visible light microscopy is a standard and widely utilized tool with a broad range of applications in science, industry and everyday life. Besides standard bright-field imaging, many more contrast mechanisms have been developed, and dark-field imaging, phase contrast, confocal and fluorescence microscopy are routine methods in today's light microscopy applications. It is not surprising that this development has stimulated a similar progress in imaging applications with other forms of radiation. In electron microscopy, for example, where the first electron microscope image was produced in the early thirties, dark-field imaging was introduced in the late thirties, and imaging based on phase contrast in the fourties.

In x-ray microscopy, or more generally, x-ray imaging, the development of a similar range of contrast modalities proceeded much more slowly and is still a very active field of research. Despite the early pioneering work on x-ray interferometry by Bonse *et al.* in the sixties, the majority of phase contrast imaging and dark-field imaging methods were introduced in the late nineties. The development of such advanced imaging methods is particularly difficult for hard x-rays (with energies in the multi-keV range), because of the lack of efficient x-ray optics. Existing hard x-ray dark-field imaging methods, for example, rely on the use of crystal optics that can only accept a very narrow energy band-width (≈ 0.01 %) and angular divergence (≈ 1 arcsec). This is why dark-field or scattering based imaging is currently restricted in practise to applications at highly brilliant synchrotron x-ray sources and is not available for widespread applications that require a method applicable to standard x-ray tubes.

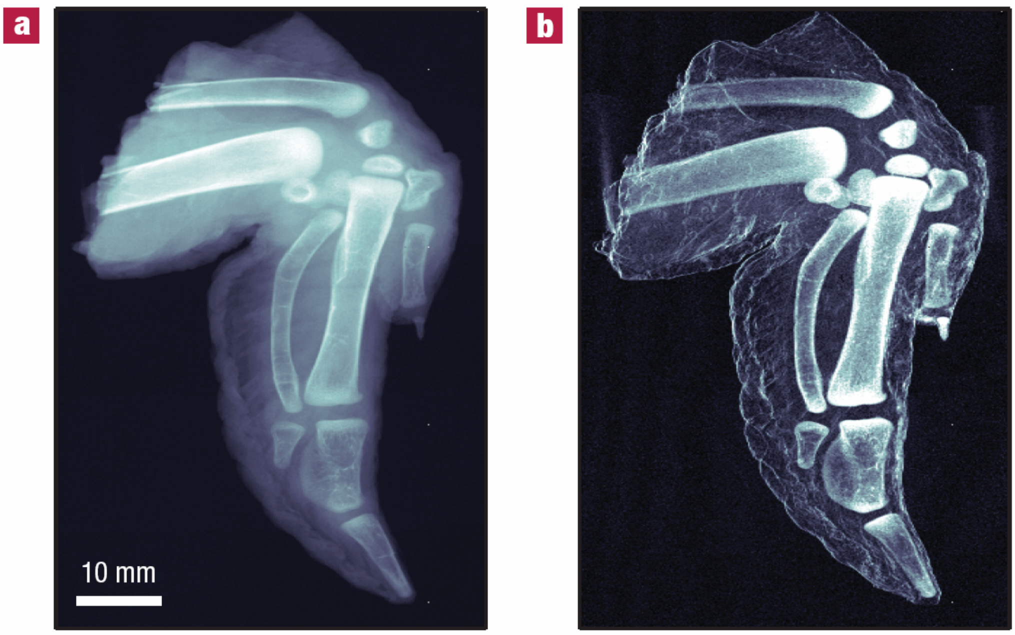

Figure 1: *Conventional transmission image (a) and new dark-field image (b) of a test specimen (chicken wing). The X-ray scattering due to the porous microstructure of the bones and the reflection at internal or external interfaces produce a strong signal in the dark-field image. The total exposure time to obtain the whole data set, from which the images were processed, was 40 s. Both images are shown on a linear grey scale corresponding to four times the standard deviation of the range of pixel grey-scale values.*

With the present work, published in *Nature Materials*, we report a new approach based on a grating interferometer that can efficiently yield dark-field scatter images of high quality, even with conventional x-ray tube sources. Since the image contrast is formed through the mechanism of small-angle scattering, it provides complementary and otherwise inaccessible structural information about the specimen at the micron and sub-micron length scale.

Figure 1 shows an example that particularly demonstrates the potential of dark-field imaging for improved contrast in medical applications. As test specimen, a chicken wing was used. The conventional transmission contrast is shown in Fig. 1a and the dark-field contrast in Fig. 1b. Note that, since both images were obtained from the same data set, the radiation dose was identical in both cases. We find that the boundaries and interfaces produce a strong signal in the dark-field image. Furthermore, we observe that the chicken bones obviously consist of a highly porous and strongly scattering micro-structure, since they are clearly visible in the dark-field contrast (Fig. 1b). We conclude that, although bones are generally already well represented in the transmission images, dark-field imaging can potentially yield a complementary and even enhanced contrast. For example, in cases of complicated bone fractures, where small splinters can intrude into the surrounding tissue, dark-field contrast could provide the necessary specificity to visualize subtle details.

The approach is potentially interesting for a wide range of applications including medical imaging, security screening, industrial non-destructive testing, food inspection, and small animal imaging. In future, a further increase in the sensitivity of the method could also provide contrast between healthy and diseased breast tissue, since breast tumors exhibit a different small-angle scattering signature than the healthy adipose matrix. Generally, we believe that the method is of particular interest for challenging x-ray imaging applications, because it simultaneously provides dark-field, transmission and differential phase contrast, thus providing maximum information about the specimen.

Publications

- **Hard-X-ray dark-field imaging using a grating interferometer**
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