Introduction: Conventional radiography renders only a measure of the x-ray attenuation of an object. This attenuation includes x-ray scatter that can obscure important details of the object being imaged. Herein, we describe a new technique, called Multiple Image Radiography (MIR), which is related to an earlier technique called Diffraction Enhanced Imaging (DEI)\(^1\). Like its predecessor, MIR shows the effects of refraction and absorption; however, MIR produces an important new type of x-ray image, based on X-ray ultra-small-angle scattering, which depicts fine textural features of tissue that are smaller than a pixel (50um). MIR also corrects inaccuracies that are inherent in images produced by DEI. MIR is sensitive to very small deflections of the x-ray beam (on the order of 1 micro-radian), and exhibits almost total scatter rejection. Thus, MIR images have significantly greater contrast than conventional radiographs, allowing clear visualization of soft tissues, such as cartilage, tendons and ligaments\(^1\). We show the application of the new MIR technology to the simultaneous imaging of soft tissue and bone of the human foot and ankle.

Methods: MIR uses highly collimated x-rays prepared by diffraction from perfect silicon crystals. An analyzer crystal, placed between the subject and a digital detector, allows the angular content of the beam to be precisely measured. Multiple images of the subject are acquired at various rotational positions of the analyzer, and the resulting data are used to compute the refraction (deflection), scattering (broadening), and attenuation (apparent absorption) of the beam. Each of these images depicts different properties of the subject, and together they can be used to characterize tissue.\(^1\) A cadaveric human foot was positioned in the beam so that it was slightly deviated from the lateral view. Images were taken at 40 keV and at five positions of the analyzer crystal using the X-15A beamline at the National Synchrotron Light Source, Brookhaven National Laboratory. These data were deconvolved to remove the effect of the intrinsic rocking curve (angular reflectivity function) of the analyzer crystal, and thus obtain an estimate of the true angular intensity spectrum of the beam at every pixel in the image. From these angular spectra, three images were computed—refraction, attenuation, and ultra-small-angle scattering—which can be displayed separately or as a color composite. The refraction image is computed as the shift in centroid of the angular spectrum; the attenuation is related to the integral of the angular spectrum; and scatter is quantified by the second central moment of the angular intensity. Thus, MIR images have significantly greater contrast than conventional radiographs, allowing clear visualization of soft tissues, such as cartilage, tendons and ligaments\(^1\). We show the application of the new MIR technology to the simultaneous imaging of soft tissue and bone of the human foot and ankle.

Results: Figure 1 shows a refraction image of the foot and ankle. Soft tissues, such as tendons, ligaments, adipose and skin, can be visualized simultaneously with the bone. The calcaneal tendon can be easily followed down to its attachment. The fibularis brevis muscle and tendon can be followed from the leg, through its superimposition by the calcaneus, to its attachment to the base of the 5th metatarsal. On the anterior aspect, tendons of tibialis anterior and extensor digitorum are visualized. Figure 2 is a scatter image of the same specimen as in Figure 1, but here, tissues such as the calcaneal fat pad and loose connective tissue are more visible because of their fine scale texture. Figure 3 is the color composite image of refraction (green), scatter (blue), and absorption (pink). Areas shaded white are a mixture of the three physical properties.

Discussion: The results of this study show that MIR is capable of rendering x-ray images of high contrast showing soft tissue refraction and scattering properties, while simultaneously detecting absorption in a human sample. Because of the contrast enhancement of this phase-sensitive imaging method, soft tissues are easily visualized with a clarity that no other radiographic technique has yet shown. Because the refraction and scattering properties of a given tissue will change with a change in morphology, such as in tumor development or interruption of connective tissue fibers, the next experimental step is to identify pathological features with MIR. We are hopeful that this technique can eventually be utilized clinically for the identification of soft tissue pathologies.

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