Diffraction-Enhanced Imaging of Musculoskeletal Tissues Using a Conventional X-Ray Tube[1]

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Rationale and Objectives. In conventional projection radiography, cartilage and other soft tissues do not produce enough radiographic contrast to be distinguishable from each other. Diffraction-enhanced imaging (DEI) uses a monochromatic x-ray beam and a silicon crystal analyzer to produce images in which attenuation contrast is greatly enhanced and x-ray refraction at tissue boundaries can be detected. The aim of this study was to test the efficacy of conventional x-ray tube–based DEI for the detection of soft tissues in experimental samples.

Materials and Methods. Cadaveric human tali (normal and degenerated) and a knee and thumb were imaged with DEI using a conventional x-ray tube and DEI setup that included a double–silicon crystal monochromator and a silicon crystal analyzer positioned between the imaged object and the detector.

Results. Diffraction-enhanced images of the cadaveric tali allowed the visualization of cartilage and its specific level of degeneration for each specimen. There was a significant correlation between the grade of cartilage integrity as assessed on the tube diffraction-enhanced images and on their respective histologic sections ($r = 0.97$, $P = .01$). Images of the intact knee showed the articular cartilage edge of the femoral condyle, even when superimposed by the tibia. In the thumb image, it was possible to visualize articular cartilage, tendons, and other soft tissues.

Conclusion. DEI based on a conventional x-ray tube allows the visualization of skeletal and soft tissues simultaneously. Although more in-depth testing and optimization of the DEI setup must be carried out, these data demonstrate a proof of principle for further development of the technology for future clinical imaging.

Key Words. Diffraction-enhanced imaging; phase contrast imaging; cartilage imaging; DEI; osteoarthritis; soft tissue imaging.

Phase contrast imaging techniques are based on the use of information arising from the modification of the amplitude and phase of x-rays as they traverse an object. This allows for the detection of subject contrast due to tissue properties such as refraction. This contrast does not depend on x-ray attenuation, as is the case with contrast in conventional radiography. Thus, tissue contrast that is difficult to detect through x-ray attenuation, particularly at high energies, at which radiation dose is comparatively reduced, may be detected with phase contrast techniques. This includes soft tissues that do not have the composition to provide the necessary attenuation of x-rays and require techniques that exploit x-ray refraction at tissue boundaries to be visualized. One such technique is based on a system in which an analyzer crystal is positioned between the object and the detector. This allows only those x-rays satisfying the Bragg condition to be diffracted to the detector. Changes in x-ray reflection angle are converted to changes in x-ray intensity, through an intensity versus reflection angle curve (measured in microradians), described as the ''rocking curve.'' By altering the angle of the analyzer, it is possible to record different refraction angles and thus extract both refraction and absorption characteristics (1–8).

What renders this technology pertinent to the study of joint disease is that soft tissues, including articular cartilage, menisci, tendons, and ligaments, are detected with reasonable

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clarity and contrast. Furthermore, it has been used to detect pathologic changes within these tissues, even at early stages of disease. The drawback has been that DEI has, until now, been used exclusively with synchrotron sources of x-rays, rendering it impractical for routine clinical use. This led to the development of a system that could use DEI technology but with a compact x-ray source, such as a commercially available tungsten tube (tube DEI).

A practical application of DEI is in the detection of musculoskeletal lesions and cartilage lesions characteristic of osteoarthritis. Because conventional radiography renders articular cartilage virtually invisible and because magnetic resonance imaging still has some drawbacks (ie, insufficient resolution for early lesions and low sensitivity for chondrocalcinosis [9]), there is room for complementary technology such as DEI, which exploits different tissue characteristics. Here, we demonstrate the efficacy of an experimental model of tube DEI for the visualization of cartilage and cartilage lesions in human tali and in intact cadaveric human joints.

MATERIALS AND METHODS

Specimens

The specimens imaged consisted of 12 human cadaveric tali (3 normal and 3 at each grade of cartilage degeneration, as described below) and a cadaveric human knee and thumb. The tali and knee were obtained from the Gift of Hope Organ and Tissue Donor Network of Illinois (with institutional review board approval). The thumb was obtained from the dissection laboratory of the first-year medical students and was returned to the cadaver after use. These specimens had been formalin preserved prior to imaging; we have previously shown that formalin fixation does not affect DEI (8). Tali were graded according to a macroscopic visual scale (10) as follows: 0 = normal, undisturbed articular cartilage surface; 1 = fibrillated cartilage surface; 2 = fissured or ulcerated cartilage; and 3 = cartilage eroded down to subchondral bone. Three tali for each grade of degeneration were chosen at random, out of a larger sample of 100 tali, for the study.

Imaging Setup

The x-ray source for the DEI system (Fig 1) is a Comet MXR-160HP/20 x-ray tube (Comet AG, Flamatt, Switzerland), with a stationary tungsten anode and a focal spot size of 0.4 mm. A Titan 160 x-ray system (GE Inspection Technologies, Ahrensburg, Germany), with a maximum voltage of 160 kV and 1 kW total power, powered the anode. A 2.0-mm-thick tantalum collimator with an aperture 25 mm wide × 1 mm high was placed over the exit window of the x-ray tube to create a fan beam (11).

A monochromator was built using a single perfect float zone silicon crystal (Shaw Monochromators, Riverton, KS)

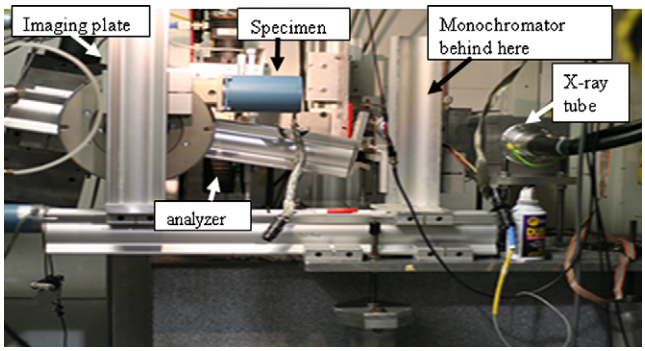

Figure 1. Tube diffraction-enhanced imaging setup.

of the 333 reflection type measuring 70 × 35 × 10 mm. The monochromator was placed 100 mm from the x-ray tube. The incident angle of the fan beam on the monochromator crystal was 5.7° to select the Kα1 (59.318 keV) characteristic emission line of tungsten. Because of the source divergence and the monochromator's crystal size, the monochromator also reflected the Kα2 (57.982 keV) emission line (11).

Imaging

Each sample, at a distance of 650 mm from the x-ray tube, was moved through the x-ray beam using a translation stage (Newport Corporation, Irvine, CA). A silicon analyzer crystal measuring 150 × 60 × 10 mm was placed behind the sample and tuned to an angle of 5.7° with respect to the imaging beam. The analyzer is the same type as used for synchrotron DEI studies at the National Synchrotron Light Source (Upton, NY) (1).

All images were acquired using a Fuji ST-VI general-purpose imaging plate (Fuji Medical Systems, Stamford, CT) that was placed perpendicular to the post–analyzer crystal x-ray beam. The imaging plates were digitized using a Fuji BAS-2500 imaging plate reader (Fuji Medical Systems) at a resolution of 50 μm. This detector plate was selected because of its fixed noise for long exposure times and its detection efficiency at 59 keV. The imaging plate was scanned using a translation stage (Newport Corporation) in the opposite direction of the sample stage to form a radiograph of the sample using the fan beam. The detector and sample scanning methods have been previously described (11). A surface dose of 0.07 mGy was used for the diffraction-enhanced image.

Histology

Macroscopic grades were verified through histologic sectioning of representative regions of the tali. Because serial sectioning of entire tali is neither reasonable nor necessary, representative regions were processed for microscopic examination by dehydration in a series of increasing alcohol concentrations, followed by paraffin infiltration and