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In-Laboratory Diffraction-Enhanced X-Ray Imaging of an Equine Hoof

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A B S T R A C T

We describe and demonstrate the first application of a laboratory-based diffraction-enhanced X-ray imaging instrument for noninvasive equine imaging. A formalin-preserved disarticulated forelimb from a near-term aborted miniature horse fetus was imaged with diffraction-enhanced X-ray imaging. The resultant calculated images—absorption, extinction, refraction, and scattering—are presented, and soft-tissues such as the dorsal digital extensor tendon, articular cartilage, as well as various joint, tendon sheath, and bursa recesses are observed in simultaneous registration with the adjacent dense bone tissue. Radiation dose calculations were performed and a calculated surface dose of 0.6 mGy for the soft muscular tissue was determined for the imaging experiment.

1. Introduction

X-ray radiography has played a significant role in the diagnosis and treatment of multiple types of pathological and systemic medical diseases and conditions. The primary advantage of conventional radiography is the ability to visualize the internal structure of a living species non-invasively; dense materials or high-Z elements located within an object or specimen, such as bone matter, can be visualized quite easily using this technique. Soft-tissues, however, are difficult to detect using conventional radiography because of the low absorptivity of the tissue and the resultant low absorption contrast between neighboring soft-tissue structures. As a result, pathological conditions that reside in regions composed of soft-tissue must be diagnosed using alternative, noninvasive techniques. To date, these techniques have included magnetic resonance imaging and ultrasonography—both of which have limitations.

A new class of X-ray imaging techniques, analyzer-based imaging, has emerged from the research performed at synchrotron radiation facilities [1-6]. Analyzer-based imaging involves placing an analyzer crystal between the object of interest and the X-ray detector or film. By placing the analyzer crystal between the sample and the X-ray detector, one can produce high contrast images that are normally not associated with X-ray imaging.

Recently, we have designed and demonstrated the first low-energy diffraction-enhanced X-ray imaging (DEXI) instrument which uses a conventional X-ray tube as its source of X-rays [7]. In the present study, the first application of DEXI technology for noninvasive equine imaging has been demonstrated. The results reported in this work are not intended to show new anatomical findings of an equine appendage; the aim of this work is to demonstrate the use of a novel imaging technique, DEXI technology, for imaging of equine appendages. To this end, a formalin-preserved disarticulated forelimb from a near-term aborted miniature horse fetus has been imaged using the DEXI instrument, and the resultant computed images show soft-tissue structures that are not visible using conventional radiography. These preliminary images show great promise for the use of this technology to assist in the detection, diagnosis, and potentially the prevention of harmful veterinary-related conditions and injuries.

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2. Materials and Methods

2.1. Formalin-Preserved Equine Hoof

Imaging was performed on a disarticulated forelimb from a near-term aborted miniature horse fetus. The sample was removed just above the metacarpophalangeal joint and preserved in formalin. The equine hoof was held in position in the DEXI instrument using a plastic clamp attached to an automated linear translational stage. The sample was oriented vertically with the monochromatic X-ray beam traversing perpendicular to the sagittal plane of the specimen.

2.2. DEXI Instrument

A detailed description of the laboratory-based DEXI instrument used in this study can be found in a previous publication [7]. In summary, the DEXI instrument uses a 2.2-kW silver X-ray source, which is operated at a voltage of 55 kV and a current of 35 mA. A mismatched, two-crystal monochromator is placed in front of the conventional X-ray source and the resulting monoenergetic 22.16-keV beam measuring 12 mm × 60 mm is passed through the sample. An analyzer crystal is placed immediately after the sample, followed by a high-resolution digital detector. The DEXI instrument has an experimentally determined spatial resolution of 160 ± 7 μm in the horizontal direction and 153 ± 7 μm in the vertical direction [7].

2.3. Imaging Procedure

According to the general DEXI operating protocol, the user should select the following three parameters: (1) number of angular positions for the analyzer crystal [1]; (2) the exposure time per angular position; and (3) number of sample positions (translational and/or rotational) for the object.

Depending on the mode of operation (eg, diffraction-enhanced imaging [DEI], multiple-imaging radiography [MIR], etc.), the number of analyzer crystal angular positions could range from a single position to multiple positions [1,8]. Once the angular positions and the sample's translational positions are determined, the user will then choose the desired exposure time per angular position and then start the experiment.

After the image acquisition is complete, the user can choose from a number of image processing methods. For the data presented in this study, MIR methodology was used to compute the reported images [8-10]. MIR, involves collecting multiple raw images of the specimen by placing the analyzer crystal at multiple angular positions along the rocking curve. A set of four new images are computed using these raw data collected at each analyzer position. The resultant computed images are apparent absorption, extinction, refraction, and scattering images.

2.4. Radiation Dose Calculations

To calculate the radiation dose deposited for this experiment, we have used the following approach:

The absorbed dose for X-rays can be described by

$$Dose = \frac{Energy\ Deposited}{Object\ Mass} \tag{1}$$

In the DEXI instrument, we use a monochromatic X-ray beam of 22.16 keV; as a result, equation 1 becomes

$$D\left(E_{ph}\right) = \frac{N_{abs}E_{ph}}{M} \tag{2}$$

where N_{abs} is the number of photons that result in energy absorption, E_{ph} is the photon energy, and M is the mass of the material. The number of photons absorbed that result in energy absorption can be expressed as follows:

$$N_{abs} = N_o\frac{\mu EN}{\mu T}\left(1-e^{-\mu Tt}\right) \equiv N_o\frac{\frac{\mu EN}{\rho}}{\frac{\mu T}{\rho}}\left(1-e^{\frac{\mu T}{\rho}\rho t}\right) \tag{3}$$

The μ/ρ values (mass attenuation coefficient) are specific to a material and are independent of the state (ie, solid, gas, liquid). They are directly related to the cross-section per atom. The total mass attenuation coefficient, μ_T/ρ, accounts for all X-ray loss mechanisms—photoelectric absorption, elastic scattering, and Compton scattering—and is used to calculate the number of X-rays transmitted through a material. The energy absorption mass attenuation coefficient, μ_{EN}/ρ, is a measure of those X-rays that are absorbed and result in energy deposition (all of the photoelectric absorption and part of the Compton scattering).

Substituting equation 3 into equation 2 gives the following equation:

$$D\left(E_{ph}\right) = \frac{E_{ph}}{\rho At}N_o\frac{\frac{\mu EN}{\rho}}{\frac{\mu T}{\rho}}\left(1-e^{-\frac{\mu T}{\rho}\rho t}\right) \tag{4}$$

where A is the cross-sectional area of the region which is hit by the beam and t is the thickness of the mass of density ρ in which the dose is to be calculated.

In the X-ray imaging regime, the maximum dose occurs at the surface of objects. Thus, the largest dose is the "surface dose." This is the dose that is usually quoted when talking about dose to objects and tissues in imaging. The surface dose is the zero thickness limit of equation 4

$$\begin{aligned} D\left(E_{ph}\right) &= \lim_{t\to 0}\frac{E_{ph}}{\rho At}N_o\frac{\frac{\mu EN}{\rho}}{\frac{\mu T}{\rho}}\left(1-e^{\frac{\mu T}{\rho}\rho t}\right) \\ &= \lim_{t\to 0}\frac{E_{ph}}{\rho At}N_o\frac{\frac{\mu EN}{\rho}}{\frac{\mu T}{\rho}}\left(1-\left(1-\frac{\mu T}{\rho}\rho t\right)\right) \\ &= \lim_{t\to 0}\frac{E_{ph}}{\rho At}N_o\frac{\frac{\mu EN}{\rho}}{\frac{\mu T}{\rho}}\frac{\mu T}{\rho}\rho t = \frac{N_oE_{ph}}{A}\frac{\mu EN}{\rho} \end{aligned} \tag{5}$$

Therefore, the surface dose is the energy deposited per unit area × the energy absorption mass attenuation coefficient. Equation 5 is used to evaluate the surface dose