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Material-specific imaging system using energy-dispersive X-ray diffraction and spatially resolved CdZnTe detectors with potential application in breast imaging

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ABSTRACT

This paper presents a coherent X-ray-scattering imaging technique using a multipixel energy-dispersive system. Without any translation, the technique produces specific 1D image from data recorded by a single CdZnTe detector pixel using subpixelation techniques. The method is described in detail, illustrated by a simulation and then experimentally validated. As the main considered application of our study is breast imaging, this validation involves 2D imaging of a phantom made of plastics mimicking breast tissues. The results obtained show that our system can specifically image the phantom using a single detector pixel. For the moment, *in vivo* breast imaging applications remain difficult, as the dose delivered by the system is too high, but some adjustments are considered for further work.

1. Introduction and context

Breast cancer is currently the most common cancer in women worldwide. Because of its frequency of occurrence, numerous scientific studies are devoted to its prevention, detection or cure. In the clinic, the main diagnostic screening tool is mammography, which involves measuring how X-rays are attenuated by the breast. The difference in attenuation between the various tissues (adipose, fibroglandular, benign or malign tumor etc.) produces contrast in the X-ray image. However, the contrast between fibroglandular and abnormal tissues is low (see Fig. 1). This low contrast can be problematic, especially in dense breasts where the proportion of fibroglandular tissue is high, and potentially results in 20% of breast cancers only becoming visible by conventional techniques once the disease is well established [17].

In addition to these false negative results, mammography is associated with a relatively high rate of false positive results. Ambiguous diagnosis is refined by applying other techniques like ultrasounds or MRI, and ultimately by breast biopsy. Biopsy is the only definitive technique in breast cancer diagnosis, but it is invasive and can be very stressful for the patient. Therefore, techniques need to be found to reduce the need to perform biopsies for the diagnosis of benign lesions.

New techniques improving breast cancer diagnosis are thus constantly being sought. This paper proposes a method for material-specific medical imaging, to be, in the long term, used as a second-line diagnostic imaging technique. The method is based on Rayleigh scattering of X-rays, in a configuration called Energy-Dispersive X-Ray Diffraction (EDXRD) combining an X-ray tube and an energy-resolved detector. *In vitro*, this technique has been shown to detect biological tissues more specifically than X-ray absorption [2]. *In vivo* systems have been considered but have rarely been studied because of problems with their sensitivity. These problems affected the dose delivered to the patient, and the spatial resolution, which tended to be low. Here, we propose a system, based on a CdZnTe (CZT) detector, and a method to localize and identify the different materials in a sample, leading to a specific imaging technique. The materials used for the study are chosen in a way that their scattering signatures are close to the ones of breast tissues. The pixelated detectors in our system provide good energy resolution. By including subpixelation the size of the pixels could be virtually reduced without degrading the energy resolution, this made it possible to open the collimator, thus increasing sensitivity without affecting the angular resolution. The improved trade-off between resolution and sensitivity is a first step for this

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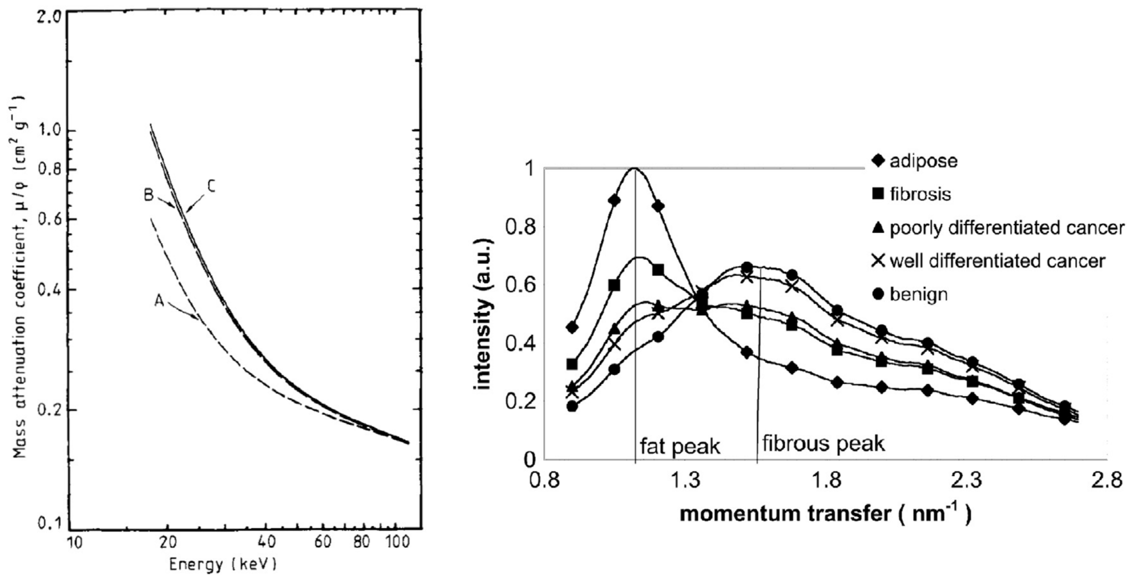

Fig. 1. Left panel: mass attenuation coefficients from several breast components. (A) Adipose tissue, (B) Fibrous tissue, (C) Infiltrating duct carcinoma [9]. Right panel: form factors for various breast tissues. [18].

technique to become compatible with clinical conditions.

The remainder of the paper is organized as follows: first, some elements of x-ray scattering theory will be explained in Section 2, followed by our system and model in Section 3; then, the processing method used to extract the specific scattering signature from the measured spectrum is described in Section 4; finally, experimental data are presented.

2. Rayleigh scattering theory and measurement systems

Rayleigh scattering of X-rays can be used to determine the atomic and molecular structures of both crystalline and amorphous matter. Indeed, the coherent scattering of photons by matter leads to more or less pronounced interference which can be interpreted, thanks to a scattering pattern known as the form factor, to determine the structure of the matter analyzed. In crystals, matter is ordered by definition, and the interference patterns only allow some combinations of energy and scattering angle for the incident photon. These combinations are directly related to the inter-atomic distances defined by Bragg's law:

$$2d\sin\left(\frac{\theta}{2}\right) = n\lambda \tag{1}$$

where d is an interplanar distance of the lattice, θ is the scattering angle, n is the diffraction order ($n \in \mathbb{N}$), and λ is the wavelength.

The form factor will therefore have Dirac distributions related to the wavelength and the diffusion angle of the photon. More precisely, the form factor depends on the momentum transfer, χ, usually expressed in nm^{-1} and the combination of energy and angle of diffusion:

$$\chi = \frac{1}{hc}E\sin\left(\frac{\theta}{2}\right) \tag{2}$$

where h is the Planck constant, c is the speed of light, E is the energy of the photon, and θ is the angle of diffusion. In combination with Eq. (1), for a crystal, the form factor will present a peak for $\chi = n/2d$ [5,12].

For amorphous matter, such as biological tissues, the inter-atomic distance is not constant, but privileged inter-molecular distances do exist. Thus, the form factor will have a smoother aspect with some broad peaks (see Fig. 1).

The form factor can therefore be sufficiently differentiated to distinguish between different materials if their scattering patterns are measured accurately enough. Many applications can thus be considered, ranging from security to healthcare. In this study, we consider using this technique for a medical application: breast imaging for cancer detection.

Two approaches to develop a scattering measurement device are of particular interest. The first is called Angular-Dispersive X-Ray Diffraction (ADXRD) [13,4,3]. In this configuration the scattering pattern is measured at different angles using monochromatic x-rays (usually produced by a synchrotron radiation device) associated with an integration mode detector. Because it requires such specific X-rays, this technique would not be feasible in a hospital setting for routing diagnosis. The second approach is called Energy-Dispersive X-Ray Diffraction (EDXRD) [8,11,18], it measures the scattering pattern at a fixed angle using polychromatic X-ray tubes and an energy-resolved detector.

For this study, we chose to develop a material-specific imaging system based on an EDXRD configuration, taking advantage of the gain of one dimension when measuring the scattering signal. Indeed, in the ADXRD configuration, a whole pixel line (or the motion of a single pixel) is needed to record the scattering signal from a voxel, while a single stationary pixel is sufficient in EDXRD. This technique will therefore be more suitable for imaging, as a 2D spectrometric detector can be used to image a whole object plane in one shot. The expertise of our laboratory in the development of energy-resolved photon counting detectors and data processing, e.g. through subpixelation techniques, will also be advantageous in this sort of configuration [1,15]. The pixelation of our detector provides spatial information about the object configuration as each pixel will view a different part of it. A simplified schematic representation of this type of system is presented in Fig. 2, in a pinhole configuration. Other collimation types, such as parallel slits [7] or coded aperture [10], could also be considered.

The physical model used in our study - an EDXRD system using a pixelated detector - will be presented in the next section.

3. Model

Eq. (3) describes the physical model of a coherent scattering spectrum acquired on a pixelated energy-resolved detector. The pixelation will produce a spectrum in 2D: pixel and energy level.