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Energy Dispersive X-Ray Diffraction System as a Promising Virtual Biopsy in Mammography

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I. INTRODUCTION

X-ray diffraction is a powerful technique to provide information on the molecular structure of samples. Thanks to this property, it has been found to be useful in different fields of applications such as security check and cancer research, especially breast cancer [1]. A diffraction imaging might be more specific than conventional mammography, especially to distinguish dense healthy fibroglandular tissues from carcinoma. Hence, the idea is to realize a virtual biopsy using X-ray diffraction rather than a breast biopsy if mammography outcome is unsure.

X-ray diffraction imaging suffers from low sensitivity and system optimization for the given application is a very important issue. We propose to optimize an energy dispersive X-ray diffraction (EDXRD) system because it allows to use a conventional X-ray tube, and thanks to good performances of room-temperature semiconductor X-ray detectors, e.g. $CdTe$, it can be used in clinical conditions.

The influence of different system parameters on sensitivity and resolution was studied by using analytical calculations. This allowed to develop an optimization strategy for mammography application to find the compromise between sensitivity and resolution, taking into account the deposited radiation dose as well.

The purpose of this study is to demonstrate the possible performance of an analytically optimized X-ray diffraction system in mammography in terms of resolution and sensitivity by analytical calculations as well as its discrimination power with associated required dose by means of realistic phantom simulations.

II. OPTIMIZATION OF AN EDXRD IMAGING SYSTEM

X-ray diffraction patterns depend on photon momentum transfer $\chi = E \sin(\theta/2)/hc$ (nm^{-1}), where E (keV) is the photon energy, θ $(°)$ the diffraction angle, h $(keV \cdot s)$ Planck's constant and c $(nm \cdot s^{-1})$ the speed of light. EDXRD spectra are measured at a fixed scattering angle Θ with varying energy. A classical EDXRD setup consists of a collimated polychromatic X-ray source and of a secondary collimation associated with a spectroscopic detector. The finite system resolution adds energy variant blurring to the observed spectrum [2]. In order to separate diffraction pattern of fibroglandular tissues and carcinoma (Fig. 1) χ-resolution should be at least about 0.2 nm^{-1}.
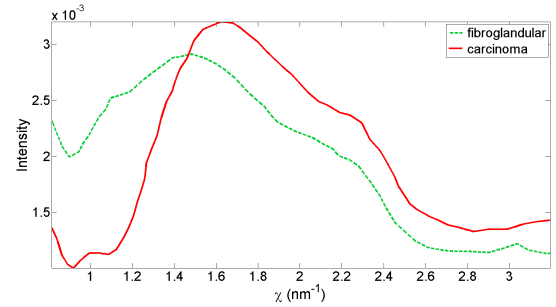
Fig. 1. Diffraction signatures of fibroglandular tissue and carcinoma [1].

We propose to use a very thin pencil beam (about 1 mm) associated to a convergent secondary collimation, which we optimize, to inspect the suspicious location, identified in conventional mammography.

Optimization process starts from the scattering profiles of fibroglandular and cancerous tissues, and the absorption properties of breast tissue. The first one fixes the χ-range to be accessed, which is between 1 and 2.5 nm^{-1}. The second one helps to fix the energy range of the incident X-ray spectrum by defining a compromise between diffraction signal and dose deposit. Knowing the E-range allows to determine the range of scattering angles to meet the momentum transfer requirements. Combined with a given detector dimension L_d the θ-range permits to determine the collimation height H. Collimation hole size h is used to balance sensitivity and required momentum transfer resolution.

Following this strategy, two collimation systems (Fig. 2) were parameterized: a monofocal collimation targeting only one sample point and a multifocal collimation with different target points over the whole sample depth. The two collimation systems were optimized in a way to have similar sensitivity and resolution.
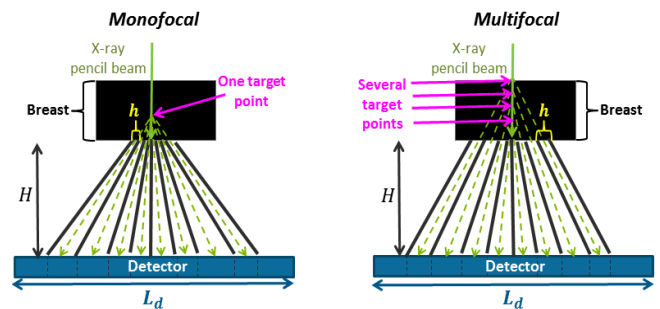

Fig. 2. Schematic representation of the two collimation systems.

III. SIMULATIONS

In order to evaluate the systems' discrimination power, simulations of the whole EDXRD acquisition system were

realized using PENELOPE calculations adapted to X-ray diffraction. Fig. 3 shows the breast phantom, that was used: a 50 mm thick cylinder (gray) of adipose tissue containing a fibroglandular tissue ellipsoid (red) with thicknesses from 20 to 40 mm and in the center a nodule of 4 mm (yellow). The nodule was either made of fibroglandular tissue or of pure carcinoma. The incident X-ray spectrum was chosen to be a filtered (energies below 20 keV) tungsten spectrum with a maximum energy of 150 keV. The simulated detector was a 5 mm thick $CdZnTe$ detector with 2.5 mm pixel size (monofocal 24×24 pixels, multifocal 20×20 pixels in order to have the same global sensitivity).
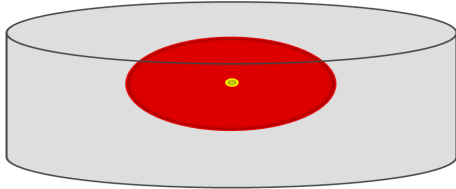

Fig. 3.   Breast phantom with 4 mm nodule (yellow) in the center.

IV. PERFORMANCES

To assess the system performances, different figures of merit (FOM) were used. Collimation sensitivity and spatial, angular as well as momentum transfer resolution were determined using detective quantum efficiency (DQE) [3]. Discrimination power between fibroglandular and cancerous tissues was evaluated with the help of contrast to noise ratio (CNR) and receiver operation characteristic (ROC) curves [4].

A. Collimation sensitivity and resolution

Sensitivity and the different resolutions of collimation systems were calculated analytically. Fig. 4 shows the sensitivity profiles of the mono- and multifocal collimation system. It can be seen that sensitivity of the monofocal system is maximum around the target point, whereas it is distributed much more uniformly in the sample for the multifocal system. Monofocal collimation was configured to target the upper end of the breast. It is necessary to realize a vertical scan in order to image the entire breast depth. Mean resolutions of both collimation systems are very similar and are summarized in table I. Spatial mean resolution of both systems is rather poor. On the contrary, the angular resolution of about 0.2° leads to a χ-resolution, which is acceptable at the lowest and at the highest photon energy. However, it has to be noted that energy resolution of the detector was not taken into account in resolution calculations. This will slightly decrease momentum transfer resolution.

TABLE I
MEAN RESOLUTION RESULTS FOR THE TWO COLLIMATION SYSTEMS.

	Spatial (mm)	Angular (°)	χ at 20 keV (nm^{-1})	χ at 150 keV (nm^{-1})
Multifocal	7.7	0.22	0.032	0.23
Monofocal	7.1	0.20	0.029	0.22

B. Discrimination power

System discrimination power was assessed by evaluating the separability of simulated spectra with fibroglandular nodule
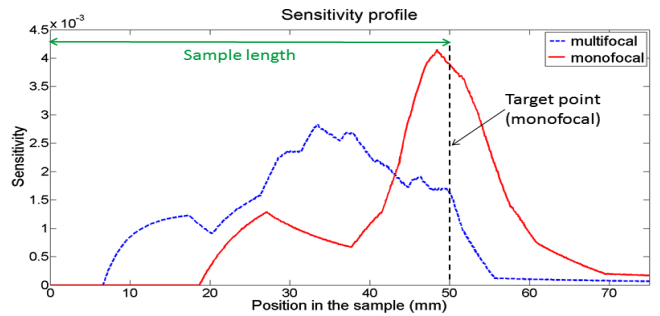

Fig. 4.   Collimation sensitivity profiles in the sample with maximum around target point for the monofocal system and a more homogeneous sensitivity distribution for the multifocal system.

and carcinoma nodule. Here, the whole system (X-ray source, collimation, sample nature, detector response) as well as the different interaction types were taken into account, and monofocal collimation was positioned to target the nodule. The number of incident photons required to obtain a separation of 3σ between the two types of spectra, was determined using the CNR. This corresponds to an area under the ROC curve of about 0.9986, which is very close to an ideal discrimination. Table II shows the corresponding doses for different thicknesses of the fibroglandular ellipsoid. For both systems a dose between 0.3 and 0.4 mGy is necessary to distinguish between fibroglandular nodule and carcinoma nodule. Compared to conventional mammography, where the dose is about 2 mGy, this is very low. The thickness of the fibroglandular region has no significant impact on dose requirements.

TABLE II
REQUIRED DOSE (mGy) FOR 3σ SEPARATION.

	fibroglandular thickness (mm)		
	20	30	40
Multifocal	0.296	0.312	0.317
Monofocal	0.367	0.361	0.369

V. CONCLUSIONS AND FUTURE WORK

In this study, we optimized and characterized two collimation systems (mono- and multifocal) for EDXRD-based virtual biopsy in mammography. It was shown that their performances are very similar, and that they seem to be adequate to separate fibroglandular tissue from pure carcinoma. Hence, EDXRD as a tool for virtual biopsy is very promising. In future work, the shape of the incident spectrum might be taken into account in optimization, and the impact of tissue variability and nodule position should also be further analyzed.

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