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Conical slit and conventional X-ray sources: Challenging steps for calcium spots detection

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ABSTRACT

An easy and simple to build conical slit (CS) was designed and tested, in a sample model approach, in order to check its possible use to detect Calcium Oxalate (CO) breast microcalcifications (MC) using conventional X-ray sources. A single-cone conical slit (SCCS) and a multi-cones conical slit (MCCS) were designed and constructed. Also, the CS apertures were calculated in order to maximize the diffracted intensity, while also providing sufficient angular resolution. The detection was done by scintillation detector and by films. The alignment of SCCS and MCCS is straightforward. The SCCS and MCCS capability in resolving CO diffraction cones were tested under different background scattering condition. For this, composite samples made up of CO embedded in different soft materials (paraffin wax or polypropylene or polyamide) have been explored. SCCS showed some limitation especially due to the superposition with low order CO powder diffraction cones and diffraction cones arising from paraffin wax and polypropylene. On the other hand MCCS showed to be efficient to resolve the CO diffraction cones in any case. MCCS shall be useful for next step tests with real in-vitro breast samples.

1. Introduction

X-rays have been increasing their capability as a diagnostic tool not only with new powerful X-ray sources (X-pinch and Z-pinch, metal-jet and high flux third generation synchrotron sources) [1–3], but also with high quality X-ray optics (Fresnel zone plate, compound refractive lenses, kinoform lenses and multilayer Laue lenses) [4–7] and with high resolution and efficient area detectors (CCDs, flat panels). Specifically for mammography, different approaches have been proposed, especially involving phase contrast imaging techniques [8–10] for assisting early detection of breast neoplasia.

The major part of breast neoplasia can be correlated to microcalcifications (MC) which can be found in human body in both crystalline and non-crystalline forms [11]. These breast MC have been classified in two types depending on chemical composition [12] and in five types depending on shape [13]. On the chemical composition MC can be formed of calcium oxalate [weddellite phase—$CaC_2O_4 \cdot 2H_2O$ or $CaC_2O_4 \cdot (2 + x)H_2O$ with $x < 0.5$] [12,14] or in the form of calcium phosphate [hydroxyapatite phase—$Ca_{10}O_{26}P_6H_2$] [12]. Calcium oxalate (CO) is found in crystalline form [12,15] and it is mostly associated to secretory calcification [15]. Calcium phosphate (CP) is found in crystalline [12] and non-crystalline form [15]. Also, CO MC are more likely related to benign breast disease than CP MC [12,15,16]. On the other hand, a subtype of a complex hydroxyapatite form (magnesium substituted hydroxyapatite) has been detected only in malignant lesions [17]. On the shapes, the MC can be classified as [13]: (i) annular, (ii) regularly punctiform, (iii) too fine for defining precise shape and (iv) irregular punctiform or vermicular. According to the study of M. Le Gal et al., [13] which involved the study of 227 cases of breast MC without palpable tumor, 100% of annular shape was benign lesion and 100% of vermicular shape was malignant.

Clearly, detection of MC as early warning signs of breast neoplasia is, therefore, an important issue. However, commercial mammography systems offer spatial resolutions ranging from 50 to 100 μm, with the images formed by attenuation projection (radiography); i.e., not only the MC are projected on the film but, also, all other surrounded tissues. This raises a problem found in general radiography images where, sometimes, the photoelectric absorption and scattering by the surrounding tissues are strong enough to prevent the detection of different details (for mammography, e.g., the MC). This can be circumvented by X-ray beam restrictors and grids [18–20], by radiographic positioning

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Table 1
Calcium oxalate (CO) and calcium phosphate (CP) phases and their properties: crystal system, space group number and space group.

Name	Crystal system	Space group number	Space group
Hydroxyapatite (CP)	Hexagonal	176	*P63/m*
Whevellite (CO)	Monoclinic	14	*P21/c* or *P21/n*
Weddellite (CO)	Tetragonal	87	*I4/m*

techniques [21], by using contrast agents [18,19] or, even, by applying the termed phase contrast imaging techniques [8–10,22–25] in order to detect breast MC [8–10,26–30].

Conical slit (CS) has been used to increase the depth resolution in materials science applications [31–33]. In this work, a Conical Slit (CS) was designed, assembled and tested to check its possible use to detect CO MC in a sample model approach. A CS is required to select the CO MC powder diffraction cones. In terms of practical application, the main challenge is to distinguish the CO diffraction cone from the strong background scattering condition (including, elastic and inelastic scattering) arising from all other soft surrounding tissues. Also, the CS needs to be able to distinguish CO and CP (when the last is crystalline). Indeed, to be in accordance with conventional mammography systems, which usually work with Rh and Mo target X-ray tubes, the CS should be designed to work at the characteristic emission line energies of one of those targets. At last, we are focusing our tests on CO because it is always found as CO MC in the crystalline form. Then, since CO MC is more likely related to benign breast neoplasia, such a diffraction detection technique based on the use of a CS could help to prevent biopsies which currently needs to be carried out in any case.

Note that, diffraction contrast has already been used for tomography purposes [34,35]. Also, coherent X-ray scattering imaging has been used for biomedical science [36] as well as specifically for breast images [37]. In spite of that, one cannot make confusion with diffraction contrast and diffraction enhanced imaging. The former is based on diffraction of an element in the sample while the last is one of the termed phase contrast imaging technique which is based on the image transmitted by the sample and angularly analyzed by diffraction in a single crystal.

2. Calcium powders

Standard X-ray powder diffraction (XPD) analysis of commercial CP and CO powders (Fig. 1(a) and (b)) were made to identify the diffraction peaks to be used to specify the CS geometrical parameters. Both powders were checked in order to avoid diffraction peaks overlapping between the two main different compounds found in MC. The XPD measurements (Fig. 1) were carried out by using an X-ray tube with Cu target. The radiation was Ni filtered in order to work mostly with CuKα radiation (~8.04 keV). Then, we indexed the acquired diffractograms by using an ICSD database. Following that, we identified the CO and the CP powders as ICSD 26204 and ICSD 158939 which are hydroxyapatite phase [$Ca_{10}O_{26}P_6H_2$ and whevellite phase ($CaC_2O_4{\cdot}H_2O$—monohydrated calcium oxalate), respectively]. The CO powder we used was not weddellite [$CaC_2O_4{\cdot}2H_2O$ or $CaC_2O_4{\cdot}(2+x)H_2O$ with $x > 0.5$, a di-hydrated calcium oxalate found in breast MC]. However, it is useful to test the CS methodology and also, for future tests with *in-vitro* samples since whevellite is the CO thermodynamically stable form. A summary on the properties of the main CO and CP phases and its relation with breast neoplasia is shown in Tables 1 and 2.

3. Geometrical parameters

To build a CS, geometrical parameters play important role and need to be taken into account. For that, we need to define few parameters, following the scheme shown in Fig. 2, such as: mask aperture (a), mask thickness (t), entrance mask radius (R), exit mask radius (R') and

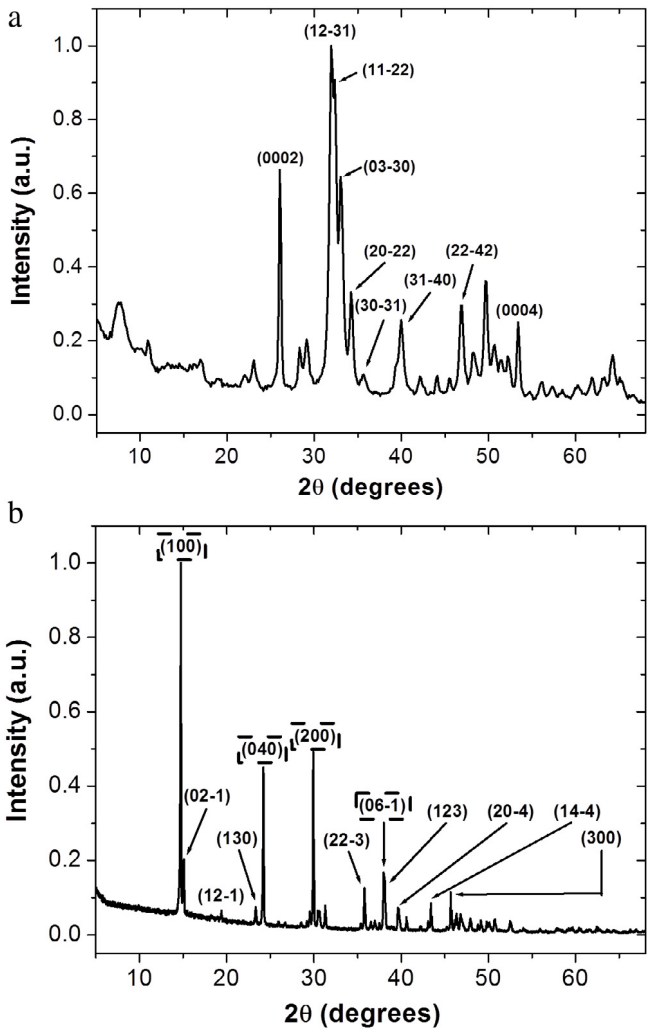

Fig. 1. Diffractograms (taken with CuKα) for the calcium powders. (a) Calcium phosphate (CP—hydroxyapatite phase) and (b) Calcium oxalate (CO—whevellite phase). The Miller index for each peak, corresponding to different diffraction planes, are pointed out.

CS angular aperture (4θ). With that, we introduced the sample to the entrance mask distance (D), the CS length (L) and the CS divergence ($\Delta\theta_{div}$, which is the CS angular resolution) given by:

$$D = \frac{R}{\tan\left(\frac{4\theta}{2}\right)} \tag{1}$$

$$L = \frac{R' - R}{\tan\left(\frac{4\theta}{2}\right)} \tag{2}$$

$$\Delta\theta_{div} = 2 \cdot \left[\frac{a - t \cdot \tan\left(\frac{4\theta}{2}\right)}{L}\right]. \tag{3}$$

Then, the CS focus (F) (Fig. 2(a)) and CS depth of focus (DoF) (Fig. 2(b)) will be given by:

$$F = \Delta\theta_{div} \cdot (D + L/2), \tag{4}$$

$$DoF = \frac{F}{\tan\left(\frac{4\theta}{2} + \Delta\theta_{div}\right)}. \tag{5}$$

In the above equations $4\theta/2$ could be written as 2θ. We kept 4θ to emphasize that the CS angular aperture parameter contributes to the other parameters.