Limit of Detection in X-ray Diffraction Measurements of Tissue Equivalent Samples

Y Zheng [1], N Vassiljev [1], A Konstantinidis [2], J Griffiths [1, 3] and R Speller [1]

[1]Department of Medical Physics and Biomedical Engineering, University College London, London WC1E 6BT, UK
[2]Diagnostic Radiology and Radiation Protection, Christie Medical Physics and Engineering, The Christie NHS Foundation Trust, Manchester M20 4BX, UK
[3]Institute of Biomedical Engineering, University College London, London WC1E 6BT, UK

E-mail: yi.zheng.11@ucl.ac.uk

Abstract. There is a suggestion of a new approach to mammography whereby following a conventional mammogram, the radiologist could interrogate suspicious regions using X-ray diffraction whilst the patient is still present and to establish the true extent of disease. A starting point for this work is to quantify the minimum detectable amount of breast cancer within a realistic thickness phantom. Perspex has a similar diffraction pattern to healthy breast tissue whilst water is similar to breast tumour, hence these two materials are used as tissue equivalent test objects for X-ray diffraction measurements. The preliminary results show linear agreement between the ratio of Perspex to water and the ratio of the diffraction peak intensities at 0.7 nm^{-1} and 1.5 nm^{-1}. The minimum detectable limit for a component of the two 'tissue' mix was found to be 4.1%. This suggests that X-ray diffraction can be used to quantify tissue like mixtures down to the 4.1% / 95.9% mix level and hence has a strong potential for delineating the extent of infiltration disease.

1. Introduction

There is a growing concern that current mammographic techniques do not satisfactorily indicate the limits of tumour involvement in infiltrating lesions [1]. This leads to insufficient tissue being removed at surgery, which can result in subsequent recurrences of breast cancer. X-ray diffraction (XRD) has been suggested to have a higher contrast than standard X-ray mammography, therefore making it a potential accurate non-invasive method of breast tumour mapping [2]. However, XRD requires a longer exposure time than mammography and results in a higher dose. One method to reduce the examination time is to reduce the number of XRD acquisitions, taking key point measurements rather than a blanket exposure. This can be achieved by using mammography guided XRD acquisitions. A starting point for this investigation is to establish the sensitivity of the technique to the fine infiltrating structures of disease that surround obvious lesions. So that it is able to validate the ability of XRD for tracing the extent of tumours in the boundaries between tumours and healthy tissues, which often

contains very small amount of cancerous cells. Two experiments have been presented in this paper to investigate this sensitivity.

2. Materials and Methods

The X-ray source used in both experiments was a laboratory Molybdenum (Mo) target source with 30µm Mo filtration. This creates a pseudo-monoenergetic spectrum dominated by Mo Kα (17.4 keV) and Mo Kβ (19.6 keV) lines (see figure 1). Water and Perspex have similar XRD features to healthy breast tissue and cancerous tissues. The diffraction peak of Perspex at 0.6 nm^{-1} represents the peak of healthy tissues at 1.1 nm^{-1}, while the peak of water at 1.6 nm^{-1} corresponds to the same peak as cancerous tissues. Therefore water and Perspex were used to form the test objects for these experiments.
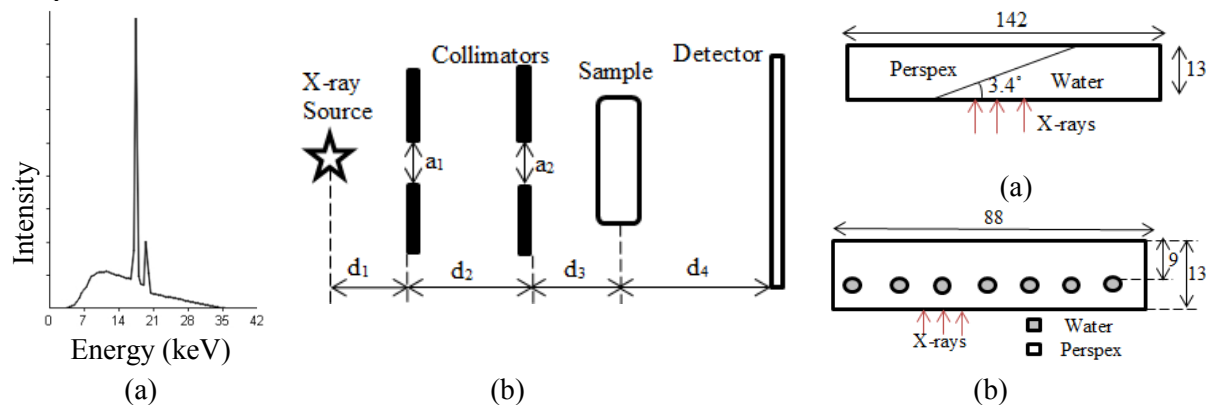

Figure 1. Experimental setup: (a) Energy spectrum of the X-ray source after the filtration; (b) schematic diagram of the geometry of the experimental setup

Figure 2. Test objects (distances given in units of mm): (a) the test object for experiment one; (b) the test object for experiment two

2.1. Experiment One

The aim of this experiment was to investigate the relationship between the XRD signal and the proportions of water and Perspex in the test object. The experimental setup is shown in figure 1. Distance d_1, d_2, d_3 and d_4 are 50 mm, 17 mm, 10.3 mm and 83.7 mm, respectively. The collimators are 3 mm thick Lead (Pb) blocks each with a circular hole of diameter (a_1 and a_2) 2 mm. The test object shown in figure 2 (a) was used in this experiment. A series of X-ray diffraction images corresponding to different proportion of water and Perspex were recorded.

2.2. Experiment Two

The second experiment was designed to investigate the minimum amount of water that can be detected by the XRD system. In other words, the aim of this experiment was to find the lower limit of detection of water. A second phantom (shown in figure 2 (b)) was designed for this purpose. It contained several holes (of diameter from 0.85 mm to 1.6 mm) filled with water within a Perspex block.

Furthermore, in this experiment, the distance between the different components in the experimental setup was altered to increase the intensity of the X-ray beam. In this experiment, d_1, d_2, d_3 and d_4 were 45 mm, 11 mm, 3.3 mm and 90.5 mm, respectively, while a_1 was 1.0 mm and a_2 was 1.2 mm.

2.3. Pre-processing

The background signal (an image without the presence of test object) was subtracted from XRD signal. Following this, pixels equidistant from the centre of the XRD pattern were averaged to transform the XRD signal from 2D data to a 1D profile.

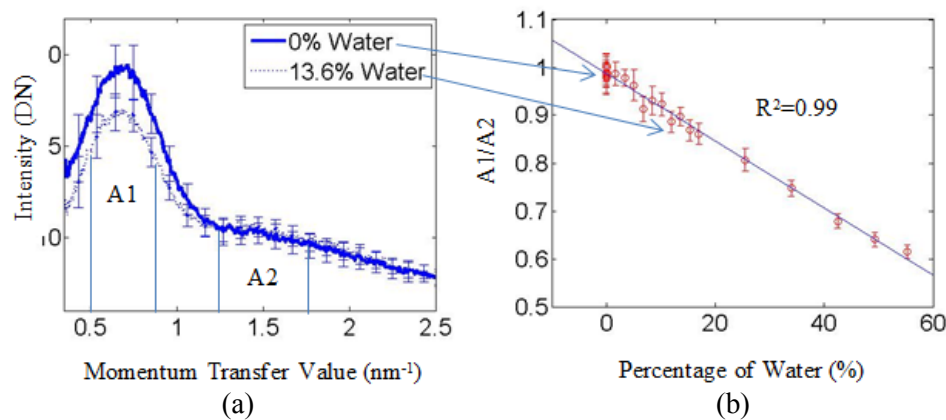## 3. Results and Discussions

Figure 3. Results of experiment one: (a) examples of XRD profiles with indications of the positions of peak area A1 and A2. DN represents 'Digital Number'. (b) The ratios of peak areas (A1/A2) versus the percentage of water

3.1. Results from experiment one

The results from experiment one are indicated in figure 3. Figure 3(a) demonstrates two examples of XRD profiles for experiment one. Each curve corresponds to a data point in figure 3(b) indicated by the arrows. The error bars in figure 3(a) are the standard deviation of 10 measurements. The vertical axis in figure 3(b) represents the normalized ratio of the area under the diffraction peaks at 0.7 nm^{-1} and 1.5 nm^{-1} (A1/A2). The error bars in figure 3(b) are the propagation error of the standard deviation of 10 measurements. The propagation error in figure 3(b) can be calculated by:

$$\sigma_R = ((\sigma_{A1}/A1)^2 + (\sigma_{A2}/A2)^2)^{1/2} R$$

where R equals to A1/A2, σ_{A1} and σ_{A2} are the errors of peak area A1 and peak area A2, respectively. As can be seen in figure 3(b), there was a linear response between the ratio of the peak areas and the percentage of water. The gradient indicates the sensitivity of the ratio of peak areas A1/A2 to the presence of water.

3.2. Results from experiment two

The diffraction profiles of Perspex and the mixture of Perspex and water are shown in figure 4. The lines and error bars in figure 4(a) and (b) are the mean value and standard deviation of 12 measurements, respectively. From figures 4(a) and (b), we can see the difference between the XRD profiles of 0% water and 4 % water are very subtle, while the difference between Perspex and 11% of water is significant (outside the error bars).
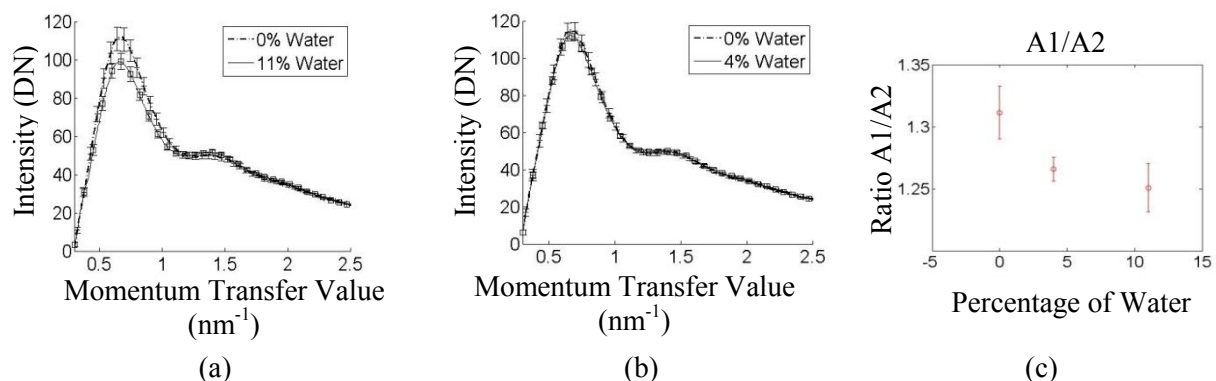

Figure 4. Comparison of XRD profiles of Perspex and the mixture of Perspex and water: (a) Perspex and 11% water; (b) Perspex and 4.1% water (c) the ratio of A1/A2 versus percentage of water in the test object

The statistics of the results can be improved by integrating the peak areas around 0.7 nm^{-1} and 1.5 nm^{-1}. The results are shown in figure 4(c). The error bars are the propagation error based on the standard deviation of 12 measurements. By calculating the ratio of the two peak areas, the difference between 0% water and 4.1%/4.6% water is greater than the error bar.

3.3. Results from transmission images
Although there were differences shown in XRD profiles when changing the proportion of water, the transmission image of the corresponding phantom did not show a significant change (as shown in figure 5). Notice that for the same position in figure 5(a), the effective percentage of water is different in the transmission image and the XRD images. This is because the size of the X-ray beam in the XRD experiment is larger than the diameters of the holes filled with water. The contrast at the position P (in figure 5(a)) is 0.029 ± 0.001 in the transmission image, while it is 0.048 ± 0.001 when using A1/A2 in the XRD profiles. Nevertheless, the difference of the linear attenuation coefficients between adipose and glandular breast tissue is bigger than that between Perspex and water. Therefore, the contrast of the transmission image in this experiment between different concentrations should be higher when using breast tissue.
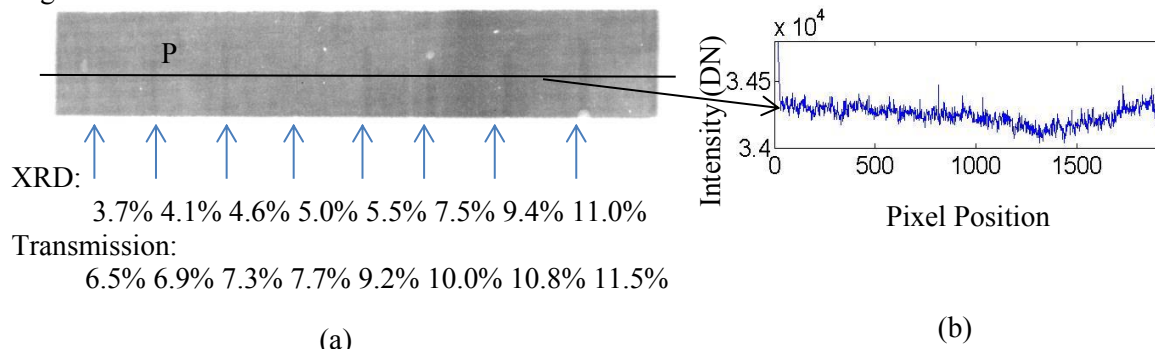

Figure 5. (a) Transmission image of the test object used in experiment two; (b) Profile plot of a line indicated in (a)

4. Conclusions and Future Work
This experiment has shown that the lower limit of detection of water (representing breast tumour) in a mixture of water and Perspex (representing healthy breast tissues) is 4.1%. This indicates that XRD has a much better performance than transmission imaging, and thus suggests that the XRD system can provide much better contrast between tumour tissue and healthy tissue than mammography. However, in order to fully understand the lower detection limit of breast cancer, real breast cancer and healthy tissue will need to be investigated. Furthermore, a more realistic phantom with a thickness similar to breast (such as 50 mm) should also be investigated.

References
[1]   Poletti M E, Gonçalves O D and Mazzaro I 2004 Measurements of X-ray scatter signatures for some tissue-equivalent materials *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **213** 595-8
[2]   Griffiths J A, Royle G J, Hanby A M, Horrocks J A, Bohndiek S E and Speller R D 2007 Correlation of energy dispersive diffraction signatures and microCT of small breast tissue samples with pathological analysis *Physics in medicine and biology* **52** 6151-64