Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v33i4.2024.321
Volume 33(4), December 2024

Analysing Spectral Imaging at Different Photon Energy Bins for Breast Lesion Contrast Visualisation from Computed Tomography Images

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ABSTRACT

The prevalence of breast cancer in Nigeria has become a source of concern as the yearly mortality rate has risen to about 102,000 cases. The National Cancer Control programme in Nigeria (NCCP) is focused on early detection and to extend the life of patients by utilising different screening modalities including the Computed Tomography (CT). However, preliminary work in breast CT has provided a number of compelling aspects that motivates the work featured in this research. These advantages include removal of the need to mechanically compress the breast which is a source of screening non-attendances, and that it provides unique cross-sectional images that removes almost all the overlying clutter seen in two dimensional (2-D) mammography. This renders lesions more visible and hence aids in early detection of malignancy. Work on breast CT to date has been focused on using scaled down versions of standard clinical CT systems. By contrast, this work proposes using a photon counting approach by investigating spectral imaging technology at different photon energy bins from conventional CT images for contrast visualization. It represents an idealized case of noiseless images that do not contain scatter or photon noise in order to study the intrinsic properties of contrast in CT. A breast phantom of diameter 100mm was analysed using a photon counting approach to simulate breast lesions. Investigations carried out in six (6) different experiments for lesion decomposition recorded higher contrasts between 1-60 keV. High contrasts values has been achieved at low energy bins which corresponds to the attenuation of glandular tissues. Photon counting approach has shown promise for the visualization of synthetic images in bins based on contrast investigations.

Keywords:
Computed Tomography,
Photoncounting,
Lesions,
Spectral imaging,
Breast cancer.

INTRODUCTION

About 2.3 million cases of female breast cancer and 670,000 deaths were estimated by the World Health Organization in February 2022 (WHO 2022), accounting for 30 percent of all female cancers. Universally, breast cancer has become the most common cancer after lung cancer especially for women aged 50 years and above (Ferlay et al., 2008; Ioannis et al., 2015). The disease represents the most frequently diagnosed cancer amongst women worldwide. In Nigeria, 49 percent of women aged 36 and above were diagnosed, thus positioning Nigeria as the 2nd highest in breast cancer amongst African countries (Edward 2010). The National Cancer Control programme in Nigeria is focused on early detection and to extend the life of patients. Although several modalities are used for screening, 2-D mammography has been recommended worldwide because of its technique for early detection (WHO 2022). Diagnosis through screening programmes and modern treatment modalities has been scanty in Nigeria in spite of the prevailing cases, making breast cancer more prevalent with lower mortality rate (WHO 2022). This is in contrast with the earlier assertion that breast cancer in developed countries has much less mortality than it is in developing countries. Although mortality rate in developed countries is more and cannot be compared to developing countries, cases of breast cancer has greatly gone above average because of divergent lifestyle and genetic considerations.

Clinically, detection of breast cancer with reduced dose and increased sensitivity in women with dense breast

has become a major concern as younger pre-menopausal women have begun to undergo screening routinely. This is because dense breast is made of more glandular and a greater volume of fibro glandular tissue, which is related to a higher risk of breast cancer (Edward 2010). Various modalities such as 2-D planar X-ray Mammography, Ultrasonography (US), Magnetic Resonance Imaging (MRI) are used. Presently 2-D planar X-ray Mammography is widely considered to be the gold standard technique for early breast cancer detection worldwide (Bliznakova et al., 2003). It however, suffers the limitations of superposition of 3D structures on to the 2-D projected image that can make the presence of breast cancer ambiguous in its appearance as seen in figure 1.

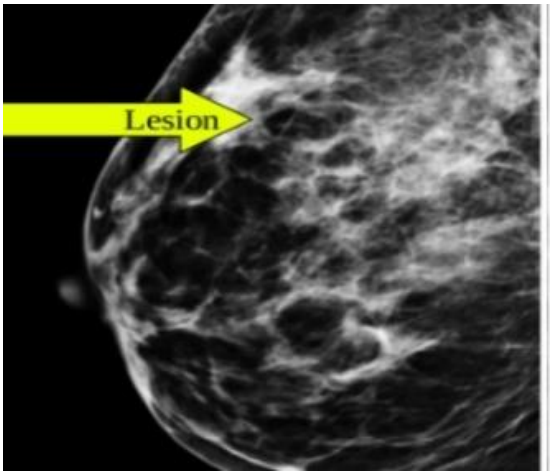

Figure 1: 2-D mammography showing presence of breast cancer (Gilbert et al., 2015)

The emergence of Dedicated Breast Computed Tomography (DBrCT) has shown potential for overcoming the overlapping tissue or superposition of lesion masses and moreover, removes the need for mechanical breast compression which is uncomfortable and, in some cases, painful (Ioannis et al., 2015). The subject lies prone on the table with a cut out for the breast in a pendate position as shown in figure 2. An X-ray tube and a detector placed under the table rotate 360 degrees around the breast from which cross-sectional slices can be reconstructed (Ferlay et al., 2010).

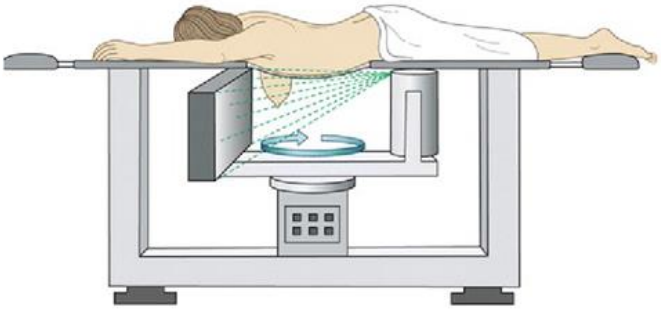

Figure 2: Breast examination with the breast in pendate position (Gilbert et al., 2015)

Dedicated breast CT has shown promise for clinical investigation to address the limitations of 2-D mammography. However, breast CT has only utilized the same approach as used in conventional CT with energy integrating detectors and do not take advantage of the polychromatic energy in the X-ray beam, which has the potential to provide better discrimination of different tissue types (Gilbert et al., 2015).This paper proposes to utilise computer simulation to analyse using spectral imaging methods for breast CT and investigate the emerging technology of dedicated breast CT based on photon counting detectors technology in bins.

Breast Anatomy

The main constituent of the breast includes dense and fatty tissues. The dense tissue, made of glandular and

connective tissues appears bright on a mammogram, while fatty tissue appears dark (Guray & Aysegul 2006). The functional tissue that makes up the breast is responsible for the generation of milk during lactation and size of the breast is dependent on the quantity of fatty tissues (Loren et al., 1997). The breast is made up of skin, fat, ducts and supporting fibre tissues as can be seen in figure 3.

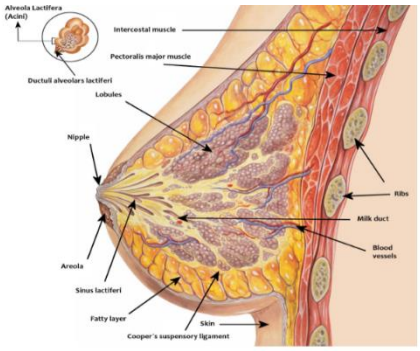

Figure 3: Anatomy of the Breast (Edwin et al., 2008)

The lobes in the breast are arranged between 15-20 segments, in a circular trend with small structures called lobules. The density of the breast is determined by connective tissues, blood vessels, lymph vessels, fat, glandular tissue and lymph (Merih & Aysegul 2006).The process of abnormal growth called cancer results in the formation of either malignant or benign tumours. Malignant cancer is the most destructive and may spread to other organs. This is unlike benign tumours that grow gradually and without spreading to other parts of the body. By extension, the anomalous growth of cells that spread by breaking away from the original tumour of breast tissue structure (soft tissue masses) are referred to as metastatic breast cancer (Timothy& Pia 2001).

Breast Cancer

Breast cancer may begin in the cells of the lobules or the duct and can be classified to be invasive or non-invasive depending on the diagnosis (Iortile and Ige 2022). The non-invasive cancer referred to as carcinoma does not penetrate normal tissues of the breast, whilst, the invasive cancer does penetrate and affect healthy tissues. About 70-80 percent of breast cancers diagnosed are invasive. Figure 4 illustrates images of clear visible cancer.

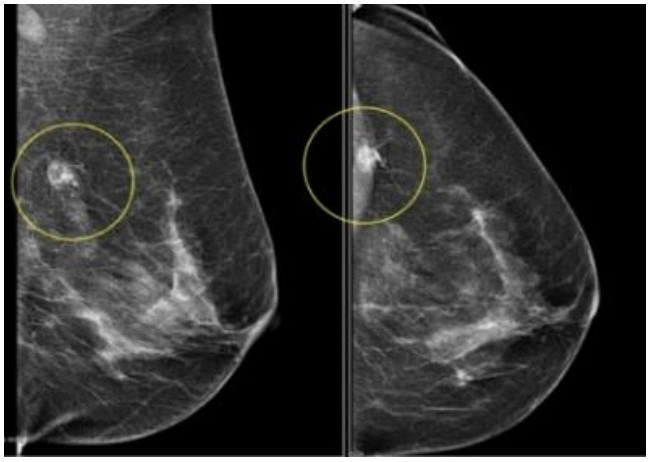

Figure 4: Mammography images of highly visible well differentiated masses showing clear signs of breast cancer (Edwin et al., 2008)

Photon Counting Breast Computed Tomography (PCBCT)

Spectral photon Counting Breast Computed Tomography (PCBCT) has been under investigation by other authors with promising results as a clinical device (Ann-Christin et al., 2017). Mammography based on photon counting detectors (PCDs) has proven to overcome the limitations of FFDM and DBT (Steven et al., 2007). The device is accompanied by a scanner that uses standard polychromatic X-ray sources and dedicated PCDs that encompasses multi energy imaging. The PCDs are able to discriminate photons of

different energy usually over a pre-defined set of energy windows. Prototype based on cadmium Telluride (CdTe), cadmium zinc Telluride (CZT) and silicon semiconductor detectors are now commercially available (Timothy & Pia 2001), which allows accurate measurement of photon energies for clinical use as shown in figure 5.

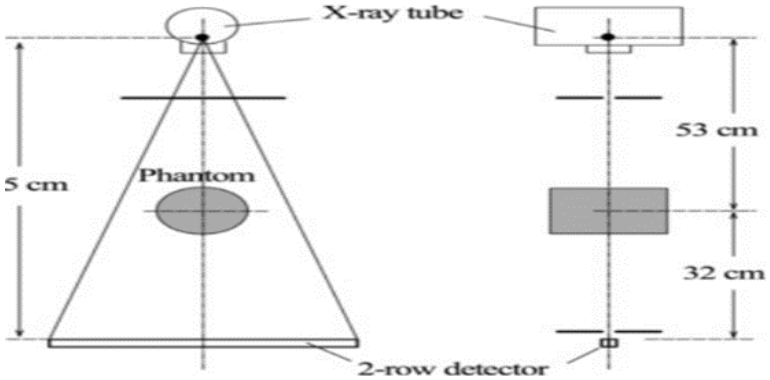

Figure 5: Schematic diagram of a two -sliced spectral CT system with photon counting CZT detector image (Rachel & Maria 2013)

Ann-christin et al., 2017 carried out a study that compared a PCBCT system with FFDM and DBT using surgical specimens, the confirmation of their results indicated that sensitivity and specificity for lesion and calcifications for PCBCT was higher by at least 7 percent in each case as seen in table 1 (Steven et al.,2007).

Table 1: Comparison of FFDM, DBT and PCBCT (Steven et al., 2007)

Systems	Sensitivity for microcalc percent	Specificity for microcalc (percent)	Sensitivity for lesion (percent)	Specificity for lesion (percent)
FFDM	82	71	45	76
DBT	70	75	62	62
PCBCT	85	83	65	76

The benefits of photon counting have previously been investigated, its use as a clinical devise has been hindered by the requirement of X-ray imaging, considering that quite a good number of photons are meant to be detected in a short time of image acquisition. Also, that large number of data are meant to be transferred to the computer and kept for use. However, the advents of chips in electronics have made it feasible for an efficient process. The ability to undertake spectral decomposition of data is a major potential advantage of photon counting CT (Ferlay et al., 2010).

This allows better discrimination of different tissue types and hence might be used to enhance the contrast of lesions within the image. These processes are carried out with a greater consideration of how much dose is being absorbed by the breast tissues (Siegel et al., 2022).

Dose in Computed Tomography

The persistent proposals of Computed Tomography CT as an imaging technology has been of concern recently, this is due to the fact that these technologies induce cancer during mammography screening, and have been a risk to women who undergo this screening, hence its clinical investigation. Radiation dose received during mammography is therefore a key issue as a result of the risk of induced cancer due to population exposure. Although adipose tissues are not at a higher risk as glandular tissues, care is taken to monitor the amount of radiation dose received by the glandular part of the breast because of its high radio sensitivity. Improvements in sensitivity according to Matthias et al. (2022) can be achieved with clinical CT as it completely removes the overlap of anatomical structures that have immense effect on mammography (Gilbert et al., 2015). Despite this advantage, there exist differences in X-ray attenuation between tissues of breast particularly glandular and tumour tissues (Agba et al., 2008). Dose assessment studies are required in breast imaging in order to determine accurately the amount of radiation dose involved during clinical application (Ozek et al., 2022). It has been demonstrated that the use of reconstruction CT algorithms could have effect on deposited dose. Other works of Siegel et al. (2022), also illustrates a quick and accurate procedure for estimating

dose using synchrotron-based studies on breast samples. Their work was aimed at establishing dose delivered in breast CT with the aid of Monte Carlo (MC) simulations and to also establish photon energy for dose minimization in CT which was based on monochromatic X-rays. Results suggests that CT imaging using monochromatic synchrotron radiation beams will allow assessment of an average dose with good accuracy in pre-clinical breast imaging (Rachel & Maria, 2013).

Based on the risk associated with radiation especially during mammography screening as the breast is exposed to ionizing radiation, dose determination during CT examination is important as it measures risks to patients and attempts to reduce Jacques et al. (2010) radiation without compromising the quality of diagnostic information. Methods such as reducing the peak tube voltage, using automatic exposure control and shielding can be useful, these methods could lead to sub optimal results (Suzuki et al., 2022).

Contrast in Mammography

Clinical studies have demonstrated that screening mammography reduces breast cancer mortality. The effectiveness of mammography can only be seen by the ability to identify tumours in breast cancer depending on the absorption of X-rays in the affected tissue, different from adipose and glandular tissues. Cancerous tissues in breast appears bright with similar intensity to glandular tissues which makes detection difficult during imaging, particularly in the dense breast (Hussein et al., 2023). At present screening mammography aims to reduce false positive results and to resolve the limitations of supper-imposed tissues in some technologies. This can be achieved if the magnitude of the signal difference between the tumour and its surrounding background is considered, which the contrast is. In breast imaging, high contrast is sought to enable differentiation of normal structures from pathological structure. The contrast also enables the detection of calcium deposits in the breast. A cancerous breast contains the lesion and other surrounding tissues as a result; the contrast is caused by the differences in X-ray attenuation properties of the lesion and the surrounding tissues. The thickness of the lesion is also a depending factor (Kuhl 2023). The work therefore aims to analyse the spectral imaging at different photon energy bins for breast lesion contrast visualisation from computed tomography images.

MATERIALS AND METHODS

This section describes simulation work in Breast CT and the method through which the data presented in section III has been realized using simulation software. The aim of this experiment is to investigate whether a spectral imaging approach (photon counting detectors) in breast CT can render lesions more visible when investigated in bins than using a conventional CT approach that relies on integrated signals

Breast phantom Design

The phantom used in this work has an approximate diameter of 100mm with two lesions inserted each measuring 5mm, representing 100 percent glandular tissue, and a calcification clutter with an average calcification diameter of 0.1mm. The breast phantom explicitly model tissues including; adipose, glandular, blood vessel, cooper ligament and air. The attenuation of each tissue changes for each energy as the energy changes along the polychromatic beam. The two-dimensional computational phantom shown in figure 6 was built for the development, optimization and evaluation of spectral imaging system aimed at reproducing breast characteristics for this work. The idea has been developed to replace the physical phantoms which are until now expensive. A code developed for this simulation work to experiment on the phantom to determine contrast at different photon energies was used with a Computer Aided Software (CAS) and reconstructed to enable the determination of contrast at different photon energies.

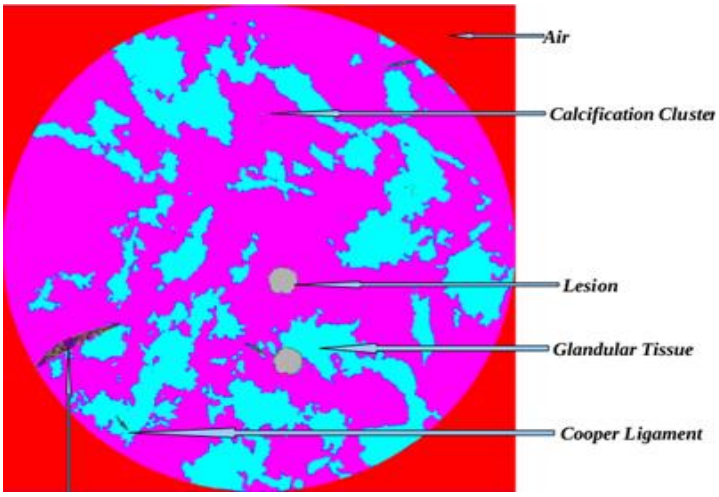

Figure 6: Breast Phantom

Simulation Framework

The process for which simulation for this work is carried out has been described using key components of the simulation frame work presented in figure 7. A series of simulation tools were used to simulate a photon counting breast CT system. A polychromatic energy spectrum was also generated from the in- software (Alabousi et al., 2021) based on the energy spectrum considered for these experiments. The geometry considered was 840mm and 740mm which are the distance from source to detector (SDD) and source to sample (SOD) respectively. In addition, the anode filtration combination used was Rh/Al. This simulation was taken to represent a CT during which a ray tracing algorithm was used to trace the photons. A phantom as previously described in section VII was then used along with the siddon algorithm and Fan beam acquisition process to generate sinograms. Reconstructed Images were processed from the generated sinograms. In the reconstruction process, an angular beam spacing of 0.5-degree, fan sensor spacing of 1 cm and line fan sensor geometry were considered.

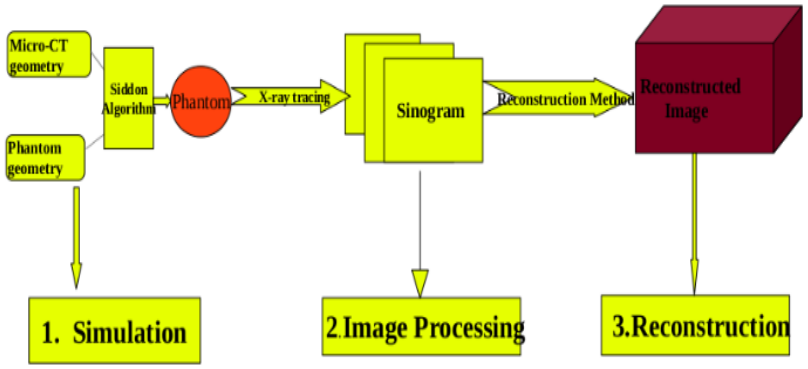

Figure 7: Block diagram of the key components used within the simulation frame work

Photon Energy Investigation

In order to examine whether photon counting technology can be used to enhance lesion contrast, photon energies between 0 and 120 keV were investigated initially using bins of 20 keV each in a first experiment, then using bins of 10 keV in a second experiment and finally in bins of 5 keV in a third experiment. The largest bin width as an initial experiment and the final test was used to look at any fine structure or other effects that may have been revealed. A region of interest (ROI) measuring 4 x 4 pixels was placed in the lesion and referred to as (ROIl). Similarly 4x4 ROIs were as used for the background in four different positions and the average value estimated, referred to (ROIbg). The contrast was then calculated using equation 1.

$$Lesion\ Contrast = ROIbg - \frac{ROII}{ROIbg} \qquad (1)$$

The ability to undertake spectral decomposition of the data is a major potential advantage of photon counting CT compared to conventional CT. This may allow better discrimination of different tissue types and hence might be used to enhance the contrast of lesions within the

image. In view of this, the lesion contrast at each energy bin was determined using equation 1.

Image Reconstruction

The whole essence of image reconstruction is to appraise a spatial dissemination of some parameters in an object from its projections. These projections are a set of measured boundaries intrinsic (integral) values of the parameters. The parameters here are attributed to the linear attenuation coefficient for X-ray transmission. For the purpose of this work the Filter back projections (FBP) method is considered. To improve the image quality of FBP ramp filters are used but regulated with some parameters that must be suitable to the given acquisition.

RESULTS AND DISCUSSION

Results

Outcome of lesion decomposition for each experiment at different energy bins and the standard approach to CT are tabulated and analysed graphically. Results of findings from the experiments are presented here with emphasis on the lesion decomposition. The results of experimental procedure follow with data generated from simulation work. The attenuation coefficients assigned to these tissue classes varies at each energy point as it changes along the energy spectrum. Figure 8 is the plot of attenuation coefficients of the main tissues concerned with, namely, calcification, fat and glandular tissues.

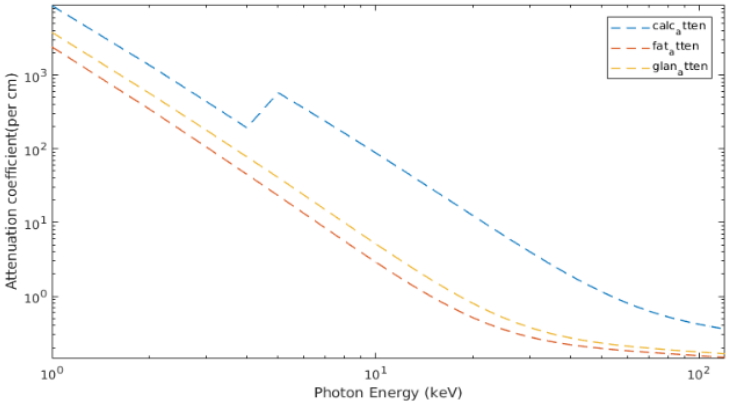

Figure 8: Attenuation plots of calcification, fat and glandular tissues

Figure 9 to 11 shows various contrasts seen at these different energy bins with figures 9 representing reconstructed images at bin width of 20 keV. Figure 10 represents reconstruction at bin width of 10 keV while Fig 11 illustrates images at 5 keV. Tables 2, 3 and table 4 are the result of the lesion contrast for the images at various bins

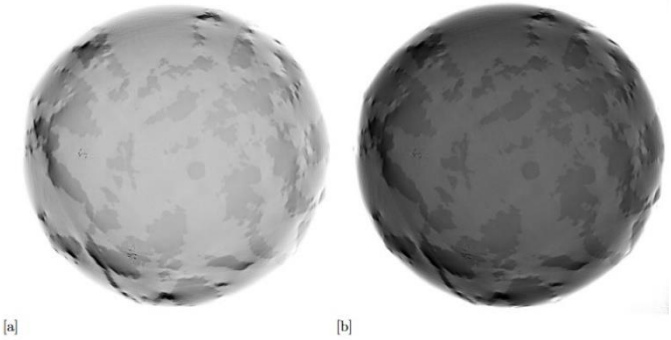

Figure 9: Reconstruction with bin width of 20keV at [a] (1- 20) keV and [b] (101-120) keV

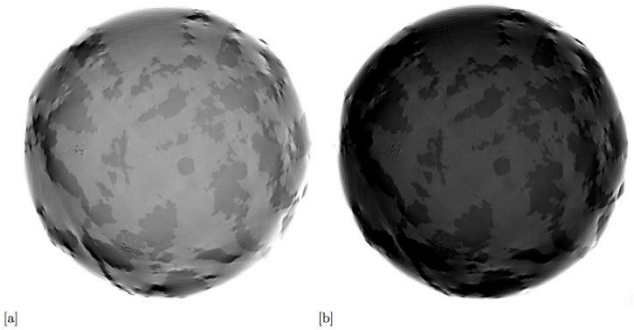

Figure 10: Reconstruction with bin width of 10keV at [a](1- 10)keV and [b] (111-120)keV

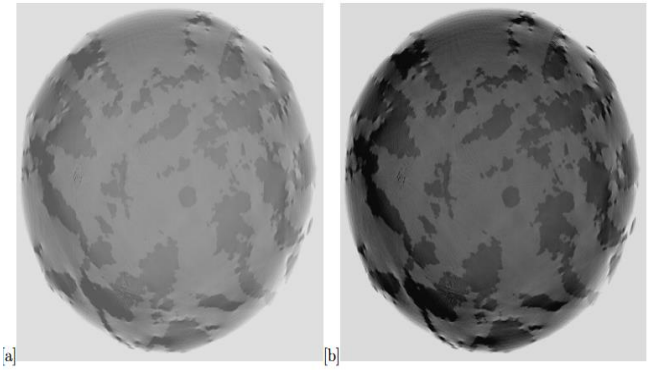

Figure 11: Reconstruction with bin width of 5keV at [a](1- 10)keV and [b] (116-120)keV

Table 2: Lesion contrast corresponding to Energy bins at bin width of 20 keV

Energy Bin (keV)	Lesion Contrast (Percentage)
1-20	22
21-40	15.6
41-60	7.8
61-80	4.4
81-100	2.5
101-120	1.6
1-120	6.83

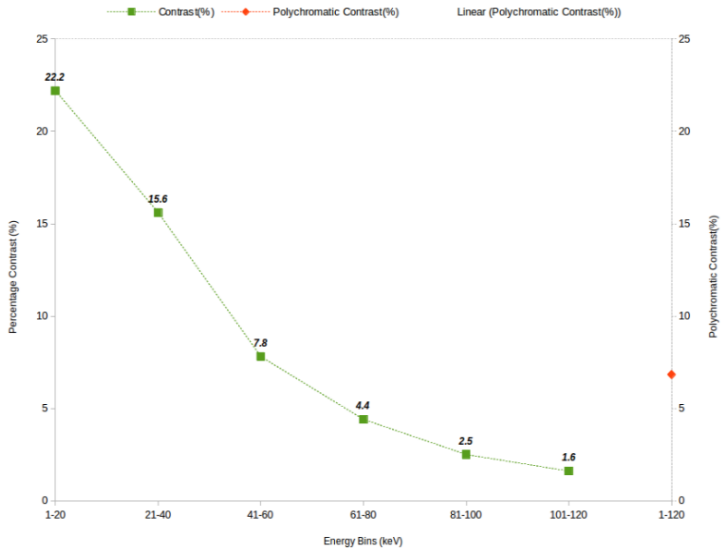

Figure 12: Graphical representation of lesion contrast versus Energy at bins of 20keV

Table 3: Lesion contrast corresponding to Energy bins at bin width of 10keV

Energy Bin(keV)	Lesion Contrast(Percentage)
1-10	21
11-20	16.5
21-30	14.5
-	-
-	-
91-100	1.6
101-110	1.4
111-120	1.2
1-120	6.83

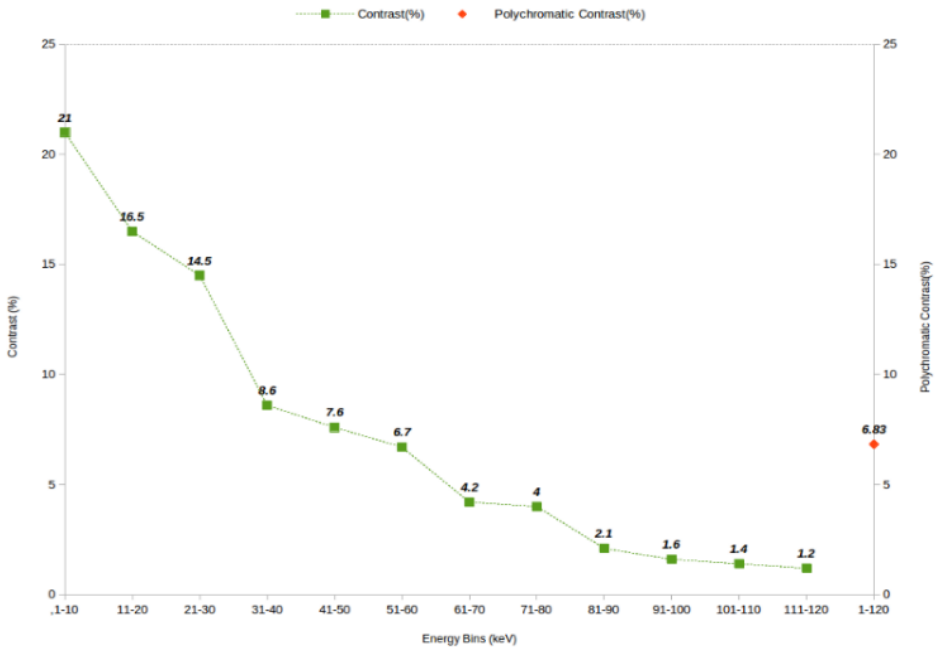

Figure 13: Graphical representation of lesion contrast versus Energy at bins of 10keV

Table 4: Lesion contrast corresponding to Energy bins at bin width of 5keV

Energy Bin(keV)	Lesion Contrast(Percentage)
1-5	20
6-10	18.3
11-15	-
16	-
106-110	1.2
111-115	1.2
116-120	0.9
1-120	6.83

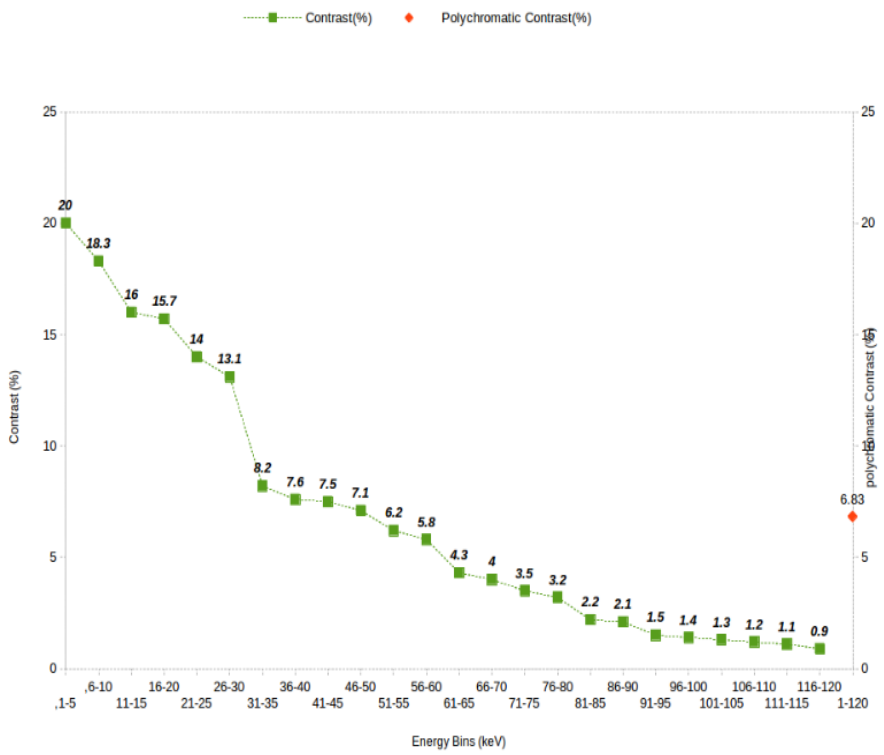

Figure 14: Graphical representation of lesion contrast versus Energy at bins of 5keV

Discussion

Investigations were carried out using the photon counting approach where photons conveying a range of energies are aggregated into a set of discrete energy windows or bins. This process is to acquire data in different energy windows and identify individual bins with the corresponding contrast and spectral energy values. Seven arbitrary energy bins of 20keV each in the first experiment were selected, this was to investigate the decomposition at each energy bin and investigate contrasts at each bin. To analyse the contrast, measurements taken were based on the method described above and equation 1. Results presented in figure 12 shows the corresponding exponential drop in contrast with the energy bins where contrast decreases with increasing photon energy. This action is attributed to the difference in linear attenuation coefficient of adipose and glandular tissues. Results of this experiment as graphically presented in figure 12 demonstrates change in contrasts and that decomposition of lesion in bins provided appreciable contrast following a pseudo-exponential relationship between contrast and energy bins, with 22 percent in bin (1-20) keV and 5 percent in bin (61-80) keV. However, decomposition for photon counting energies for bin (81-100) keV and (101-120) keV, respectively 2.5 percent and 1.6 percent were comparably lower than 22 and 5 percent. This shows that there is a distinct advantage to focusing imaging on the medium to lower energies.

In order to carry out further investigations on the photon counting approach, another twelve arbitrary energy bins of 10 keV each has been investigated, this was to examine if different choices of energy bins might improve the lesion contrast. Results obtained and analysed demonstrates the change in contrast and indicates a similar exponential drop in lesion contrast as recorded in the 20keV bin width experiment, with 21 percent contrast at the lowest energy bin of (1-10) keV and 1.2 percent at the highest energy bin of (111-120)keV as shown in table 3. Differences in the percentage values compared to the first experiment are attributed to the energy bin width and the rate at which different tissues were attenuated. Further experiments were carried out by reducing the energy width to 5keV each thereby having twenty four energy bins in total, this was to re-examine lesion decomposition in much smaller bin widths. Investigation of lesion decomposition in each of the bin shows an exponential relationship between contrast and energy bin with 20 percent being the highest contrast at bin (1-5) keV and 0.9 percent at bin (116-120) keV. The trend as observed in all three experiments corresponds to attenuation of glandular tissues. High contrasts values have been achieved at low energy bins (photon counting approach) which corresponds to the attenuation of glandular tissues. However, our work in comparison with Shim et al., 2019 used a similar phantom-based approach to evaluate the feasibility of spectral CT for breast lesion

characterization, but did not investigate the photon counting approach specifically. The study therefore shows that photon counting approach has shown promise for the visualization of synthetic images based on contrast as described in this work.

CONCLUSION

This study showed that, contrast is highest at lower energies. This is where photoelectric absorption dominates and moreover where absorption in breast tissue is highest. However, in order to form an image, the highest differential absorption is needed to generate contrast, but this competes with the need for maximum transmission to minimize dose to the patient, and also minimize the effect of dose limiting noise. Therefore, a medium range of spectral energies is ideal, between 40-60keV for optimizing contrast in spectral breast imaging.

ACKNOWLEDGMENT

The authors will like to acknowledge the Centre for Vision Speech and Signal Processing University of Surrey and Late Veronica Alumuku for their contribution.

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