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Detective Quantum Efficiency of a CsI-CMOS X-ray Detector for Breast Tomosynthesis Operating in High Dynamic Range and High Sensitivity Modes

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Abstract

The spatial frequency dependent detective quantum efficiency (DQE) of a CsI-CMOS x-ray detector was measured in two operating modes: a high dynamic range (HDR) mode and a high sensitivity (HS) mode. DQE calculations were performed using the IEC-62220-1-2 Standard. For detector entrance air kerma values between $\sim 7 \mu\text{Gy}$ and $60 \mu\text{Gy}$ the DQE is similar in either HDR mode or HS mode, with a value of ~ 0.7 at low frequency and $\sim 0.15 - 0.20$ at the Nyquist frequency $f_N = 6.7 \text{ mm}^{-1}$. In HDR mode the DQE remains virtually constant for operation with K_a values between $\sim 7 \mu\text{Gy}$ and $119 \mu\text{Gy}$ but decreases for K_a levels below $\sim 7 \mu\text{Gy}$. In HS mode the DQE is approximately constant over the full range of entrance air kerma tested between $1.7 \mu\text{Gy}$ and $60 \mu\text{Gy}$ but kerma values above $\sim 75 \mu\text{Gy}$ produce hard saturation. Quantum limited operation in HS mode for entrance kerma as small as $1.7 \mu\text{Gy}$ makes it possible to use a large number of low dose views to improve angular sampling and decrease acquisition time.

Keywords

detective quantum efficiency; breast tomosynthesis; CMOS; sensitivity; hybrid imaging

1 Introduction

X-ray tomosynthesis of the breast promises to improve upon planar mammography in terms of visualization of small lesions, especially among women with radiodense breast tissue. However, the requirements associated with the acquisition of a series of rapid, low exposure projection images place greater demands on x-ray detectors used in tomosynthesis compared to those in planar FFDM. In particular, high quality, low dose tomosynthesis requires detectors with high x-ray absorption efficiency, high frame rates with low read noise, and low dark noise.

We are developing a dual modality tomosynthesis (DMT) breast scanner that merges x-ray tomosynthesis and molecular imaging tomosynthesis modalities within a single system to provide co-registered three-dimensional (3D) anatomic images and radiotracer maps [1]. When acquiring x-ray tomosynthesis images, the x-ray tube and detector simultaneously

rotate about the stationary, mildly compressed breast. Because of our use of the step-and-shoot method, tomosynthesis image acquisition time is longer than desirable (nearly 2 minutes), significantly increasing the possibility of motion artifacts. With the goal of decreasing overall acquisition time, we would like to replace the acquisition method with continuous gantry motion with the help of the 2923MAM CMOS detector from Dexela, a PerkinElmer company (London). The 2923MAM has 75 micron detector elements in a 3888x3072 matrix, for an overall sensitive area of approximately 29 cm × 23 cm. With no pixel binning the maximum frame rate is 17 fps, rising to up to 78 fps for 4x4 binning. The 2923MAM tested here includes a columnar CsI converter. All measurements described here were performed without pixel binning.

The spatial dependent detective quantum efficiency (DQE(u)) is the most generally used indicator of how efficiently the detector can process the input x-ray signal. For this reason, the widely accepted IEC-62220-1-2 Standard was followed to test the Dexela 2923MAM CMOS x-ray detector [2]. There are two possible operating modes for the Dexela detector: a high dynamic range (HDR) mode and a high-sensitivity (HS) mode. A comparison was made between the DQE for HDR mode operation and HS mode operation over a range of entrance exposures that were less than or comparable to a single projection view in a typical tomosynthesis acquisition.

2 Methods and Materials

The IEC Protocol 62220-1-2 was followed in calculating the DQE for the Dexela 2923MAM CMOS detector, though minor modifications were made as described in the following sections. As given in the IEC protocol, the equation for the frequency dependent DQE is:

$$DQE(u) = T^2(u) \cdot (NPS_{in}(u) / NPS_{out}(u)) \quad (1)$$

$T(u)$ is the modulation transfer function (MTF), $NPS_{in}(u)$ is the noise power spectrum at the input of the detector, and $NPS_{out}(u)$ is the noise power spectrum of the output images. The posterior-to-anterior direction (23 cm dimension of the detector) is parallel to the rows in the image and is designated as x in position space or u in frequency space. The direction parallel to the image columns in the 29 cm dimension of the detector will be denoted as y in position space or v in frequency space. NPS_{in} is determined by Eq (2):

$$NPS_{in} = K_a \cdot SNR_{in}^2 \quad (2)$$

where K_a is air kerma in units of $1/(\text{mm}^2 \cdot \mu\text{Gy})$ and SNR_{in}^2 is the squared signal-to-noise ratio of the input signal per unit air kerma, which is a constant provided in Table 2 of IEC-62210-1-2 for a given target/filter combination.

2.1 Geometry and Radiation Quality

The distance between the focal spot and the closest point on the detector surface is 81cm. The x-ray tube contains a tungsten target, exit window filtration of 0.76 mm of beryllium,

and an external filter of 0.050 mm of rhodium. Addition external filtration of 1.4 mm of Al was added to match the half value layer (HVL) of 0.75mm of Al specified in the IEC Protocol for W/Rh target/filter systems operated at 28 kVp. As per protocol requirements, all images and measurements were taken at a tube voltage of 28 kVp. From this setup, we were able to use $5975 \text{ (mm}^2\cdot\mu\text{Gy)}^{-1}$ as the SNR_{in}^2 value for a tungsten target, 50 μm rhodium filter at 28 kVp.

2.2 Detector Response and Determination of Conversion Function

The conversion function is the relationship between the large area detector output (i.e. average pixel value) in a corrected image and the input x-ray fluence. Prior to the determination of the average pixel value in all of the images used, corrections were made to the raw images (replacement of bad pixels, dark image subtraction, and flat-fielding) as permitted by the standard. The conversion function was then used to convert pixel values into units of fluence. For many digital x-ray detectors, this relationship is linear to a high degree in which case the conversion function reduces to a proportionality constant and a pixel value offset.

The detector response was measured for each mode by recording the average pixel value over a range of input kerma values in the uncorrected images. A Radcal Accu-Pro ion chamber was used for determining the air kerma, and inverse square law corrections were made to calculate the exposure at the detector surface

2.3 MTF and NPS_{out}

The MTF was measured using a straight-edged piece of tungsten rather than the aluminum test device suggested by the IEC Standard. The presampling MTF was calculated using a program based upon the method described by Fujita et al [3]. It was written by our lab in the Interactive Data Language programming environment (IDL; Research Systems, Boulder, Colorado).

The protocol was followed in determining NPS_{out} for each exposure. An ROI chosen within the image for the NPS calculation had dimensions of $17.85 \text{ cm} \times 27.48 \text{ cm}$ corresponding to an area of 8720320 pixels^2 . The final 2D NPS_{out} was found by averaging over noise power spectra from 459 overlapping 256×256 pixel sub-regions within the ROI. The 1-D $\text{NPS}_{\text{out}}(u)$ was obtained by averaging over 7 rows above and 7 rows below the $v = 0 \text{ mm}^{-1}$ frequency axis. The same was done for $\text{NPS}_{\text{out}}(v)$ about the $u = 0 \text{ mm}^{-1}$ frequency axis. Additionally, per the IEC standard an optional 2D second-order polynomial fit was subtracted from each ROI to remove low frequency noise prior to NPS estimation.

3 Results

3.1 Detector Response and Conversion Function

Figure 1 is a plot of the mean pixel value, within a region of interest (ROI) drawn at the focal spot projection in uncorrected images, versus exposure. The portion of each curve in Figure 1 that is linear has been fit with a linear equation and projected forward to show the detector's deviation from a linear response at higher input fluences. The highest tested air

kerma levels chosen for each mode are just below the point at which the detector stops behaving linearly with increasing fluence. The air kerma levels tested here are 1.69 μGy , 3.57 μGy , 7.34 μGy , 15.1 μGy , 30.0 μGy , and 60.1 μGy for HS mode. The same levels were tested in HDR mode with two additional levels at 89.9 μGy and 119 μGy .

The conversion function for both modes is shown in Figure 4. In HDR mode, the conversion function slope is 0.008388 $\text{ADU}\cdot\text{mm}^2/\text{photon}$ and in HS mode it is 0.02750 $\text{ADU}\cdot\text{mm}^2/\text{photon}$. The zero fluence values shown in Fig. 4 are due primarily to DC offset values digitally added to each pixel value during the dark subtraction and uniformity correction procedures.

3.2 NPS_{out}

As an additional quantification of image noise, a log-log plot of the standard deviation σ in the NPS_{out} images versus K_a is shown in Fig. 3 for both HS mode and HDR mode. In all cases it was verified that the integral of the 2-D NPS between $\pm$ Nyquist frequencies was equal to σ^2 . As a measure of quantum limited behavior a power fit was applied to both curves. The fit equation and the R^2 value are shown next to each curve.

3.3 DQE

Figs. 4 and 5 are plots of DQE(u) and DQE(v), respectively, for HDR mode. Figs. 6 and 7 are plots of DQE(u) and DQE(v), respectively for HS mode. A subset of all exposures tested is shown in each figure. Data are plotted within a frequency range of 0 mm^{-1} to the Nyquist frequency of 6.67 mm^{-1} . The 0 mm^{-1} frequency points were omitted since it does not correspond to an achievable physical quantity.

4 Discussion and Conclusion

For K_a values between $\sim 7 \mu\text{Gy}$ and 60 μGy the DQE is similar in either HDR mode or HS mode, with a value of ~ 0.7 at low frequency and $\sim 0.15 - 0.20$ at the Nyquist frequency $f_N = 6.7 \text{ mm}^{-1}$. As would be expected, the change in DQE at either very low or very high input fluence differs between the two modes of operation. In HDR mode, the DQE remains virtually constant for operation with K_a values between $\sim 7 \mu\text{Gy}$ and 119 μGy but decreases for K_a levels below $\sim 7 \mu\text{Gy}$. In HS mode, the DQE is approximately constant over the full range of entrance air kerma tested between 1.7 μGy and 60 μGy but, as seen in Figure 1, kerma values above $\sim 75 \mu\text{Gy}$ produce hard saturation.

Comparison of DQE(u) and DQE(v) show that for either HDR mode or HS mode operation, a slight difference exists between the shapes of the DQE in the x- and y-directions, with DQE(v) having a more linear drop off with increasing spatial frequency compared to DQE(u). The results show a slightly better detector performance in the posterior-to-anterior direction than in the orthogonal dimension. Higher efficiency in the x-direction will be necessary, especially when focal spot blur will degrade the resolution further in this orthogonal dimension if the gantry is put into continuous motion during acquisition.

The power law relationship between the image noise and the input kerma with exponent of ~ 0.5 (Figure 3) shows that the image variance increases approximately linearly with

increasing input fluence as would be expected for quantum limited operation. However, in addition to the deviation from quantum limited operation at low exposure in HDR mode operation, there is a slight deviation at high exposure in either mode; most prominently in HDR mode.

The fact that quantum limited operation is available in HS mode for entrance kerma as small as 1.7 μGy makes it possible to use a very large number of very low dose views in order to improve angular sampling and decrease artifacts since there would be minimal penalty in terms of the effects of system noise. However the choice of number of views must also take into account the maximum acceptable tomosynthesis scan time, maximum available detector frame rate, and the optimal x-ray tube settings for a given subject. For example, a tomosynthesis scan of a 5 cm thick acrylic phantom using a Hologic Dimensions scanner in Autofilter mode results in a full scan detector entrance kerma of 340 μGy , corresponding to 200 1.7 μGy views. Operated at its maximum full resolution frame rate of 17 fps, this would correspond to an 11.8 second scan time for the 2923MAM. A more practical choice might be 85 views in 5 seconds with a detector entrance kerma of 4 μGy per view. Of course, for a given breast type the desirable full scan kerma is dependent on the detector, beam quality, and reconstruction algorithm used. Using the maximum possible number of views may not necessarily maximize image quality, so these are example possibilities only. System-specific image optimization studies are required to determine the best acquisition parameters.

In summary, the two operating modes of the 2923MAM together provide high DQE over a large exposure range. The combined abilities of very low dose operation and rapid readout make dense angular sampling tomosynthesis feasible with acceptably short overall scan time and without image degradation from system noise.

Acknowledgments

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Fig. 1.

Mean pixel value versus air kerma. Pixel values come from uncorrected images taken with nothing in the x-ray beam except for the internal and external filters. Least squares fits are shown to the portion of each curve exhibiting linear behavior.

Fig. 2.

Conversion function in both HDR mode and HS mode. A linear fit was applied to each curve and the fit equation and R-squared values are shown next to each curve.

Fig. 3.

Log-log plot of standard deviation of the linearized NPS_{out} images σ versus air kerma for both HS mode and HDR mode. A power fit was applied to both curves. The fit parameters and the R^2 values are displayed next to each curve.

Fig. 4.

DQE along detector rows at the tested exposure levels of 1.69 μGy , 7.34 μGy , 30.0 μGy , 60.1 μGy , 89.9 μGy and 118.9 μGy in HDR mode

Fig. 5.
DQE along detector columns at the tested exposure levels of 1.69 μGy, 7.34 μGy, 30.0 μGy, 60.1 μGy, 89.9 μGy and 118.9 μGy in HDR mode

Fig. 6.
DQE along detector rows at the tested exposure levels of 1.69 μGy, 7.34 μGy, 30.0 μGy, and 60.1 μGy in HS mode

Fig. 7.
DQE along detector columns at the tested exposure levels of 1.69 μGy, 7.34 μGy, 30.0 μGy, and 60.1 μGy in HS mode