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Comparison of High Resolution X-Ray detectors with Conventional FPDs using Experimental MTFs and Apodized Aperture Pixel Design for Reduced Aliasing

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Abstract

Apodized Aperture Pixel (AAP) design, proposed by Ismailova et. al, is an alternative to the conventional pixel design¹. The advantages of AAP processing with a sinc filter in comparison with using other filters include non-degradation of MTF values and elimination of signal and noise aliasing, resulting in an increased performance at higher frequencies, approaching the Nyquist frequency³. If high resolution small field-of-view (FOV) detectors with small pixels used during critical stages of Endovascular Image Guided Interventions (EIGIs) could also be extended to cover a full field-of-view typical of flat panel detectors (FPDs) and made to have larger effective pixels, then methods must be used to preserve the MTF over the frequency range up to the Nyquist frequency of the FPD while minimizing aliasing. In this work, we convolve the experimentally measured MTFs of an Microangiographic Fluoroscope (MAF) detector, (the MAF-CCD with 35 μ m pixels) and a High Resolution Fluoroscope (HRF) detector (HRF-CMOS50 with 49.5 μ m pixels) with the AAP filter and show the superiority of the results compared to MTFs resulting from moving average pixel binning and to the MTF of a standard FPD. The effect of using AAP is also shown in the spatial domain, when used to image an infinitely small point object. For detectors in neurovascular interventions, where high resolution is the priority during critical parts of the intervention, but full FOV with larger pixels are needed during less critical parts, AAP design provides an alternative to simple pixel binning while effectively eliminating signal and noise aliasing yet allowing the small FOV high resolution imaging to be maintained during critical parts of the EIGI.

Keywords

High Resolution Fluoroscope (HRF); Microangio Fluoroscope (MAF); Apodized Aperture Pixel (AAP) design; MTF

INTRODUCTION

Imaging needs during neurovascular interventions require high resolution detectors. Generally, this is established by using a small field of view (FOV) region of interest (ROI) detector during critical parts of the intervention and otherwise using a larger area Flat Panel

Detector (FPD). The Microangio Fluoroscope (MAF) and High Resolution Fluoroscope (HRF) are such small FOV ROI prototype detectors. The attainable resolution with Flat Panel Detector, even though with the same scintillator material (CsI) as with an ROI detector, is limited by the aperture function in the spatial domain and the display matrix size limitations. A single panel solution would be optimal for clinical practice and this detector should have smaller pixels for high resolution ROI needs. Extending this to a Flat Panel Detector using moving average pixel binning of smaller pixels, low pass/high pass filters or other image processing methods, would reduce the MTF near the Nyquist frequency³; however, with resulting aliasing as a consequence. Apodized Aperture Pixel (AAP) design^{1,2} provides an alternative means to maintain the high resolution over an ROI while expanding the FOV with larger effective pixels yet with minimized aliasing. The present work explores the use of an AAP design for parameters of two high resolution detectors.

MATERIALS AND METHODS

The overall resolution performance of a linear detector in image formation in the Fourier domain is given by the Modulation Transfer Function (MTF). The cascaded stages in conventional-pixel-design based indirect detectors consist of integration of secondary quanta formed after conversion of photons in a convertor layer such as CsI, and then sampling the detector output with sensor elements of dimension 'a', resulting in an image of pixel dimension 'a'. For a detector with Apodized Aperture Pixel (AAP) based design, secondary quanta formed after conversion of photons in the convertor layer are integrated and sampled in sensor elements of ' ϵ ' dimension, where $\epsilon < a$, resulting in super-sampled images. The images formed at this stage are convolved with a sinc filter function in the spatial domain. The Fourier transform of the sinc function is a box and multiplying the MTF with this function maintains the MTF at high values but removes signal and noise aliasing effectively. Once this pre-sampled signal is attained, it can be sampled with sensor elements at 'a' interval. Designing the box function in the Fourier domain to have a cut off at a Nyquist corresponding to a desired aperture size allows flexibility in changing the effective pixel size.

Two detectors were used for this study. The first detector is a custom-built Microangiographic Fluoroscope (MAF) with 35 μ m CCD readout (pixel pitch), and a 500 μ m (High Resolution) CsI phosphor, hereafter designated the MAF-CCD35. The second detector is a Teledyne Dalsa, prototype mammographic detector with 49.5 μ m pixel pitch (CMOS readout) and a 300 μ m (High Resolution) CsI phosphor (HRF-CMOS50). The comparison here is with a Varian Paxscan 2020 Flat Panel Detector with 194 μ m pixel pitch and 600 μ m CsI phosphor (FPD).

The detector MTFs were measured using the standard slanted edge method described by Samei et. al⁴. A straight edge was machined after sandwiching a lead plate between two aluminum sheets. The lead edge was placed at the detector surface with a magnification of 1 and at angles varying from 1–3°. Keeping the SID at 110 cm, 120 frames were acquired for a range of voltages from 60 – 110kVp, with the edge being parallel and perpendicular to readout direction. The Edge Response Functions (ESFs) thus measured were flat field and dark field corrected and integrated into one image for reduced noise. The Line Spread

Functions (LSFs) were calculated from the ESF and Fourier transformed to obtain MTFs of the detector^{4,6}.

The AAP design assumed super-sampling sensor elements of 35 μm for the MAF-CCD and 50 μm for HRF-CMOS50. The AAP design was compared with the effect of 5x moving average binning for the MAF-CCD35 and 4x moving average binning for HRF-CMOS50 to approximate the FPD pixel pitch. The MAF-CCD35 has a Nyquist of 14.28 cycles/mm, whereas the HRF-CMOS50 has its Nyquist at 10 cycles/mm. The 5x binned version of MAF-CCD35 has an effective pixel of 175 μm and its Nyquist at 2.85 cycles/mm and HRF-CMOS50 when 4x binned has an effective pixel size of 200 μm and Nyquist of 2.5 cycles/mm. The MTF values at the desired Nyquist were compared to the values after convolution with the sinc filter function of AAP design.

When these high resolution detectors are used to image objects which have components above the Nyquist frequency, they are subjected to undersampling. The undersampled frequencies are wrapped back into the 0 – Nyquist range. In the case of digital detectors, subjected to undersampling the interpretation of the MTF is not straight forward. There are inconsistencies in the definition of MTF as explained in Dobbins et. al⁵. Because the aliased high spatial frequencies add and result in values greater than the original magnitude of the lower frequencies we have designated these simply as Transfer Function (TF) which represents the output signal frequency distribution for a delta function input. Depending upon the phase relation of the sampling comb with respect to the input function, there are three different Transfer Functions (TFs) including maximum TF, minimum possible TF and expectation TF. In this work we have only made use of the maximum possible aliased TF.

Using these TFs, an infinitesimal point object can be imaged containing uniform frequency components throughout the Fourier domain. These TFs are made symmetric in the Fourier domain by mirroring them to –Nyquist and then Inverse Fourier transforming to get the image of the object/point spread function for the detectors with various filters. They are normalized and then compared to those of an FPD and equivalent FPDs based on AAP designs.

RESULTS

The AAP design maintains high resolution for neurovascular interventions as shown in Figures 1 and 2. The values maintained are close to the presampled MTF whereas FPD's MTF degrades faster due to among other things the 200-micron aperture function. The ratio of MTF values at the Nyquist of 2.5 cycles/mm after convolution, with respect to the Paxscan 2020 FPD is 7 for HRF CMOS50 and 3.5 for MAF CCD35 as indicated in table 1 below. The MTFs after convolution with AAP/sinc filter have a ringing artifact. The ideal approach to designing the filter is to start out with a box function in Fourier domain with drop down at the desired Nyquist and reverse designing the AAP filter in the spatial domain; however, in practice this inverse transform results in only an approximate filter function leading to the ringing artifact in the MTF.

To account for the aliased high frequencies Figures 3, 4, and 5 show the TFs resulting from wrapping around the equivalent Nyquist for two ROI detectors and their binned FPD equivalents.

The advantages of AAP design in minimizing signal aliasing is shown in Figure 6. In the case of the MAF-CCD35 FPD equivalent the high frequency content is increased and the maximum value of TF is 1.13 whereas for that of the HRF-CMOS the maximum TF at 0 cycles/mm is around 1.36 and both amount to significant aliasing of the high frequency range. The AAP design is a solution to this issue as the box function in Fourier domain floors TF to zero beyond the desired Nyquist.

The TFs obtained from this step were multiplied with the frequency spectrum of an infinitesimal point object and inverse Fourier transformed to find the point spread function. The resulting normalized PSF with oscillations were smoothed out with a running average window of 4 and 5 respectively for HRF-CMOS50 and MAF-CCD35. This resulted in images with less oscillation. The sampling was kept at 50 μm and 35 μm for HRF-CMOS50 and MAF-CCD35 up to this point. The resampling to an FPD pixel pitch was done by selecting data points spaced approximately 200 μm apart from the 35 μm and 50 μm data sets, which results in the final images with AAP equivalent FPD detector. The stages described above are shown in Figures 7, 8, and 9; however, for demonstration purposes only HRF CMOS50 is shown with complete set of results of PSFs.

DISCUSSION

The case of undersampling and its effect on detector MTF is not straight forward. The phasing of the sampling comb with respect to the input function results in three different MTFs as described by Dobbins⁵. In the case of perfect alignment of a function being digitized results in Maximum MTF; the worst case of perfect misalignment by half a pixel with respect to sampling comb results in Minimum MTF and the Expectation MTF (EMTF) provides an averaged value for any alignment in between. For simplicity, in this study we have used a Transfer Function equivalent to the case of Maximum MTF. The case with Minimum or Expectation MTF would be more complicated in practice and beyond the scope of this work.

For the PSFs developed in this work under the simplified transfer function assumptions, the sampling at the initial stage was kept at 50 μm and 35 μm for HRF-CMOS50 and MAF-CCD35 respectively. Due to the sharp discontinuity in the TFs in the Fourier domain, the inverse Fourier transforms resulted in oscillation in the spatial domain. However, these oscillations manifest themselves only during 50 μm and 35 μm sampling. Since the goal of developing a larger FOV FPD-like detector would only provide larger final pixel samples we simulated these results by introducing a filter to smooth out the oscillations apparent because the smaller pixels were maintained during the inverse Fourier transform. In our case we used a running average window of 4 data points to create data set corresponding to a 200 μm aperture for the HRF CMOS and 5 elements for the MAF CCD35 (185 μm). This data was then further sampled at every 4th and 5th point to make an equivalent FPD sampling.

Figures 7 shows the PSFs for the HRF-CMOS50 comparing the original PSF derived from the pre-sampled MTF with the AAP derived PSF and that from the 200 μm aliased TF. Figure 8 shows the comparison where the running average window smoothing was used indicating a 30% reduction in oscillations for both. In Figure 9 the comparison is drawn between the PSFs of the FPD, and the FPD-like PSF derived from the AAP filtered HRF-CMOS50 and the 200 μm Aliased HRF-CMOS50. The Full Width Half Maxima and Full Width Tenth Maxima for the PSFs are shown in Table 2 and appear to indicate high resolution for the FPD derived from the HRF-CMOS50 data; however, the tails are higher due to increased low frequency content especially for the aliased HRF-CMOS50.

CONCLUSIONS

The Apodized Aperture Pixel design is a novel method to reduce signal aliasing and maintaining high spatial resolution up to the Nyquist frequency as shown here and previous works^{3,7}. Compared to standard pixel binning kernels, the AAP design retains MTF values at higher frequencies without aliasing due to undersampling. A high resolution ROI detector with small pixel design could then be extended to the size of a full FOV FPD with equivalent effective pixels while maintaining small FOV high resolution capability within a ROI.

Acknowledgments

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Fig 1.

Shown here are the pre-sampled MTFs for both the HRF-CMOS50 and the 4x binned equivalent FPD as well as the result of convolving the AAP filter with the presampled MTF. The comparison is with that of the FPD.

Fig 2.

Shown here are the pre-sampled MTFs for both the MAF-CCD35 and the 5x binned equivalent FPD as well as the result of convolving the AAP filter with the presampled MTF. Again they are compared to that of the FPD

Fig 3.

The effect of undersampling and resulting maximum possible aliased TF. The TF extends from 0 – 10 cycles/mm and the successive cycles are wrapped around to the new Nyquist of 2.5 cycles/mm. All the successive cycles are then added together to get the maximum possible aliased transfer function.

Fig 4.

The calculations with wrapping around is done for both the pre-sampled MTF and 4x moving average binning kernel.

Fig 5.

The wrapping around is done for both the pre-sampled MTF and 5x moving average binning kernel for MAF-CCD35.

Fig 6.

Comparisons of TFs which include aliasing with that of the AAP filtered design with no aliasing in the case of a) HRFCMOS50 and b) MAF-CCD35.

Fig 7.
PSFs determined from respective

Fig 8.
PSFs obtained from Fig. 7 are smoothed out with a running average window

Fig 9.
PSFs obtained from Fig. 8 for aliased and AAP case, re-sampled to 200 μm pixel pitch and compared to that of FPD

Table 1

This shows the variation of MTFs at selected frequencies up to the Nyquist of an FPD.

Detector	Descriptor	Frequency1 (1 cycles/mm)	Frequency2 (2 cycles/mm)	Frequency3 (2.5 cycles/mm)
FPD	Pre-sampled	0.47	0.13	0.07
MAF CCD 35	Pre-sampled	0.53	0.31	0.25
MAF CCD 35	Pre-sampled 5xMoving Average Binning	0.51	0.26	0.19
MAF CCD35	AAP filtered	0.53	0.31	0.25
HRF CMOS 50	Pre-sampled	0.78	0.58	0.49
HRF CMOS 50	Pre-sampled 4xMoving Average Binning	0.75	0.48	0.36
HRF CMOS 50	AAP filtered	0.78	0.58	0.49

Table 2

Comparison of PSF characteristics for FPD and FPD-like detector designs

Detector	FWHM (μm)	FWTM (μm)
Presampled FPD	400	800
HRF CMOS 50 AAP	300	700
HRF CMOS 50 Aliased	300	1200