Measurement of the Optical Response of a High Resolution CMOS Imaging Detector

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Abstract
The spectral response of a light detector is crucial for the selection of the optimum scintillator in order to be used in a particular light detection system. The aim of the present study was to investigate the Modulation Transfer Function (MTF) of a high resolution RadEye HR CMOS photodetector under optical light irradiation. Three light emitting diodes (LEDs) were used in order to irradiate the active area of the CMOS sensor. MTF was measured by using a pinhole collimator with diameter of 50 μm in direct contact with the CMOS photodiode array. The photodetector exhibited excellent resolution properties when irradiated with red light. Since the spectral response is crucial for selecting the optimum scintillator for a particular light detection system, our results indicate that the sensor under investigation should be coupled to red emitting scintillators in order to take fully advantage of their spectral sensitivity.

Introduction
Digital X-ray detectors, such as charged couple devices (CCD), complementary metal-oxide semiconductors (CMOS) and amorphous Silicon flat panels (a-Si:H) in combination with various scintillating screens, have been used for medical imaging applications (Kalyvas, 2014). Among the most commonly used scintillating materials are Thallium doped Cesium Iodide (CsI:Tl) and Gd_2O_2S based detectors being the most efficient and popular (Arnold, 1979, Michail, 2011, Michail, 2015a, Michail, 2015b). However, since most silicon (Si) based optical sensors (i.e. CCD and CMOS) show maximum spectral sensitivity to longer wavelength ranges, and particularly in the red wavelength range, it would be of interest to investigate the impact on the imaging performance under various spectral conditions. Knowledge of the precise detector's optical response is essential for the selection of the optimum scintillator for a particular light detection system. In the present study the spectral response of a high resolution, CMOS based, digital imaging detector is investigated with respect to the influence on image resolution under irradiation with various direct light sources. The resolution of the CMOS sensor was investigated in terms of the Modulation Transfer Function (MTF).

Materials and Methods
The detector was an optical readout device including a CMOS Remote RadEye HR photodiode pixel array (Michail, 2011, Seferis, 2013). The CMOS photodiode array consists of 1200x1600 pixels with 22.5 μm pixel spacing and a fill factor of 0.8 (Michail, 2011, Seferis, 2014), consisting of an N-well diffusion on p-type epitaxial Silicon.
Three light emitting diodes (LEDs) were used for the measurements, emitting in the blue (L-7113QBC-D, Kingbright Electronic Co.), green (L-7113CGCK, Kingbright Electronic Co.) and red (L-1513SURC-E, Kingbright Electronic Co.) part of the optical spectrum. The intensity of the light emitting diodes, used in this study, was measured by using a stable current source (Power supply, M30-TP Series, MCP, Shanghai Corp.), a digital multimeter (Agilent U1253B, Agilent Technologies Inc.) and a 1 $k\Omega$ resistance. The voltage was set at 12 Volts and the

current was allowed to vary from 5 to 15 mA (measured by the digital multimeter). The CMOS sensor's light sensitive area was placed perpendicular to the LED's emitting surface within a solid angle of ~10 degs, at a fixed distance within a custom made light tight box. LED intensity, falling on the surface of the CMOS sensor, was measured by replacing CMOS sensor with a Newport 918D-ST-UV Metal Wand Detector with OD3 Attenuator (Stick-type UV / Si detector, Newport Corporation, JP.) connected with a single channel Optical Power Meter (841-P-USB, Newport Corporation,JP), using the same settings.

Spectral Matching Factor (α_S)

To determine both the mean light photon energy $\overline{E}_\lambda$ and the spectral matching factor α_S the emitted light of the three LEDs was measured. The spectral matching factor expresses the capability of the optical detector to detect the emitted light photons of a light source, determined by:

$$\alpha_S = \int S_L(\lambda) S_D(\lambda) d\lambda / \int S_L(\lambda) d\lambda \quad (1)$$

where $S_L(\lambda)$ is the emitted light spectrum of the light source and $S_D(\lambda)$ is the spectral sensitivity of the optical detector (Michail, 2014a). The $S_L(\lambda)$ of the LEDs were measured by using an optical spectrometer (Ocean Optics Inc., HR2000), while the spectral sensitivity of the CMOS optical detector was obtained from manufacturer's data (Michail, 2010). The light emitted by the irradiated LEDs was transferred to the spectrometer through a 2.0 m long, 1000 μm fiber optic, (Ocean Optics GP 1000 2 UV-VIS). Corrections for light signal degradation due to fiber optic light losses were taken into account.

Modulation Transfer Function (MTF)

The modulation transfer function (MTF) is a measure of resolution of the image. The response of a system to the incident signal amplitudes passing through the imaging chain can be described by the Modulation Transfer Function (MTF), which expresses system's response in the spatial frequency domain. The MTF was measured using the point spread function (PSF). MTF calculation was obtained by the utilization of a custom-made software (Fountos, 2012, Karpetas, 2014).

Point Spread Function (PSF)

In order to measure the modulation transfer function, the powder phosphor screen was manually removed in order to examine directly the response of the CMOS sensor to optical light. The pin hole was obtained from Amptek's EXVC Collimator Kit, having a thickness of 1 mm and a pin diameter of 50 μm. The collimator was placed directly on the active area of the CMOS sensor and digital images were obtained after irradiation with the three LEDs, used for the experiment. The center of the collimator's point image was determined (x_0, y_0 coordinates) and line profiles passing from this point were obtained, covering various angles ranging from 0^o to 180^o with a 2^o angle step. The PSF profiles were averaged to produce a 1D-PSF profile (Fujita, 1992, Chen, 2009).

The average PSF was fitted using four different functions: a Gaussian, a sum of two Gaussians, a Lorentzian, and a hybrid (sum) of a Gaussian and a Lorentzian functions. The fitting function providing the optimum correlation coefficient (R^2) was selected. Fourier transformation and subsequent normalization were then applied on the final LSF to compute the MTF (Boone, 2001).

Results and Discussion

The maximum spectral response of the CMOS sensor lies between 600 and 650 nm, which is extremely close to the peak of the red emitting LED and decreases rapidly above 750 nm and below 450 nm. The spectral matching factor values were α_S =0.71 for the blue diode, α_S = 0.86 for the green and α_S =1.00 for the red emitting diode. The red emitting LED has excellent compatibility with the CMOS RadEye HR electronic optical sensor, thus all emitted photons involved in formation of the resulting image.

In Fig. 1 the MTFs of the CMOS system irradiated by the three light emitting diodes, are shown. All curves are shown up to the Nyquist frequency of the specific CMOS sensor. The MTF values of the CMOS sensor irradiated by the red LED are higher in all the spatial frequency range, in comparison with the MTF values of the CMOS sensor irradiated by the green and blue LEDs, respectively. The MTF values, under red light irradiation, are very close to unity in almost all the spatial frequency range, showing in this case, that the total system MTF will be influenced only from the MTF of the scintillator. Only the MTF values of the blue LED irradiated image fall below the threshold of 10% MTF corresponding to a frequency value of 18.4 cycles/mm, which however is much higher than the limiting resolution of Mammographic applications (It is necessary to visualize structural details as small as 100 μm or less) (Michail, 2014b).

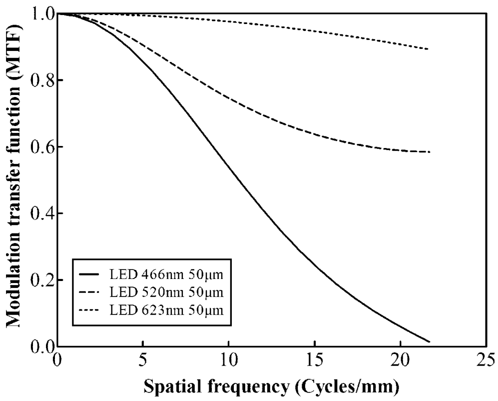

Figure 1. Comparison of the MTFs of the CMOS sensor irradiated by three light emitting diodes (blue LED-466nm, green LED-520nm and red LED-623nm)

Conclusions

In the present study the Modulation Transfer Function of a high resolution RadEye HR CMOS photodetector was investigated, under optical light irradiation. Three light emitting diodes were used in order to irradiate the active area of the CMOS sensor. The MTF was measured by using a pinhole collimator with diameter 50 μm in direct contact with the CMOS photodiode array. The photodetector showed excellent resolution properties when irradiated with red light. These results indicate that the particular sensor should be coupled to red emitting scintillators in order to take fully advantage of the spectral sensitivity in this wavelength, since the spectral response is crucial for the selection of the optimum scintillator for a particular light detection system.

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