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Radiation Effects on Digital Radiography

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1. Introduction

In the moment of any given imaging task and thus over the lifetime of a detector, the deposition of certain amount of radiation dose in an electronic pixel element is inevitable. This radiation effect can give rise to a change of the pixel-element characteristics such as the leakage current of a photodiode and the threshold voltage of thin-film transistors (TFTs) [1], and which may consequently result in the degradation of image quality of imaging detectors. While a large amount of effort has been invested in the evaluation of performance degradation of the pixel element devices themselves due to the radiation damage, there has been no sufficient attention paid to the evaluation of image-quality degradation although that is an important issue regarding the quality control and assurance of detectors and thus their lifetime.

In this study, we have studied radiation effects on the image quality of a photodiode array detector made by complementary metal-oxide-semiconductor (CMOS) process in conjunction with a phosphor screen. We report the observation of an image-quality degradation by assessing MTF (modulation-transfer function), NPS (noise-power spectrum) and DQE (detective quantum efficiency) with respect to the total ionizing dose at the detector entrance.

2. Materials and Methods

We prepared a CMOS sample detector with commercial phosphor screens and CMOS photodiode arrays having a format of 512 × 1024 pixels with a pitch of 48 μm (RadEye^{TM}, Rad-icon Imaging Corp., USA). Various thicknesses of the phosphor screens were used to construct the CMOS detector. Physical configuration, parameters, and specifications of the screen are well described and tabulated in reference [2].

In order to simulate a heavy load of x-ray irradiation, an x-ray source (Series 5000 Apogee, Oxford Instruments, USA) having a fixed tungsten anode was used. In general, the radiation effect on a device is evaluated with respect to the total ionizing dose (briefly, total dose). It is, however, difficult to directly measure the actual energy absorbed in the device. Instead, we measured the exposure rate at the detector entrance surface by using a calibrated ion chamber (Victoreen 6000-528, Inovision, USA). For various configurations of the detector, the irradiation was simultaneously performed using a 45-kVp x-ray spectrum tailored by a 1-mm-thick aluminum filter, which gives an exposure rate of 13 R/min measured at the distance of 200 mm apart from the source. Total dose designated in the following measurement results is the exposure rate multiplied by the elapsed irradiation time at the entrance surface of the CMOS photodiode array considering the attenuation through the overlying phosphor screens.

The image quality of the CMOS detector has been measured in terms of MTF, NPS and DQE. A detailed description of measurement procedures can be found in reference [3].

3. Results and Discussions

Figure 1(a) shows the measured dark signal of CMOS detectors as a function of the total dose. It is noted that the dark signal is expressed in ADC unit (ADU). As the total dose increases, the dark signal also increases and is almost independent on the thickness of the overlying phosphor screens. The dark current measured at the pixel output depends on the photodiode, the transistors and the interconnectivity in the pixel [4]. The main physical mechanism responsible for the increasing dark current in the photodiode is the buildup of positive charge in the oxide layer, silicon dioxide (SiO_2) in this study. The charge distributions and electric fields at the perimeter of the photodiode, where the depletion region intersects with the device surface, are very sensitive to disturbances. Positive charges in the oxide layer cause electrons to accumulate underneath the surface, modifying the charge density in the depletion region and thereby increasing the leakage current across the *p-n* junction of the photodiode. From the measurements in this study, we found that the dark signal almost linearly increased with respect to the total dose except that the screen type of MR, which is the thinnest screen among those used in this study, showed the enhanced increase at large total dose (> 1 kR). The general increasing trend was characterized by the power law of the total dose, and the power was about 1.26.

In Fig. 1(b) a log-log plot of noise versus dark signal demonstrates a signal-dependent noise contribution over signal values. The signal dependency of noise was characterized with 3 regimes for the dark signal values; the signal-independent, or constant regime, the proportion regime in square root of the signal and the linear proportion regime. Unlike quantum statistical noise which varies as the square root of the number of quanta comprising the signal if the quanta obey the Poisson statistics, the magnitude of the dark current noise is relatively independent of signal size. The constant regime is probably due to the dominant recombination process at small amount creation of interface traps from lower absorbed dose. As the absorbed dose increases so does the trap density, the well-known shot noise, which is proportional to the square root of the number of generated charges, is added to the constant component. This additional noise can be due to the radiation-induced thermal generation. Further addition of noise is shown at larger signal values, which is probably due to the field-enhanced charge generation at the interface between the SiO_2 layer and the substrate.

The measurement results of the image quality with respect to the total dose are shown in Fig. 2. From the measured MTFs of various configurations of CMOS detectors with respect to the total dose, it was found that the MTF performance was not affected by the irradiation until the total dose was larger than 1 kR. However, since the slit images became more noisy as the dose increased, it was difficult to analyze whether the degradation is due to the irradiation or not. Also, the NPS's were almost unchanged with respect to the total dose except the MR/CMOS detector configuration [see Fig. 2(b)], in which the noise spectral densities were increased as the dose was enhanced. This is due to the unattenuated direct x-ray photons from the MR screen, while for the other screens the photon energy considered in this study is not enough to directly effect on the CMOS photodiode array. The increase of the spectral density is not dependent on the spatial frequency so that the noise due to direct x-ray photons acts as white noise. From the measured MTF and NPS, the resultant DQE of the MR/CMOS detector, which was the most sensitive to radiation effects, with respect to the total dose degrades by the addition of white noise.

Interface traps are in general positive ions. Some of missing electrons can be restored by providing the electrons in silicon substrates enough energy to jump back into the oxide layer. Thermal energy may be this activation energy. As shown in Fig. 3, we have had some success with annealing the damaged CMOS photodiode array by baking in a vacuum oven at temperature around 100 °C for 58 hours with very caution not to degrade the materials inside the array at higher temperatures. If we can apply higher temperatures, the deeper traps could be relieved.

Results of measured MTF, NPS, and DQE will be presented in detail at the conference.

4. Conclusions

We have measured the radiation damage in image quality of CMOS photodiode array in conjunction with phosphor screens having various thicknesses in terms of MTF, NPS and DQE. We believe that these measurements are first. For the detector with thinnest phosphor screen, the NPS was increased as the total dose was enhanced, which was independent on the spatial frequency. This implies that the additional noise source is from direct absorption of x-ray photons. As a consequence, the change of NPS with respect to the total dose degraded the DQE. This study gives an initial motivation that the periodic monitoring of the image-quality degradation is an important issue for the long-term and healthy use of digital x-ray imaging detectors.

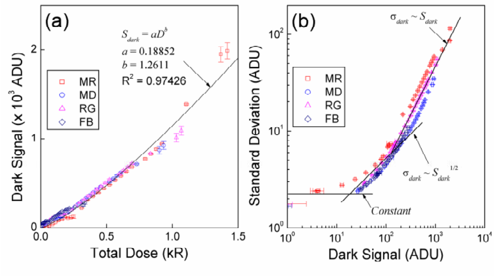

Figure 1. (a) Dark signal of CMOS detectors as a function of the total dose. (b) Log-log plot of noise versus dark signal of CMOS detectors.

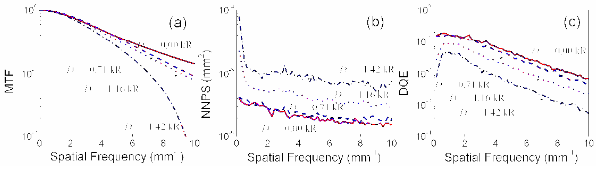

Figure 2. Measured image quality with respect to the total dose. (a) MTF, (b) Normalized NPS, and (c) DQE.

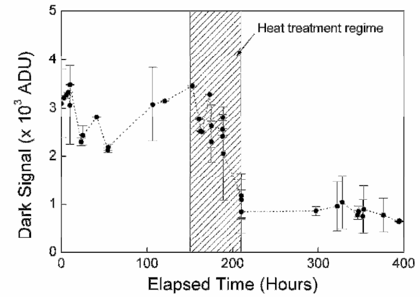

Figure 3. Annealing effect on the restoration of signal in a CMOS detector.

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