Monte Carlo Modeling for Performance Optimization of Imaging Detectors for Radiation Therapy

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Abstract

Radiation therapy relies on megavoltage x-ray imaging detectors referred to as electronic portal imaging devices (EPIDs) to verify patient set-up and dose delivery. Currently, commercial EPID systems typically consist of thin phosphor screens coupled to a-Si photodiodes. However, the poor attenuation (< 2% for 6 MV therapy beams) of these detectors results in poor portal image quality and high imaging dose and therefore, the development of improved megavoltage imaging detectors is of prime interest in radiation therapy. The use of Monte Carlo simulations to model the transport of incident x-ray photons and secondary electrons within the imaging detector has been proven to be a useful tool in detector development. In this work, we present a methodology that utilizes Monte Carlo modeling to optimize the detector geometry, characterize its intrinsic radiographic performance and predict overall system performance prior to actual implementation.

In our analysis, detector performance is characterized by three metrics: quantum efficiency (QE), detective quantum efficiency (DQE), and modulation transfer function (MTF). In this case, QE represents the attenuating capability of the detector in terms of the fractional number of x-ray photons that interact in the detection medium. DQE represents the degradation of the signal-to-noise ratio (SNR) in the detected x-ray image relative to that associated with the incident x-ray spectrum. DQE is widely considered to be an excellent indicator of overall perceived image quality and is typically expressed as a function of spatial frequency, i.e. DQE(f). Lastly, detector MTF indicates imaging

spatial resolution. Monte Carlo simulations were used to model particle transport of an open-field radiation beam of a specified energy spectrum within a given detector geometry while an absorbed energy distribution (AED) pulseheight spectrum was tallied. The moments of the AED pulseheight spectrum were used to compute the detector QE and zero-frequency DQE or DQE(0). On the other hand, a separate simulation of a point x-ray source incident on the detector was used to score energy deposition events in discrete detector voxels to obtain a point spread function (PSF) from which the MTF was computed by Fourier analysis.

Besides providing insight into intrinsic detector performance, the above Monte Carlo based metrics are valuable in the initial selection of an optimal detector geometry (i.e. material, thickness, build-up, pixel fill factor, etc). One of the fundamental design constraints in identifying an ideal detector geometry is the trade-off between QE, which increases with detector thickness, and MTF, which decreases with detector thickness. This trade-off can be mediated by evaluating $DQE(f) \approx DQE(0)MTF^2(f)$ for various detector thicknesses and identifying the minimum thickness that meets the target requirements of image quality expressed in terms of DQE. These intrinsic metrics can also be extended to overall system metrics (i.e. overall system MTF and DQE) using a standard linear cascaded systems quantum accounting analysis where the imaging system performance is accurately described analytically in serial cascaded stages of various physical processes (primary interactions, secondary electron transport, ionization or optical conversion and sampling, etc) that are involved in the generation of the imaging signal.

The above methods of detector evaluation were used as design tools prior to developing bench-top prototypes of EPID systems for proof-of-principle evaluation. Three commercial Monte Carlo code systems (ITS 3.0, EGSnrc and MCNPX) were used in our analysis and the accuracy of our methods were validated for several types of megavoltage imaging detectors including a conventional gadolinium oxysulfide phosphor screen, and three high DQE prototype imagers: a high-pressure xenon ion-chamber, a monolithic cesium iodide scintillator, and a structured array of fiber-optic scintillation glass. In conclusion, Monte Carlo simulations of fundamental imaging metrics can be used for initial detector optimization and as primary design limits, which can then be used to predict actual imaging performance using cascaded systems modeling.