Performance Optimization of Thick, Segmented Scintillators for Radiotherapy Imaging

Thick, segmented scintillators, incorporating a 2-dimensional matrix of optically-isolated scintillator elements, have shown considerable potential for improving the performance of megavoltage active matrix, flat-panel imagers (MV AMFPs). Small-area prototypes consisting of CsI(Tl) and BGO segmented scintillators up to ~40 mm thick with an element-to-element pitch of 1016 µm have demonstrated DQE values up to ~25%¹ – values that are more than 20 times larger than those of conventional MV AMFPs. (Conventional MV AMFPs, which employ relatively thin phosphor screens, such as ~133 mg/cm² of Gd₂O₂S(Tb) material, detect only ~2% of a 6 MV radiotherapy photon beam, resulting in an upper limit on DQE of only ~1% ²). As a result of such significant improvement in DQE, a prototype MV AMFPI based on an ~11 mm thick segmented BGO scintillator demonstrated low contrast visualization from reconstructed MV cone-beam CT images at a scan dose of only ~4 cGy ³ – an amount of radiation similar to that required for a single portal image. Such enhancement in performance with thick, segmented scintillators was found to be more effective at low spatial frequencies. However, for higher spatial frequencies, many factors contribute to reduce DQE improvements, including: less-than-optimal optical isolation of the septal walls that separate the scintillator elements, beam divergence effects for off-central-axis locations, ⁴ and mis-registration of the elements to the underlying AMFPI array pixels. The realization of good registration is challenging since (a) it requires an accurate technique for aligning the scintillator with the array and (b) it becomes impossible to achieve due to less-than-optimal element-to-element alignment. For example, for segmented scintillators developed by our group, the misalignment that occurs in the fabrication process is significant relative to the highly precise photolithography employed in array fabrication. As a consequence, optical light emitted by a given scintillator element may be captured by more than one (similar pitch) underlying array pixel, resulting in spatial resolution loss and thus reduction in DQE. In this presentation, a method to address the challenge of mis-registration will be reported.

In a first step to overcome the challenge of mis-registration, a high-resolution (127 µm pitch) AMFPI array was coupled to the 1016 µm pitch segmented scintillator prototype. With a factor of eight smaller pitch, the array allows the acquisition of x-ray images that give a pictorial representation of the structure of the segmented scintillators. Such over-sampling simplifies the process of optimal registration during imager assembly, making only angular alignment necessary and eliminating the need for further mechanical registration of the scintillator elements.⁵ An example of an x-ray image obtained with an ~11 mm thick BGO scintillator with a 50 µm thick septal walls, is shown in Fig. 1a. The image, which shows a portion of the scintillator, identifies the scintillator elements as well as the septal walls. Note the less-than-optimal alignment of some of the scintillator elements, whose locations deviate from a regular grid, as shown in Fig. 1b. The missing segments in Fig. 1b represent those septal wall segments in the x-ray image of Fig. 1a that do not overlap with an ideal grid. The availability of over-sampled images such as that of Fig. 1a facilitates precise 8x8 binning of the array pixels to match the locations of the scintillator elements – with the exception of those elements that are misaligned.

To quantify the effect of mis-registration on the performance of AMFPs based on segmented scintillators, a mathematical model employing geometrical consideration of scintillator and array design details, in combination with differential attenuation through objects, was used to characterize spatial resolution degradation by means of determination of the modulation transfer function (MTF) as well as through realization of reconstructed images of a resolution phantom in a cone-beam CT geometry. Figure 2 shows degradation of MTF for various offsets with respect to an ideal 8x8 binning. While 0 offset results in an MTF that overlaps with a sinc function representing the aperture size of the scintillator elements (1016 µm), increasing the offset up to half the element pitch (i.e., deliberate mis-binning which leads to worse mis-registration) results in progressively more pronounced deterioration of the MTF. This observation is confirmed by images of a hypothetical resolution phantom, consisting of a cylinder imbedded with high contrast inserts of variable spacing. Reconstructed images of the phantom using 180 projections per 360° scan result in progressively degraded spatial resolution for a larger offset (i.e., from left to right), as seen in Fig. 3. The results of Figs. 2 and 3 illustrate the importance of proper registration (i.e., matching) of the scintillator elements with the underlying binned pixels.
The next step in overcoming the challenge of mis-registration due to misalignment is through use of selective binning to minimize, or even prevent, the use of pixel information in which signals from multiple scintillator elements are present. In this analysis, only the signal from pixels corresponding to inner locations in a scintillator element are binned – thus avoiding cross-binning. A demonstration of such analysis is shown in Fig. 4 in which MTF and DQE results for a BGO scintillator operated at radiotherapy energies are shown for a 6×6 binning in comparison with an 8×8 binning.

As seen in Fig. 4a, the 6×6 binning provides significant improvement in MTF by virtue of minimizing cross-binning due to element-to-element misalignment as well as, perhaps, intrinsic improvement in resolution due to the omission of near-septal wall signal information (which may contain relatively more optical photons due to cross talk). Such improvement results in a performance approaching that of a conventional MV AMFPI, but is still lower than the ideal upper limit obtained from radiation transport in the absence of optical effects. DQE results obtained for 1 beam pulse corresponding to a dose of 0.022 cGy is shown in Fig. 4b. 6×6 binning results in DQE levels similar to, or slightly higher than, those of 8×8 binning, despite a reduction of about half in the binned signal. Note that these DQE results are similar to previously published results obtained with the same BGO prototype and a 512 µm pitch array – demonstrating input-quantum-limited behavior for the new (i.e., over-sampled) results even at a dose corresponding to 1 beam pulse. In this presentation, results for various binning techniques will be shown along with tradeoffs on imaging performance.

In conclusion, the use of high-resolution AMFPI arrays combined with selective binning allows prototype MV AMFPIs incorporating thick, segmented scintillators to achieve imager performance limited only by scintillator performance.

References