Technical Note: EPID’s response to 6 MV photons in a strong, parallel magnetic field

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Purpose: Electronic portal imaging devices (EPIDs) are potentially useful for dosimetric verification in integrated MRI-linac systems. This work presents the reproducibility, linearity, image lag, and radiation field profiles in a conventional EPID, with and without a 0.5 T parallel magnetic field present in a 6 MV photon beam.

Methods: An aS500 EPID was modified to function in strong magnetic fields. All measurements were made using the linac-MR installed at the Cross Cancer Institute. The EPID remained stationary on the couch between the measurements made with and without magnetic field. We measured short-term reproducibility of dark and flood fields, signal linearity from 1 to 500 MU irradiations, and image lag post 100 MU irradiation. An ion chamber was used to measure any linac output variations to correct the EPID signal due to these variations for the duration of experiment. X-axis and Y-axis radiation field profiles were obtained from the EPID image resulting from a 10 × 10 cm² radiation field delivery.

Results: The average pixel value (±standard deviation) of flood field with and without magnetic fields were 57,876 ± 379 and 57,703 ± 366, respectively, and the corresponding average dark field pixel values were 32.05 ± 0.85 and 32.19 ± 0.97. The maximum difference in image linearity data with and without magnetic field is 0.2% which is well within the measurement uncertainty of 0.65%. Similarly, the image lag curves, with and without the magnetic field, were nearly identical. The first measured point, with mean lag signal of 1.44% without and 1.41% with magnetic field, shows that the largest difference is well below the uncertainty in the EPID signal measurement. The radiation field profiles obtained with and without magnetic fields were nearly identical; 91.3% of the X-axis and 95.2% of the Y-axis profile points pass a gamma criterion of 1% and 1 mm.

Conclusions: A conventional EPID imager with a 0.1 cm copper plate responds to 6 MV photons similarly irrespective of the strong magnetic field being off or on in the parallel orientation to the radiation beam. Thus, the EPID is a potentially useful tool for pretreatment dosimetric verification in linac-MR systems using parallel magnetic field. © 2018 American Association of Physicists in Medicine [https://doi.org/10.1002/mp.13285]

Key words: EPID, linac-MR, MRI-linac

1. INTRODUCTION

Electronic portal imaging devices (EPIDs), originally used to obtain 2D megavoltage (MV) radiographs for patient position verification, are routinely used for both pretreatment and transit dosimetric verifications. EPIDs on conventional linacs are based on phosphor screens in association with amorphous silicon (a-Si) photodiode arrays and have been shown to have very suitable dose–response characteristics for dosimetric verification.

In the recent past, magnetic resonance guided radiotherapy (MRgRT) systems have been investigated and developed, where the tele-therapy unit is integrated with the magnetic resonance imaging (MRI) system. In these hybrid units the magnetic field is oriented either parallel or perpendicular to the treatment beam. The MRI is able to image during patient irradiation and provides tumor specific contrast in images for real-time treatment guidance, where the inherent design of MRgRT systems allows the delivery of intensity modulated radiation therapy and on-line adaptive methods.
Therefore, independent dosimetric verification of the complex delivery methods associated with MRgRT systems, by using a-Si EPIDs, is highly desirable.

A number of groups have implemented or investigated the use of EPIDs for imaging and dosimetry in the presence of a magnetic field. The Elekta MR-linac\textsuperscript{13} system has an a-Si EPID mounted on the rotating gantry, directly opposite to the linac head. For this design, the basic imaging characteristics in a bench-top setting were reported by Raaymakers et al.\textsuperscript{14} while dosimetric-verification characteristics for the integrated system were reported by Torres Xirau et al.\textsuperscript{15} In the integrated Elekta MR-linac system, the EPID experiences a magnetic field strength of approximately 10 mT; therefore, measurable magnetic field impact on EPID’s performance was neither expected nor found. Thus, the magnetic field did not change the relative dose profiles, on EPID’s plane, for several square field sizes. The linearity of EPID’s response to irradiations ranging from 5 to 1000 MU resembled that of a similar EPID in a conventional linac. Similarly, the reproducibility and image lag at 10 mT magnetic field were comparable to the case without magnetic field. In the bench-top experiment, the magnetic field at the EPID was ~80 mT, and the authors argued that the degraded contrast to noise ratio, relative to a conventional EPID-linac combination, was largely due to the increased distance (2.58 m) of the EPID from the radiation source.

The radiographic imaging performance of an a-Si based active matrix flat panel imager in a hybrid x-ray/0.5 T MRI system was investigated by Fehrig et al.,\textsuperscript{16} where the measured modulation transfer function (MTF) on the detector plane, and the noise power spectrum (NPS), did not show any impact of magnetic field. In addition, a Monte Carlo-based study (abstract only) was performed by Oborn et al.\textsuperscript{17} where the EPID’s operation in a 1 T parallel and perpendicular magnetic fields was investigated; no impact on the EPID’s operation in the presence of the parallel magnetic field was found.

Although the effect of strong magnetic fields (>80 mT) on the MTF and the NPS of flat panel imager has been studied, basic dosimetric characteristics which are critical for EPID dosimetry such as image reproducibility, linearity, lag, and radiation field profile have not been investigated. In addition, these metrics have not been measured in magnetic fields that are oriented in the direction of the treatment beam. In this note, we present measurements of reproducibility, linearity, lag, and radiation field profile of an a-Si EPID in the MRgRT experimental linac-MR design at the Cross Cancer Institute, which is comprised of a 0.5 T bi-planer magnet and a 6 MV linac beam directed parallel to the direction of magnetic field.\textsuperscript{18}

\section*{2. MATERIALS AND METHODS}

The linac-MR system currently installed at the Cross Cancer Institute (Edmonton, Canada) is an experimental system that uses a biplaner magnet at 0.5 T magnetic field.\textsuperscript{18} The radiation beam passes through the central opening of the pole plate to direct the radiation beam in the direction of main magnetic field. The radiation system is a refurbished Clinac 600C (Varian Medical Systems, Palo Alto, CA) with the flattening filter in place, mounted on the same gantry as the magnet; the gantry rotates through 360°. The pole plate hole dictates the maximum, circular radiation field of 25 cm diameter at a source to axis distance (SAD) of 126 cm. The radiation port is defined by both x and y-jaws, and Varian’s 80-leaf multileaf collimator. A cross-sectional illustration of our system with possible clinical EPID placements can be seen in Fig. 1: all work done in this study was performed with the EPID at isocentre (position A).

Similar to the modifications made to the a-Si EPID to work in magnetic field by Fehrig et al.,\textsuperscript{16} we adapted an old aS500 (Varian Medical Systems) a-Si EPID working with an older hardware/software image acquisition version (IAS2). The housing of this EPID is largely nonmagnetic except for the screws in the aluminum cover and power supply module. The screws were replaced with brass ones. There are inductive elements on the power supply module which would saturate in the strong magnetic field. Thus, the supply module was removed far away from the magnetic field by using an auxiliary cable between the power supply module and the corresponding connector on EPID’s mother board. No other modifications were made to the EPID; it still contains 0.1 cm Cu plate atop the phosphor screen. Standard cables from IAS2 computer to the EPID as well as to the Clinac 600C console computer were used such that the image acquisition is synchronized to the radiation pulses, and the IMRT mode is used to integrate the image for the set number of monitor units (MUs). IAS Monitor Software version 7.1 is used to acquire images.

All measurements were performed with the EPID placed on the linac-MR treatment couch such that the EPID’s imaging centre was aligned with the isocentre; placement at this location ensures that the EPID is immersed in a strong and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Illustration of the geometry of the linac-MR system used for the EPID measurements and possible placements of the EPID for clinical use.}
\end{figure}
homogeneous field for testing purposes. A gantry angle of 0° was used to direct the radiation beam vertically down to the EPID which experiences the main, uniform magnetic field of 0.5 T parallel to the beam. For EPID reproducibility and linearity measurements, in order to account for small variations in the linac’s output between EPID acquisitions, simultaneous ion-chamber measurements were taken with a cylindrical (IC-10, IBA Dosimetry, Bartlett, TN) ion chamber (with 0.2 cm brass buildup cap) connected to an electrometer (Uni-32.05/C6, IBA Dosimetry, Bartlett, TN) ion chamber (with 0.2 cm brass buildup cap) connected to an electrometer (Uni-32.05/C6, IBA Dosimetry, Bartlett, TN). The ion chamber was positioned with a stand-off of 1.5 cm from the surface of the EPID, and 3 cm into the radiation field as illustrated in Fig. 2. The MLC leaves were retracted and linac’s jaws set to 10 cm2; thus the beam aperture was limited by the 19 cm circular opening in the magnet’s pole plate, projecting a 25 cm diameter circular radiation field onto the EPID. For lag measurements the MLC leaves were retracted and the jaws were set to 10 × 10 cm2. Our linac-MR is conduction-cooled, and only takes 40 min to fully ramp the magnetic field up or down. Therefore, we performed all our measurements (with and without a magnetic field) such that both the ion chamber placement and the EPID position on the couch remained stationary during the entire experiment. The IAS2 computer and EPID are constantly powered, therefore no warm up procedure was necessary to ensure operational stability of the electronics.

Flood and dark field reproducibility, image linearity, image lag, and radiation field profiles were all measured in our linac-MR system both with and without magnetic field. To assess flood field stability in magnetic field, several (23) integrated 50 MU flood-field images were acquired and spaced at least 30 min apart over a period of 26 h. With the magnetic field off, we acquired 10 integrated flood-field images over a period of 20 h. The IMRT mode of the IAS2 software provides frame-averaged image, therefore all images were multiplied by the number of frames to restore their integrated values. During the flood-field acquisitions, ion chamber readings were acquired to later correct for any variation in the linac output. Dark-field stability was assessed by acquiring a dark-field image (averaged over 50 frames) prior to each flood field delivery. The average and standard deviation in a 10 × 10 cm2 measurement ROI was then calculated to assess the short-term reproducibility of both flood and dark field images. For assessment of EPID image linearity, we acquired integrated flood field images for irradiations from 1 to 500 MUs, and multiplied the frame-averaged images by the acquired number of frames. In order to minimize the impact of signal lag in linearity measurements, we waited for 5 min between EPID irradiations to reduce any signal carry-over from previous EPID irradiations. The average EPID signal within a 10 × 10 cm2 measurement ROI divided by the ion chamber reading obtained during image acquisition, normalized to a 100 MU delivery, was used to assess image linearity. The image lag19,20 was investigated by acquiring EPID images during and after beam on in cine mode. The EPID was irradiated with 100 MUs at a dose rate of 250 MU/min, and the images were acquired at approximately every 2 s until 60 s postdelivery. The average signal response from a 5 × 5 cm2 measurement ROI was then used to assess the extent of EPID image signal, or lag, postirradiation relative to the average beam-on EPID signal. We waited for at least 45 min between the magnetic field on and off lag measurements. X and Y axes radiation field profiles were obtained from an EPID image, which was acquired by delivering a 10 × 10 cm2 radiation field to the EPID at 200 MU/min in “High” acquisition mode (4 frame averages). The EPID image was flood and dark-field corrected at each field strength prior to acquisition, where X and Y profiles were taken through the central axis, and then normalized to the average EPID image pixel value in a 1 × 1 cm2 area at field centre.

3. RESULTS AND DISCUSSION

No differences were observed in flood and dark field reproducibility, image linearity, image lag, or radiation field profiles when EPID images were acquired with or without a 0.5 T magnetic field present. In the absence of a magnet field, flood and dark-field values (±standard deviation) in our measurement ROI were 57,703 ± 366 and −32.19 ± 0.97 respectively. In the presence of a magnetic field, these values were 57,876 ± 379 and −32.05 ± 0.85. Mean flood and dark-field pixel values, and their associated standard deviations, with the magnetic field on and off are statistically the same. The data from our EPID linearity tests are plotted in Fig. 3. The linearity with and without a magnetic field varies from 0.968 to 1.002, and from 0.970 to 1.001, respectively, for EPID irradiation ranging from 1 to 500 MUs. The linearity curves seen in Fig. 3 resemble those previously measured.19,20 Moreover, the curves with and without magnetic field are the same within the statistical uncertainty of the EPID measurements. Lag measurements, with and without a magnetic field present, are shown in Fig. 4, where approximately 1.4% of the mean beam-on signal is still present 1 to 2 s postirradiation. The lag curves obtained with and without magnetic field follow each other nearly identically, exhibiting no difference outside of statistical variations in EPID measurements as indicated by the standard deviation in flood field values above. X and Y axis field profiles from
the $10 \times 10$ cm$^2$ acquired EPID images with and without a magnetic field present are shown in Figs. 5(a) and 5(b), where no magnetic field-dependent effects are observed. Aside from statistical variations, the profiles are nearly identical; 91.3% of the X-axis and 95.2% of the Y-axis profile points pass a gamma criterion of 1% and 1 mm.

The dosimetric impact of delivering radiation in the presence of a parallel magnetic field within our linac-MR has been studied earlier by our group, and while slightly more electrons reach isocentre, there is no increase in the EPID signal. The additional electrons liberated from the air column have been shown to be low energy (mostly <1.5 MeV), and therefore do not penetrate the 0.2 cm brass buildup cap of the ion chamber or the protective cover and inherent 0.1 cm of copper buildup in the aS500 EPID. As a result, the measured ion chamber and EPID signals with and without a magnetic field present are the same.

Flood field reproducibility and image linearity both relied on ion-chamber corrections to give the most accurate results. Although magnetic fields can strongly effect ion-chamber readings in some orientations between the chamber and the transverse magnetic field, it should be noted that with parallel magnetic fields the dose–response change in similar ion chambers is minimal at 0.5 T. Therefore, any differences (or lack thereof) with and without a magnetic field reported in this note should be due only to the EPID’s change in response due to the magnetic field.

In this study, the EPID was placed at the system’s isocentre (“position A” in Fig. 1); however, it can also be positioned behind the MR’s yoke at “position B” (Fig. 1). At the isocentre the EPID can only be used for pretreatment dosimetry verification and to conduct machine QA (no in vivo measurements), where the full radiation field (dotted lines) is visible/detected by the EPID. In the experimental linac-MR system used in this study in this radiation field is 25 cm in diameter, and in our clinical system it is 31.5 cm in diameter. When placed at position B, the EPID can be used for...
transit-beam *in vivo* dosimetry, however, because of the thickness of the MR yoke which acts as a radiation shield, the amount of the radiation field detected by the EPID is limited (dashed lines) by the size of hole in the yoke. This hole has a diameter of 19 cm in the experimental system and 24 cm in the clinical system. This limited FOV when the EPID is positioned behind the yoke may or may not impact its use for *in vivo* studies depending on the field size needed to be imaged for the study.

4. CONCLUSIONS

The use of EPID for pretreatment and transit dosimetry in current and future MR-linacs may be very useful. This note shows that the standard EPID, after displacing magnetic components outside the magnetic field, can function appropriately in 0.5 T magnetic field oriented parallel to the radiation beam. Moreover, the reproducibility, linearity, signal lag, and the radiation field profiles are unaffected by the presence of the magnetic field.

DISCLOSURES

One of the authors, BGF, is a cofounder and CEO of MagnetTx Oncology Solutions. SR and SS have no conflict to disclose.

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