Dose-response characteristics of an amorphous silicon EPID

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Electronic portal imaging devices (EPIDs) were originally developed for the purpose of patient setup verification. Nowadays, they are increasingly used as dosimeters (e.g., for IMRT verification and linac-specific QA). A prerequisite for any clinical dosimetric application is a detailed understanding of the detector’s dose-response behavior. The aim of this study is to investigate the dosimetric properties of an amorphous silicon EPID (Elekta IVIEWGT) with respect to three photon beam qualities: 6, 10, and 25 MV. The EPID showed an excellent temporal stability on short term as well as on long term scales. The stability throughout the day was strongly influenced by warming up, which took several hours and affected EPID response by 2.5%. Ghosting effects increased the sensitivity of the EPID. They became more pronounced with decreasing time intervals between two exposures as well as with increasing dose. Due to ghosting, changes in pixel sensitivity amounted up to 16% (locally) for the 25 MV photon beam. It was observed that the response characteristics of our EPID depended on dose as well as on dose rate. Doubling the dose rate increased the EPID sensitivity by 1.5%. This behavior was successfully attributed to a dose per frame effect, i.e., a nonlinear relationship between the EPID signal and the dose which was delivered to the panel between two successive readouts. The sensitivity was found to vary up to 10% in the range of 1 to 1000 monitor units. This variation was governed by two independent effects. For low doses, the EPID signal was reduced due to the linac’s changing dose rate during startup. Furthermore, the detector reading was influenced by intrabeam variations of EPID sensitivity, namely, an increase of detector response during uniform exposure. For the beam qualities which were used, the response characteristics of the EPID did not depend on energy. Differences in relative dose-response curves resulted from energy dependent temporal output characteristics of the accelerator. If ghosting is prevented from affecting the results and all dose-response effects are properly corrected for, the EPID signal becomes independent of dose rate, dose, and exposure time. © 2005 American Association of Physicists in Medicine. [DOI: 10.1118/1.2040711]

I. INTRODUCTION

Electronic portal imaging devices (EPIDs) were developed for the purpose of patient setup verification. The aim was to replace radiographic films, which were originally used to verify patient positioning during radiotherapy treatments. Detectors which are based on two different principles, liquid-filled matrix ionization chambers and camera-based fluoroscopic EPIDs, became commercially available in the mid 1990’s. Despite all the advantages of these devices (e.g., feasibility of on-line patient setup correction, no film processing), their image quality was not satisfactory. The current generation of EPIDs is based on semiconductor materials, namely, amorphous selenium photoconductors as well as amorphous silicon photodiodes. These devices exhibit an improved image quality close to that of radiographic films. While amorphous selenium EPIDs are primarily used for diagnostic applications, ion chamber based and fluoroscopic EPIDs used in radiotherapy tend to be replaced by amorphous silicon devices.

The dose distributions acquired with modern portal imaging systems can be used for a broad variety of applications. With respect to the verification of IMRT treatment plans, the measured distributions of primary fluence can be compared with the data predicted by the treatment planning system. In combination with patient CT data, portal dose images (PDIs) can be used to reconstruct the dose distribution within the patient, i.e., for two-dimensional (2D) or 3D in vivo dosimetry. EPIDs also offer the possibility to verify the leaf position during dynamic beam delivery. Recently, an amorphous silicon EPID was developed which allows in-phantom dosimetry. Another possible application is linac specific quality assurance, e.g., monitoring leaf calibration or beam flatness and symmetry measurements.

Compared to former designs of EPIDs, amorphous silicon devices are expected to be superior for portal imaging and portal dosimetry. An understanding of the relationship between pixel value reading and dose or fluence is a prerequisite for portal dosimetry. Two prototype amorphous silicon
EPIDs$^{13,14}$ as well as the device of another manufacturer (aS500, Varian Medical Systems)$^{15,16}$ exhibit an EPID signal which is highly linear with dose. An EPID of the same type that we are using (Elekta IVIEWGT) was investigated by McDermott et al.$^{17}$ using photon beam qualities ranging from 4 to 18 MV. The authors found variations of the EPID response with pulse repetition frequency and dose per pulse up to 5 and 8 %, respectively. Furthermore, changes of response with exposure time (up to 5 % over the range investigated) were explained by the combined effects of image lag and ghosting. A correction factor was defined as a function of beam-on time.

The purpose of the present study is to understand and quantify the relationship between EPID response and dose delivery parameters, such as dose and dose rate. In addition, the detector’s temporal stability as well as ghosting effects, i.e., modifications of EPID response due to preceding exposures,$^{18-20}$ were studied. Because little data is available for energies higher than 18 MV, we investigated if the IVIEWGT behaves differently for 25 MV compared with 6 and 10 MV, respectively.

II. MATERIALS AND METHODS

II.A. Linac and detector

All measurements were performed with 6, 10, and 25 MV photon beams provided by an Elekta Sli precise accelerator (Elekta Oncology Systems, Crawley, UK) equipped with a MLC. The linac is calibrated to yield 1 cGy absorbed dose to water per monitor unit (MU), at a depth of 10 cm on the central axis in isocentric reference conditions, for a field size of 10 × 10 cm$^2$.

The EPID attached to the linac is the IVIEWGT (Elekta) based on the amorphous silicon type detector panel XRD 1640 AL5 (PerkinElmer Optoelectronics, Fremont, US-CA). The detector contains an internal copper plate having a thickness of 1 mm, which acts as build-up material. The radiation sensitive layer is based on amorphous silicon sensors operating as a two-dimensional photodiode array. A scintillator screen on top of this layer is used to create optical photons. Absorption of light in the sensors generates electron-hole pairs. In the presence of an electric field, these charges form a measurable current, which is proportional to the incident light flux.$^{21}$ A more detailed description of the functionality and basic properties of such devices can be found in the literature.$^{4,13,22}$ The detector has a fixed source-surface-distance of approximately 157 cm. Its radiation sensitive layer consists of 1024 × 1024 pixels with a pitch of 400 µm, resulting in an active area of 409.6 × 409.6 mm$^2$. Back-projected to the source-isocenter distance, this corresponds to an area of 259 × 259 mm$^2$ and a pitch of 253 µm.

All measurements were performed with gantry and collimator at the 0° position and, except for the investigation of ghosting, a reference field size of 10 × 10 cm$^2$ was used. Although the detector contains a copper plate acting as build-up material, electron equilibrium is not provided for the high energy photon beams. Several authors have reported that portal dosimetry requires additional build-up material to avoid oversensitivity due to scattered radiation, particularly at short phantom-detector distances.$^{17,23-25}$ For that reason, additional copper plates having a thickness of 1.5 mm (6 and 10 MV beam) and 3.0 mm (25 MV beam), respectively, were placed on top of the detector for all measurements described in the present study. These thicknesses correspond roughly to the depths of maximum dose and were derived from previous measurements which were performed to determine the EPID’s build-up characteristics.

II.B. Image acquisition and evaluation

The EPID is connected to a PC with appropriate software packages for detector signal processing. Most of the portal dose measurements described in this paper were carried out using the IVIEWGT software (release 3.1), which was distributed with the detector. This system provides synchronization between the detector and the linac, i.e., image data are read between the radiation pulses. Furthermore, it automatically applies a set of corrections to all images measured, including offset and gain correction as well as a bad pixel map correction. The offset correction image is subtracted from the measured image to correct for any leakage current or other fixed signals. When the detector is not exposed to radiation for a certain time, an offset image is created and stored which is then used to correct all subsequent images. If necessary, this automatic update of the offset correction image can be disabled. The gain correction image accounts for sensitivity variations from pixel to pixel. It is obtained by irradiating the panel with an open field covering the entire sensitive area of the detector. The value of each pixel in the offset corrected image is divided by the corresponding pixel value of the normalized gain correction image. Finally, the resulting image is processed using a bad pixel map for identifying pixels which do not respond properly. The corresponding pixel values are set to the mean value of the neighboring pixels.

Using the IVIEWGT software, all portal dose images were measured in a way that the signal was integrated over the total beam-on time. A frame is defined as the signal $s(x,y)$ from one readout of the entire panel. $x$ and $y$ indicate the coordinates of a certain detector pixel. The EPID signal $S_S(x,y)$, i.e., the portal dose image, is considered to be the sum of all acquired frames.

$$S_S(x,y) = \sum_{i=1}^{n} s_i(x,y),$$

where $n$ denotes the number of frames. \hspace{1cm} (1)

In the normal operation mode, the IVIEWGT software does not record the pixel values of each individual frame, but their mean value $\bar{s}(x,y)$. The EPID signal is then calculated by multiplying $\bar{s}(x,y)$ by the number of acquired frames $n$. These quantities can be directly extracted from portal dose images which are recorded using the standard EPID software.

In order to investigate variations of the EPID signal from frame to frame, we recorded $s_i$, i.e., sequences of EPID images. The experiments were performed using the HIS soft-
ware (version 2.3.2, PerkinElmer) for image acquisition. This application supports the detector’s intrinsic minimum integration time of 285 ms and allows the frame rate to be varied. In the standard iVIEWGT software, the integration time is set to 320 ms and cannot be changed.

All portal dose images were evaluated in-house using in-house developed software written in the C++ programming language. Apart from the investigation of ghosting, the EPID dose-response behavior was investigated at the central axis, i.e., only the central area of the detector. EPID signal values were obtained by calculating the arithmetic mean of certain detector areas, usually the central 5 × 5 mm² (20 × 20 pixels). In the following, the detector was characterized by its response $R$, which was defined as the signal $S_\infty$ divided by the number of monitor units delivered.

$$R = \frac{S_\infty}{\text{MU}}$$  \hspace{1cm} (2)

II.C. Reproducibility and temporal stability

The accuracy of dose measurements may be limited by the detector’s short term stability, i.e., reproducibility. The stability throughout the day as well as the long term stability determine the frequency for the acquisition of calibration images. The temporal stability of the iVIEWGT was investigated using all three beam qualities.

To evaluate the short term stability, the EPID was exposed under identical conditions (30 MUs, maximum dose rate). Short term stability tests were performed on three different days, each irradiation was repeated five times. Based on the results presented in Sec. III B, the EPID was not irradiated for at least four minutes prior to each measurement. By doing so, ghosting was prevented from affecting the results.

The stability throughout the day was determined on nine different days, within time intervals ranging from two to six hours. On average, the detector was exposed to eight reference fields per day. The measurements were generally performed after the detector was in use for several hours. The long term stability was investigated over a period of six months. The EPID signal induced by a reference field was determined from three measurements and corrected for interday variations of linac output using ionization chamber measurements.

In addition, the EPID’s warm-up behavior was studied. The linac was turned on after being in the stand-by state overnight and measurements were started. In order to determine the minimum period until the detector signal reached a stable value, it was exposed to a reference field (6 MV, 30 MUs, maximum dose rate) every five to ten minutes. On two different days, the warm-up behavior was studied without any additional irradiations at all. On a third day, the EPID was exposed to a total of 600 MUs (6 MV, 25 MV) between reference exposures to check if irradiating the detector accelerated warming up. From previous ionization chamber measurements it is known that the linac output does not vary by more than 1% during a single day.

II.D. Ghosting

The term ghosting generally describes the modification of detector response due to foregoing irradiations. This effect was investigated by exposing the EPID to a 6 × 6 cm² field followed by a 20 × 20 cm² field. All ghosting measurements were performed using the highest available dose rate (i.e., 400 and 560 MU/min, respectively) and a constant frame integration time of 320 ms. The PDs of the second field were evaluated by averaging the detector signal over the central 5 × 5 mm² as well as along the outline (thickness 5 mm) of the square area of 14 × 14 cm² located around the detector center. The quotient of both values (center versus outline) of an image obtained without any preirradiation (and the same number of MUs for the reference field) served as the reference value. Ghosting was quantified by determining variations in the quotient with respect to this reference value, i.e., determining the enhancement of the EPID signal at the central axis, as a result of the foregoing exposure.

The magnitude of ghosting can depend on the number of monitor units delivered by the two fields as well as the time interval in between. The minimum time intervals between two subsequent irradiations were 7.5 s (6 and 10 MV beams) and 9.5 s (25 MV beam), respectively, which is the minimum time between segments in the (step-and-shoot) IMRT mode, due to the linac’s inherent safety checks. Under these conditions, ghosting was investigated for a variety of combinations of dose values. The experiments included a constant preirradiation of 25 MUs with different dose levels for the test field as well as preirradiations at varying dose levels with the test field dose being constant (2.5 MUs). Additional measurements were performed with a fixed MU ratio of five for both fields.

For standard treatment plans (non-IMRT), the time between two fields could be varied manually. By doing so, the minimum time interval between two exposures of approximately 25 s was determined by the linac’s inherent safety checks. With the number of monitor units being 50 (first field) and 2.5 (second field), ghosting was investigated as a function of time interval (up to 4 min) between the two exposures. All measurements were performed for 6, 10, and 25 MV.

We furthermore tried to identify the cause of ghosting. In principle, one can influence the detector’s response from one exposure to another by modifying the offset signal or the sensitivity of detector elements. As a consequence, either the offset or the gain correction image does not reflect the actual background signal or pixel sensitivity distribution. Thus, the “ghost” of the previous treatment field appears in the portal dose image of the current one. It was investigated if disabling the automatic update of the offset correction image had any effect on the magnitude of ghosting. This could only be done for a time interval of 25 s between the two exposures. Concerning time intervals typical for IMRT, the image acquisition software was not able to update the offset correction image prior to the second field.
II.E. Dose-response characteristics

The EPID response $R$ was determined for the dose range of 1 to 1000 MUs. The corresponding irradiations were performed using the maximum available nominal dose rate, i.e., 400 MU/min at 6 and 10 MV and 560 MU/min at 25 MV, respectively. The linac’s control system offers the possibility to reduce the pulse repetition frequency and therefore dose rate by factors of two. To investigate any influence of pulse repetition frequency on EPID sensitivity, irradiations were performed by delivering the same amount of radiation (30 MUs) to the detector, but with varying nominal dose rates down to 12 MU/min (6 and 10 MV beam) and 17 MU/min (25 MV beam), respectively.

In order to identify parameters influencing the dose-response characteristics of our detector, measurements were performed using different frame integration times. The minimum integration time of 285 ms can be increased by factors of two up to 18.24 s. Longer readout cycles require lower dose rates in order to avoid detector saturation. For an integration time of 1140 ms, the maximum available dose rate at each energy already led to saturation. For a dose of 5 MUs, the EPID signal was determined for all possible combinations of nominal dose rate and frame integration times up to 9.12 s.

Linear accelerators generally exhibit a start-up phase of irradiation. The dose rate starts at a low level to finally reach a stable value. Using our linac, it took about two seconds until the beam stabilized. The characteristics of linac output at the central axis were measured as a function of time using a linear array of ionization chambers (LA48, PTW-Freiburg, Freiburg, Germany) with a temporal resolution of 22 ms.

In addition, we were interested in EPID sensitivity variations during exposure. Performing the respective measurements, we recorded each individual frame. The central axis value of these individual frames was investigated as a function of time and dose. Due to limitations of the PC which was used for image acquisition, the number of frames that could be stored at once was limited to 50. As a consequence, we needed to reduce the frame acquisition rate to cover sufficiently long time intervals. As longer integration times require reduced dose rates to avoid detector saturation, the sequences of frames were measured using nominal dose rates of 100 MU/min (6 and 10 MV) and 140 MU/min (25 MU/min), respectively.

III. RESULTS

III.A. Temporal stability

The EPID’s temporal stability characteristics are summarized in Table I. Similar characteristics were obtained for all beam qualities. For the identical exposures acquired to test reproducibility, the standard deviation of the detector reading (averaged over the central 20 × 20 pixels) was typically less than 0.1%. Within time intervals up to six hours, we did not measure a single EPID signal deviating more than 0.31% from its reference value. Over a period of six months, the standard deviation of detector readings, which were corrected for linac output variations, was 0.21%. The maximum observed deviation amounted to 0.52%.

The EPID’s warm-up behavior is illustrated in Fig. 1. The two different symbols indicate EPID signal values determined on two different days for the 6 MV beam. These values were normalized to their saturation value, which was calculated by fitting an exponential function through the data points. After an extended period in the stand-by state, the detector sensitivity was reduced by 2.5% compared to the stable value, which was approached rather slowly. After approximately 2.5 h, the sensitivity was within 1% of the predicted equilibrium value. Even five hours after switching on the EPID, its sensitivity did not reach a plateau. Preirradiating the detector with 600 MUs had no influence on warming up.

III.B. Ghosting

Under certain circumstances, preirradiations considerably increased the EPID response. The ghosting results for IMRT conditions (shortest accessible time interval between two exposures) are presented in Table II for different combinations of beams. Ghosting became more pronounced with an increasing ratio of the dose of the first field to that of the second (test) field. For a constant dose ratio of five, the percentage ghosting varied little irrespective of the absolute

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Table I. Temporal stability of the iVIEWGT. For all three time scales, several data sets were collected. Each set is characterized by the mean value of the measured EPID signals and the standard deviation (SD), as a percentage of the mean value. For each stability test, the mean SD of all data sets (including photon beam qualities 6, 10, and 25 MV) as well as the maximum deviation from the average value of all corresponding measurements are presented. With regard to long term stability, the detector was investigated for six months.

<table>
<thead>
<tr>
<th></th>
<th>Reproducibility (%)</th>
<th>Throughout the day (%)</th>
<th>Long term (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean SD</td>
<td>0.09</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>Max. dev.</td>
<td>0.20</td>
<td>0.31</td>
<td>0.52</td>
</tr>
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</table>
just prior to the measurements. The values denote the enhancement of the EPID reading at the detector center as a result of the preirradiation.

<table>
<thead>
<tr>
<th>MU5x6</th>
<th>MU20x20</th>
<th>6 MV (%)</th>
<th>10 MV (%)</th>
<th>25 MV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>2.5</td>
<td>2.9</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>1.6</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
<td>0.9</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>2.5</td>
<td>2.5</td>
<td>1.0</td>
<td>1.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>1.2</td>
<td>1.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>12.5</td>
<td>2.5</td>
<td>2.1</td>
<td>2.1</td>
<td>0.6</td>
</tr>
<tr>
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<td>2.5</td>
<td>5.5</td>
<td>4.9</td>
<td>8.9</td>
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<tr>
<td>50</td>
<td>10</td>
<td>1.6</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Figure 2 shows an example of how ghosting appears in portal dose images for the case where the effect was most pronounced (25 MV, 50 and 2.5 MUs). The flat profile (dashed line) corresponds to the reference PDI which was acquired after the detector was not irradiated for more than five minutes. The second image (solid line) was measured about 11 s after the preirradiation. Local modifications of EPID response of up to 16% were observed. It can be seen that ghosting even influenced the sensitivity of pixels that were located more than 4 cm outside the field edges.

Figure 3 illustrates the dependence of EPID response on dose rate. Measurements were performed with a constant frame acquisition rate. Therefore, different dose rates corresponded to different dose per frame values. For each beam quality, the relative dose rate $D_{rel}$ was normalized to the respective maximum value. For the lowest dose rate under investigation, the detector sensitivity was reduced by about 7% compared to the maximum one. This reduction was independent of the total number of MUs (results not shown). The effect was most pronounced for the 6 MV beam but generally rather similar for all energies. The curves in Fig. 4 were obtained by fitting the parameters of the class of functions given in Eq. (3) to the data points.

III.C. Dose-response characteristics

In order to prevent dose-response measurements from being affected by ghosting, for all following experiments the time between the acquisition of portal images was at least four minutes.

Figure 4 illustrates the dependence of EPID response on dose rate. Measurements were performed with a constant frame acquisition rate. Therefore, different dose rates corresponded to different dose per frame values. For each beam quality, the relative dose rate $D_{rel}$ was normalized to the respective maximum value. For the lowest dose rate under investigation, the detector sensitivity was reduced by about 7% compared to the maximum one. This reduction was independent of the total number of MUs (results not shown). The effect was most pronounced for the 6 MV beam but generally rather similar for all energies. The curves in Fig. 4 were obtained by fitting the parameters of the class of functions given in Eq. (3) to the data points.
For each beam quality, the parameters $a$ and $b$ were fitted through measured data using the Levenberg-Marquardt algorithm.\textsuperscript{29} This iterative optimization procedure resulted in the following parameter sets: $a=9.988\cdot10^{-1}$, $b=2.100\cdot10^{-2}$ for 6 MV, $a=9.989\cdot10^{-1}$, $b=1.953\cdot10^{-2}$ for 10 MV, and $a=9.995\cdot10^{-1}$, $b=1.925\cdot10^{-2}$ for 25 MV. The maximum deviation of all measured values from the curves was 0.2%.

In order to discover the effects that caused the variation of EPID response with dose rate, we investigated if the sensitivity changes with frame acquisition rate when dose delivery parameters are kept constant. When integration time and therefore dose per frame were doubled, the EPID signal was generally increased by a certain fraction. This increase was found to be independent of dose rate as well as the magnitude of frame rate. If it is assumed that the critical parameter is the dose per frame, doubling the dose rate has the same effect as doubling the integration time, namely, an increase of the EPID reading by a fixed fraction. Consequently, Eq. (3) can be rewritten using the relative dose per frame $\hat{D}$.

$$R(D_{rel}) = a \cdot \hat{D}_{rel}^b. \quad (3)$$

As already shown in Fig. 4, the given class of functions can actually be used to fit the experimentally determined data with a high accuracy. According to Eq. (3), doubling the dose rate increases the EPID signal by a factor of $2^b$. If the dose per frame is the only parameter governing the dose rate dependence, the values of $2^b$ should correspond to the quotients of measured EPID signals with integration times differing by factors of two. For each energy, a comparison between the estimated value ($2^b$) and the average of all measured values is given in Table III. Indeed, a good agreement was observed for each beam quality under investigation, with the maximum deviation being 0.17%. However, Eq. (4) only holds if a constant frame integration time of 320 ms is used. Portal images which are taken using varying frame rates cannot be directly compared because intrabeam variations of EPID sensitivity, which are discussed below, are more pronounced for longer integration times (results not shown).

The relationship between EPID response and dose is shown in Fig. 5. The curves represent analytical functions which were used to describe the contributing effects, i.e., linac beam start-up and intrabeam variations of detector response. They can be obtained by adding up the functions accounting for the two effects, which are given in Eqs. (5) and (6) (see text below). It can be seen that the curves are almost identical for the 6 and 10 MV beam qualities while the effect, namely, decreasing sensitivity for lower doses, was more pronounced for the 25 MV beam. With respect to the normalization value at 30 MUs, the EPID response was approximately 2% higher for 1000 MUs, while it was decreased by 5.5% (6 and 10 MV beams) and 7% (25 MV beam), respectively, for a dose of 1 MU. Except for very low numbers of monitor units, the measured data could be reproduced rather accurately by the analytical function. For dose values ranging from 4 to 500 MUs, the agreement was better than 0.35%. For a dose of 1000 MUs, the EPID sensitivity was overestimated up to 0.5% (25 MV beam). Down to 1 MU, deviations up to 2% were observed.

For each energy, a typical linac output variation for the very first seconds after beam start is presented in Fig. 6. The values of relative linac output (corresponding to relative dose per frame) were normalized to the maximum dose rate. It can be seen that the linac behaved differently for 25 MV photon beams when compared to the lower energies. Before the 25 MV beam started, a small amount of radiation (about 1/2 MU) was emitted at a low dose rate. Then the linac stopped for approximately two seconds until the irradiation actually began. This behavior was used to simulate the rel-
The influence of beam start-up on EPID sensitivity corresponds to those of relative dose per frame, which were used to estimate a temporal resolution of 320 ms. Hence, the values of relative linac output were weighted using the respective detector sensitivity according to Eq. (4). The simulated EPID’s dose-response relationship due to beam startup is presented in Fig. 7. For doses less than 10 MUs, the reduction in EPID response was greater than 0.5%. It amounted up to 3% (6 and 10 MV beam) and 3.5% (25 MV beam), respectively, for a dose of 1 MU. The best agreement between analytical functions and calculated data points was achieved by optimizing the parameters of the following class of functions:

\[ R(MU) = 1 - c \cdot MU^{-d}. \]  

Least squares minimization resulted in the following parameter sets: \( c = 3.147 \cdot 10^{-2}, d = 1.135 \) for 6 MV, \( c = 2.976 \cdot 10^{-2}, d = 8.892 \cdot 10^{-1} \) for 10 MV, and \( c = 4.742 \cdot 10^{-2}, d = 7.643 \cdot 10^{-1} \) for 25 MV.

Figure 8 shows the experimentally determined dose-response relationship (Fig. 5) corrected for beam startup (Fig. 7). It can be seen that the corrected EPID sensitivity is still increasing with dose. Hence, linac output was not the only parameter governing the dose-response relationship. To be able to quantify the second effect, it was necessary to record each individual frame. The variation of the EPID reading during uniform exposure (6 MV beam) is presented in Fig. 9. This EPID measurement was started after the linac output has reached equilibrium. Nevertheless, the frame signal increased by 3.5% within a time interval of three minutes. Its correlation with time (or dose) can be described by a logarithmic function (see Fig. 9). It can be shown that when the EPID signal increases logarithmically with cumulative dose, the detector response has to be a logarithmic function of dose, too. The measured values of dose-response corrected for beam startup were fitted using Eq. (6).

\[ R(MU) = g \cdot \ln(MU) + h. \]  

A single parameter set was determined for all data points and energies. Indeed, the resulting values \( g = 7.779 \cdot 10^{-3}, h = 9.739 \cdot 10^{-2} \) were in good agreement with measured data (see Fig. 8, straight line). Additional measurements were performed, investigating the variation of EPID response with dose for nominal dose rates being only 25% of the maximum values (data not shown). From these results we concluded that for constant dose values, intrabeam variations of detector sensitivity are independent of dose rate. Therefore, the
response of our EPID is considered to be function of dose (not time).

IV. DISCUSSION

IV.A. Temporal stability

Although our EPID was shown to be a very stable dosimeter, it exhibited a pronounced warm-up effect which took several hours. The detector sensitivity needed about 2.5 h to be within 1% of the predicted stable value. It took more than 4 h until the EPID signal was as close as 0.5% to the equilibrium value. This warming up does not only affect EPID sensitivity to radiation but offset signal, too. Both quantities are approaching their stable value exponentially, having similar decay constants (data not shown). Even exposing the EPID to high doses did not accelerate warming up. Another amorphous silicon flat-panel imager (prototype, PerkinElmer) was reported to have a much shorter warm-up period. The dark signal of that detector stabilized asymptotically within 1–2 h. Besides detector warming up, the IVIEWGT showed an excellent stability throughout the day. For time intervals up to six hours, we did not observe considerable drifts of the EPID response.

Over a period of six months, the long term stability of our EPID was 0.21% (1 SD), with a maximum deviation from the reference value of 0.52%. Another detector of the same type (IVIEWGT), which was investigated over 23 months, showed a similar standard deviation of 0.5%. However, the maximum and minimum signal values of that detector, which were corrected for output variations of the accelerator, differed by more than 2%.

IV.B. Ghosting

EPIDs, which are based on semiconductor materials, are known to exhibit artifacts such as image lag and ghosting. Image lag is defined as residual signal, i.e., the carryover of trapped charge into subsequent frames acquired with no exposure. With regard to amorphous silicon detectors, the dominant source of image lag has been identified as trapping and release of charge in the sensor elements. A second source of image lag is phosphor afterglow, i.e., the carryover of trapped charge into subsequent frames. With regard to amorphous silicon detectors, the dominant source of image lag has been identified as trapping and release of charge in the sensor elements. An increase in pixel sensitivity is a modification of the electric field distribution in the semiconductor layer. This can either cause a reduction or an increase in pixel sensitivity. The interaction of captured charge with newly generated charge is the dominant effect for ghosting in amorphous selenium EPIDs, where sensitivity is generally reduced due to irradiations. Concerning the IVIEWGT amorphous silicon detector, ghosting increased detector sensitivity. It is therefore expected that alterations of the electric field in the amorphous silicon photodiodes are responsible for the observed effects. It was shown that for a time interval of 30 s between two exposures, the EPID signal of the second field was not influenced by changes in the offset signal due to image lag. However, the rise in magnitude of ghosting for time intervals around 10 s indicates a contribution of image lag. This would be consistent with the findings of McDermott et al. The authors showed that 10 s after beamoff, the residual signal of the IVIEWGT amounted up to 1% (depending on exposure time) of the signal during irradiation.

In our study, it was found that for a fixed frame acquisition rate, the two critical parameters of ghosting were the ratio of delivered doses and the time interval between two subsequent irradiations. Generally, ghosting effects became more apparent with increasing ratio of the number of MUs for the first and second field. For 9.5 s between the delivery of two IMRT segments, modifications of the second field’s EPID signal up to 9% were observed for 25 MV beams. For the lower energies, ghosting amounted to 5% for a beam weight ratio of 20. After one minute, ghosting did not exceed 1% for the same combination of beams. The device of another manufacturer (Varian aS500) has been reported to exhibit almost no ghosting. For a time interval of 15 s, the effect amounted to only 0.2%. However, the authors made no statement about the doses used for these measurements. The finding of another group using the Varian aS500 EPID was that ghosting did not exceed 1% for an exposure of 500 MUs and a test field of 10 MUs (time interval 10 s).

Our experiments demonstrated that ghosting potentially poses difficulties for the verification of step-and-shoot IMRT treatments using the IVIEWGT system. As the intensity of ghosting is nonuniformly distributed across the exposed detector area and it is even apparent outside the geometrical field edges of the previous beam (see Fig. 2), an iterative correction procedure is a challenging task. With regard to dynamic delivery techniques it will become even more complicated. Another way of avoiding ghosting effects is to increase the time gaps between single exposures. Although this method is definitely feasible, the amount of time required for the verification of an IMRT treatment plan could become rather high. Further investigation is needed to assess the influence of ghosting on PIDs obtained with the IVIEWGT for clinical IMRT verification. Lower limits for the time gap after single segments could be defined to reach an acceptable accuracy. These time gaps do not have to be static, they could be defined as a function of the number of MUs which are delivered by the preceding segments.

IV.C. Dose-response characteristics

The dose-response characteristics of amorphous silicon EPIDs are described in several publications. McCurdy, Luchka, and Pistorius investigated the aS500 and observed a linear response with dose. The sensitivity of that EPID was more or less independent of dose rate, even though the dose per frame was varied. For the same type of detector, Van Esch, Depuydt, and Huyskens found deviations from lin-
earity with dose up to 6% below 30 MUs, which were attributed to internal rounding errors. The product of another manufacturer (prototype, PerkinElmer) has been reported to be extremely linear, with the maximum nonlinearity being 0.13%.13

A detailed investigation of detector response for the same type of detector as used in the present study was performed by McDermott et al.17 (photon beams ranging from 4 to 18 MV). In contradiction to the results described above, they observed systematic deviations from linear behavior. Changes of detector response up to 8 and 5% were reported for varying dose per pulse and pulse repetition frequency, respectively. Concerning dose dependence, they detected a response variation of up to 5% for doses ranging from 5 to 1000 MUs. For the same dose range and beam qualities of 6 and 10 MV, our detector exhibited almost the same change in response. Larger variations were observed for 25 MV as well as doses below 5 MUs. These deviations from an “ideal” detector with constant response become particularly important for the verification of IMRT treatment plans, where different parts of the detector receive considerably varying doses. With regard to dose rate, the sensitivity of our detector showed a variability of about 7%. Combining previously published data and the findings of the present study, it was concluded that the dose rate dependence originates from a dose per frame effect. This was experimentally verified, i.e., the dependence of EPID response on dose rate was attributed to a nonlinearity in detector sensitivity with dose per frame. When the dose per frame was doubled, the sensitivity of our detector was increased by 1.5%.

With regard to portal imaging, the start-up phase of irradiation as well as pulse-to-pulse variations of linac output have been investigated in several publications. Sonke, Brand, and van Herk23 analyzed the focal spot motion (during the phase of beam startup) and its effect on portal image analysis. Partridge, Evans, and Mosleh-Shirazi26 found that fluctuations in source intensity can give rise to ring artifacts in reconstructed (MVCT) images. For absolute portal dosimetry, the variations of linac output over longer time scales are generally too low to significantly influence EPID signal values via the dose per frame dependence of detector response. In contrast to that, the linac’s beam start-up behavior dominates the relationship between response and dose for short exposure times. Due to startup, the first frames of an image are always acquired at a low dose rate and consequently detector sensitivity is low. The resulting EPID signal is smaller than that caused by an ideal radiation beam characterized by constant dose rate. The influence of beam startup on the EPID signal is more pronounced for lower doses (<15 MUs). After the measured dose-response curves were corrected for beam startup, differences in dose-response relationship from one beam quality to another could almost be eliminated (see Fig. 8).

Considerable variations remained for very low doses, i.e., 1–2 MUs. At this dose level, variations from one beam to another (the linac’s start-up behavior is not precisely reproducible) can affect detector reading. Further calculations pointed out that the EPID reading depends on the exact time of the beginning of radiation production with respect to detector readout (data not shown). Due to the dose per frame dependence of detector sensitivity, it makes a difference if a small amount of radiation is delivered within a single frame or at the end of one frame and the beginning of another. Hence, identical exposures can give different readings. According to our simulations, this effect can be responsible for a difference in the EPID signal of up to 1% for a dose of 1 MU. The influence of this effect decreases rapidly with increasing dose.

Furthermore, identical doses caused different EPID readings, if they were delivered using different beam qualities (data not shown). Concerning relative dose-response curves, the IVIEWGT did not exhibit an intrinsic energy dependence. The differences which were observed were solely a consequence of the energy specific output characteristics of the accelerator.

To fully explain the dose-response behavior of an amorphous silicon EPID, intrabeam variations of its sensitivity need to be considered (see Sec. IV B). The effects which are responsible for these variations are image lag and ghosting. Ghosting is known to cause modifications of the EPID signal due to foregoing irradiations. If two beams are temporally separated, the dose delivered by the first beam influences the EPID response during the second beam. It is obvious that when there is not time gap between two exposures, the first fraction of the beam is substantially influencing the EPID’s response to the second one. During a single exposure, the detector response is a function of accumulated dose, which was experimentally verified. It was shown that for a stable linac output, the EPID frame signal increased logarithmically with dose (see Fig. 9). This behavior resulted in the logarithmic increase of integrated EPID response with dose (see Fig. 8).

McDermott et al.17 investigated the response of the IVIEWGT down to a dose of 5 MUs. To account for image lag and ghosting, the authors suggested the use of a ghosting correction factor being a function of irradiation time. In contrast to their findings, our results indicated that such a correction should be a function of dose. We compared the ghosting correction factor with our correction method. Assuming a dose rate of 400 MU/min (in order to convert time to dose), for dose values higher than 10 MUs the agreement between the two curves was better than 1%. However, the two curves are diverging significantly for smaller doses. Furthermore, the ghosting correction factor as a function of time is only applicable for a single nominal dose rate, whereas the correction method described in the present study [see Eq. (6)] is applicable to any dose rate. This has been experimentally verified for exposures at 25% of the maximum dose rate.

V. CONCLUSIONS

The purpose of the present study is to investigate the Elekta IVIEWGT amorphous silicon EPID for dosimetric purposes. It exhibited an excellent temporal stability, on short as
well as long term scales. With regard to intraday variations of its sensitivity, the warm-up behavior of this device had to be taken into account.

The dose-response behavior of the IVIEWGT was by far not ideal. The sensitivity varied with both, dose and dose rate (up to 10%). The dose rate dependency was successfully attributed to a dose per frame effect, i.e., a nonlinear relationship between frame signal and dose which is deposited in the detector between two readouts. The response variation with dose was influenced by two independent effects. First, as a consequence of beam startup, the response decreased with decreasing exposure time for low doses (<15 MUs). Second the dose-response behavior was governed by intrabeam variations of detector sensitivity. The EPID response, corrected for beam startup, was found to increase logarithmically with dose. Using the IVIEWGT for portal dosimetry, it is essential to separately consider these two effects. In principle, a low EPID signal can be either due to low dose rate (e.g., because of an absorber) or due to short irradiation time. In the first case, the signal is primarily influenced by intrabeam ghosting which is a function of the accumulated dose. In the latter case, the dominant factor is beam startup, which actually is a function of total irradiation time.

An important dosimetric application of portal dosimetry is the verification of IMRT treatment plans. Ghosting effects are a limiting factor for such measurements. In order to avoid ghosting, the time intervals between single beam segments can be increased compared to the standard procedure of treatment. A compromise between accuracy and workload has to be found. Step- and-shoot IMRT treatment plans frequently contain segments delivering low doses. It is therefore essential to correct for the variations of EPID response summarized above. In order to convert EPID signal distributions to dose or fluence, scatter processes which occur inside the build-up material and the detector have to be taken into account. The most accurate way of modeling the resulting influence of field size and shape on EPID response is the application of appropriate scatter kernels. The description and evaluation of scatter kernels and the verification of clinical IMRT treatment plans including correction methods based on the findings of the present study are currently investigated. These items will be described in a separate communication.

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