Electron beam quality control using an amorphous silicon EPID

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Short Title: Electron beam QC with an amSi EPID

Abstract

25 An amorphous silicon EPID has been investigated to determine whether it is capable
of quality control constancy measurements for linear accelerator electron beams. The
EPID grayscale response was found to be extremely linear with dose over a wide dose
range and, more specifically, for exposures of 95-100MU. Small discrepancies of up
to 0.8% in linearity were found at 6 MeV (8 and 10 MeV showed better agreement).
30 The shape of the beam profile was found to be significantly altered by scatter in air
over the approximately 60 cm gap between the end of the applicator and the EPID.
Nevertheless, relative changes in EPID-measured profile flatness and symmetry were
linearly related to changes in these parameters at 95 cm focus to surface distance
(FSD) measured using a 2D diode array. Similar results were obtained at 90° and
35 270° gantry angles. Six months of daily images were acquired and analysed to
determine whether the device is suitable as a constancy checker. EPID output
measurements agreed well with daily ion chamber measurements, with a 0.8%
standard deviation in the difference between the two measurement sets. When
compared to weekly parallel plate chamber measurements, this figure dropped to
40 0.5%. A Monte Carlo (MC) model of the EPID was created and demonstrated
excellent agreement between MC-calculated profiles in water and the EPID at 95cm
and 157cm FSD. Good agreement was also found with measured EPID profiles,
demonstrating that the EPID provides an accurate measurement of electron profiles.
The EPID was thus shown to be an effective method for performing electron beam
45 daily constancy checks.

Introduction

The use of electronic portal imaging devices (EPIDs) as quality control (QC) devices for linear accelerator (linac) X-ray beams has been described by numerous authors. They have been used variously to measure beam flatness and symmetry (Kirby & Williams 1995, Liu *et al* 2002), X-ray field size (Samant *et al* 2002, Chang *et al* 2004, Baker *et al* 2005, Parent *et al* 2006a Mohammadi & Bezak 2007, Clarke & Budgell 2008), X-ray/light field co-incidence (Curtin-Savard & Podgorsak 1997, Dunscomb *et al* 1999), beam output (Dirkx *et al* 1995, Vieira *et al* 2006), low dose linearity and beam start-up characteristics (Budgell *et al* 2005, Vieira *et al* 2006), matchlines (Holmberg *et al* 1994, Curtin-Savard & Podgorsak 1997), fixed wedge factors (Dirkx *et al* 1995, Budgell *et al* 2007) and dynamic wedge profiles (Greer & Barnes 2007). Moreover, they are now commonly used as an IMRT verification method (e.g. Van Esch *et al* 2004, van Zijtveld *et al* 2006) which is effectively an indirect check of standard linac beam QC parameters.

We have previously described the use of an amorphous silicon (amSi) EPID as a quick and simple daily monitoring device for linac photon beams (Budgell *et al* 2007), potentially able to replace a daily check device with a single image acquired for each photon energy available on a linac. The usefulness of this system is limited on a dual modality linac if it can only be used for the photon beams. A second measuring device would still be required to measure the electron beam output thus negating the efficiency advantage of the EPID. The purpose of this work was therefore to determine whether an amSi EPID can be used to measure the consistency of electron beam parameters in a manner similar to that used for photon beams.

The use of EPIDS as a method for electron beam QC has not been previously reported. Their potential for the *imaging* of electron beams has been recognized. Grimm *et al* (1999), Pouliet *et al* (2001), Aubin *et al* (2002, 2003), Jarry & Verhaegen (2005), Geyer *et al* (2006). In all these examples the imaging is carried out using the brehmsstrahlung photons generated within the patient. However, in the work described here the electron beam is directly incident upon the EPID. In order to better understand the image formation of an electron beam directly incident upon an amSi EPID a Monte Carlo model of the electron beam and EPID has been constructed and

used to investigate the generation of an electron image using an EPID (Parent 2006b, Roberts 2008).

Methods

85 *Electron image acquisition*

An Elekta Precise linear accelerator with an iViewGT amSi EPID (Elekta Oncology Systems, Crawley, UK) mounted at a fixed FSD of approximately 157 cm was used for the investigation. The EPID was extended to its default position, central to the axis of the beam. A 20x20 cm electron applicator with an open field lead insert was
90 attached to the linear accelerator for all measurements. The full range of available electron energies on the linac was investigated: 6, 8, 10, 12 and 15 MeV. Images were acquired using the standard clinical acquisition software. Images displayed by the EPID had a resolution of 1024 x 1024 pixels and were produced via acquiring a series of frames continuously during the exposure. The frames were integrated into a 64 bit
95 buffer and then renormalised to the highest greyscale value to give a 16 bit image. In addition, the image undergoes a series of modifications by the iViewGT software. A continuous dark current (offset) calibration was applied by the panel. All images were subject to an energy-specific flood field correction, thus minimising variations in individual pixel sensitivity. Finally a bad pixel map replaced known inconsistent pixel
100 values with average values obtained from neighbouring pixels. When used to acquire electron images, the system was found to default to use ?????? photon flood-field calibration.

EPID sensitivity to changes in dose and beam profile

105 Beam output measurements were initially studied over a wide monitor unit (MU) range from 50-1000 MU to check whether the EPID response is linear with dose over a wide dynamic range. Subsequently, more detailed measurements were made at 1 MU intervals over a narrower range of 95-105 MU. This was because daily output measurements are made using 100 MU hence this range covers the normal dosimetric
110 range over which the daily dose is expected to vary. Three images were acquired on each occasion and the mean used for analysis. An in-house developed software program written using the IDL (Interactive Data Language, Research Systems Inc.) programming language was used to convert the images to their original greyscale

values and subsequently analyse the images. A 50 x 50 pixel (12.5 x 12.5 mm) region
115 of interest based on the image centre was used by the software for determining output.
Flatness and symmetry were obtained by extracting GT (in-plane) and AB (cross-
plane) profiles from the approximate centre of the panel. The 50% points on the
penumbra were determined and the true beam centre defined as the halfway point
between the two 50% points in each direction. New GT and AB profiles were then
120 extracted based on the true centre, consisting of the average of the 15 central profiles
(a width of 3.75mm). Flatness and symmetry were then measured from these profiles
as defined by the IEC (International Electrotechnical Commission 1989):

$$125 \quad \text{Symmetry} = (D_{\text{left}}/D_{\text{right}})_{\text{max}} \times 100$$

$$\text{Flatness} = (D_{\text{max}}/D_{\text{min}}) \times 100$$

Where $(D_{\text{left}}/D_{\text{right}})_{\text{max}}$ is the maximum ratio of the dose from two symmetric points
either side of the beam centre within the flattened area of the beam and D_{max} and D_{min}
130 are the maximum and minimum doses in the profile within the flattened area of the
beam. The flattened area along the GT and AB axes is defined as the area
corresponding to the 50% dose points minus $0.1 \times$ field size as defined by the 50%
level. The profiles were averaged over 2mm to obtain symmetry and flatness values.

135 The ability of the EPID to detect changes in beam flatness and symmetry was tested
by introducing a series of systematic asymmetries into the electron beam profile. This
was achieved by systematically varying the 2R and 2T steering currents using the
functionality provided in the linac service mode. Beam profiles were initially
measured using a 2D Schuster diode array. We have previously verified that the
140 symmetry and flatness values measured using this device are linearly proportional to
those measured using an ion chamber in a water phantom. Symmetry and flatness
from the Schuster software were recorded together with the corresponding 2R and 2T
error value measured using the linear accelerator ion chamber. The experiment was
then repeated, using the same steering current changes as used with the Schuster
145 scanner but this time capturing an image using the EPID. Images were acquired from
100MU exposures. The images were then analysed as described above and the flatness
and symmetry values expressed relative to the zero error condition; therefore the
symmetry and flatness values shown are not a true value as defined by the IEC

definition (International Electrotechnical Commission 1989). The reason for this is
150 that due to the shape of the EPID electron profiles (figure 1(b)), the absolute flatness
values (of 125-130%) and to a lesser extent the symmetry values are very different
from those measured at $D_{\max}$ in water or using the Schuster scanner. To enable a direct
comparison of the changes in measured symmetry/flatness it was therefore necessary
to use relative values. The work was also performed at gantry angles of 90 and 270
155 degrees to investigate the influence of gantry position on the EPID image obtained.

Daily monitoring

A six-month study was also carried out to monitor electron beam output and
symmetry / flatness on a daily basis. Three 100 MU images were acquired each
160 morning as previously described on a clinical machine at the available electron
energies (6, 8 and 10 MeV) prior to starting the working day. The EPID output results
were then compared with either weekly parallel plate measurements or daily Farmer
ionisation chamber measurements that are used at our centre as the daily output check.
Typically both measurements were made within an hour of each other. The data was
165 analysed and inconsistencies and anomalies in the results were used to identify any
known problems or modifications that were made to the machine over the 6 month
period which may possibly explain the variation in the values.

Monte Carlo Model

170 A 10 MeV electron model for a 20x20 cm applicator was commissioned and modelled
using BEAMnrc (Rogers *et al* 1995) and DOSXYZnrc (Walters *et al* 2004). Depth
dose curves and water profiles were matched with experimental data. The electron
parameters for the model were a truncated Gaussian energy spectrum with a mean of
8.8MeV, FWHM of 3.7MeV and min and max cut-offs of 10.2MeV and 12.2MeV
175 respectively. The electron spot was a circle with radius 0.1cm. A good match was
obtained to depth dose curves but only a reasonable match to the beam profiles. To
obtain a better match the thickness/shape of the scattering foils would have to be
adjusted. However, a perfect fit was not required in order to address the questions to
be studied in this work therefore this model was judged to be adequate for this
180 purpose. To simulate EPID images a previously published model of the iViewGT
panel was used (Parent *et al* 2006b, Roberts 2008). An experimentally acquired EPID
image of a 20x20 cm field was compared with a Monte Carlo simulation using the

previously commissioned Monte Carlo model and a model of the iViewGT panel. It must be noted that the experimental image had the flattening/gain image removed and therefore will contain artefacts relating to the non-uniform sensitivities of different regions of the panel.

Results

Figure 1(a) shows a typical electron image obtained using the EPID; figure 1(b) is a profile taken through the GT (in-plane) axis of the electron image. It is immediately evident that the electron profile is dissimilar to the familiar profiles normally measured at $d_{\max}$ at an FSD of 95cm; the EPID profile has a very broad penumbra. The same shape is shared by profiles at all electron energies, with the lower energy profiles displaying a wider penumbra and the higher energy profiles a slightly less broad penumbra. Given this large difference between an EPID-measured electron beam and standard electron QC measurements, the question is whether the relative differences measured in the EPID image can be related to changes measured under standard measuring conditions.

EPID sensitivity to changes in dose

Figure 2 demonstrates a highly linear relationship between delivered monitor units and EPID greyscale over the 50 to 1000 MU range at 15 MeV. Similar results were obtained at all other electron energies. The experiment when repeated between 95 and 105 MU produced the graphs in figure 3 for 15 MeV and 6 MeV energies respectively. Again a linear result can be seen, but at the lowest clinical energy of 6 MeV there is a degree of variation from the linear best fit line at 97 and 102 MU of approximately +0.8% and -0.8% respectively. This variation is random in appearance with lower and higher dose values showing better agreement. This was extremely reproducible with subsequent repeats of the same measurement. This result was further investigated by measuring the electron output at this energy using a Farmer chamber placed at a similar FSD to the panel of 160 cm measuring at 15 mm deep in a Perspex block. This was performed to ascertain whether or not this variation was as a result of limitations within the EPID imaging system or was a real variation in linac output. It can be seen from figure 3b that this variation is not present in the ion chamber results suggesting that the anomalous results at 97 and 102 MU are due to

the EPID rather than variation in linac output. {this is very strange. Is it worth comment how many times these experimental points were repeated?}

Daily output monitoring

220 The results of 6 months measurements of linac output can be seen in figure 4 for 10 MeV; figure 4(a) includes both weekly parallel plate and daily Farmer chamber readings, figure 4(b) only the parallel plate chamber results. The EPID results were normalised relative to a single parallel plate chamber measurement. This normalisation was reset following any significant hardware changes: for example, 225 EPID panel replacement or recalibration of the EPID. Such modifications of the normalisation occurred on days 43 and 100. Figure 4 displays large fluctuations in machine output in the early days of the study reflected in both the chamber and EPID results. This was a real variation caused by a failing magnetron and hence shows that the EPID is capable of detecting machine output problems.

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The study shows a close correlation between the EPID and daily output results (figure 4a) with a standard deviation in the differences of 0.78% at 10 MeV. Inconsistencies in the results can be seen between the EPID panel and the Farmer ionization chamber, particularly between days 20 and 40 but this was resolved by the renormalization of 235 the EPID output on day 43 and over the 6 month period these anomalies are relatively infrequent. When only the more accurate parallel plate chamber results are compared with the EPID results (figure 4b) this figure drops to 0.49% which suggests that EPID-measured output is an excellent method of detecting relative dose changes in an electron beam. Very similar results were obtained for the other electron energies; at 240 10MeV the standard deviations were 0.87% and 0.47% for all output results / parallel plate chamber only respectively and at 6MeV the standard deviations were 0.76% and 0.46%.

On day 38, a striping artefact is known to have developed on the EPID electron 245 images, which lasted until day 100. Although this is the reason why the results from day 43 required renormalization, there was still reasonable agreement between the EPID and chamber results through this period. This suggests that the method is robust even in the presence of image artefacts. The imaging panel was replaced on day 100 and the results renormalized again from that day.

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EPID sensitivity to changes in beam profile

Figure 5(a) demonstrates the relationship between the induced 2R error and the recorded percentage GT (in-plane) flatness and symmetry values from both the Schuster scanner and EPID panel for 6 MeV. A direct linear relationship can be seen
255 between the two for both Schuster and EPID results; this makes the panel suitable for detecting changes in beam symmetry and flatness. Figure 5(b) shows the relationship between the induced 2T error and the recorded percentage AB (cross-plane) flatness and symmetry value from the Schuster scanner and EPID panel for 15 MeV. Due to the difficulty in producing tilts in the AB axis above approximately 4%, figure 5(b) is
260 plotted with the scale suitably adjusted. Again, a near-linear relationship can be seen between the 2T error value and the flatness and symmetry figures recorded for both devices. Similar results were observed for the other energies measured in all cases. The results obtained at 90° and 270° gantry angle for multiple electron energies were also very similar to those of figures 5(a) & (b).

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The 6 month study results for EPID symmetry and flatness can be seen in figure 6 for 8 MeV. EPID results were measured and then subtracted from the initial result obtained on day hence the results indicate percentage change in symmetry and flatness relative to this date. Symmetry and flatness results were collected until day
270 38. The electron image artefacts present between days 38 and 100 prevented symmetry and flatness values from being measured hence these results have been omitted and results recorded again from day 101 when the panel had been replaced. Days 39-123 in figure 6 therefore correspond to days 101-185 in figure 4.

275 Detailed analysis of the results shows that the AB symmetry and flatness are extremely stable, as expected since the AB plane is unaffected by beam bending and variations in beam energy. The GT values are much more variable; however they do appear to be more variable after the installation of the second panel. The reason for this is not known – there is nothing in the QC results from this period to suggest that
280 this is a real linac effect so it appears to be connected with the EPID. But the levels of variation are still relatively low so this is not a cause for concern.

Monte Carlo modelling

Figure 7a shows a Monte Carlo calculated profile for the EPID overlaid onto the experimentally measured EPID profile. Good agreement is seen between the two profiles. To investigate whether measuring with the EPID significantly influences the electron profile, EPID profiles were compared to water tank profiles at the normal detector distance (SSD=157.1cm) and at the normal experimental distance (SSD=95cm). To take into account the different densities of the various EPID layers, profiles in water were obtained at 1.76cm deep; the water equivalent depth for the iViewGT panel. This number was obtained by multiplying each EPID layer's density by its thickness and adding them together. The total gives the equivalent thickness of water. As the image is formed in the gadox scintillator layer the above procedure was only conducted for layers up to the amorphous silicon diodes i.e. the last layer was gadox. Figure 7(a) shows that the Monte Carlo EPID profiles, experimental EPID profiles and equivalent depth Monte Carlo water profiles are in good agreement at 157cm FSD whilst figure 7(b) shows good agreement between Monte Carlo EPID profiles and equivalent depth Monte Carlo water profiles at 95cm FSD. This therefore highlights the EPID profiles are mainly affected by the electrons scattering in air.

Discussion

The first observation from the results reported in this paper is that the EPID studied was found to be a suitable method for measuring both electron output consistency and beam profile consistency. This was by no means a foregone conclusion. EPIDs are specifically designed for imaging photons and, unlike photon beams, electron beams undergo significant degradation due to scattering interactions with electrons in the air gap between the end of the applicator and the EPID. However, the experimental results demonstrate that despite this high level of scatter, the EPID-measured output is highly linear with dose and that changes in the beam profile measured with the EPID are linearly proportional to changes measured at D_{max} . The Monte Carlo simulation of the EPID demonstrated that the EPID is capable of imaging electrons accurately, with the EPID profiles shown to be the same as water profiles at both 95 and 157cm FSD. When photons are incident on this type of EPID they are first converted to electrons and then to light photons for detection by the phototransistors in the amorphous silicon – the so-called indirect detection method. It is not surprising therefore that an electron beam is capable of being imaged. What was not certain was whether the

thickness of the layers in the EPID, designed to ensure sufficient photons interact to produce a high enough signal, would not be too thick to yield a reasonable signal from an electron beam. This work demonstrates that this is not the case. The previously reported examples of electron images through a patient were generated not directly by electrons but by the brehmstrahlung photons generated within the patient hence direct comparison with these results is not meaningful.

These results are particularly encouraging in that they confirm that our previously reported technique for daily monitoring of photon beams can be readily extended to electron beams as well, making the EPID a suitable device to replace daily output check devices. The results reported here were based on the mean of three images per day, as it was felt that the electron measurements might be more variable than photon measurements. However, the reproducibility of the results on any one day was found to be excellent – hence only one image per energy per day would be required, as for photons. The results also suggest that the EPID will be suitable for post-service checks and checking beam profile variation with gantry angle, as previously suggested for photons (Budgell *et al* 2007).

The anomalies seen in the dose linearity at 6 MeV suggest that using the EPID for an output check device might be less accurate at this low energy. A discrepancy of 0.8%, whilst readily measurable, is still acceptable if using the device as a constancy checker for which a tolerance of 5% would typically be applied. Moreover, the actual result from 6 months comparison with daily ion chamber results showed that the 6MeV results were no less accurate than the 8 or 10 MeV results, thus suggesting that this effect is not a significant problem in practice. This may be because on a daily basis it is unusual for the machine output to be close to the values where the discrepancies were observed.

The EPID is plainly only suitable as a consistency checker. If discrepancies are found by the EPID measurements will still need to be made more accurately at 95cm FSD since the beam shape is so different at 157cm FSD. There were also changes found with EPID calibration and when an artefact developed in the electron beam images. Interestingly, the same artefact was not observed in the photon images acquired during the same period. Another effect causing a difference between the actual

incident profile and the measured profile is the fact that the EPID automatically applies a flood field derived from a photon field. This will introduce a systematic error since the electron profiles will be divided by the photon beam profile inherent in the flood field. However, since the same flood field is used each time, this is a
355 constant systematic error and does not affect the use of the EPID as a consistency check device.

We have recently reported the development of software interfaced to an EPID of this type to enable daily monitoring using an EPID to be performed automatically without
360 user intervention whenever a specified beam is run (Mackay *et al* 2007). This software is applicable both to photons and to the electron measurements described in this paper. This automation completes the chain to allow rapid daily output checks for electrons and photons using an amSi EPID in only the time taken to deploy the EPID and deliver a beam at each available clinical energy. This method is now undergoing
365 testing in our department.

Conclusions

An amSi EPID has been demonstrated to be an effective method for measuring electron beam output and beam profile parameters and is thus suitable as a device for
370 rapid linac daily constancy checks.

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Figure 1 (a) A 10 MeV EPID image of a 20x20 cm electron field. (b) An in-plane (GT) profile through the image. Higher and lower energies display the same shape but sharper/broader penumbrae respectively.

Figure 2 Relationship between delivered monitor units and greyscale at 15 MeV.

(a)

(b)

Figure 3 Relationship between delivered monitor units and normalized greyscale at (a) 15 MeV and (b) 6 MeV for 95-105 MU. (b) also shows the normalized dose vs mu results for a Farmer chamber measurement at the same FSD as the EPID panel.

(a)

(b)

Figure 4 Six month study results at 10 MeV of (a) EPID and ion chamber daily output check. (b) EPID and weekly parallel plate absolute dose measurement.

Figure 5 EPID and Schuster symmetry and flatness values normalized to 100 at zero error versus linac error signal. For (a) 6 MeV 2R profiles, (b) 15 MeV 2T profiles. Note the axes scales are much smaller in (b) since the beam could not be made any more asymmetric in this plane.

Figure 6 8 MeV EPID measured symmetry and flatness results over a 6 month period – a period during which an artefact existed and sensible results were unobtainable has been omitted.

Figure 7 (a) Monte Carlo calculated EPID and water profiles at SSD=157.1cm overlaid onto the EPID-measured profile. (b) Monte Carlo calculated EPID and water tank profiles at SSD=95cm {can you use the same symbols in the 2 graphs?}