Validation of a prototype DiodeAir for small field dosimetry

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Abstract

Standard commercial diode detectors over-respond within small radiation fields, an effect largely attributable to the relatively high mass-density of silicon. However, Monte Carlo studies can be used to optimise dosimeter designs and have demonstrated that ‘mass-density compensation’—for example, introducing a low-density air-gap upstream of a diode’s high-density silicon volume—can substantially improve instrument response. In this work we used egsc_chamber Monte Carlo simulations to predict the ideal air-gap thickness for a PTW 60017 unshielded diode detector. We then developed a prototype instrument incorporating that air-gap and, for a 6 MV linac, tested it experimentally against EBT3 film. We also tested a further three prototypes with different air-gap thicknesses. Our results demonstrate that for a 10 × 10 cm² reference field the DiodeAir, a PTW 60017 diode with a built-in air-gap of 1 mm, has on-axis correction factors near unity. Laterally the DiodeAir performs very well off-axis and reports FWHM and penumbra values consistent with those measured using EBT3. For PDD measurement, the performance of the DiodeAir matches that of the original PTW 60017. The experimental focus of this work was 6 MV but we also simulated the on-axis response of the DiodeAir within 15 MV beams and found that our modification proved robust to this substantial increase in beam energy. However, the original diode 60017 does exhibit low energy scatter dependencies and may over-respond to high...
linac dose-rates such that applying the mass-density compensation method to 
an alternative instrument (particularly a diamond detector) could ultimately 
take us even closer to the small-field ideal.

Keywords: small field dosimetry, correction factors, detector design, Monte 
Carlo simulations, EBT3 film, Linac commissioning

(Some figures may appear in colour only in the online journal)

1. Introduction

Dosimetry within small radiation fields remains highly challenging, principally due to the 
breakdown of lateral electronic equilibrium. Dosimeters both perturb and average particle 
fluence, so that measured doses do not match those delivered to undisturbed water. For very 
small fields (∼5 mm across) point dose measurements from different dosimeters can vary by 
tens of percent, even when the sensitive volume is 1–3 mm across (McKerracher and Thwaites 
1999, Zhu et al 2000, Sanchez-Doblado et al 2007).

In 2008, a working group formed by the IAEA and AAPM proposed the use of correction 
factors, \(k_{Q_{\text{clin}},-Q_{\text{msr}}}\), to convert detector measurement ratios into water point-doses (Alfonso 
et al 2008). However various groups (Francescon et al 2011, Cranmer-Sargison et al 2012, 
Francescon et al 2012, Pantelis et al 2012, Sterpin et al 2012, Underwood et al 2013a, 
Azangwe et al 2014, Benmakhlouf et al 2014, Francescon et al 2014) have shown that such 
correction factors are inconvenient to use in practice as they must be calculated for the spe-
cific combination of detector, beam-energy and field-size considered. They are also sensitive 
to the detector position and azimuthal angle within the field and the linac model. Therefore, 
a greatly preferable solution would be to design a detector which did not require correction 
factors under small field conditions.

Scott et al (2012) demonstrated that the mass-density, rather than atomic number, of a cavity 
impacts most strongly upon the cavity’s water-equivalence under non-equilibrium condi-
tions. The mass-density perturbation effect was further characterised using cavity-theory by 
Fenwick et al (2013). Underwood et al (2012) showed how the water-equivalence of various 
detectors might be improved via minor design modifications, based on the principle of ‘mass-
density compensation’. This method was then applied in two further simulation-based studies 
(Charles et al 2013) and Underwood et al (2013b)) before the first experimental validation 
was performed by Charles et al (2014), who modified two unshielded diode detectors. For 
each a removable cap was used to introduce an air-gap above the standard instrument, and the 
eperimental effect of the modifications was compared to that predicted via Monte Carlo 
simulation for on-axis output measurements.

In this study we have experimentally evaluated the performance of a set of prototype diodes 
in which air gaps of different thicknesses were built directly into the detectors. The response 
of the prototypes was compared to that of EBT3 film (Ashland Inc.) both on- and off-axis, for 
output factors, lateral profiles and PDDs.

2. Methods

2.1. Design of prototype density-compensated diode detectors

Within each of our four prototypes, a cylindrical ‘spacer’ constructed from PMMA was used to 
introduce a precisely-formed air-gap between the standard detector’s RW3 ‘lid’ and the
structures containing its sensitive volume (figure 1). The inner diameter of the PMMA spacer was 4.7 mm so that, laterally, the air-gap extended far beyond the 1.2 mm diameter of the silicon sensitive region. In addition to the un-modified diode 60017, we considered (both experimentally and via simulation) detectors containing air-gaps with the following thicknesses: 0.5, 1, 1.2 and 1.5 mm.

2.2. Calculation of correction factors, $k_{Q_{\text{clin}}, Q_{\text{msr}}}$

The IAEA/AAPM small-field correction factor of Alfonso et al (2008) is defined as:

$$k_{Q_{\text{clin}}, Q_{\text{msr}}} = \frac{D_{w, Q_{\text{clin}}, x}}{M_{\text{w}}^{Q_{\text{clin}}, x}} / \frac{D_{w, Q_{\text{msr}}, x}}{M_{\text{w}}^{Q_{\text{msr}}, x}}$$

in which $D_{w, Q_{\text{clin}}, x}$ and $M_{\text{w}}^{Q_{\text{clin}}, x}$ are the dose to a point of water and the dosimeter measurement in field $x$ ($x \in \text{clin, msr}$). For a linearly responding detector the ratio $D_{w, Q_{\text{clin}}, x} / M_{\text{w}}^{Q_{\text{clin}}, x}$ corresponds to dose-in-water divided by dose-in-detector-sensitive-volume. In equation (1) ‘clin’ denotes a clinical field, and ‘msr’ denotes a machine specific reference field. For a theoretically ideal instrument $k_{Q_{\text{clin}}, Q_{\text{msr}}} = 1$ for all detector positions and orientations, and for all field sizes, shapes and energies.

We calculated and measured $k_{Q_{\text{clin}}, Q_{\text{msr}}}$ values using a square msr field of side-length 10 cm, for an SSD of 100 cm and at a water-depth of 5 cm. Our measurement depth of 5 cm corresponded to the position of the EBT3 film in experiment, the centre of the water-voxel in which dose is scored in simulations, and the top surface of the sensitive volume of each diode detector in both experiment and simulation. We might have used the detector effective point of measurement instead of the top surface of the sensitive volume; however a detector translation of <2 mm in depth would have negligible impact upon the small field correction factors which, being ratios of readings in two fields, vary little with small changes in depth.

2.3. Monte Carlo methods

The simulations presented here used validated 6 MV and 15 MV Clinac iX accelerator beam models constructed using the BEAMnrc Monte Carlo system (Rogers et al 2011) and physical machine data provided by Varian Medical Systems. For a full description of the linac simulation parameters the reader is referred to Underwood et al (2013b) and Scott et al (2008). Phase space files from BEAMnrc were used as input for the egs_chamber (Wulff et al 2008) code.
Using detailed technical drawings, the un-modified 60017 detector and all prototypes were modelled within egs_chamber using the EGS++ geometry package. ECUT and PCUT values of 512 keV and 1 keV were utilised within the detector and a surrounding water-shell that extended at least 2 mm beyond the detector in every direction. Elsewhere values of ECUT = 521 keV and PCUT = 10 keV were applied. For calculated $k_{\text{lin}}^{\text{ff}}$, values, the ‘point-like’ water structure in which doses $D_{\text{lin}}^{\text{ff}}$ and $D_{\text{lin}}^{\text{msr}}$ were scored was a $0.25 \times 0.25 \times 0.25$ mm$^3$ water voxel.

For simulated data, 1 s.d. Type A statistical uncertainties are included as error bars on data plots. Type B uncertainties are expected to be $<0.7\%$ (Francescon et al 2011).

2.4. Linac and tank set-up

All measured data were obtained using a 6 MV Varian 2100 iX Clinac with the dose-rate maintained at 600 MU min$^{-1}$ and the collimator rotation set to 0°. A PTW scanning water tank was used in conjunction with the MEPHYSTO mc$^2$ software.

2.5. EBT3 gafchromic film methods

EBT3 has high spatial resolution ($\sim25 \mu m$), near tissue equivalence$^5$ and exhibits energy independence for photon energies exceeding 100 kV (Bekerat et al 2014). Larraga-Gutierrez (2014) used Monte Carlo simulations to determine correction factors for EBT3 film and found these factors to be consistent with unity to within the statistical uncertainties of their simulations. Consequently, EBT3 film may be utilised as an experimental ‘gold standard’ for small-field dosimetry.

Our EBT3 film was all drawn from the same box (lot number A05151201), shaped using a laser-cutter and handled using nitrile gloves.

A custom-built holder enabled us to submerge $6 \times 6$ cm$^2$ pieces of film within our water tank; magnetic grips at the edges of the holder permitted us to fix each film under-water in a very flat, stable, horizontal position. Thus no air-gap or barrier was introduced between the water and the surface of the film. The holder allowed us to position each film at a depth of 5 cm in order to match the set-up utilised for the diode detectors. The performance of EBT2 film in water was comprehensively tested by Aldelaijan et al (2010) who concluded that, for routine measurements in external beam radiotherapy, the effects of water immersion can be neglected. The major evolution in design between EBT2 and EBT3 was symmetrisation of the polyester base; the sensitive emulsion and polyester have the same composition across the two models (Bekerat et al 2014).

Every film utilised in this study (whether for EBT3 calibration or diode response experiment) underwent the same procedure: i.e. being submerged within the water-tank for approximately the same time ($<5$ min), before being dried thoroughly using microfibre towels. As EBT3 results depend strongly upon the orientation of the film, we carefully tracked the horizontal/vertical positioning of each piece of film relative to the original sheets. For calibration, 16 films were irradiated using a $3 \times 3$ cm$^2$ field and doses in the range 0.5–5 Gy. Two additional films were submerged—but not irradiated—in order to obtain experimentally consistent data for 0 Gy.

For each experiment comparing diode response to dose-in-water measured using EBT3 film, six successive EBT3 irradiations were performed in order to assess the repeatability of the film measurements. For all field sizes, the number of linac monitor units was scaled to deliver a dose of $\sim2.5$ Gy to the EBT3 at the field centre.

$^5$ EBT3 has mass-densities of 1.2 g cm$^{-3}$ and 1.35 g cm$^{-3}$, $Z_{\text{eff}}$ values of 7.26 and 6.64, and thicknesses of 28 $\mu$m and 125 $\mu$m for the active layer and surrounding polyester respectively (Bekerat et al 2014).
The scanner utilised was an EPSON Expression 10000XL. Ten high-resolution scans of the whole scanner bed were performed to warm up the device. All films were then scanned at least 12 h after irradiation, one at a time within a jig fixed at the centre of the scanner. 48-bit color scans were obtained with a resolution of 150 dpi (and other scanner settings as per the Ashland recommendations). Files were saved as uncompressed tiffs.

Using custom-written python code, scanned images were converted to dose maps using the triple channel method. For on-axis dose measurements, a calibration curve was generated based upon 15 × 15 pixel regions located at the centre-of-mass (COM) of the dose-map of each calibration film. Doses at the centre of small fields were calculated as the average dose over a 3 × 3 pixel region, centered upon the COM of the dose-map. Consequently, \( D_{f_{\text{COM}}} \) values calculated using film considered a ‘point-like’ water structure with lateral dimensions \( \sim 0.5 \times 0.5 \text{ mm}^2 \). Later, a second calibration curve was generated for off-axis measurements of field profiles, penumbrae and full width half-maximum (FWHM) values. This second calibration curve utilised the same input data as the first, plus a series of additional 15 × 15 pixel averages taken from the un-irradiated film scans at twelve non-central film positions (three along the positive x-axis, three along the negative x-axis etc). Film profiles were then obtained using 3 × 3 pixel region (\( \sim 0.5 \times 0.5 \text{ mm}^2 \)) averaging, with profiles centred on the dose-map COM.

2.6. Diode methods

A bias of 0 V was applied to all diode detectors which were used in conjunction with the PTW TANDEM electrometer and the MEPHYSTO mc² software system. The detectors were positioned with their stems running parallel to the beam axis and were centered laterally using the PTW centre-check software. The zero depth of the detector was provisionally defined as the the top surface of the lid for PDD measurement, and was defined as the top surface of the sensitive volume for \( k_{\text{Q}_{\text{LINAC}}/\text{Q}_{\text{AIR}}} \) determination.

3. Results

3.1. On-axis output factors

For the five diode detectors, figure 2 shows \( k_{\text{Q}_{\text{LINAC}}/\text{Q}_{\text{AIR}}} \) values obtained from (a) Monte Carlo simulations and (b) EBT3 experiments, plotted against field size.

Whilst the Monte Carlo simulations assume perfect jaw calibration, the measured data are subject to inaccuracies in the real linac jaw positioning. For each field size considered, all detector and EBT3 measurements were made at a single fixed jaw position; therefore the real field sizes set for the detector measurements can be obtained from the FWHM values of the EBT3 film. These data are listed in table 1 and show that across all field sizes our linac jaws ‘over-closed’ by \( \sim 0.5 \text{ mm} \), relative to the nominal (set) values.

For the original diode detector and the prototypes with 0.5 mm and 1 mm air-gaps, figure 2(b) is a strong experimental validation of the simulations shown in figure 2(a). For the prototypes with the thickest two air-gaps (1.2 mm and 1.5 mm) the agreement between simulation and experiment is slightly poorer.

3.2. Off-axis profiles

The data marked by crosses in figure 3 indicate profile full-width half maxima (FWHMs) and 80% :20% penumbra values obtained experimentally for a nominal 5 mm field using the
In all cases, the FWHM and penumbra values obtained using the original diode 60017 fall below the EBT3 CIs, the uncorrected diode detector over-sharpening the off-axis profiles. In contrast, the diode prototype with a 1.5 mm air-gap generally reported FWHM and penumbras exceeding the EBT3 CIs: this detector over-broadened profiles. The 1 mm air-gap DiodeAir performed best for off-axis profile measurements: all FWHM and penumbras measured using this detector lie within or close to the EBT3 CIs.

Table 1. Nominal versus experimental jaw openings quoted at isocentre for 6 MV beams.

| Nominal Field Size | Experimental X-jaw FWHM | Experimental Y-jaw FWHM |
|--------------------|-------------------------|--------------------------|
| 5                  | 4.77 (4.75–4.78)        | 4.88 (4.85–4.92)         |
| 6                  | 5.59 (5.56–5.62)        | 6.01 (5.98–6.04)         |
| 7                  | 6.54 (6.51–6.57)        | 6.73 (6.69–6.76)         |
| 8                  | 7.62 (7.60–7.63)        | 7.50 (7.48–7.53)         |
| 10                 | 9.50 (9.47–9.54)        | 9.54 (9.52–9.56)         |
| 15                 | 14.22 (14.19–14.25)     | 14.51 (14.48–14.45)      |
| 30                 | 29.34 (29.31–29.37)     | 29.70 (29.66–29.74)      |

Note: All values are in units of mm. 95% confidence intervals estimated from 6 repeat EBT3 irradiations are shown in brackets.

original diode 60017, and the four modified prototypes. These data are overlaid upon mean values and 95 and 99% confidence intervals (CIs) obtained from EBT3 film, our experimental gold-standard.

In all cases, the FWHM and penumbras values obtained using the original diode 60017 fall below the EBT3 CIs, the uncorrected diode detector over-sharpening the off-axis profiles. In contrast, the diode prototype with a 1.5 mm air-gap generally reported FWHM and penumbras exceeding the EBT3 CIs: this detector over-broadened profiles. The 1 mm air-gap DiodeAir performed best for off-axis profile measurements: all FWHM and penumbras measured using this detector lie within or close to the EBT3 CIs.

$k_{\text{clinical}}$ values calculated according to equation (1)—but now with the clinical field data obtained at various positions off-axis—are shown as a function of off-axis distance in the top plots of figure 4. There is good agreement between the data obtained from simulation (figure
For the original diode detector \( k_{Q_{0.5},Q_{0}} \), values for the 1 mm DiodeAir remain close to unity and its uncorrected readings are always accurate to within 1% of the field-centre dose (compared to an over-response of 8% on-axis for the original detector). The off-axis \( k_{Q_{0.5},Q_{0}} \) performance of the diode detectors with 1 mm and 1.2 mm air-gaps is very similar, but figure 4(a) enables us to conclude that both outperform the prototype with a 1.5 mm air-gap.

Figure 3. Profile FWHM and penumbras measurements for 6 MV beams, a nominal 0.5 cm field at SSD = 100 cm and depth = 5 cm. Measurements made using diodes with different air-gaps are shown in comparison to EBT3 film data. The horizontal lines show the mean values obtained from six repeat irradiations of EBT3 film. 95% and 99% confidence intervals for the six repeat EBT3 irradiations are indicated by the dark grey and light grey bands, respectively. (a) Y-jaw FWHM. (b) X-jaw FWHM. (c) Y-jaw 80:20 Penumbra. (d) X-jaw 80:20 Penumbra.

Off-axis simulations were performed for the 1 mm DiodeAir and original diode only (rather than the full set of detector prototypes) due to the considerable computation time.
For all diode detectors, PDD data for fields with side-lengths 0.5 cm and 3 cm are included in figure 5. A 3 cm field PDD measured using the air-filled PTW PinPoint ionisation chamber 31006 is also included in the figure.

Figures 5(a) and (b) demonstrate that neither introducing an air-gap into the diode detector nor varying its thickness affects the measured PDD shape. From figure 5(a) it is evident that relative to the PinPoint PDD, the PDDs for all of the diode detectors decrease slightly more sharply with depth. However, the PinPoint versus diode discrepancy always remains within 1\% of the global maximum ($d_{\text{max}}$) value.

3.3. Percentage depth dose curves (PDDs)

For all diode detectors, PDD data for fields with side-lengths 0.5 cm and 3 cm are included in figure 5. A 3 cm field PDD measured using the air-filled PTW PinPoint ionisation chamber 31006 is also included in the figure.

Figures 5(a) and (b) demonstrate that neither introducing an air-gap into the diode detector nor varying its thickness affects the measured PDD shape. From figure 5(a) it is evident that relative to the PinPoint PDD, the PDDs for all of the diode detectors decrease slightly more sharply with depth. However, the PinPoint versus diode discrepancy always remains within 1\% of the global maximum ($d_{\text{max}}$) value.
The incorporation of a relatively thin air-gap above a diode detector’s sensitive region does not perceptably affect the instrument’s effective point of measurement (EPOM), which is dominated by the thickness and material of the instrument’s lid. For each of our diode prototypes the manufacturer-published EPOM for the original Diode 60017 (1.33 mm below the top surface of the detector) remained valid. Figures 6(a) and 6(b) use simulations to demonstrate that PDDs defined according to the top surface must be shifted by 1.33 mm if a match to the water simulations is to be obtained. From the simulated data in figure 6(a) it is also clear that a sharp transition in PDD gradient (a ‘kick’) occurs when the diode detector is first submerged and no longer capped by a column of air, but instead capped by a column of water. Experimentally, if PDDs are obtained from a starting position where the diode lid is above the surface of the water, the position of the PDD ‘kick’ can be used to fine-tune the zeroing of detector depth. Figure 6(c) shows experimental data with each ‘kick’ shifted to a depth of 1.33 mm: the PDDs measured using the different detectors are aligned well, suggesting the EPOM does lie a constant distance below the detector top regardless of the spacer.
Excellent agreement also exists between the PDD shapes and depths of maximum dose obtained in this way and via Monte Carlo simulation (figure 6(c) versus (b)), indicating that the shift of 1.33 mm is correct.
3.4. 15 MV simulations

Figure 7 shows on-axis Monte Carlo $k_{Q_{clin},Q_{10}}$ values at a beam energy of 15 MV, calculated for the original 60017 and modified prototype diode detectors. Error bars show 1 standard deviation statistical uncertainties.

4. Discussion

For the original 60017 PTW diode detector, the results shown in figure 2(a) agree well with those found in previously published studies: for a similar set-up (10 cm reference field, 100 cm SSD, but depth of 10 cm compared to 5 cm utilised here), Bassinet et al (2013) reported a $k_{Q_{clin},Q_{10}}$ of 1.008 for the 60017 diode detector, compared to the value of 1.014 simulated here. For 5 mm fields, Francescon et al (2011) obtained a $k_{Q_{clin},Q_{10}} \sim 0.95$ (with an SSD of 75 cm and a depth of 5 cm) compared to our value of $k_{Q_{clin},Q_{10}} \sim 0.92$. For a 1 cm field, Francescon et al (2011) quoted $k_{Q_{clin},Q_{10}} = 0.975$, Benmakhlouf et al (2014) quoted $k_{Q_{clin},Q_{10}} = 0.992$ (SSD = 100 cm, depth = 10 cm), here we simulated $k_{Q_{clin},Q_{10}} = 0.978$.

This work experimentally validates the principle of mass-density compensation which we first proposed via a simulation study (Underwood et al 2012). For the original diode detector and the two thinnest air-gaps (0.5 mm and 1 mm), the agreement between simulation and experiment was very good, although for the prototypes with 1.2 mm and 1.5 mm air-gaps the agreement was somewhat poorer. This could be attributed to unknown discrepancies between the modelled and real instruments in terms of material composition and/or dimensions, although we took images of the modified detectors using a micro-CT scanner and the imaged air-gap thicknesses were found to match the nominal values. As predicted by simulation, an air-gap of 1 mm was found to be optimum out of those tested here experimentally. The
performance of our 1 mm air-gap DiodeAir prototype was substantially improved relative to that of the original diode detector, both on- and off-axis in small fields. On-axis all DiodeAir $k_{\text{sim,ref}}^{\text{lin,ref}}$ values from both simulation and experiment agreed with unity to within the statistical uncertainties, for field sizes 5 mm–10 mm.

Due to the over-response of (relatively high-Z) silicon to the low energy scattered photons found within large fields, the response of any diode detector should be expected to change between small fields and the wider fields conventionally used for reference conditions. This is a classical spectral effect, not a small-field effect: whilst changes in the spectrum of scattered photons are minimal between one small-field and another (e.g. a 0.25 cm field versus a 1 cm field), they do influence readings in fields that are relatively small ($\leq 4$ cm) compared to fields that are relatively large (e.g. 10 cm) fields. The influence of spectral changes between a 10 cm field and an intermediate reference field (e.g. 4 cm) may be accounted for by cross-calibrating a small detector against a medium sized detector in the intermediate field, a process referred to as daisy-chaining by Dieterich and Sherouse (2011). In their diode modification study, Charles et al (2014) optimised their correction factors relative to a $3 \times 3 \text{ cm}^2$ reference field: in their case, daisy-chaining would be required for larger reference fields.

For all $k_{\text{sim,ref}}^{\text{lin,ref}}$ factors detailed in this work, $10 \times 10 \text{ cm}^2$ was chosen as the reference field size. We chose such a field since, in many cases, its use would allow clinical physicists to use the DiodeAir to directly measure the small-field output factors required by their treatment planning system, with no requirement for daisy-chaining. However, at field sizes of 15 mm and 30 mm, spectral effects lead to a slight under-response of the DiodeAir (indicated by correction factors exceeding unity) compared to the $10 \times 10 \text{ cm}^2$ reference conditions, seen in both simulations and experimental results. If a $3 \times 3 \text{ cm}^2$ field were to be used as the reference, then correction factors for the DiodeAir would be 1–2% both in a $10 \times 10 \text{ cm}^2$ field and in smaller fields. It is interesting to note that Charles et al (2014) also determined an air-gap thickness of 1 mm (7 mm diameter) to be optimal for the diode detector 60017, despite their substantially smaller reference field. Our simulations suggest that an air-gap thickness of approximately 1.2 mm would be preferable for a 3 cm reference field, compared to 1 mm for a 10 cm reference field (we considered air-cavities 4.7 mm in diameter). Generally, problems associated with changing the diode reference field size (and the requirement for daisy-chaining) could be avoided if the principle of mass-density compensation was applied to a low Z instrument, such as a diamond detector.

Our previous work Underwood et al (2013b) used Monte Carlo simulations to demonstrate that high-density dosimeters such as diamond detectors over-sharpen profiles relative to the ideal case in water. Here we experimentally showed this to be the case for the original diode 60017 also. However our DiodeAir modified detector measured lateral profile FWHM and penumbrae values close to those obtained using EBT3 film and also required near-unit correction factors off-axis.

Introducing an air gap and varying its thickness exerted no effect upon the shape of the diode PDDs. A slight discrepancy was evident between the PDDs of a $3 \times 3 \text{ cm}^2$ field measured using an air-filled PinPoint 31006 chamber and the diode detectors (less than 1% of the maximum value). This discrepancy could result from a diode detector over-response at high linac dose-rates, and although only small for the linac dose-rate of 600 MU min$^{-1}$ used here, might be larger in measurements of flattening-filter-free (FFF) beams.

The impact of varying SSD upon DiodeAir correction factors was not investigated here, but results from previous studies performed with different SSDs (Francescon et al 2011, Bassinet et al 2013, Bemmakhlouf et al 2014) indicate that any SSD effect is likely to be small.
While the focus of this paper is detector response at 6 MV, we also simulated on-axis response at 15 MV and found the 1 mm DiodeAir to perform very well, suggesting that the degree of mass-density compensation required for a detector is determined mainly by the densities and geometries involved, rather than by the linac energy.

The IAEA/AAPM formalism of Alfonso et al (2008) defines detector correction factors $k_{\text{ff},\text{clin msr}}$, relative to a ‘point-like’ water-structure. Our DiodeAir was designed to deliver $k_{\text{ff},\text{clin msr}}$ close to unity under small field conditions within a 6 MV treatment beam. Whilst data with ‘point-like’ resolution theoretically forms the optimal input for sophisticated model-based treatment planning systems (TPSs), it may not prove ideal in the case of output factors used in more measurement based TPSs. For such systems $k_{\text{ff},\text{clin msr}}$ should perhaps be considered relative to a water-structure similar to a TPS voxel, i.e. with a side-length of $\sim 1$ mm. This is an issue yet to be addressed by the IAEA/AAPM. In the context of our study, had we considered water doses delivered to 1 mm wide voxels rather than point-like volumes then within the smallest fields correction factors for the DiodeAir would have worked out at $\sim 0.99$ rather than unity.

EBT3’s low cost and very high water-equivalence make it a useful gold-standard for small-field dosimetry. However, EBT3 film experiments are time-consuming and can suffer from relatively large statistical uncertainties: future studies might consider using plastic scintillation detectors as an alternative (Lacroix et al 2011).

5. Conclusions

Our study experimentally validated a prototype DiodeAir with an optimised air-gap of 1 mm for a range of field-sizes (with side-lengths 0.5–10 cm) both on- and off-axis within a 6 MV linac beam. Relative to a gold-standard of EBT3 film, the DiodeAir substantially outperformed the original 60017 for small-field measurements using a 10 $\times$ 10 cm reference field: specifically its on-axis correction factors were found to be consistent with unity for field sizes 1–10 mm, within $\sim 1\%$ for a field size of 15 mm and $<2\%$ for a field size of 30 mm.

Laterally the DiodeAir performs very well off-axis and reports FWHM and penumbra values consistent with those measured using EBT3. For PDD measurement, the performance of the DiodeAir matches that of the original PTW 60017. The experimental focus of this work was 6 MV but we also simulated the on-axis response of the DiodeAir within 15 MV beams and found that our modification proved robust to this substantial increase in beam energy. However, the original diode 60017 does exhibit low energy scatter dependencies and may over-respond to high linac dose-rates such that applying the mass-density compensation method to an alternative instrument (particularly a diamond detector) could ultimately take us even closer to the small-field ideal.

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