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Doseimetry

Can small field diode correction factors be applied universally?

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Background and purpose: Diode detectors are commonly used in dosimetry, but have been reported to over-respond in small fields. Diode correction factors have been reported in the literature. The purpose of this study is to determine whether correction factors for a given diode type can be universally applied over a range of irradiation conditions including beams of different qualities.

Materials and methods: A mathematical relation of diode over-response as a function of the field size was developed using previously published experimental data in which diodes were compared to an air core scintillation dosimeter. Correction factors calculated from the mathematical relation were then compared those available in the literature.

Results: The mathematical relation established between diode over-response and the field size was found to predict the measured diode correction factors for fields between 5 and 30 mm in width. The average deviation between measured and predicted over-response was 0.32% for IBA SFD and PTW Type E diodes. Diode over-response was found to be not strongly dependent on the type of linac, the method of collimation or the measurement depth.

Conclusions: The mathematical relation was found to agree with published diode correction factors derived from Monte Carlo simulations and measurements, indicating that correction factors are robust in their transportability between different radiation beams.

The measurement of dose with sufficient accuracy for contemporary clinical practice in high-energy photon fields of small size, is challenging. In fields smaller than 30 mm in width, a combination of volume averaging, loss of charged particle equilibrium, occlusion of the radiation source and beam perturbation can cause the standard dosimetric techniques, established for larger fields, to become unsuitable [1]. The output factor of a radiation field is defined as the ratio of the absorbed dose in water at a point located at the isocentre for the given field, relative to that at the same point in the reference field. In small fields, the measurement of the output factor is subject to large uncertainties [2].

Silicon diode detectors are commonly used in small field dosimetry due to their relatively small sensitive volumes and their high radiosensitivity. However in the measurement of output factors, diodes have been reported to over-respond in small fields. The diode over-response can be large (up to 11% [3]) and must be corrected to ensure that the prescribed dose is accurately delivered. To address the difficulties of small field dosimetry, a formalism has been proposed by Alfonso et al. [4] with a correction factor, $k_{Q_{\mathrm{clin}},Q_{\mathrm{msr}}}^{f_{\mathrm{clin}},f_{\mathrm{msr}}}$. The correction factor is used to account for the differences in detector response in the field f_{clin} (a clinical small field) and the field f_{msr} (a machine specific reference field) relative to water.

Tables of correction factors have been published for a range of diode detector and linear accelerator (linac) combinations. These correction factors have been calculated from Monte Carlo (MC) simulations [5–8] or determined by measurement with detectors that are approximately water-equivalent such as scintillation dosimeters [9,3,10–12], alanine [13,14] and radiochromic film [15]. The published correction factors allow institutions without direct access to MC simulations or suitable small field dosimeters to correct measurements from diode detectors and improve the validity of beam parameters used in their treatment planning systems. However, the use of the published correction factors may not be a viable long-term solution for small field dosimetry. As new diode detectors, linacs, multi-leaf collimators (MLCs) and other radiation delivery technologies are developed, the calculation of correction factors for all detector and delivery method combinations would become increasingly inconvenient.

MC modeling [16] and cavity theory studies [17] have attributed diode over-response in small fields largely to the density effects of non-water equivalent materials used in diode construction. Scott et al. [16] have suggested that one set of correction factors could be calculated for a wide range of linacs, despite variations in beam quality with linac type and field size [18]. The

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aim of this study was to develop a mathematical relation from experimental data that predicts the magnitude of diode over-response in a range of linacs. The mathematical relation was validated by comparison with the correction factors available in the literature [5–8,13,15,14,11]. A further aim was to determine the universality of the correction factors across different diode and beam combinations.

Materials and methods

Small field detectors and measurements

The diode over-response in small fields was characterized using measurements made with an air core scintillation dosimeter, previously described by Lambert et al. [19]. Measurements with the air core scintillation dosimeter have shown an average deviation from MC simulations of 0.2% [12] and an average deviation from EBT2 film measurements of 0.5% [3] and are of sufficiently high quality to use as inputs to the mathematical relation for diode correction.

The air core scintillation dosimeter used a cylindrical BC-400 scintillator measuring 1 mm in both diameter and length. The scintillator was coupled to an air core waveguide 120 mm in length that avoids the generation of Cerenkov radiation in the primary beam [20]. The air core dosimeter was irradiated with its stem perpendicular to the central beam axis and the light signal was measured with a photomultiplier array system [21].

The unshielded diode detectors used in this study were the PTW Type E 60012, PTW Type E 60017, IBA SFD and IBA EFD. The active widths of the silicon chips in these diodes are 1.1, 1.1, 0.6 and 2.0 mm respectively. All diodes were irradiated with their stems parallel to the central beam axis, so that the plane of the silicon chip was facing the beam, and read with a PTW Unidos E electrometer with zero voltage bias.

Relative output ratios were measured with the above detectors on three different linacs: Varian Novalis [3], Elekta Synergy [10] and Siemens Oncor [12]. All relative output ratio measurements were performed in a water tank under a 6 MV X-ray beam with the detector at the isocentre and a source to detector distance of 100 cm. Supplementary Table 1 lists the combinations of diode detector, linac and irradiation conditions.

Mathematical relation for diode over-response

The mathematical relation for diode over-response in small fields was established by plotting the over-response (expressed as a percentage), $r^{f_{\text{clin}},f_{\text{msr}}}_{Q_{\text{clin}},Q_{\text{msr}}}$, as a function of the effective field size. This process is described in the Supplementary Material. The effective field size, defined by the full-width at half-maximum (FWHM) [22], was determined using radiochromic film for the Varian and Siemens linacs and using diodes for the Elekta linac.

The mathematical relation between the over-response and the equivalent square field width based on the FWHM was determined in OriginPro (OriginLab Corp., Northampton, MA) by fitting the data to the two parameter exponential function:

$$r^{f_{\text{clin}},f_{\text{msr}}}_{Q_{\text{clin}},Q_{\text{msr}}} = Ae^{-Bx}. \quad (1)$$

The quality of the fit of the mathematical relation was quantified using two methods. The first method was to calculate the average absolute percentage deviation between the measured over-response and the fitted over-response. The second method was to calculate the fraction of measurements where the deviation was less than 1%.

To identify the factors that significantly affect diode over-response, a multiple linear regression analysis was performed with field size, measurement depth, collimation method, linac type and diode type as independent variates. The data were transformed to a linear relation by taking the natural logarithm of the over-response. A multiple linear regression analysis with a 95% confidence interval was performed using OriginPro. Type A measurement uncertainties were included in all regression calculations for both over-response and field width.

Comparison to literature

To benchmark the mathematical relation, the predicted over-response was compared to available diode correction factors reported in the literature. Supplementary Table 2 lists known publications with diode correction factors for the IBA SFD and the PTW Type E diodes and their measurement conditions. To perform the comparison, the over-response was calculated from published values of $k^{f_{\text{clin}},f_{\text{msr}}}_{Q_{\text{clin}},Q_{\text{msr}}}$. Where necessary, the data were renormalized using the 30 mm field as the machine specific reference field. As the FWHM of each field is not listed in the majority of the publications in Supplementary Table 2, the diode over-response in these publications is plotted against the equivalent square field width based on the nominal field size rather than the effective field size. Although the use of nominal field sizes can reduce the accuracy of the mathematical relation, it enables the published data to be compared with the data measured using the air core dosimeter.

Results

Multiple linear regression analysis of the experimental data showed that diode over-response was most significantly affected by the field size ($p_{\text{field size}} < 0.0001$) and diode type ($p_{\text{diode type}} < 0.0003$). This agrees with the MC simulations of Fenwick et al. [17] that show the over-response to be predominantly dependent on the degree of lateral electron disequilibrium (a function of field size) and detector density (dependent on the detector composition).

In Fig. 1A, 19% of measurements deviated from the best fit by more than 1%, indicating that the diode over-response cannot be accurately predicted by a mathematical relation encompassing all diodes and irradiation conditions. The linac type was found to be statistically insignificant ($p_{\text{linac}} < 0.06$), despite differences in the beam quality of each machine (the beam quality index $\text{TPR}_{20/10}$ was 0.659 for the Varian Novalis, 0.679 for the Elekta Synergy and 0.675 for the Siemens Oncor). This is supported by Fig. 1A, where the mean deviations from the line of best fit for each linac type were close to zero (0.03%, −0.07% and −0.43% for Varian, Elekta and Siemens respectively). The type of collimation was found to be statistically insignificant ($p_{\text{collimation}} < 0.48$). This is supported by the lines of best fit in Fig. 1B, which are almost superimposed for fields larger than 5 mm.

The measurement depth was found to be statistically significant in determining diode over-response ($p_{\text{depth}} < 0.02$). This is supported by the results of Fig. 1C. The lines of best fit for measurements at depths of 15 and 50 mm are almost superimposed, while the line of best fit for measurements at a depth of 100 mm lies above those at the two shallower depths.

As the multiple linear analysis suggests, separating the data according to diode type, as shown in Fig. 2 and Supplementary Fig. 1A, improved the accuracy of the mathematical relation. In fields larger than 5 mm, Eq. (1) accurately predicted the magnitude of over-response, regardless of the measurement depth, the type of collimation and the type of linac. The average percentage deviation between the measured and fitted over-response was 0.25% for the PTW Type E diodes and 0.32% for the IBA SFD diode. The majority of the measured data (97%) deviated by less than 1% from the values predicted by Eq. (1). In Supplementary Fig. 1B, the larger IBA EFD