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Investigation of a synthetic diamond detector response in kilovoltage photon beams

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Abstract

Purpose: An important characteristic of radiation dosimetry detectors is their energy response that consists of absorbed-dose and intrinsic energy responses. The former can be characterized using Monte Carlo (MC) simulations, whereas the latter (i.e., detector signal per absorbed dose to detector) is extracted from experimental data. Such a characterization is especially relevant when detectors are used in non-relative measurements at a beam quality that differs from the calibration beam quality. Having in mind possible application of synthetic diamond detectors (microDiamond PTW 60019, Freiburg, Germany) for non-relative dosimetry of low-energy brachytherapy (BT) beams, we determined their intrinsic and absorbed-dose energy responses in 25-250 kV beams relative to a ^{60}Co beam, which is usually the reference beam quality for detector calibration in radiotherapy.

Material and Methods: Three microDiamond detectors and, for comparison, two silicon diodes (PTW 60017) were calibrated in terms of air-kerma free in air in six x-ray beam qualities (from 25 to 250 kV) and in terms of absorbed dose to water in a ^{60}Co beam at the national metrology laboratory in Sweden. The PENELOPE/penEasy MC radiation transport code was used to calculate absorbed-dose energy response of detectors (modeled based on blueprints) relative to air and water depending on calibration conditions. The MC results were used to

extract the relative intrinsic energy response of detectors from the overall energy response. Measurements using an independent setup with a single ophthalmic BEBIG I25.S16 ^{125}I BT seed (effective photon energy of 28 keV) were used as a qualitative check of the extracted intrinsic energy response correction factors. Additionally, the impact of the thickness of the active volume as well as the presence of extra-cameral components on the absorbed-dose energy response of a microDiamond detector was studied using MC.

Results: The relative intrinsic energy response of microDiamond detectors was higher by a factor of two in 25 and 50 kV beams compared to the ^{60}Co beam. The variation in the relative intrinsic energy response of silicon diodes was within 10% over the investigated photon energy range. The use of relative intrinsic energy response correction factors improved the agreement among the absorbed dose to water values determined using microDiamond detectors and silicon diodes, as well as with the TG-43 formalism-based calculations for the ^{125}I seed. MC study of detector design features provided a possible explanation for intra-detector response variation at low-energy photon beams by differences in the effective thickness of the active volume.

Conclusion: MicroDiamond detectors had a non-negligible variation in the relative intrinsic energy response (factor of two) which was comparable to that in the absorbed-dose energy response relative to water at low-energy photon beams. Silicon diodes, on the other hand, had an absorbed-dose energy dependence on photon energy that varied by a factor of six, whereas the intrinsic energy dependence on beam quality was within 10%. It is important to decouple these two responses for a full characterization of detector energy response especially when the user and reference beam qualities differ significantly, and MC alone is not enough.

1 INTRODUCTION

Commercial natural diamond detectors and custom-made synthetic diamond detectors have been used for dosimetry in high energy photon and electron beams and brachytherapy (BT) due to their water-equivalence (carbon atomic number $Z = 6$ compared with water $Z_{\text{eff}} = 7.4$). However, their use diminished over the years due to scarcity of high-grade natural crystals and expensive and non-reproducible manufacture of synthetic diamond crystals. The main reason was that the quality of the crystal (e.g., the amount of impurities) affected their dosimetric properties, such as dose-rate dependence and dose linearity. Recently diamond detectors have regained interest because the current manufacturing technology allows for reproducible high-purity crystal growth. Commercially-available synthetic diamond detectors microDiamond (PTW 60019, Freiburg, Germany) have been used in small-field dosimetry of high-energy photon and electron beams,¹⁻⁴ as well as in proton and carbon beams.⁵⁻⁸ These studies showed that the detectors have low absorbed-dose energy dependence, negligible dose-rate dependence and do not require high pre-irradiation doses (up to 2 Gy). These characteristics shown in high energy beams combined with the closeness of the effective atomic numbers of water and carbon prompted a question about diamond detector's applicability in low-energy photon beams, such as BT and diagnostic x-ray fields. It has been shown that the microDiamond detector is suitable for determination of absorbed dose to water⁹ and for relative measurements in HDR ^{192}Ir beams,¹⁰ and percentage depth-dose curve determination in kilovoltage (kV) x-ray beams.¹¹

Having in mind the possible application of microDiamond detectors for experimental non-relative dosimetry of, e.g., electronic BT treatments (40 to 100 kV) or treatments using ^{125}I seeds, the purpose of this study was to further investigate the response of microDiamond detectors at low photon energies (from 25 to 250 kV x-ray beams) and compare it with that in a ^{60}Co beam. Determination of absorbed dose to water around BT sources in absolute units of Gy is required to verify Monte Carlo (MC) single-source dosimetry data before use in treatment

planning.^{12,13} The currently-recommended dosimetry system is lithium fluoride thermoluminescent dosimeters (LiF TLD) calibrated in ^{60}Co or 6 MV beams using external beam protocols.^{14,15} Although these detectors have low absorbed-dose energy dependence, they have an intrinsic energy dependence at low photon energies compared to a high-energy photon calibration beam.¹⁶⁻¹⁸ Additionally, they are passive readout detectors which are less convenient to use compared to direct readout detectors.

To investigate whether microDiamond detectors have an intrinsic energy dependence, we extracted the intrinsic energy response (detector signal per average absorbed dose to detector) from the overall energy response. We accounted for the absorbed-dose energy response of detectors using blueprints and detailed MC simulations and, given the complexity of detector construction, further investigated intra-detector variation among the three tested microDiamond detectors. For comparison, we included two silicon diode detectors (PTW 60017, Freiburg, Germany) that have the same outer dimensions and fit into our measurement setup. Furthermore, it was of interest to compare the intrinsic energy response of two solid-state direct readout detectors.

The obtained results may allow for better understanding of detector response and could be used to optimize future design so that the detector's energy dependence and radiation field perturbations in low energy photon beams such as those used in BT are minimized.

2 MATERIALS AND METHODS

2.1 Dosimetry formalism

The quantity of interest in radiation therapy dosimetry usually is absorbed dose to water, hence detectors used for non-relative measurements are calibrated in terms of absorbed dose to water in a reference beam quality Q_0 . Although it is desirable that calibration beam quality would resemble user's beam quality Q , it is not always possible and detector response to beam quality

Q has to be corrected for possible differences between the two beam qualities. Absorbed dose to water in the beam quality Q can be determined as follows

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}, \quad (1.1)$$

where M_Q is the reading of the dosimeter corrected for influence quantities in a measurement phantom in beam quality Q , N_{D,w,Q_0} is the calibration coefficient of the detector in terms of absorbed dose to water in the reference beam quality Q_0 , and k_{Q,Q_0} is the beam quality correction factor. N_{D,w,Q_0} is determined as $[D_w/M]_{Q_0}$, which relates the detector signal M to the absorbed dose to water D_w and defines the overall response of detector in beam quality Q_0 .

The beam quality correction factor k_{Q,Q_0} can be calculated as follows

$$k_{Q,Q_0} = \frac{[D_w/\bar{D}_{\text{det}}]_Q}{[D_w/\bar{D}_{\text{det}}]_{Q_0}} \cdot \frac{[M/\bar{D}_{\text{det}}]_{Q_0}}{[M/\bar{D}_{\text{det}}]_Q} = \frac{[D_w/\bar{D}_{\text{det}}]_Q}{[D_w/\bar{D}_{\text{det}}]_{Q_0}} \cdot \frac{R_{Q_0}}{R_Q}, \quad (1.2)$$

where $\bar{D}_{\text{det}}$ is the average absorbed dose to the active volume of the detector at the point of measurement, and D_w is the corresponding absorbed dose to a small volume of water at the point of measurement in the absence of the detector in beam qualities Q and Q_0 . Quantities R_Q and R_{Q_0} characterize the physical signal generation and its collection-efficiency in the detector at a given beam quality, i.e., detector signal per average absorbed dose to the detector, $R = [M/\bar{D}_{\text{det}}]_i$ ($i = Q, Q_0$). This quantity may depend on, e.g., the ionization density of secondary electrons, dose-rate or the accumulated absorbed dose in the detector. Since it cannot be obtained through MC calculations (unless they implement mathematical models describing the conversion from absorbed dose to detector signal), it has to be determined from measurements. It can be extracted from experimentally-determined detector calibration coefficients by accounting for absorbed-dose energy dependence between water and detector medium in a given beam quality as

$$R_{Q_0} = \left[\frac{M}{\bar{D}_{\text{det}}} \right]_{Q_0} = \frac{1}{N_{D,w,Q_0}} \cdot \left[\frac{D_w}{\bar{D}_{\text{det}}} \right]_{Q_0} = \left[\frac{M}{D_w} \right]_{Q_0} \cdot \left[\frac{D_w}{\bar{D}_{\text{det}}} \right]_{Q_0}, \quad (1.3)$$

where N_{D,w,Q_0} is the detector calibration coefficient in terms of absorbed dose to water determined experimentally and traceable to the primary standards. Usually $[D_w/\bar{D}_{\text{det}}]_{Q_0}$ is an MC calculated ratio of absorbed dose to water D_w at a measurement point in the absence of the detector and the average absorbed dose $\bar{D}_{\text{det}}$ to the active volume of the detector at the point of measurement. When detectors are calibrated in terms of air-kerma free in air, the same approach applies but N_{D,w,Q_0} is replaced with $N_{K,\text{air}}$ which is the detector calibration coefficient in terms of air-kerma free in air at a given beam quality Q and traceable to the primary standards. Similarly, the MC calculated quantity D_w in Eq. (1.3) is replaced with the calculated K_{air} values.

Finally, the relative intrinsic energy dependence can be written as

$$\frac{R_{Q_0}}{R_Q} = \frac{[M/\bar{D}_{\text{det}}]_{Q_0}}{[M/\bar{D}_{\text{det}}]_Q} = \frac{[M/D_w]_{Q_0}}{[M/D_w]_Q} \cdot \frac{[D_w/\bar{D}_{\text{det}}]_{Q_0}}{[D_w/\bar{D}_{\text{det}}]_Q} \quad (1.4)$$

For a detector calibrated in terms of air-kerma free in air K_{air} in beam quality Q , Eq. (1.4) becomes

$$\frac{R_{Q_0}}{R_Q} = \frac{[M/\bar{D}_{\text{det}}]_{Q_0}}{[M/\bar{D}_{\text{det}}]_Q} = \frac{[M/D_w]_{Q_0}}{[M/K_{\text{air}}]_Q} \cdot \frac{[D_w/\bar{D}_{\text{det}}]_{Q_0}}{[K_{\text{air}}/\bar{D}_{\text{det}}]_Q} \quad (1.5)$$

It is important to note that N_{D,w,Q_0} , and subsequently k_{Q,Q_0} (given by Eq. (1.2)), consists of two parts. The absorbed-dose energy-response of a detector, i.e., the ratios $[D_w/\bar{D}_{\text{det}}]_Q$ and $[D_w/\bar{D}_{\text{det}}]_{Q_0}$, describes the energy absorption properties of a detector compared to those of the medium of interest. This absorbed-dose energy response of a detector can be quantified using MC simulations for a given beam quality when detector geometry and materials are well known. The ratio R_{Q_0}/R_Q accounts for the remaining properties.

When detectors are calibrated in a ^{60}Co or MV beam, k_{Q,Q_0} is commonly calculated using MC simulations which neglect the energy dependence of the intrinsic energy response of the detector $R(E)$. In practice, this energy dependence is not accounted for in high-energy photon beam dosimetry using ion chambers because the variation in energy needed to create an ion pair is assumed to be negligible.¹⁵ However, it cannot be ignored for other detector types when they are calibrated in high-energy beams but used in low energy beams, e.g., in BT. It has been shown that, for instance, some types of TLDs,¹⁶⁻¹⁸ radio-photoluminescent glass dosimeters¹⁹ and EPR dosimeters^{20,21} calibrated in high energy photon beams exhibit a non-negligible variation in their intrinsic energy response when used in kV beams. This was attributed mainly to the difference in the ionization density of secondary electrons between the calibration beam and the measurement beams (where the effective photon energy ranges from 13 to 375 keV) that affected either radical production in EPR dosimeters or traps formation in TLDs in addition to the dependence on TLD readout process.¹⁸

2.2 Detectors and calibration

Three microDiamond detectors PTW 60019 [referred to as mD1 (s/n 122518), mD2 (s/n 122840) and mD3 (s/n 122043)] and two PTW 60017 silicon diodes [referred to as SiD1 (s/n 780) and SiD2 (s/n 974)] were used. The nominal active volume of microDiamond was a 1 μm thickness cylinder with 1.1 mm radius. The silicon diode had a 30 μm thickness cylindrical active volume with a radius of 0.6 mm. All detectors were calibrated in terms of absorbed dose to water in a ^{60}Co beam following the TRS-398 protocol¹⁵ and in terms of air-kerma free in air in six CCRI x-ray beam qualities²² from 25 to 250 kV (see Table 1) at the Swedish Radiation Safety Authority Secondary Standards Dosimetry Laboratory (SSDL). At calibration in the 25 and 50 kV beams, the reference-point (marked with a red or grey ring) of the detector was placed at 50 cm from the source where the diameter of the irradiation field was 9.6 cm. At other kV beam qualities, the respective values of distance to the source and irradiation field diameter

were 100 cm and 10.5 cm. The geometric depth of the active area was at 0.95 mm and 0.76 mm measured from the detector tip for microDiamond and silicon diode detectors respectively. Detectors were oriented with their longitudinal axis parallel to the beam direction. MicroDiamond detectors were pre-irradiated with approximately 5 Gy before measurements as recommended in the specifications.

Table 1 X-ray beams used for detector calibration in terms of air-kerma free in air. Effective energy was calculated as the energy of a monoenergetic beam which would have the same half-value layer as a given spectrum. Air-kerma rate is given at a source-to-detector distance where detectors were calibrated. Beam quality data were provided by the SSDL.

Beam	Generating potential (kV)	Effective energy (keV)	HVL (mm)	Air-kerma rate (mGy/s)
CCRI-25	25	13.9	0.25 Al	2.1
CCRI-50(b)	50	22.6	1.00 Al	3.0
CCRI-100	100	38.5	0.14 Cu	1.0
CCRI-135	135	59.4	0.47 Cu	0.9
CCRI-180	180	77.7	0.93 Cu	1.3
CCRI-250	250	126.9	2.49 Cu	1.6

2.3 Monte Carlo simulations

MC simulations were used i) to calculate the absorbed-dose energy dependence ($D_w/\bar{D}_{\text{det}}$ and $K_{\text{air}}/\bar{D}_{\text{det}}$) of each detector type in a given beam quality so that the intrinsic energy response could be calculated using Eqs. (1.4) and (1.5), and ii) to investigate the impact of detector design features, such as the thickness of the active volume and the presence of extra-cameral components, on its absorbed-dose energy response.

Calculations were made using a general-purpose main program penEasy²³ (v. 2015-05-30) for the PENELOPE (v. 2014) MC system.²⁴ PENELOPE-2014 implements detailed simulation of photon and electron transport. Photon interactions include photoelectric effect, Compton scattering based on impulse approximation²⁵ accounting for Doppler broadening and electron binding effects and Rayleigh scattering using the non-relativistic atomic form factors from the

EPDL tables.²⁶ Emission of characteristic x-rays and Auger electrons is not simulated in vacancies above the N shell. Though PENELOPE-2014 allows detailed simulation of electron interactions, a mixed simulation scheme was used to speed up the calculations even in the thin active volume of the detector. A built-in geometry package PENGEOm was used to define detector and experimental setup geometries with quadric surfaces. Calibration beam spectra (see Table 1) were taken from Adolfsson et al.²⁰ The material composition and geometry of microDiamond and PTW 60017 silicon diode detectors were modeled according to detailed blueprints obtained under a non-disclosure agreement from the manufacturer.

$D_{w,MC}$ and $\bar{D}_{det,MC}$ from Eq. (1.5) were calculated by dividing the scored energy imparted to a small volume of water in the absence of the detector and to the active volume of the detector, respectively, with the mass of the volume. The scoring volume of water was equal to the nominal active volume of the microDiamond detector. $K_{air,MC}$ for a given beam quality was calculated as

$$K_{air,MC} = \int_E E \phi_E \left(\frac{\mu_{tr}}{\rho} (E) \right)_{air} dE \quad (1.6)$$

The photon fluence differential in energy ϕ_E was scored using photon-fluence track-length tally in a volume of air equal to the active volume of the microDiamond detector. Since the radiative fraction g is negligible in air in the investigated x-ray energy range below 250 keV, the mass energy-transfer coefficient $(\mu_{tr}/\rho)_{air}$ was approximated by the mass energy-absorption coefficient $(\mu_{en}/\rho)_{air}$. For consistency, numerical values were calculated using the *mutren* code included in the PENELOPE-2014 package. The difference between these and NIST values²⁷ was estimated to be up to 3% below 100 keV for the air medium.²⁸

Both electron and photon transports were used to calculate $D_{w,MC}$ and $\bar{D}_{det,MC}$ for a given beam quality in Eq. (1.5). Electron cutoff energies were 1 keV in the scoring volume and neighboring regions and 10 keV in other regions. Photon transport cutoff energy was 1 keV in all regions.

The threshold kinetic energy for inelastic collisions (W_{CC}) was 10 keV, the threshold energy for radiative collisions (W_{CR}) was 1 keV, the elastic collision parameters (C_1 and C_2) were 0.05 in the scoring volume and neighboring regions within the secondary electron range and 0.1 in other regions.

2.4 Measurements and calculations for an ^{125}I BT seed

To test the MC model used for the determination of R_Q/R_{Q_0} in calibration beams, an independent set of measurements was performed with a single ^{125}I seed I25.S16-C (Eckert & Ziegler Bebig, Germany). The seed was placed at the center of a cubic PMMA phantom (20 x 20 x 20 cm³). Measurements were made at 5 and 10 mm distances from the detector tip to the seed center. Longitudinal axis of the detector was perpendicular to the longitudinal axis of the seed and aligned with its center. Three series of ten one-minute measurements were made with all detectors using an electrometer (PTW Unidos E, Freiburg, Germany) operating in the integrated current mode at zero nominal voltage. The average of all readings of a detector at a given distance was used in further calculations and data analysis.

The PENELOPE/penEasy code was used to score energy imparted to the nominal active volume of the detector and in a volume of water in the absence of the detector (the volume was taken as equal to that of the nominal active volume of microDiamond detector). A full seed geometry was modeled based on the I25.S06 seed model²⁹ (it is identical to the I25.S16 model in its design). The same electron and photon transport parameters were used as described in Section 2.32.3. The obtained values were used to calculate $D_w/\bar{D}_{\text{det}}$ to account for the absorbed-dose energy dependence of the detectors and the absorbed dose to water was determined as

$$D_w = M_Q N_{D,w,Q_0} k_{Q,Q_0} = M_Q N_{D,w,Q_0} \frac{[D_w/\bar{D}_{\text{det}}]_Q^{\text{MC}} R_{Q_0}}{[D_w/\bar{D}_{\text{det}}]_{Q_0}^{\text{MC}} R_Q}, \quad (1.7)$$

where Q corresponds to the ^{125}I beam quality at either 5 or 10 mm, M_Q is the corresponding average detector reading, and Q_0 is the ^{60}Co calibration beam quality. Other quantities are

described in Section 2.1. The R_Q value for the photon energy of 28 keV, which is the fluence-weighted photon energy of the ^{125}I seed, was obtained by interpolating R_Q values from kV beam calibration data. Furthermore, we compared our experimentally-determined values of D_w with the TG-43 formalism¹² based BT treatment planning system (TPS) BrachyVision (version 13.6) (Varian Medical Systems, Inc., Palo Alto, CA, USA). Source air-kerma rate specified by the vendor was used for calculations. This value was verified using a Standard Imaging HDR 1000 Plus well-type ion chamber calibrated at SSDL and it agreed to within 2%, which is within the relative expanded measurement uncertainty.

2.5 Uncertainty analysis

Uncertainty analysis was carried out following the “Guide to the expression of uncertainty in measurement”.³⁰ All uncertainties are given as expanded relative uncertainties ($k = 2$). Uncertainties in MC-calculated quantities account only for statistical uncertainties. Uncertainty analysis of the intrinsic energy response R_Q is given in Table 2.

Table 2 Uncertainty components in the intrinsic energy response R_Q of detectors used in the study. All values are given with a coverage factor $k = 2$.

Component	Type	Uncertainty (%)	
		25 and 50 kV	Other kV beams
Detector calibration coefficient $N_{K,\text{air}}$	B	1.4	0.8
MC-calculated $K_{\text{air,MC}}$			
Statistical	A	0.2	0.1
Source spectrum	B	0.6	0.4
MC-calculated $\bar{D}_{\text{det,MC}}$			
Statistical	A	0.4	0.4
Total combined uncertainty in R_Q		1.6	1.0

The combined relative expanded uncertainty in R_{Q_0} (1.2% for $k = 2$) was calculated as a quadratic sum of the individual uncertainties of N_{D,w,Q_0} , which was 1.0%, and $D_{w,MC}$ and $\bar{D}_{\text{det,MC}}$, both of which were 0.4%.

The impact of possible variation in manufacturer's provided atomic composition and density of detector components on MC-calculated quantities was not evaluated but possible influence is discussed in Section 4.2. Uncertainty analysis of experimentally-determined absorbed dose to water D_w in the ^{125}I beam is given in Table 3.

Table 3 Uncertainty components in the experimentally determined absorbed dose to water D_w in the ^{125}I beam using microDiamond and silicon diode detectors. Uncertainties with a range corresponding to different source-to-detector distances (SDDs) and detector types. All values are given with a coverage factor $k = 2$.

Component	Type	Uncertainty (%)
Detector readout M_Q		5.2 - 9.2
Signal readout	A	1.8 - 6.0
Detector positioning (5 and 10 mm SDD)	B	8 and 4
Electrometer calibration	B	0.5
Detector calibration coefficient N_{D,w,Q_0}	B	1.0
MC-calculated $[D_w/\bar{D}_{\text{det}}]$	A	0.6
Relative intrinsic energy response $[R_{Q_0}/R_Q]$	B	2.0
Total combined uncertainty in D_w		5.7 - 9.5

The uncertainty in detector positioning was assumed to have a rectangular probability distribution with a half-width of 0.3 mm and was estimated based on TG-43 calculations of absorbed dose to water around ^{125}I sources (a line source approximation).

The relative expanded uncertainty in $D_{w,\text{TPS}}$ for the TG-43 formalism based TPS calculations was 11.4% at 1 cm distance from the source.¹² It is a combined uncertainty of source air-kerma strength, dose-rate constant and radial dose function.

3 RESULTS

3.1 Detector-to-detector variation

3.1.1 Calibration data

Calibration coefficients of microDiamond detectors and silicon diodes in terms of air-kerma free in air $N_{K,\text{air}}$ and absorbed dose to water N_{D,w,Q_0} in ^{60}Co beams shown in Figure 1 reveal the

intra-detector variability of microDiamonds (see Table 1 for conversion of beam quality to a corresponding effective photon beam energy).

Figure 1 Calibration coefficients in terms of air-kerma free in air $N_{K,air}$ of all detectors as a function of the effective photon beam energy and in terms of the absorbed dose to water N_{D,w,Q_0} in ^{60}Co beam (1250 keV energy).

Numerical values are provided in the supplementary material. *All SiD1 and SiD2 values were multiplied by ten.

The bar size of the expanded uncertainty ($k = 2$) was comparable to the marker size and hence is not displayed.

Variation in N_{D,w,Q_0} of microDiamond detectors by 30% may be caused by different thicknesses of active volumes as described by Marinelli et al.³¹ However, it is evident from Figure 2, where $N_{K,air}$ was normalized to N_{D,w,Q_0} of a corresponding detector, that the difference in active volume alone could not explain the observed detector behavior at low energies where a proportionality between $N_{K,air}$ and N_{D,w,Q_0} no longer holds.

Figure 2 Calibration coefficients in terms of air-kerma free in air $N_{K,\text{air}}$ of all detectors normalized to their respective calibration coefficients in terms of the absorbed dose to water in ^{60}Co beam N_{D,w,Q_0} as a function of the effective photon beam energy. The bar size of the expanded uncertainty ($k = 2$) was comparable to the marker size and hence is not displayed.

Contrary to microDiamond detectors, it is interesting to point out that calibration coefficients N_{D,w,Q_0} of the silicon diodes differed by 7% in the calibration beam quality ^{60}Co compared with one another, and the difference in $N_{K,\text{air}}$ between the two detectors was approximately the same (7 to 13%) over the entire kV energy range.

3.1.2 MC simulations of effects associated with detector design

Size of the active volume

Figure 3 shows that an increase in the active layer thickness from 1 to 2 μm resulted in a decrease in the average absorbed doses to detectors by 7-8% in 25 and 50 kV photon beams,

4% in the 100 kV beam, and no statistically significant changes were observed for other kV beams. Poppinga et al.³² estimated the thickness of 2 μm using a proton microbeam. They hypothesized that there is a diffusion zone in addition to the depletion layer where electron-hole pairs are collected.

Figure 3 Intrinsic energy response of mD1 as a function of the effective photon beam energy. “mD1 1 μm ” refers to the nominal detector model, “mD1 2 μm ” has an active volume layer of 2 μm thickness in MC simulations. The uncertainty bars correspond to the total expanded uncertainty in R_Q ($k = 2$).

This decrease in the average absorbed dose to the detector (an increase in $R = M/\bar{D}_{\text{det}}$ in Figure 3) is caused by a decrease in the average fluence of secondary electrons in a thicker active volume. When the thickness of the active volume is increased, low energy secondary electrons from the neighboring regions do not have enough energy to penetrate to the central region of the active volume and thus the average absorbed dose in it is decreased. Figure 4 shows that the distribution of fluence with respect to energy ϕ_E for secondary electrons produced by a 25 kV photon beam peaks at an energy close to 10 keV. The continuous slowing down approximation range of 10 keV electrons in diamond is approximately 0.8 μm . An increase in the thickness

from 1 to 2 μm thus decreased ϕ_E in the low-energy part of the spectrum and resulted in volume averaging effect (most of the electrons are absorbed in the first half of the active layer). No significant difference in either electron fluence spectrum or energy deposited per unit mass was found when we increased the nominal thickness of 30 μm by 6% based on the difference between calibration coefficients N_{D,w,Q_0} of the two SiDs.

Figure 4 MC-calculated electron fluence spectra ϕ_E scored in the active volume of detectors as a function of secondary electron energy for a 25 kV photon beam. “mD 1 μm ” refers to the detector model provided by the manufacturer, “mD 2 μm ” refers to the nominal model but with a 2 μm thickness active layer.

Extra-cameral components

A replacement of all the metallic extra-cameral components with the resin-like encapsulation material decreased the energy imparted to the active volume by 10.7 and 2.5% in 25 kV and 250 kV photon beams respectively.

3.2 Absorbed-dose energy response of detectors

The MC-calculated absorbed-dose energy response of detectors with respect to air is shown in Figure 5 together with the two ideal cases of a large and a small cavity of bare active materials.

In the first case, energy imparted to the cavity is due to secondary electrons produced inside the cavity under charged-particle equilibrium. For monoenergetic photons, the ratio $\bar{D}_{\text{det}}/K_{\text{air}}$ can be approximated as a ratio of mass-energy absorption coefficients $[\mu_{\text{en}}/\rho]_{\text{air}}^{\text{det}}$. In the second case, no secondary electrons are produced in the cavity and the electron fluence of electrons produced outside the cavity is not perturbed by the presence of the cavity. Hence the ratio $\bar{D}_{\text{det}}/K_{\text{air}}$ can be approximated as a ratio of mass electronic stopping powers weighted over the energy distribution of the electron fluence $[\bar{S}_{\text{el}}/\rho]_{\text{air}}^{\text{det}}$. Figure 5 shows mass electronic stopping power ratios calculated for monoenergetic electrons. Since the function varies little with energy, similar behavior is expected for the weighted mass electronic stopping power ratios.

Figure 5 MC calculated $\bar{D}_{\text{det}}/K_{\text{air}}$ ratios as a function of the effective photon beam energy (see Table 1) for silicon diode (left) and microDiamond (right) detectors used in the study. Solid and dotted lines represent the ratio of mass electronic stopping powers $[S_{\text{el}}/\rho]_{\text{air}}^{\text{det}}$ and mass energy-absorption coefficients $[\mu_{\text{en}}/\rho]_{\text{air}}^{\text{det}}$ respectively of the detector cavities to air for monoenergetic beams.

Although the absorbed-dose energy dependence of both silicon diode and microDiamond detectors was closer to the large-cavity case, none of the ideal cases were fulfilled. The detector perturbs the radiation field at the point of measurement compared to a configuration without the detector. Additionally, electron absorption on the spot could no longer be assumed for the

microDiamond detectors due to small thicknesses of the active volumes compared to the electron range. For instance, approximately 40% of the energy deposited in the active volume in 25 kV photon beam was due to electrons entering from outside the cavity.

3.3 Intrinsic energy response of detectors

The determined intrinsic energy response of microDiamond detectors, i.e., the detector signal per average absorbed dose to the detector ($R = M/\bar{D}_{\text{det}}$), substantially increases with decreasing photon energy compared to that in the ^{60}Co beam as shown in Figure 6.

Figure 6 The relative intrinsic energy response of microDiamond and silicon diode detectors as a function of the effective photon beam energy (here Q is the kV calibration beam quality and Q_0 is the ^{60}Co calibration beam). Numerical values are provided in the supplementary material. Dashed lines are for visual guidance. The bar size of the expanded uncertainty ($k = 2$) was comparable to the marker size and hence is not displayed.

Compared to detector response in ^{60}Co beam, the detector is approximately twice as efficient in 25 and 50 kV photon beams, i.e, approximately 1.8-2.5 nC/Gy versus 1 nC/Gy. The intrinsic energy dependence of the two silicon diodes did not vary by more than 10% over the same energy range. Since we extracted the intrinsic energy response of detectors from their calibration coefficients $N_{K,\text{air}}$ and N_{D,w,Q_0} , any intra-detector variation discussed in Section 3.1 is seen in these results.

3.4 Measurements with an ^{125}I BT seed

The applicability of the relative intrinsic energy response R_{Q_0}/R_Q correction factors was checked for an ^{125}I BT seed in an independent setup. Experimentally-determined and TPS-calculated absorbed dose to water values D_w in ^{125}I beam are shown in Table 4.

Table 4 Experimentally-determined absorbed dose to water D_w values for 5 and 10 mm source-to-detector distances (SDDs). For comparison, treatment planning system (TPS) calculated values are also shown.

SDD (mm)	TPS (mGy)	mD1 (mGy)	mD2 (mGy)	mD3 (mGy)	SiD2 (mGy)
5	5.9 ± 0.7	6.2 ± 0.6	5.9 ± 0.5	5.8 ± 0.5	4.4 ± 0.4
10	1.7 ± 0.2	1.3 ± 0.1	1.4 ± 0.1	1.3 ± 0.1	1.3 ± 0.1

D_w values calculated using Eq. (1.7) agree within the experimental uncertainties among all the detectors for both SDDs. The R_{Q_0}/R_Q values used for ^{125}I beam were interpolated from Figure 6 and were from 0.45 to 0.51 for the three microDiamond detectors and 0.96 for SiD2. The remaining discrepancy of 5-30% from the TPS could be partly due to the use of correction factors derived using broad kV spectra, whereas ^{125}I can be considered as a monoenergetic source. Furthermore, irradiation geometries differed in the two setups. Given that, the comparison with the TPS should be taken more as a qualitative check of the calculated relative intrinsic energy response ratios.

4 DISCUSSION

4.1 Detector-to-detector variation

4.1.1 Calibration data

Results in Figure 2 indicate that microDiamond intra-detector variability is affected by factors other than detector active volume size; either related to their energy absorption properties, e.g., differences in their construction affecting their water-equivalence or related to solid state physics and charge collection. The scope of this paper was to extract the intrinsic energy response of microDiamond detectors using the MC-calculated absorbed-dose energy response. However, as shown in several studies on synthetic diamond detectors the response may also depend on other factors. For instance, changes in charge collection due to non-conformity of electric field in the detector,³³ the presence of impurities,³⁴ higher responsivity to low-energy x-rays³⁵ and field-size dependent charge imbalance in the structural components of the detector.³⁶ The latter effect explained discrepancies between measurements and MC simulations in 6 MV small fields, but it cannot explain the intra-detector variability reported in this article.

There have been indications that the homogeneity of microDiamond detector response could be energy-dependent and affect detectors to a different extent. Local and gradual variations from 15 to 30% were observed in microDiamond detector response (homogeneity) when detectors were irradiated with a narrow synchrotron beam (the weighted average energy of 95 keV) whose impact position was varied over the active surface of the detector.³⁷ On the other hand, a lower average homogeneity of 3.6% was reported for diamonds studied in a 35 kV photon beam.³¹ The microDiamond detectors used in our study were most likely also affected by such non-uniform response which contributed to the intra-detector variation and its dependence on beam quality. No such non-uniformity in response was observed for other investigated

detectors, e.g., PTW 60017 silicon diodes.³⁷ This agrees with our results where differences in $N_{K,\text{air}}$ between the two investigated PTW 60017 silicon diodes could be explained by differences in N_{D,w,Q_0} calibration coefficients alone (Figure 2), i.e., a difference in the active volume size.

4.1.2 MC simulations of effects associated with detector design

Change in detector active volume thickness could account for microDiamond intra-detector variability by up to 8% at the lowest energy kV spectra. Results of extra-cameral component influence on detector response complement the experimental findings by Butler et al.³⁷ where it is estimated that approximately 8% of the measured signal is produced in components other than the active volume when the detector is irradiated from a side with a narrow synchrotron beam. It must be noted that we determined the perturbation caused by non-water equivalent extra-cameral components which affect energy deposition in the active volume (hence the absorbed-dose energy response of the detector), whereas Butler et al.³⁷ hypothesize that the measured extra signal could be due to charge induced and collected in the extra-cameral components not reaching the active volume.

4.2 Intrinsic energy response of detector

The reason for a large variation in the intrinsic energy response of microDiamond could be that physical electron-hole pair generation and collection processes, such as charge recombination, trapping, diffusion from nearby layers into the active volume, were beam quality dependent. Nevertheless, we must emphasize that the intrinsic energy response is extracted from the overall response of the detectors using MC calculations (see Eq. (1.5)), and hence it relies highly on detector model accuracy. Any mismatch between the actual detector model and blueprints would affect the magnitude of MC-calculated absorbed-dose energy response values, and subsequently, the shape of the intrinsic energy response function in Figure 6. For example, the

presence of any high-Z element contamination near the active volume may result in larger values of the absorbed dose to detector at low energies, and that would reduce R_Q/R_{Q_0} values. The observed decrease in R_Q/R_{Q_0} at the effective photon energy of 13.9 keV (25 kV beam spectrum) could be due to detector under-response when the linear energy transfer (LET) of secondary electrons increases. An under-response of a microDiamond was reported in high-LET carbon and oxygen beams,⁷ but in proton beams the reported results were inconclusive indicating either no significant LET dependence^{7,8} or under-response.⁶

The R_Q/R_{Q_0} values are higher only at the lowest energies and approach unity with increasing energy. Our results hence do not contradict findings in high-energy photon and electron beams reporting negligible beam quality dependence.^{1,38,39} Furthermore, no significant relative intrinsic energy dependence was observed in our previous study⁹ of microDiamond detectors in ¹⁹²Ir beam which had an effective photon energy close to 300 keV.

4.3 Measurements with an ¹²⁵I seed

It is evident that the use of the relative intrinsic energy response correction factors improved the agreement between both types of detectors and with the TPS calculated D_w values. Without them, the microDiamond detectors would overestimate absorbed dose to water by almost a factor of two compared to the TPS.

Figure 7 shows ratios of SiD2 and mD1 detector readings in ¹²⁵I beam at 5 mm and 10 mm distance from the source and in calibration beams. For comparison, the corresponding detector reading ratios in the ¹⁹²Ir beam for three SDDs (15, 25 and 55 mm) are included from a previous study.⁹ If the detectors' response would be affected only by their absorbed-dose energy response (Section 3.2), the change in detector reading-ratio per absorbed dose to water or air-kerma (depending on measurement setup) would be approximately equal to MC-calculated ratios $\bar{D}_{SiD}/\bar{D}_{mD}$ or a given beam quality (see insert in Figure 7). The shape of detector reading ratios

and MC-calculated $\bar{D}_{SiD}/\bar{D}_{mD}$ ratios as a function of photon energy is approximately the same but the difference in magnitude indicates the presence of intrinsic energy response. Most importantly, the data from experimental measurements in ^{125}I and ^{192}Ir beams agree well with the data from calibration beams traceable to the primary standards.

Figure 7 The ratio of SiD2 and mD1 detector readings per absorbed dose to water (in ^{125}I , ^{192}Ir and ^{60}Co beams) and per air-kerma (kV calibration beams) as a function of the effective photon beam energy. Data for ^{125}I and ^{192}Ir beams is shown for different source-to-detector distances corresponding to different photon fluence-weighted energies. Data points for ^{192}Ir beam were taken from Kaveckyte et al.⁹ Insert: The MC-calculated ratio of average absorbed dose to SiD and mD for the corresponding beam qualities. All data points are normalized to ^{60}Co beam. The bar size of the expanded uncertainty ($k = 2$) was comparable to the marker size and hence is not displayed.

Since the measurement setup with an ^{125}I BT seed and simulation input files were completely independent from those used in kV calibration measurements and simulations (apart from blueprints), such a comparison serves as a qualitative validation of our current data on the intrinsic energy dependence of detectors presented in Figure 6.

4.4 Uncertainty analysis

The presented model uses a large number of input parameters describing cross sections, materials and geometry. Though reasonable assumptions on uncertainties of these parameters can be made, covariances between these parameters required by the “Guide to the expression of uncertainty in measurement” are difficult to estimate. Also, the analysis requires multiple runs of the CPU-time demanding code to properly sample the input parameter space. A full-scale analysis may be the subject of a future work, but currently, it is beyond the time and resources of the authors. For these reasons, only rough estimates of upper bounds of uncertainty are provided in the following text.

Cross sections in the studied energy range are dominated by photoelectric effect (PE). An increase by 2% in the PE cross sections of all considered materials lead to an increase by 1.4% and 2.3% in energy deposited in the active volume of microDiamond for the 25 kV and ^{125}I sources, respectively. Absorbed dose to water at a point of measurement in the absence of the detector increased by 1.6% in ^{125}I beam. Since the quantity used to determine the intrinsic energy response of detectors is the ratio of D_w and $\bar{D}_{\text{det}}$, the resulting effect depends on the correlation between D_w and $\bar{D}_{\text{det}}$; a positive correlation will lead to a decreased effect, a negative correlation will lead to an increased effect. Thus, it is reasonable to assume that the uncertainty arising from uncertainty in cross section data is on the order of a few percent.

Uncertainties in the PMMA phantom composition and density and their effect on the MC-calculated absorbed dose to detector active volume in the PMMA phantom ($\bar{D}_{\text{det}}$) were not evaluated. Rodriguez et al.⁴⁰ estimated that an uncertainty in solid water composition and density would result in a 3% uncertainty in MC-calculated quantities in ^{125}I BT beams. In contrast to solid water or RW3 plastic phantoms, which can have varying amounts of calcium and titanium dioxide additives,⁴⁰⁻⁴² phantoms made of PMMA have more uniform and better-

known composition.^{12,43} Thus it is reasonable to assume that the uncertainty associated with material composition is on the order of a few percent.

5 CONCLUSIONS

In this study we found that the intrinsic energy response of microDiamond detectors increased by a factor of two at the lowest energy photon beams compared to that in a ^{60}Co beam. Moreover, the overall energy response varied by up to 30% among the three investigated microDiamond detectors in low energy photon beams. The significant relative intrinsic energy dependence implies that the generic beam quality correction factors calculated using MC are not enough for use in low energy photon beams when detectors are calibrated in high energy photon beams as it is commonly done and recommended in the BT TG-43 dosimetry protocol.¹² Silicon diode detectors, which have a pronounced absorbed-dose energy dependence compared to air and water, have an intrinsic energy dependence similar to that of passive readout detectors studied elsewhere, i.e., deviating from unity by up to 5%.

These findings show that it is important to determine both the absorbed-dose and the intrinsic energy responses for certain types of detectors and beam qualities. Though the results and analysis of this study are very dependent on the MC model used to model absorbed-dose energy response of detectors, detector blueprints were as accurate as possible according to the manufacturer. The cause of the large variation of the relative intrinsic energy response of the microDiamond detector with respect to energy, however, is yet to be determined.

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7 CONFLICTS OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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Numerical values of data shown in Figure 1 are given in Table S-1.

Table S-1 Detector calibration coefficients in terms of air-kerma free in air $N_{K,\text{air}}$ and in terms of absorbed dose to water N_{D,w,Q_0} . Effective energy for kV beam spectra was calculated as the energy of a monoenergetic beam which would have the same half-value layer as a given spectrum.

Beam	Generating potential (kV)	Effective energy (keV)	mD1	mD2	mD3	SiD1	SiD2
$N_{K,\text{air}}$ (mGy/nC)							
CCRI-25	25	13.9	1037.0	1041.4	1086.8	32.1	28.3
CCRI-50(b)	50	22.6	719.5	766.1	796.1	16.5	14.7
CCRI-100	100	38.5	698.2	777.1	845.0	16.2	14.6
CCRI-135	135	59.4	725.2	823.4	927.3	21.3	19.7
CCRI-180	180	77.7	734.3	838.9	954.2	29.3	27.3
CCRI-250	250	126.9	744.6	854.0	976.9	55.4	52.4
N_{D,w,Q_0} (mGy/nC)							
^{60}Co		1250	889.0	1027.3	1187.3	103.7	96.7

Numerical values of data shown in Figure 6 are given in Table S-2.

Table S-2 The relative intrinsic energy response R_Q/R_{Q_0} values of detectors as a function of the effective photon beam energy (Q is the kV calibration beam quality and Q_0 is the ^{60}Co calibration beam). The total expanded uncertainties ($k = 2$) were 2.0% for 25 and 50 kV beams and 1.9% for other beams.

Beam	Generating potential (kV)	Effective energy (keV)	R_Q/R_{Q_0}				
			mD1	mD2	mD3	SiD1	SiD2
CCRI-25	25	13.9	1.83	2.11	2.33	1.03	1.09
CCRI-50(b)	50	22.6	2.04	2.21	2.46	1.03	1.08
CCRI-100	100	38.5	1.69	1.75	1.86	0.96	1.00
CCRI-135	135	59.4	1.37	1.40	1.43	0.95	0.96
CCRI-180	180	77.7	1.21	1.23	1.25	0.96	0.96
CCRI-250	250	126.9	1.07	1.08	1.09	0.98	0.97