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FULL PAPER

Evaluation of a synthetic single-crystal diamond detector for relative dosimetry measurements on a CyberKnife™

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Objective: To evaluate a new commercial PTW-60019 microDiamond™ (PTW, Freiburg, Germany) synthetic single-crystal diamond detector for relative dosimetry measurements on a clinical CyberKnife™ VSI (Accuray Inc., Sunnyvale, CA) system.

Methods: Relative output factors (ROFs) were measured for collimator diameters from 5 to 60 mm, and compared with diode [PTW-60017, PTW-60018 and IBA Dosimetry (Schwarzenbruck, Germany) SFD] and ionization chamber (PTW-31014 PinPoint® and PTW-31010 Semiflex) measurements. Beam profiles were measured at a range of depths, and collimator sizes, with the detector stem oriented both parallel and perpendicular to the central axis (CAX). Percentage depth-dose (PDD) curves were obtained for the 60-mm collimator and compared with natural Diamond Detector (PTW-60003) and ionization chamber curves to evaluate energy dependence.

Results: Penumbra broadening was noted on profile measurements made with the microDiamond oriented

with the stem parallel to the CAX, in comparison with diodes. Oriented perpendicular to the CAX, the profile penumbra was sharper, but stem effects could not be ruled out. The PDD measurements were within 0.5% of ionization chamber measurements, indicating insignificant dose-rate dependence. The ROF for the microDiamond fell between diode and ionization chamber results. Published Monte Carlo-derived CyberKnife-specific factors were applied to the PTW-60017, PTW-60018 and PTW-31014 ROFs, and the microDiamond factors agreed within 2.0% of the mean of these.

Conclusion: Over a range of small field relative dosimetry measurements, the microDiamond detector shows excellent spatial resolution, dose-rate independence and water equivalence.

Advances in knowledge: The microDiamond is a suitable tool for commissioning stereotactic systems.

The CyberKnife™ (Accuray Inc., Sunnyvale, CA) system allows submillimetre positional accuracy for stereotactic radiosurgery (SRS) and stereotactic ablative body radiotherapy treatments. It is operated without a flattening filter, with small field sizes (5- to 60-mm-diameter circular beams) and at a dose rate of the order of 10 Gy min^{-1} , as defined at the depth of maximum dose (15 mm deep) for a 60-mm collimator at an 800-mm source-axis distance. This places an increased demand on the accuracy of dosimetric measurements used for commissioning and quality assurance. The absence of a flattening filter in radiotherapy machines is becoming more widespread, which in turn is leading to an increase in clinical dose rates. It is therefore important to consider dose-rate effects of detectors used for commissioning both stereotactic and conventional fields.

Although standard detectors are recognized to be unsuitable for small field applications, owing to dose averaging and

perturbation effects, SRS-specific detectors have also been shown to have limitations. Silicon diode detectors exhibit an over-response to low-energy scatter. The relative contribution of this scatter increases with field size, and, for regular field sizes, shielding has been used to compensate for this over-response.¹ In small fields, shielding introduces perturbations, and for detectors used exclusively for small field dosimetry unshielded detectors (as considered in this article) are appropriate.² For measurements such as relative output factors (ROFs), however, it is conventional to renormalize to a larger standard field size ($100 \times 100 \text{ mm}$), in which the unshielded detector will over-respond.

Air-filled ionization chambers produce a low signal per unit volume, limiting the practical size to which they can be made and requiring a compromise between noise and volume averaging effects to be made. The increasing relative proportion of the central electrode also increases perturbations

to the field.¹ Liquid ion chambers have the potential for increased signal per unit volume but are limited by high ionization recombination rates, due to low ion mobility, that cannot be fully compensated for by high bias voltages.³

The use of natural diamond for radiation detectors has been investigated for such fields, owing to its high sensitivity, low leakage, resistance to radiation damage and near tissue equivalence; however, dose-rate dependence and variability of individual detector volume of these detectors makes depth-dose determination difficult.⁴

In this work, a new commercially available diamond detector, PTW-60019 microDiamond™ (PTW, Freiberg, Germany), has been evaluated for dosimetry measurements on a clinical CyberKnife VSI system. The CyberKnife VSI system is equipped with both fixed and an IRIS™ (variable aperture) collimator system. In our department, and at other centres, the IRIS collimator is not typically used to produce clinical field sizes <10 mm owing to limits in reproducibility of the 5- and 7.5-mm fields.⁵ This work has therefore been performed using the fixed collimator set, to characterize the smallest clinically relevant fields.

METHODS AND MATERIALS

The microDiamond is a synthetic single-crystal diamond detector (SCDD), in a Schottky diode configuration, operating with a zero bias voltage. The use of research SCDDs has been reported^{6–8} in conjunction with conventional linear accelerators, with square field sizes from 100 × 100 mm² down to 10 × 10 mm² as measured at a 1000-mm source-to-detector distance (SDD). In this work, we present the results using a dedicated stereotactic linear accelerator with circular fields for fixed collimators ranging from 5 to 60 mm, at a nominal SDD of 800 mm, in a 6-MV unflattened photon beam.

The microDiamond detector is waterproof and features a 1-μm-thick, 1.1-mm-radius circular active layer, with a sensitive volume of 0.004 mm³. The effective point of measurement is 1 mm

from the detector tip, and it has a nominal response of 1 nC Gy⁻¹ for cobalt-60. The stability of the microDiamond is 0.25% per 1 kGy at 18 MV, and has a directional response in water of less than ±0.9% for rotation around the detector axis (radial incidence) and less than ±1% for an axial incidence of ±40°.^{6,9}

A range of additional detectors was used during this study for comparison and are detailed in Table 1, with the dimensions of their active areas for comparison.

Off-axis ratio profiles

The microDiamond was pre-irradiated with 5 Gy in accordance with the manufacturer's guidelines. Cross- and in-line beam profiles were acquired using a Blue Phantom² (IBA Dosimetry, Schwarzenbruck, Germany) plotting tank. A continuous 3-mm s⁻¹ scan speed, 0.1-mm output step width and a scan range extending 50 mm beyond the full width half-maximum was used for each profile acquisition. Profiles were taken using 5-, 7.5-, 10-, 30- and 60-mm collimators, at depths of 15, 50 and 100 mm, at a fixed source-to-surface distance (SSD) of 800 mm. Equivalent profiles were taken using PTW-60017, PTW-60018 and IBA SFD p-type silicon diode detectors. In each case, the detector was oriented with the stem parallel to the beam axis, to minimize stem effects.

Further profiles were acquired with the microDiamond stem oriented perpendicular to the radiation central axis (CAX), scanning along the stem axis in both directions, at depths of 15, 50 and 100 mm, for fixed collimator sizes (5, 30 and 60 mm).

The CyberKnife system includes a reference detector port, which enables a reference detector to be placed in such a way so as to not perturb the radiation beam, even for 5-mm field sizes. An IBA reference field diode has been used as the reference detector, thereby correcting the field detector results for any dose-rate changes of the machine for all the profiles and depth-dose curves examined in this work.

Table 1. Detectors available for comparison with the microDiamond™ (PTW, Freiburg, Germany), with active volumes (V_{Active}) and radii (r)

Detectors	V_{Active} (mm ³)	r (mm)
PTW microDiamond detector (PTW-60019)	0.004	1.1
p-Type silicon diodes		
PTW Diode E (PTW-60017)	0.03	0.6
PTW Diode SRS (PTW-60018)	0.3	0.6
Scanditronix/IBA SFD	0.017	0.3
Ionization chambers		
PTW Semiflex (PTW-31010)	125	2.75
PTW PinPoint® (PTW-31014)	15	1.0
Scanditronix-Wellhöfer microFarmer chamber: FC23	230	3.2
Wellhöfer/IBA CC01	10	1.0
Natural diamond detectors		
PTW Diamond Detector (PTW-60003)	1.0–6.0	1.0–2.2

Relative output factors

ROF measurements were made using the microDiamond detector for 5-, 7.5-, 10-, 12.5-, 15-, 20-, 25-, 30- and 60-mm fixed collimator sizes. The chamber was positioned 15-mm deep in water, with a fixed SDD of 800 mm (785 mm SSD). Triplicate readings were taken with 100-MU exposures, and the charge measured using a PTW UNIDOS® E electrometer.

Measurements in the same reference conditions were also made using the PTW-60017, PTW-60018 and IBA SFD diodes, and IBA-CC01, PTW PinPoint® and Semiflex ionization chambers.

Percentage depth-dose

Percentage depth-dose (PDD) curves were acquired for a fixed 60-mm collimator, using the Blue Phantom² plotting tank, with a fixed 800-mm SSD. Readings were acquired from a depth of 310 mm to the water surface in discrete 0.2-mm steps with a 1-s step acquisition time. Curves were acquired with the microDiamond, PTW Semiflex, Scanditronix-Wellhöfer FC23, PTW Diode SRS and PTW natural Diamond detectors.

RESULTS AND DISCUSSION

Off-axis ratio profiles

Figure 1 shows a comparison of the penumbra region for 5- and 60-mm fixed collimators, acquired with the microDiamond and PTW Diode SRS (PTW-60018), the difference (detector – Diode SRS) is shown beneath for the full range of detectors used. The figure indicates that there are in-plane volume-averaging effects, owing to the larger radius of the microDiamond ($r = 1.1$ mm)

compared with the PTW Diode SRS ($r = 0.6$ mm), leading to broadening of the penumbral region. As the active layer of the diamond is only 1 μm thick, the larger radius of the microDiamond is necessary to ensure adequate signal-to-noise ratio. The PTW Diode E, the detector currently recommended by Accuray, agreed within 1.1% with the newer Diode SRS. The IBA SFD ($r = 0.3$ mm) agreed with the diodes in small fields but tended to over-respond in the out-of-field region for the 60-mm collimator.

Figure 2 shows a comparison of profiles made with the chamber oriented to use the 1- μm dimension to achieve the optimal spatial resolution, showing visibly less penumbral broadening. No significant profile asymmetry was noted, as would be indicative of stem effects.¹ To characterize the detector fully for stem effects, however, a series of repeat measurements, for a given collimator, would be required to account for random errors in the profile measurement.

Relative output factors

Figure 3 shows the ROFs for the detectors in Table 1, each measured at 15 mm deep in water, with an SDD of 800 mm. The figure shows that the microDiamond measured factors fall between the silicon diodes and ion chamber ROFs. Measurements comparing silicon diodes and micro ion chambers to alanine have shown that diodes tend to overestimate the output factors for the smallest CyberKnife collimators, whereas ionization chambers underestimate them.^{10–12} It should be noted that, for the CyberKnife, ROFs are normalized to the largest possible 60-mm-diameter collimator; when normalizing to larger (100×100 cm) fields, as would be available on a standard accelerator, the over-

Figure 1. Penumbra region from 50-mm-deep profiles acquired with the PTW Diode SRS and microDiamond™ (PTW, Freiburg, Germany) for (a) 5-mm and (c) 60-mm fixed collimators; (b) and (d) show the difference (detector – Diode SRS) for the microDiamond and the other diodes used for profile measurements, which are not displayed on (a) and (c) for clarity.

Figure 2. (a) Orientations and scan directions used for acquiring profiles at (b) 50 mm deep with the microDiamond™ (PTW, Freiburg, Germany) and (c) deviation to the profiles acquired in Orientation 1.

response of silicon diodes to low-energy scatter may lead to underestimating small-field ROFs.

For the CyberKnife system, detector-specific correction factors $K_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$, as described in the study by Alfonso et al,¹³ have been derived using Monte Carlo simulation¹² validated against

alanine. These factors convert detector ratio to dose ratio, where the ratio is of a measurement made in a clinical field (f_{clin}) to a measurement made in the machine-specific reference field (MSR) (f_{msr}) and accounts for field size and quality index (Q) differences. For CyberKnife, the MSR is defined as the fixed 60-mm collimator, and factors are provided for each of the other collimator sizes.

Figure 3. Output factors for the variety of different detectors outlined in Table 1. All relative output factors acquired at 15 mm deep, with a fixed frequency-division duplexing of 800 mm. Insert shows enlargement of fixed collimator sizes <25 mm. SRS, stereotactic radiosurgery.

Figure 4. Output factors corrected using published (Francescon et al¹²) Monte Carlo-derived CyberKnife (Accuray Inc., Sunnyvale, CA) factors for PTW 60017, 60018 and 31014 detectors against microDiamond™ (PTW, Freiburg, Germany) measurements.

Figure 4 shows a comparison between the microDiamond and three PTW detectors, corrected using these published factors. The ROF measured during this study with the ion chamber and diodes, once corrected, are in good agreement, with a maximum variation of 1.1% for the 5-mm fixed collimator. For the microDiamond detector, the measured factors fall above the mean of the three corrected ROFs for all collimator diameters and are within 2%. The ratio of the microDiamond ROF to the mean corrected ROF is shown in Table 2, together with the correction factors used for each detector. It can be seen that this ratio is closer to unity than the correction factors required for either diode or ionization chamber, indicating that a smaller correction factor would be required.

Percentage depth-dose

Figure 5 shows the PDD curve produced using the PTW microDiamond, the PTW natural Diamond Detector (uncorrected for dose rate) and the PTW Diode SRS for the 60-mm fixed collimator; the average of two ionization chamber curves

(PTW Semiflex and Scanditronix-Wellhöfer FC23) is also shown. The differences from the ion chamber curve are shown beneath the PDD curves. It can be seen that, whilst the difference (detector – ion chamber) is $<0.5\%$ for both the Diode and microDiamond, the Diode shows a greater systematic error at depth. The microDiamond does not show a pronounced variation with depth, unlike the curve measured with the natural Diamond Detector, indicating that the dose-rate dependence is not significant within this range.

The dose-rate dependence of natural diamond detectors is well known, and a relationship between the measured current (I) and dose rate ($\dot{D}$) has been found as $I \propto \dot{D}^\Delta$ with $0.5 \leq \Delta \leq 1.0$.⁴ By plotting the natural logarithm of the normalized diamond and microDiamond detector readings against the natural logarithm of the ionization chamber reading, which should be directly proportional to the dose rate, an estimate of Δ can be made from a linear fit. For the natural Diamond Detector and microDiamond, respectively, values of 0.9522 ± 0.0001 and 1.0034 ± 0.0001 were

Table 2. Ratio of microDiamond™ (PTW, Freiburg, Germany) to mean corrected relative output factors from Figure 4, with published correction factors of Francescon et al,¹² for fixed collimator diameters ($\emptyset$)

$\emptyset$ (mm)	microDiamond	Monte Carlo correction factor		
		Diode E	Diode SRS	PinPoint®
60.0	1.000	1.000	1.000	1.000
30.0	0.999	1.000	1.000	1.000
25.0	0.999	1.003	1.002	0.997
20.0	0.997	0.999	0.998	1.001
15.0	0.996	0.995	0.994	1.005
12.5	0.992	0.989	0.990	1.008
10.0	0.988	0.981	0.980	1.018
7.5	0.981	0.970	0.968	1.029
5.0	0.990	0.956	0.950	1.102

Figure 5. (a) Percentage depth-dose curve for the 60-mm fixed collimator; ion chamber is the average of the Semiflex and Scanditronix-Wellhöfer FC23 ionization chambers (agreement 0.35% maximum deviation). (b) Difference between the detectors and ionization chamber, for depths >15 cm (normalization point). Both diamond detector curves are uncorrected for dose-rate dependence.

obtained, for fits with r^2 of 0.99997 and 0.99998. The effect of increased low-energy scatter with depth has not been included in this analysis, as the water equivalence of diamond detectors has been demonstrated by our ROF measurements and by other works with larger field sizes.⁶

CONCLUSION

The 1.1-mm radius of the microDiamond detector leads to increased volume-averaging effects over dedicated SRS diodes (0.3–0.6 mm radii) for profile measurements, made with the detector oriented parallel to the CAX. This leads to broadening of penumbral regions, which has not been quantified here in terms of 20–80% width changes, as this metric is not relevant in small fields. Measurements made with the chamber oriented perpendicular to the CAX, to take advantage of the 1- μ m dimension, lead to less penumbral broadening; however, potential stem effects have not been sufficiently discounted. Measurements made in this orientation also pose practical limitations, as detector and water tank set-up must be repeated for both in-line and cross-line profiles, introducing the possibility for further errors.

A significant advantage of the microDiamond detector can be seen from the comparison of the ROFs with the Monte Carlo diode and ionization chamber corrected measurements. These results indicate that the microDiamond detector has much better water equivalence than the other types of detectors, and that smaller corrections will be required for measurements. This is important as correction factors can only be calculated for specific reference conditions. The advantage of this is most evident for the smallest

fixed collimator diameters (≤ 10 mm), which by their nature are the hardest to measure. For the 5-mm collimator, the microDiamond is within 1% of the Monte Carlo corrected values, compared with the 5% and 10% correction factors for the diodes and ionization chambers, respectively. This increases the confidence of ROF measurements made using the microDiamond in the smallest of stereotactic fields.

In addition, the microDiamond detector did not exhibit the dose-rate dependence effects of previous natural diamond detectors, which coupled with an excellent z-axis spatial resolution makes an excellent tool for measuring PDD. The PTW microDiamond detector is therefore a suitable instrument for performing the relative dosimetry measurements required for commissioning small-field stereotactic systems such as the CyberKnife.

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CONFLICTS OF INTEREST

The data presented in this work are independent of PTW, and the authors acknowledge no conflict of interest.

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