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Dosimetry of cone-defined stereotactic radiosurgery fields with a commercial synthetic diamond detector

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Abstract

Purpose: Small field x-ray beam dosimetry is difficult due to a lack of lateral electronic equilibrium, source occlusion, high dose gradients and detector volume averaging. Currently there is no single definitive detector recommended for small field dosimetry. The objective of this work was to evaluate the performance of a new commercial synthetic diamond detector, namely the PTW 60019 microDiamond, for the dosimetry of small x-ray fields as used in stereotactic radiosurgery (SRS).

Methods: Small field sizes were defined by BrainLAB circular cones (4 – 30 mm diameter) on a Novalis Trilogy linear accelerator and using the 6 MV SRS x-ray beam mode for all measurements. Percentage depth doses were measured and compared to an IBA SFD and a PTW 60012 E diode. Cross profiles were measured and compared to an IBA SFD diode. Field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, were calculated by Monte Carlo methods using BEAMnrc and correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, were derived for the PTW 60019 microDiamond detector.

Results: For the small fields of 4 to 30 mm diameter, there were dose differences in the PDDs of up to 1.5% when compared to an IBA SFD and PTW 60012 E diode detector. For the cross profile measurements the penumbra values varied, depending upon the orientation of the detector. The field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, were calculated for these field diameters at a depth of 1.4 cm in water and they were within 2.7% of published values for a similar linear accelerator. The corrections factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, were derived for the PTW 60019 microDiamond detector.

Conclusions: We conclude that the new PTW 60019 microDiamond detector is generally suitable for relative dosimetry in small 6 MV SRS beams for a Novalis Trilogy linear equipped with circular cones.

I. INTRODUCTION

Stereotactic radiosurgery (SRS) involves the delivery of a high radiation dose to lesions within the brain using small field size radiation beams.[1-3] The dosimetry of very small x-ray fields is challenging for several reasons including a lack of lateral electronic equilibrium, source occlusion, large dose gradients and the size of detector in respect to the field size.[4-6] There have been many investigations into the choice of appropriate radiation dosimeters for relative dosimetry measurements such as depth doses, profiles and relative output factors in very small x-ray fields.[7-9] The detectors studied have included very small ionisation chambers (pinpoint chambers), diodes, diamond detectors, plastic scintillator dosimeters and radiochromic film.[7, 10, 11] The incorrect choice of detector can result in up to 30% difference in relative output factor leading to radiation accidents and the need for significant correction factors have been reported particularly for very small field sizes.[12-14]

Recently, there has been significant work done in the development of artificial diamond detectors for radiation dosimetry. These artificial diamonds are grown by a process of chemical vapour deposition (CVD) and they have been developed by a number of groups [15-18]. The study by Ciancaglioni *et al* showed that their CVD diamond detector gave a good agreement to within 1% for measured depth doses with field sizes down to 1×1 cm^2 as compared to ionisation chamber measurements.[18] Similar results were obtained in the study by Betzel *et al* for depth doses and relative output factors with field sizes down to 3×3 cm^2 for their CVD diamond detector.[15] More recently, an artificial diamond detector has become available commercially which has the potential for use with small field dosimetry, the PTW 60019 microDiamond detector (PTW, PTW-Freiburg, Germany).

In 2008, a new formalism for small field dosimetry was introduced by Alfonso *et al*[4] which aimed to formalize the use of Monte Carlo calculations in small field x-ray dosimetry. The proposal was to introduce a field factor, $\Omega^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$, that converts absorbed dose to water, $D^{f_{msr}}_{w,Q_{msr}}$, for a machine-specific reference field (f_{msr}), with a beam quality Q_{msr}, to the absorbed dose to water for the clinical field size of interest (f_{clin}) of beam quality Q_{clin} . This can mathematically expressed as:

$$D^{f_{clin}}_{w,Q_{clin}} = D^{f_{msr}}_{w,Q_{msr}} \cdot \Omega^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$$

Alfonso *et al* noted that the field factor, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, can be calculated directly as a ratio of absorbed doses to water using Monte Carlo simulations alone or can be measured as a ratio of detector readings multiplied by a Monte Carlo calculated correction factor $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$.

In the present work we evaluate a newly released synthetic diamond detector, the PTW 60019 microDiamond, for small field size x-ray beam dosimetry. Reference dosimetry data used to compare the microDiamond detector were taken with a IBA SFD and a PTW 60012 E diode. These diodes were recently used by Chalkley *et al*[19] to compare with the microDiamond detector for a CyberKnife system. Monte Carlo methods were used to calculate field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, for a Novalis Trilogy linear accelerator equipped with circular cones in the range of 4 to 30 mm diameter. From these field factors, we have derived the correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, for the new PTW 60019 microDiamond detector for 6 MV stereotactic radiosurgery x-ray beam.

II. METHODS AND MATERIALS

The 6 MV SRS x-ray beam used in this work was produced by a Novalis Trilogy linear accelerator (Varian Medical Systems, Palo Alto, USA). This beam uses a thin flattening filter in order to produce a higher dose rate of up to 1000 MU per minute.[20-22] Beam collimation for the SRS x-ray beams was achieved by using the BrainLAB circular cones (BrainLAB, Germany) of 4, 7.5, 10, 20 and 30 mm diameter as defined at the isocentre. The X and Y collimator jaws were set to 5 cm for all measurements with these circular cones.

The PTW 60019 microDiamond detector was compared with the PTW 60012 E diode detector (PTW, PTW-Freiburg, Germany) and an IBA SFD solid state diode (IBA, Germany). Relative dosimetry data were collected consisting of percentage depth doses and cross profiles measured for the SRS circular cones. All measurements were acquired in a large scanning PTW MP3 water phantom (PTW, Freiburg, Germany) at an SSD of 100 cm. For the depth dose measurements, we used a step size of 1 mm for the first 20 mm from the surface and a step size of 2.5 mm for greater depths.

For all measurements with the IBA SFD diode and the PTW 60012 E diode the detectors were oriented parallel to the central axis of the x-ray beam. Similarly, percentage depth dose and field factor measurements with the PTW 60019 microDiamond detector were acquired with the detector oriented parallel to the x-ray beam as per manufacturer recommendations. For measurements of cross profiles with the PTW 60019 microDiamond detector, one set of measurements was obtained with the detector oriented parallel to the central axis of the beam, and another obtained with the perpendicular orientation.

Field factors were measured with the IBA SFD and PTW 60012 E. The field factors were derived by using the daisy-chaining approach outlined by Dietrich *et al*[23]. These field factors were used as the reference values to compare with the values measured by PTW 60019 microDiamond detector. A previously verified and published Monte Carlo model using BEAMnrc for a Novalis linear accelerator equipped with circular cones was used to calculate field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, for cone diameters in the range of 4 to 30 mm.[24] In this model, the DOSXYZnrc user-code (V4 r2-3-0) was used to calculate these field factors in water. Voxel sizes of $0.25\times0.25\times0.25\text{mm}^3$ were used to score the dose. To model electron transport as accurately as possible, a global ECUT of 0.521 MeV was specified and the EXACT boundary crossing algorithm was turned on for the dose calculations.[25-27] We then used these Monte

Carlo calculated field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, to determine the correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, for the PTW 60019 microDiamond detector.

III. RESULTS

III.A. Percentage depth doses

Fig. 1 shows the depth doses measured with the PTW 60019 microDiamond, the PTW 60012 E and the IBA SFD diode detector for the 4, 7.5, 10 and 30 mm circular cones. The agreement in depth doses between the two detectors for all the field sizes studied was generally better than 1% with a maximum difference of 1.5%. This level of agreement is consistent with the results of Ciancaglioni *et al* who found differences of up to 2% for their CVD depth doses of a 1×1 cm^2 10 MV x-ray beam which were compared to a PTW PinPoint ionization chamber.[18]

It should be noted that for the depth dose measurements, no corrections were made for dose rate response variations, such as those that have been applied for dose measurements often performed when using natural diamond detectors. In addition, no corrections have been made in terms of the ratio of the stopping power of the PTW 60019 microDiamond detector and the stopping power of water. Both the PTW 60012 E and the IBA SFD diode detectors were tested for dose rate dependence by measuring a PDD in a 10x10 cm^2 field size and compared to a PDD measured with an ionisation chamber. All PDDs were within 0.5% of each other at all depths. This confirms that the diodes were not dependent on dose rate.

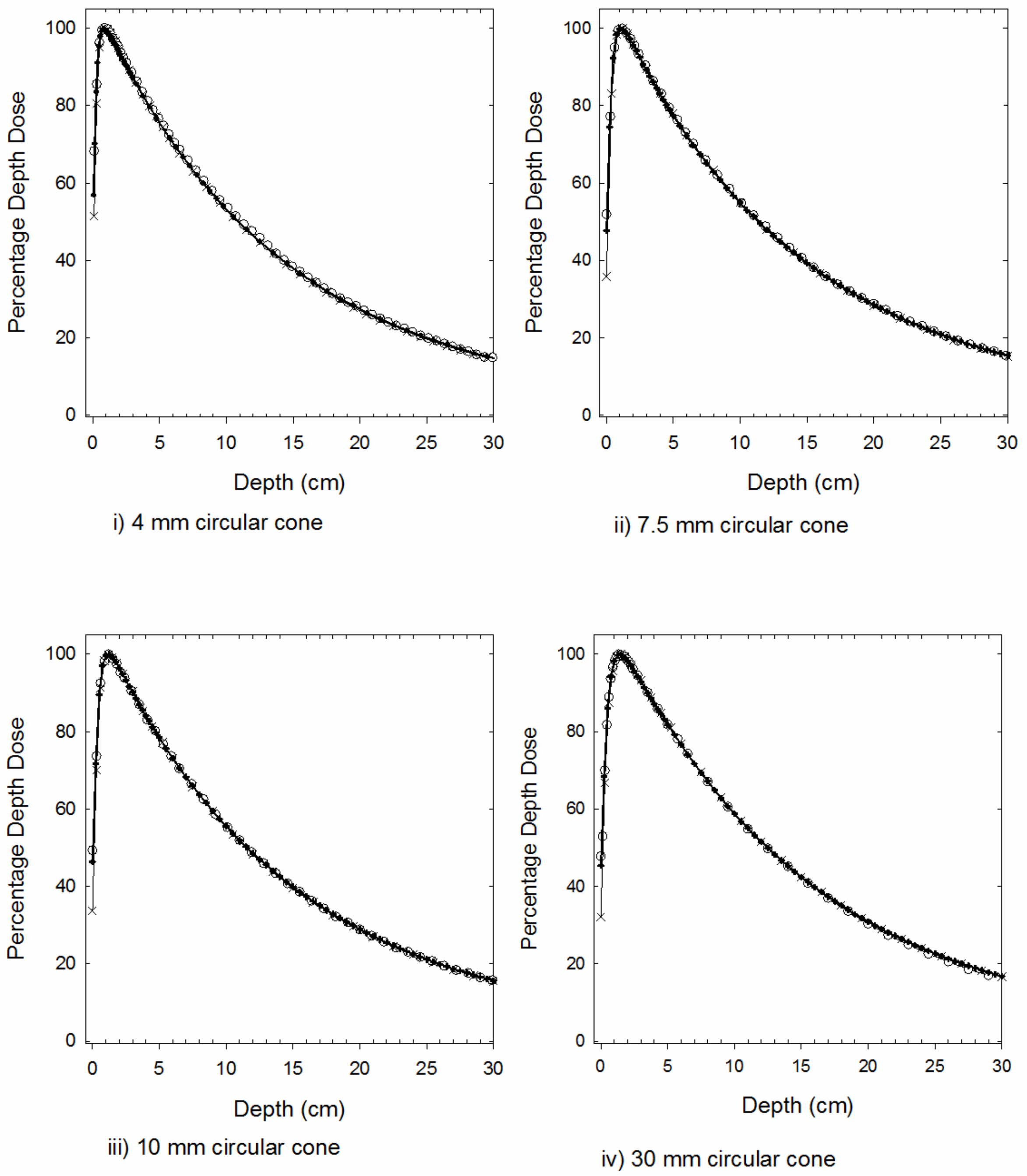

FIG. 1. Percentage depth doses measured with a PTW 60019 microDiamond detector (O), IBA SFD Diode (X) and PTW 60012 E Diode detector (+) for 4, 7.5, 10 and 30 mm circular cones at SSD of 100 cm.

III.B. Cross profiles and penumbra

Cross profiles measured with the PTW 60019 microDiamond and the IBA SFD diode for the 4, 7.5, 10 and 30 mm circular cones at a depth of 10 cm are shown in Fig. 2 and Table I. Note that in Fig. 2 only half profiles are presented to highlight the penumbral effects for the three cases. For comparison, the IBA SFD diode was chosen over the PTW 60012 E diode for these measurements due to its small diameter which gives a superior spatial resolution by minimizing volume averaging effects across the penumbra.

The influence of the orientation of the PTW 60019 microDiamond detector is most apparent in the data shown in Table I; with the detector oriented perpendicular to the beam central axis the penumbrae are consistently smaller than the IBA SFD diode, whereas with parallel orientation the penumbrae are broader. This is attributed to the cross sectional area of the detector causing volume/area averaging during the measurements, with the IBA SFD diode being 0.6 mm in diameter and the PTW 60019 microDiamond detector being 2.2 mm in diameter for parallel orientation and 1 μm thickness for perpendicular orientation. Qualitatively this is most apparent in the 4 mm cone profiles as shown in figure 2.

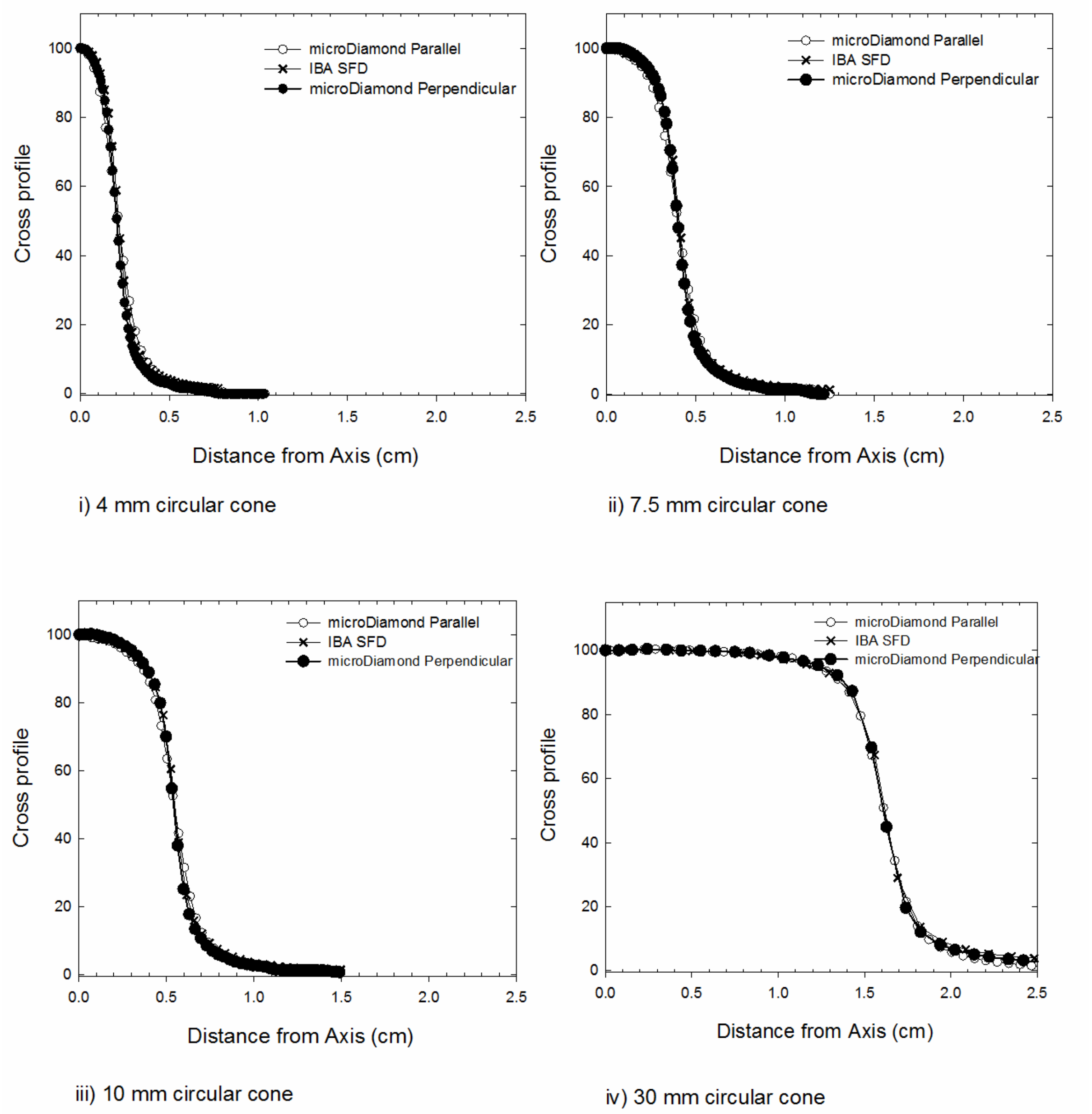

FIG. 2. Half cross profiles measured at depth of 10.0 cm with a PTW 60019 microDiamond detector in parallel orientation (o), perpendicular orientation (●) and IBA SFD diode (x) for 4mm, 7.5 mm, 10 mm and 30 mm circular cones at SSD of 100 cm.

Table I. Penumbra (80-20 %) and FWHM measurements by an IBA SFD diode and a PTW 60019 microDiamond detector

Cone Diameter (mm)	Penumbra			FWHM		
	IBA SFD (mm)	microDiamond (mm)		IBA SFD (mm)	microDiamond (mm)	
		Parallel	Perpendicular		Parallel	Perpendicular
4	1.2	1.7	1.1	4.3	4.3	4.1
7.5	1.5	2.0	1.4	8.1	8.0	8.0
10	1.7	2.3	1.5	11.0	10.9	10.8
30	2.4	2.7	2.3	32.3	32.2	32.2

III.C. Field factors $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ and Correction factors $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$

Table II also shows the field factors measured with PTW 60012 E, IBA SFD and PTW 60016 microDiamond detectors. Monte Carlo calculated field factors, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, are also shown in this table. The uncertainty in our Monte Carlo simulations was within 0.5%. The type A uncertainty for our measurements was estimated to be within 0.5% (1 SD).

Table III shows the corrections factor, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, derived from the Monte Carlo field factors and measurements for the PTW 60016 microDiamond detector for a Novalis Tx equipped with circular cones and using a 6 MV SRS x-ray beam.

Table II Field factors obtained using a PTW 60012 E diode , an IBA SFD diode and a PTW 60019 microDiamond detector at a depth of 1.4 cm for a 6 MV SRS beam on a Novalis Tx equipped with circular cones at an SSD of 100 cm. The uncertainties were up to 0.5% (1SD) for all detectors.

Cone diameter (mm)	Depth (cm)	PTW 60012 E	IBA SFD	PTW 60019 microDiamond	Monte Carlo relative output factor, $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$
30	1.4	0.940	0.943	0.944	0.959
20	1.4	0.927	0.925	0.929	0.955
10	1.4	0.860	0.851	0.856	0.870
7.5	1.4	0.808	0.798	0.799	0.811
4	1.4	0.664	0.662	0.644	0.649

Table III. Monte Carlo calculated correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ for PTW 60019 microDiamond detector at depth of 1.4 cm for a Novalis equipped with circular cones using a 6 MV SRS x-ray beam.

Cone (mm)	Correction factor, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$
30	1.016
20	1.027
10	1.015
7.5	1.013
4	1.006

IV. DISCUSSION

The field factors shown in table II are within 2.7% to those published by Garcia *et al* which included BEAMnrc Monte Carlo calculations and Gafchromic EBT2 measurements.[28] However, there was a very close agreement in the relative output factor for the 4 mm cone to within 0.2% as compared to this work. The difference in Monte Carlo derived field factors can be attributed to parameterization of the head component in the Monte Carlo model used. In addition, the selection of the energy of the incident electron beam onto the target as well as spot size distribution has been shown to affect output correction factors.[29-31] Therefore we expect that there will be differences in field factors due to the uncertainties in the measurements and Monte Carlo calculations on linear accelerators even between studies that used the same model of linear accelerator.

Bassinet *et al* derived the output field factors from passive detector measurements, Gafchromic EBT2 film and LiF TLDs and subsequently derived a field factor from the mean doses from both detectors.[7] Our results differ from those of Bassinet *et al* by up to 3.7% which is attributed to several factors. Firstly, the work by Bassinet *et al* was performed on a Varian Clinac accelerator using a standard 6 MV x-ray beam. In comparison, the present work was performed on a Novalis Trilogy with a 6 MV SRS beam which has a special flattening filter to produce higher dose rate x-ray beams for SRS treatments. This difference can contribute to a different spectrum and different output even for linear accelerators with a similar head geometry. Additionally, the present work utilized a 5 × 5 cm^2 jaw size for all measurements and simulations where Bassinet *et al* varied their jaw size with differing cones.

A recent paper by Chalkley et al[19] demonstrated that the new PTW 60019 microDiamond detector has an excellent spatial resolution, dose-rate independence and water equivalence for small fields ranging from 5 to 60 mm in diameter and for a CyberKnife system. Those findings agree with the present work with the experimental exception that we used a Novalis Trilogy linear accelerator. Our results also show minimal dose rate dependence when compared to the PDDs measured by the IBA SFD and PTW 60012 E detectors. They found that 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[19].

According to the Alfonso *et al*[4] formalism the correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, are machine specific which in this case it is a Novalis Trilogy equipped with circular cones. Therefore, it should be noted that these correction factors only apply to the cones and at an SSD of 100 cm.

V. CONCLUSION

In this work we have evaluated the PTW 60019 microDiamond detector for the dosimetry of small x-ray fields as used in stereotactic radiosurgery. This synthetic diamond detector has been shown to possess good dosimetric properties for depth doses, profiles and field factor measurements in the fields studied. The correction factors supplied in this study apply for use in a Novalis Trilogy linear accelerator equipped with BrainLAB circular cones and in a 6 MV SRS x-ray beam. For cross profile measurements, sharper penumbra measurements can be obtained with the detector oriented perpendicular to the beam central axis.

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