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Assessment of basic physical and dosimetric parameters of synthetic single-crystal diamond detector and its use in Leksell Gamma Knife and CyberKnife small radiosurgical fields

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ABSTRACT

▶ ***Original article***

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Background*:** To determine the basic physical and dosimetric properties of a new synthetic single-crystal diamond detector and its application for relative small field dosimetry. ***Materials and Methods*:** The pre-irradiation dose required to stabilize detector response, dose rate dependence, photon and electron energy dependence, temperature dependence and angular dependence of MicroDiamond detector response were evaluated. Output factors on Leksell Gamma Knife Perfexion and on CyberKnife were measured to assess detector feasibility in small radiation field dosimetry. For all measurements, the detector was connected to Unidos electrometer set to 0 voltage. ***Results: Relative output factors measured on Leksell Gamma Knife Perfexion for 4 mm and 8 mm collimators were in agreement with Monte Carlo reference values from the manufacturer, with deviations of 0.3% and 2.1%, respectively. For CyberKnife and fixed circular collimators, the difference in output factor values did not exceed 2% from vendor-supplied values, even for the smallest radiation field with a diameter of 5 mm. ***Conclusion:*** Our results indicate that the MicroDiamond detector is a promising tool for relative small field dosimetry. For output factor measurements on Leksell Gamma Knife Perfexion and CyberKnife, the detector can be used with minimal response corrections applied (correction factors not larger than 2%).

Keywords: *Small field dosimetry, synthetic diamond detector, output factor, radiosurgery.*

INTRODUCTION

Modern radiotherapy techniques often involve very small radiation fields or highly modulated radiation fields that are composed of very small field segments. Small radiation fields are used on accelerators or radionuclide machines for stereotactic radiotherapy and radiosurgery (e.g. Leksell Gamma Knife, CyberKnife, TomoTherapy, stereotactic linear accelerators or linear accelerators equipped with stereotactic cones or microMLC collimators), and are defined as fields smaller than 3 × 3 cm^2 [(1)].

Small fields are challenging with regard to accurate dosimetry and verification of basic field parameters. Due to the collimation system, there is partial occlusion of the direct beam source. This effect becomes important in radiation fields with sizes of the order of the size of the direct beam source, which is typically not greater than 5 mm for beams produced with modern linear accelerators [(2)]. The use of an additional external collimator (micro multileaf collimator) in combination with secondary shielding jaws can also modulate beam output for small radiation

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fields [3].

Additional dosimetric challenges include lateral charged particle disequilibrium, which occurs in high energy photon beams and narrow radiation fields when the beam radius becomes small in comparison to the maximum range of secondary electrons [2]. The lateral range of these electrons is energy dependent and can be calculated according to the quality index of the primary photon beam [4]. Issues related to detector volume and material are also important when considering small field dosimetry. Due to the relatively large volume of even small detectors compared to the measured field size, significant perturbation may occur.

Considering the challenges stated above, detectors for small radiation field dosimetry should be chosen carefully. There are a variety of detectors with different sensitive volume sizes available, and the use of an inappropriate detector can lead to incorrect calibration and subsequent adverse events on patients. The size of sensitive detector volume is crucial for reliable results, especially in small field dosimetry.

Recently, a prototype single-crystal diamond detector (SCDD) was developed at the Industrial Engineering Department, Tor Vergata University (Rome, Italy). The basic dosimetric properties have been investigated in photon beams and relative output factors have been measured for small radiation fields. Subsequent measurements in electron and proton beams followed and the results were promising [5,6]. Thus, a commercial version of this detector (PTW 60019 MicroDiamond; Sikalisch Technische Werkstatten [PTW], Freiburg, Germany) is currently available.

According to manufacturer, the detector has a very small sensitive volume (0.004 mm^3), excellent radiation hardness, temperature independence and near tissue equivalence [7]. Although the detector seems promising for relative small field dosimetry, its basic physical and dosimetric properties need to be independently verified and clinical dosimetric results need to be compared to detectors routinely clinically used before it can be used in clinical practice. Some measurements have been reported previously [8-17].

The aim of the present study was to measure and verify basic dosimetric properties of the new MicroDiamond detector and to measure relative output factors for Leksell Gamma Knife and CyberKnife small radiosurgical fields. The results were compared with data provided by the manufacturer [18] and those reported previously (basic dosimetric parameters [8-11], Leksell Gamma Knife [12] and CyberKnife [13] output factor measurements).

MATERIALS AND METHODS

The PTW 60019 MicroDiamond detector is waterproof and its sensitive volume is a disc-shaped synthetic single-crystal diamond 0.004 mm^3 in volume, with a radius of 1.1 mm and thickness of 1 µm. The sensitive volume is perpendicular to the detector axis and effective point of measurement lies 1 mm under the detector top. During measurements, the detector was connected to PTW Unidos electrometer (PTW, Freiburg, Germany) and voltage was set to 0 V.

The basic physical and dosimetric parameters of the MicroDiamond detector verified in the present study included response stabilization at the beginning of measurement (e.g. pre-irradiation dose), dose rate dependence, energy dependence, temperature dependence and the angular dependence of detector response. These measurements were performed on Varian accelerators (Varian Medical Systems, Palo Alto, USA).

All measurements, with the exception of angular response dependence, were performed in a water phantom with an automatic positioning system (PTW MP3 water phantom and/or Wellhofer IBA Dosimetry Blue Phantom). For all physical and dosimetric properties, the following irradiation settings were used for water phantom measurements (except energy dependence, where particular calibration depths in water were used): SAD = 100 cm with depth in water 5 cm, radiation field size 10 x 10 cm^2.

To assess detector feasibility in small radiation field dosimetry, relative output factors

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(ROF) on cobalt radiosurgery device (Leksell Gamma Knife Perfexion; Elekta Instrument AB, Stockholm, Sweden) and on a linear accelerator based robotic radiosurgery system (CyberKnife; Accuray, Inc., Sunnyvale, CA, USA) were measured. The results of these measurements were compared with data recommended by the manufacturer [(18) for Gamma Knife output factor and latest composite data collected by Accuray for CyberKnife].

Stabilization of detector response (Pre-irradiation)

For stabilization of detector response, Varian Clinac 2100C/D (Varian Medical Systems, Palo Alto, USA) with photon energy 6 MV was used and two different MicroDiamond detectors were compared. The detector was positioned in the center of the radiation field and measurement was performed in integral mode with PTW Unidos electrometer (1 minute used for integration).

Dose rate dependence

The evaluation of MicroDiamond detector response dependence on dose rate was performed on Varian TrueBeam STx (Varian Medical Systems, Palo Alto, USA). To access higher dose rates, a photon energy of 10 MV and flattening filter free (FFF) beam were used, which allows dose rates of 400–2400 cGy/min. The corresponding dose-per-pulse range was from 0.19 to 1.11 mGy/pulse. Dose-per-pulse values were calculated based on reference [(19)] for the dose rate range used in the present study. Before starting measurements in the FFF beam, the detector was positioned in the center of the radiation field by measuring the dose profiles and correcting the position accordingly. Measurement was again performed in the integral mode with PTW Unidos electrometer.

Energy dependence

The energy dependence of MicroDiamond response was measured on Varian Clinac 2100C/D, with photon energies of 6 and 18 MV, electron energies 6, 9, 12, 16 MeV (with corresponding R_{50} values for electron energies: 2.4 cm, 3.6 cm, 5.0 cm and 6.7 cm, respectively). The detector was set to depth in water 5 cm in 6 MV photon beam and 10 cm in 18 MV photon beam. Varying reference depths were set for electron beams (with SSD = 100 cm). All results were corrected using actual absorbed dose measurements in the same irradiation setup with calibrated Farmer ionization chamber (PTW 30011) for photons and Roos ionization chamber (PTW 34001) for electrons.

Temperature dependence

Temperature dependence of the response was investigated using Varian Clinac 2100C/D, photon energy 6 MV. The water in the water phantom was gradually heated by adding hot water to the phantom and proper stirring. Six measurements were performed for each water temperature, which ranged from 16.2–34.4°C.

Angular dependence

Angular response dependence was measured on Varian Clinac 2100C/D, photon energy 6 MV. The detector was positioned in free air in the isocenter of the accelerator with its axis parallel to treatment couch axis (figure 1) and perpendicular to it (figure 2). Plastic buildup was used during both measurements. MicroDiamond response was read at every 10° position through the entire 360° of gantry rotation.

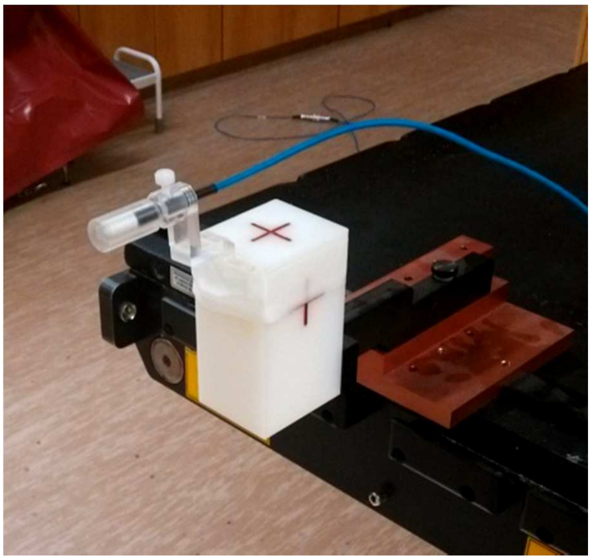

Figure 1. Irradiation setup for angular dependence measurement (detector axis parallel to treatment couch axis).

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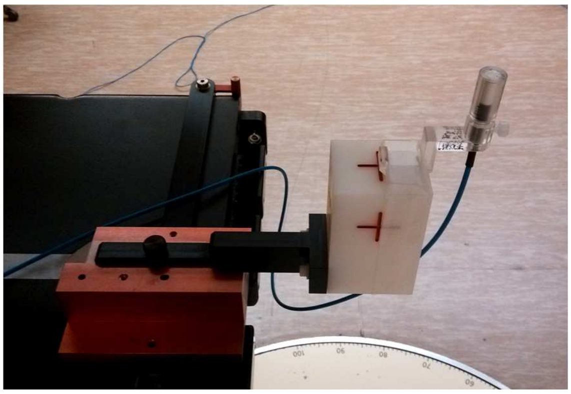

Figure 2. Irradiation setup for angular dependence measurement (detector axis perpendicular to treatment couch axis).

ROF measurement on Leksell Gamma Knife Perfexion

The first output factor measurement was performed on Leksell Gamma Knife Perfexion, which is stereotactic radiosurgery device with 192 ^{60}Co sources and collimator sizes of 4, 8 and 16 mm.

The MicroDiamond detector was positioned in the center of the Elekta ABS plastic spherical phantom and fixed in the phantom adapter by a docking device to the Leksell Gamma Knife Perfexion robotic couch (figure 3). ROFs at 4 and 8 mm collimation were calculated by normalizing the detector response to the response for the largest (16 mm) collimator. Two measurements were performed for each collimator, one with the detector axis parallel to the treatment couch axis and one perpendicular to this axis.

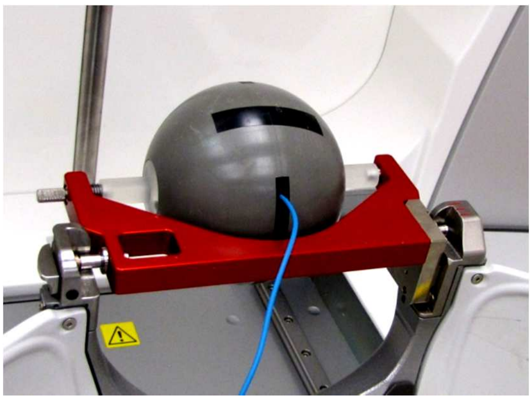

Figure 3. MicroDiamond detector irradiation setup in Leksell Gamma Knife Perfexion, detector positioned in an Elekta ABS plastic spherical phantom with special plate insert manufactured for the detector.

ROF measurement on CyberKnife

The second output factor measurement was performed on CyberKnife device; a radiosurgery system with a linear accelerator attached to a robotic arm, allowing irradiation with 6 degrees of freedom. The detector was set in water phantom and positioned in the center of the radiation field by measuring the dose profiles and correcting the position accordingly. Output factors of fixed circular collimators were investigated. There were 12 collimator sizes available and their diameters ranged from 60 mm to 5 mm. ROF of each collimator was calculated by normalizing the detector response to the response for the largest cone (60 mm in diameter).

MicroDiamond detector ROF measurements were compared to vendor composite data values (Accuray, Sunnyvale, CA) and measurements from clinically routinely used PTW 60017 Dosimetry Diode Type E. Composite data represented mean measured relative output factor values from various CyberKnife sites globally.

RESULTS

Stabilization of detector response (Pre-irradiation)

To achieve response stability better than 0.1% (calculated as the difference between maximum and minimum response values relative to mean response), pre-irradiation doses of 34 and 22 Gy were required for detectors 1 and 2, respectively (figure 4). The manufacturer suggested pre-irradiation of the MicroDiamond detector with 5 Gy. After irradiation with this dose, detector response stability was within 0.3% (calculation made using our data for detector stability).

Dose rate dependence

Results related to MicroDiamond response dependence on dose rate are shown in figure 5. Detector response slightly decreased with increasing incident radiation beam dose rate. The difference between maximum and minimum response values relative to the mean value of responses was 0.1%.

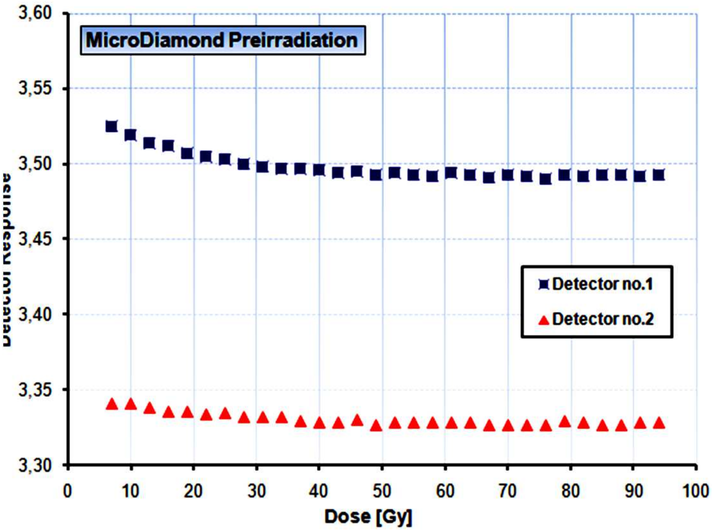

Figure 4. Stabilization of MicroDiamond detector response during pre-irradiation, two measurements with two different detectors were performed to validate the results, irradiation was performed with 6 MV Varian Clinac photon beam, field size 10 x 10 cm2, SAD = 100 cm, depth in water 5 cm.

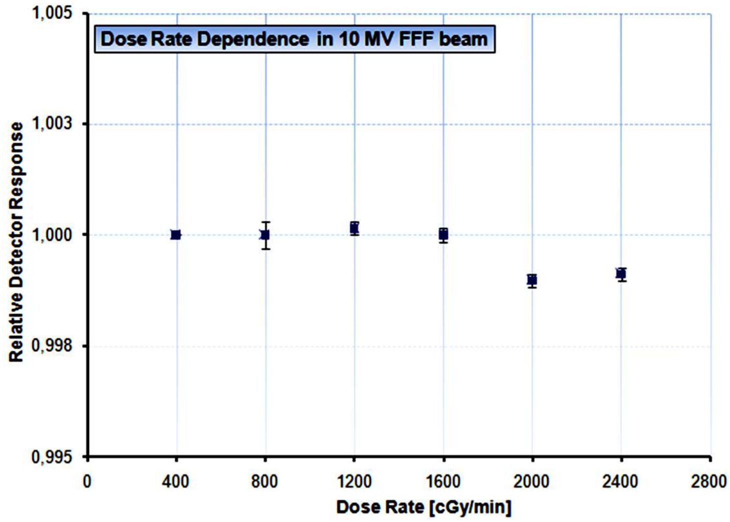

Figure 5. Dose rate dependence of MicroDiamond detector response (response values normalized to lowest dose rate), irradiation performed on Varian TrueBeam STx with 10 MV FFF photon beam, detector positioned in SAD = 100 cm and depth in water 5 cm, field size 10 x 10 cm^2.

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Energy dependence

The difference between maximum and minimum response values relative to the mean value for photons was 0.12%. These two measured energies (6 and 18 MV) represent the range of clinically used photon energies for modern radiotherapy devices. Most clinical cases in current radiotherapy are treated with the beam energies between 6 MV and 18 MV. Moreover, mass stopping power ratio for water and carbon is constant in the tested photon energy range; therefore, no energy dependence was expected.

For the investigated electron energy range (6 – 16 MeV), mass stopping power ratio for water and carbon changes slightly [(8)], thus energy dependence of the MicroDiamond detector response can be expected. The difference between maximum and minimum response values relative to the mean value was 1.6%. Results are shown in figure 6.

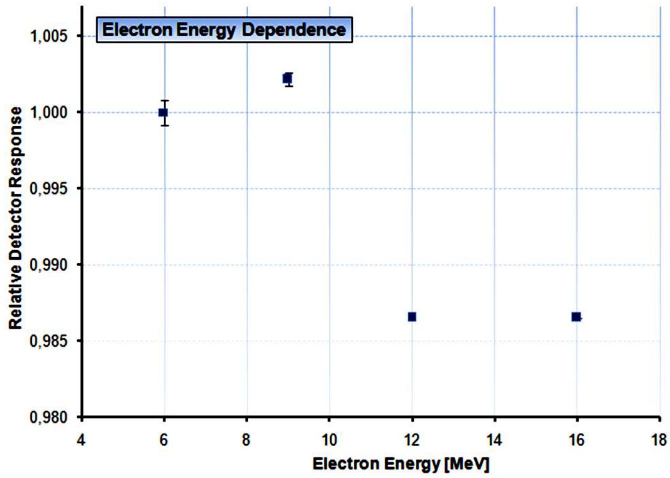

Figure 6. Electron energy dependence of MicroDiamond detector response, measurement performed on Varian Clinac using 6, 9, 12, 16 MeV electron energies, field size 10 x 10 cm^2, SSD = 100 cm and detector positioned at particular depths in water according to calibration of the Clinac for each energy.

Temperature dependence

The dependence of MicroDiamond detector response on temperature was studied in the range of 16.2–34.4 °C. The difference between maximum and minimum response values relative to the mean value was 0.52%. Our measurements suggested slightly decreasing trend of detector response values with increasing water temperature. However, through the normal range of temperatures under clinical conditions (approximately 18–25° C), detector response dependence on temperature was negligible. Results are shown in figure 7.

Angular dependence

The dependence of detector response on gantry angle with the detector axis oriented perpendicular to the beam axis is shown in figure 8. Detector response was normalized to the value at 0° gantry rotation. Resulting angular dependence may be influenced by incorrect detector positioning in the isocenter, however, our results did not indicate this. Thus, there was a slight dependence of detector response on gantry angle. The difference between maximum and minimum response values relative to the mean value was 0.9%.

Dependence of the detector response on gantry angle with the detector axis oriented parallel to the beam axis is shown in figure 9. Detector response was normalized to the value at 0° gantry rotation. The precision of this measurement is very sensitive to proper detector positioning in the isocenter, however, considering symmetrical response results, the detector was positioned accurately. Response dependence on gantry angle was clearly significant (up to 36% with maximum response observed for 140° and 210°).

ROF measurement on Leksell Gamma Knife Perfexion

To show the utility of the MicroDiamond detector in small field dosimetry and to evaluate detector performance during clinical dosimetric tasks, output factors for very small field sizes were measured. First, the output factors were measured on Leksell Gamma Knife Perfexion with 4 mm and 8 mm collimators. Measured values were compared with calculated Monte Carlo reference values recommended by the manufacturer (table 1). Output factor values were in good agreement with reference values, with maximum differences of 0.3% and 2.1% for 8 mm and 4 mm collimators, respectively.

ROF measurement on CyberKnife

The second output factor measurement was performed on CyberKnife device and all its fixed circular collimators. Results for ROF measured by the MicroDiamond detector compared to vendor composite data and measurements from PTW 60017 Dosimetry Diode Type E are shown in figure 10.

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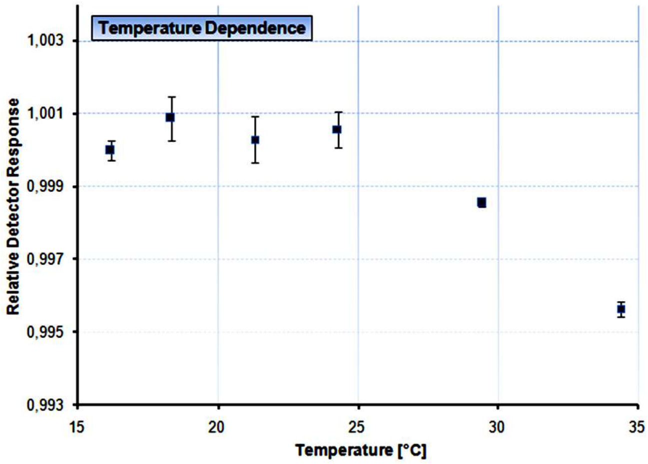

Figure 7. Temperature dependence of MicroDiamond detector response, measurement performed on Varian Clinac with 6 MV photon beam, field size 10 x 10 cm^2, SAD = 100 cm, detector depth in water 5 cm.

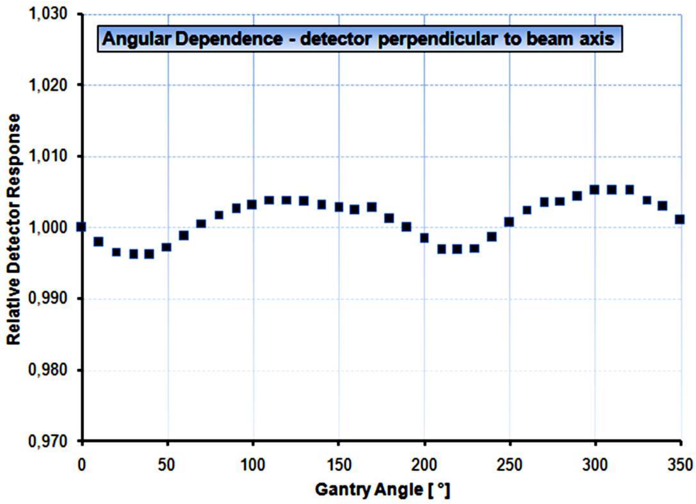

Figure 8. Angular dependence of MicroDiamond detector response (detector axis parallel to treatment couch axis), measurement was performed in free air using plastic buildup and 6 MV photon beam on Varian Clinac, detector was positioned into the isocenter of the accelerator, field size 10 x 10 cm^2.

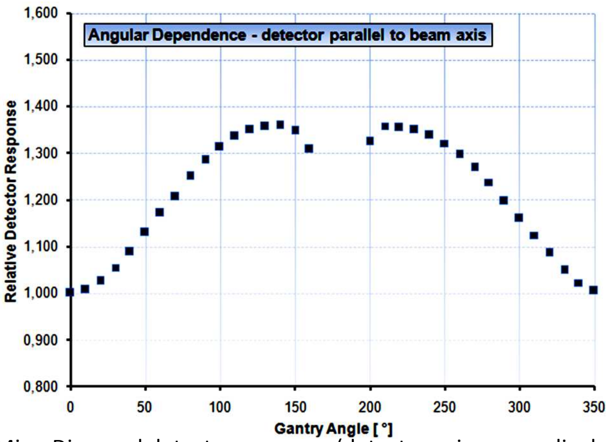

Figure 9. Angular dependence of MicroDiamond detector response (detector axis perpendicular to treatment couch axis), measurement was performed in free air using plastic buildup and 6 MV photon beam on Varian Clinac, detector was positioned into the isocenter of the accelerator, field size 10 x 10 cm^2.

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Table 1. Output factors of Leksell Gamma Knife Perfexion measured with MicroDiamond detector in an Elekta ABS plastic spherical phantom, detector positioned with its axis parallel and perpendicular to treatment couch.

Detector position	4mm ROF	8mm ROF	Deviation from vendor values [%]	
			4mm ROF	8mm ROF
MicroDiamond (axis parallel to couch)	0.831±0.001	0.900±0.001	2.1	-0.1
MicroDiamond (axis perpendicular to couch)	0.830±0.001	0.903±0.001	2.0	0.3

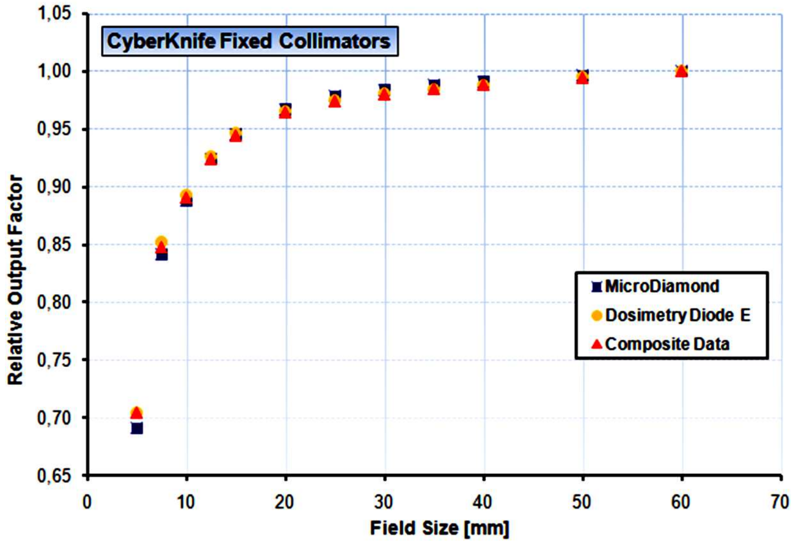

Figure 10. Relative output factors for CyberKnife circular fixed cone collimators measured by different detectors, MicroDiamond detector (blue squares) and Dosimetry Diode (yellow circles), measurement was performed using 6 MV FFF photon beam, SSD = 80 cm, detector depth in water 1.5 cm.

DISCUSSION

In the present study, the synthetic single-crystal diamond detector PTW 60019 MicroDiamond with a very small sensitive volume was evaluated, including its feasibility in small radiation field dosimetry. First, the basic physical and dosimetric properties important for detector reliability were verified, and subsequently results in relative small field dosimetry were evaluated on Leksell Gamma Knife Perfexion and CyberKnife devices.

Regarding pre-irradiation of the MicroDiamond detector, we found that more than 22 Gy dose was necessary to achieve response stability better than 0.1%. Thus, in contrast with the recommendation of the manufacturer (5 Gy pre-irradiation), the MicroDiamond detector needs to be pre-irradiated with at least 22 Gy to obtain reliable data. Measured data in this study are in close agreement with the results of Akino *et al.* [5], where response stability of 0.2% after 12 Gy pre-irradiation was reported, and similar to the results of Ciancaglioni *et al.* [6], Pimpinella *et al.* [20] and Laub *et al.* [8]. These authors presented response stability within 0.5% after pre-irradiation dose lower than 2.5 Gy.

According to our measurements, there was no significant influence of dose rate on charge collection efficiency when the MicroDiamond crystal was irradiated. This is in agreement with Brualla-González *et al.* [9] and Stravato *et al.* [10], where dependence of detector response less than 0.1% and 0.5%, respectively, was reported for the same dose rate range. Another study by Lárraga-Gutiérrez *et al.* [11] showed that, concerning dose rate dependence, the MicroDiamond detector was superior to stereotactic field diode (IBA Dosimetry, Germany), with a response dependence of 0.2% compared with 0.8% in the range of 160–800 cGy/min.

Energy dependence of the detector in photon beams was found to be minimal (0.12%), as expected. This result is in agreement with the

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work of Pimpinella *et al.* [20] and Laub *et al.* [8], where energy dependence of less than 1% for photon energy range of 6–15 MV was reported. However, energy dependence of detector response in megavoltage electron beams was found to be considerable (1.6%), so this value must be taken into account when precise electron measurements are performed with the MicroDiamond detector. Other studies showed less energy dependence on electron energy in the investigated energy spectrum (Pimpinella *et al.* [20] under 1% and Laub *et al.* [8] under 0.5%).

The dependence of MicroDiamond response on temperature was found to be negligible. In the current study, a temperature range of 16.2°C to 34.4°C was investigated, and detector response did not vary more than 0.52% in this range. The variation would be even smaller for a normal clinical temperature range (18–25°C). These results are in agreement with those of previous studies. Akino *et al.* [5] reported temperature dependence of MicroDiamond detector response less than 0.7% in the temperature range of 4–41°C, while Ciancaglioni *et al.* [6] showed temperature dependence less than 0.4% in the range of 18–40°C.

The angular dependence of detector response with the detector axis orientated parallel to the treatment couch axis was found to be less than 0.9%, with maximal response deviation from 0° gantry angle at approximately 90° and 270° (response deviated from basic gantry settings by nearly 0.5%). The trend of angular dependence of the MicroDiamond response is in agreement with that reported by Ciancaglioni *et al.* [6], showing response fluctuation within 0.5% during rotation.

The angular dependence of detector response with the detector axis oriented perpendicularly to the treatment couch axis was found to be significant, however, for angles between 0° and 10° that would be expected during routine measurements, (because angular inaccuracy of the detector position will be definitely lower than 10°), the response variation was lower than 0.7%.

Considering the particular uncertainties m entioned above, the total uncertainty of measurement with the new MicroDiamond detector, calculated as the square root of the sum of squared particular uncertainties, was within 0.8%. This uncertainty was reduced by sufficient pre-irradiation of the detector before measurement. For small field dosimetry, careful detector positioning in the center of the radiation field is crucial.

Finally, two clinical applications of the new MicroDiamond detector were performed. Output factors of 4 mm and 8 mm collimators on Leksell Gamma Knife Perfexion measured by the detector were in agreement with reference values from Elekta, with differences of 0.3% and 2.1% for 8 mm and 4 mm collimators, respectively. Results were similar for orientation of the detector with its axis parallel to the treatment couch and with its axis perpendicular to the couch axis. The output factor value for a 4 mm collimator was also confirmed by Mancosu *et al.* [12], who obtained a difference of 1.6% in comparison to the vendor supplied value.

For CyberKnife device, fixed circular collimators ranging from 60 mm to 5 mm ROF measured by the MicroDiamond detector were in agreement with vendor composite data and Dosimetry Diode measurement. The difference increased with decreasing diameter of the cone collimator with a maximum deviation not larger than 2%. Feasibility of the MicroDiamond detector for CyberKnife output factor measurement was also confirmed by study of Chalkley *et al.* [13], which showed agreement of MicroDiamond ROFs with several diode measurements within 2%.

Recently, several studies evaluating output factors of small radiation fields measured with the MicroDiamond detector have reported that the detector over-estimated output factors in radiation fields smaller than 1 × 1 cm^2 by 5% and more, indicating that correction factors are necessary (Ralston *et al.* [14], Lechner *et al.* [15], Girardi *et al.* [16] and Underwood *et al.* [17]). However, this effect was not observed in the present study with Leksell Gamma Knife Perfexion and CyberKnife, where measured values were in agreement (within 2%) with Monte Carlo calculations and vendor data.

CONCLUSION

In the present study, minimal dose rate, energy, temperature and angular dependence of MicroDiamond detector response were demonstrated. However, to obtain consistent results and high precision with this detector, a relatively high pre-irradiation dose of approximately 22 Gy was required.

Our results indicate that the MicroDiamond detector is a promising tool for small field relative dosimetry. For output factor measurements on Leksell Gamma Knife Perfexion and CyberKnife, the detector can be used with minimal response corrections (correction factors not larger than 2%).

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Conflicts of interest: *Declared none.*

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