


Evaluation and Comparison of Dosimetric Characteristics of Semiflex®3D and Microdiamond in Relative Dosimetry under 6 and 15 MV Photon Beams in Small Fields

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ABSTRACT

Background: In modern radiotherapy techniques, the frequently small and non-uniformed fields can increase treatment efficiency due to their highly conformal dose distribution. Particular features including lack of Lateral Charge Particle Equilibrium (LCPE) lead to detectors with high resolution since any error in obtained dosimetric data could cause patient mistreatments.

Objective: This study aims to evaluate and compare two small detectors (Semiflex®3D and microdiamond) dosimetric characteristics in small field relative dosimetry.

Material and Methods: In this experimental study, the dosimetric properties of Semiflex®3D and microdiamond were assessed under 6 and 15 MV photon beams. The linearity and stability of the detector's response and dose rate were measured. Square-field sizes ranging from 0.6×0.6 - 5×5 cm² were used for obtaining percentage depth dose curves (PDDs) and in-plane profiles. The angular and temperature dependence of both detectors' responses were also studied.

Results: The detector response shows good stability, no deviation from linearity, and low dose rate dependence ($\leq 1.6\%$). PDDs and in-plan profiles of both detectors are in good agreement and no significant difference was observed except for the high dose gradient regions ($P\text{-value} \leq 0.017$). Both detectors demonstrated low angular dependence ($< 0.3\%$) with temperature dependence lower than 1% for both detectors.

Conclusion: The results indicate both investigated detectors were well performed in small field relative dosimetry and for measuring penumbra, it is better to use microdiamond detector.

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Keywords

Radiotherapy, Conformal; Radiotherapy, High-Energy; Radiation Dosimeters; Small Field Dosimetry

Introduction

Incremental using advanced radiotherapy techniques, including Intensity-Modulated Radiotherapy (IMRT), Volumetric-Modulated Arc Therapy (VMAT), and Stereotactic RadioSurgery (SRS), composing of small and non-uniform fields leads to implement various detection modalities, which all geared towards an improved accuracy in determining either the absolute dose or of the relative dose profiles of

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these small fields [1-3].

These small high-dose fields conduct more precise treatment and healthy tissue shielding [4-6]. On the other hand, when the maximum range of secondary electrons is larger than small-field dimensions, the loss of lateral charged particle equilibrium (LCPE) on the beam axis occurs, leading to the major drawback of these small fields. Furthermore, dose-volume effect (when dose noticeably changes across the detector) and density difference between the detector and the surrounding medium are other issues of small beams [7-9]. Dosimetric measurements of the parameters in small ionizing irradiation fields are more complex due to their characteristics and any error in dosimetry data could affect the accuracy of the delivered dose, leading to erroneous patient treatments [10, 11].

Recent research has used small dosimeters and displayed detector properties playing a vital role in small field dosimetry [4, 12-14]. Among the large variety of detectors, the choice of a suitable detector for such superimposed-small photon beams could be challenging. For a detector dedicated to small field dosimetry, characteristics such as high resolution and sensitivity, tissue equivalence, and small active volume are considered [15-17].

According to the literature, no detectors fulfilled all small field characteristics for example diode detectors due to their energy dependence in low energies and over-response of shielded diodes (because of high-Z shield) are not fully ideal despite their small dimensions and high sensitivity [18]. Microdiamond detectors are another choice for small-field dosimeters and their characteristics, including radiation hardness, near tissue equivalence, small size, and independence from radiation quality. A. Ralston *et al.* obtained acceptable results of penumbra measuring and reproducibility of the microdiamond. However, research demonstrated these detectors couldn't accomplish all of the small-field aspects and over-responded due to high density [19-21]. In addition, ion-

ization chambers are less dependent on photon beam energy than diodes but less suitable for small field dosimetry because of volume effect and air low density [14, 22-24]. Recently, a new ionization chamber Semiflex[®]3D (31021) becomes available on the market shown near water equivalence, energy independence, and three-dimensional structure and has a small active volume (70 mm³) [25]. Prior research on testing commercialized Semiflex[®]3D in relative dosimetry displayed not only under-responded on the smallest field sizes (0.6×0.6, 1×1 cm²) but also overestimated the penumbra [26]. This work aims to evaluate this ionization chamber in relatively small fields and compare its specific characteristics with microdiamond, which proved a good candidate for small fields, under 6 and 15 MV photon beams.

Material and Methods

In this experimental study, the dosimetric evaluation of microdiamond (PTW 60019) and Semiflex[®]3D (PTW 31021) were compared in small photon beams. The main nominal characteristics of these detectors are summarized in Table 1 with measurements in an MP3 motorized water phantom (PTW) system (50×50×50 cm³) and a 3D scanning system controlled by Mephysto[®] software (PTW Company, Freiburg, Germany version 4.2.1). A TRUEFIX[®] system was used to adjust the effective point of measurement and detector irradiation was conducted using a Vital Beam Varian accelerator in X-ray mode. Among available energies 6 and 15, and beam qualities were selected, the examined accelerator was calibrated to deliver an absorbed dose to water rate of 1 cGy per monitor unit (MU) for all energies in reference condition with a fixed jaw determining the maximum field size of 40 cm×40 cm, equipped by a 120 leaves multileaf collimator, and a 1 mm leaf width at isocenter. The minimum symmetric field attainable is 0.6×0.6 cm². The measurements of our study were performed as follows.

Table 1: Nominal characteristic of the detectors

Detector	Type	Active volume (mm ³)	Sensitive material	Detector orientation	Voltage (v)
Semiflex [®] 3D(31021)	Ionization chamber	70	Air	axial, radial	400
Microdiamond(60019)	Synthetic diamond	0.004	Diamond	Axial	0

a) Linearity, stability, and dose rate dependence

Linearity, stability, and dose rate dependence were determined using the 6 and 15 MV photon beams and measured at SSD=100 cm for a 10×10 cm² field size, and detectors were vertically placed at 10 cm depth in a water phantom. To know the detector's effective point of measurement at the isocenter, the specific TRUFIX[®] for each detector was applied. Before the measurement session, some pre-irradiation was performed for detectors and machine warm-ups that evaluated linearity of charge versus delivered dose for doses ranging from 5 to 50 MU at 300 MU/min. The short stability of detectors was verified by five consecutive irradiations with 100 and 200 MU. The dependence on dose rate was evaluated ranging from 60-500 MU/min for both qualities by applying 100 MU radiation and detectors reading was collected by Uni DOSE electrometer.

b) PDD and profiles

PDD curves were measured for two detectors, placed in a vertical orientation for 6 and 15 MV photon beams. In-plan dose profiles at the depth of 35 cm to water surface were acquired for field sizes ranging from 0.6×0.6 and 5×5 cm² for comparing penumbra width and dosimetric field size. For data acquisition, Mephysto software was used and set on continuous acquisition mode with a speed of 5 mm/s. The profiles were obtained in a water phantom at SSD of 100 cm for two different depths (d_{max} , 10 cm). All relative measurements were with gantry angle 0° and dose rate

300 MU/min.

c) Angular dependency

Angular dependence of detectors' response was tested at d_{max} with 3×3 cm² field size and detectors were placed in vertical orientation and rotated around their long axis concerning the beam direction. Before placing the detectors in the phantom, a goniometer was used for marking 0, 45, 90, 135, and 180° degrees on Semiflex[®]3D holder and microdiamond specified Trufix. Also, a reference line coincided with 0° was marked on the body of detectors. After any irradiation, the detector signal was integrated on the electrometer for each angle.

d) Temperature dependence

Temperature stability was studied between 21 to 30 °C using the thermal device (two 1000 W elements) in the water phantom in which water volume was reduced to 100 liters to shorten thermal equilibrium time. Further, radiation was applied when water temperature reached the specific temperature. Two different thermometers were used for checking in various sites of the phantom measuring at a depth of 10 cm and 10×10 cm² field size, and detector signals were integrated into electrometer.

Results

The current study presents the results of the dosimetric evaluation, comparison of microdiamond, and Semiflex[®]3D in relative dosimetry in small beams.

a) Linearity, short-term stability, and dose rate dependence

As shown in Figure 1 (a, b), a linear fit is

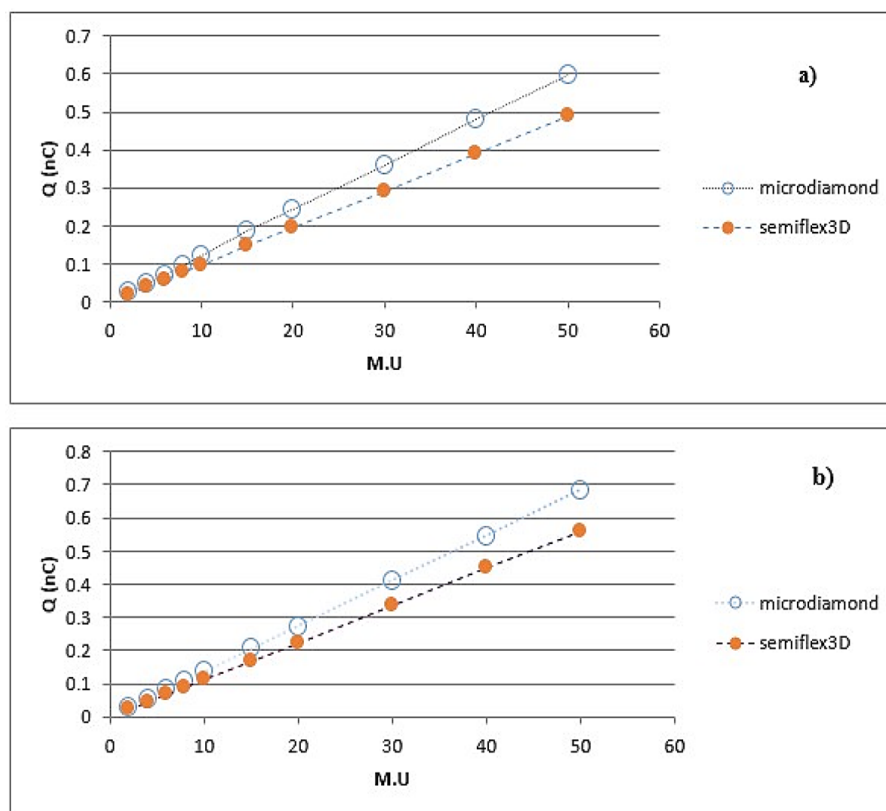


Figure 1: Linearity results in $10 \times 10 \text{ cm}^2$ at 10 cm depth a) Measured charge versus (vs) delivered Monitor Unit (MU) in 6 MV photon beams, b) in 15 MV Photon beams

applied to the experimental results: R^2 resulted in 1.000 for both energies and detectors and no deviation of linearity was for any of the detectors in the examined range.

The coefficient of variation (CV) was calculated for Semiflex[®]3D ≤ 0.1 , ≤ 0.06 and microdiamond ≤ 0.1 , ≤ 0.08 for 6 and 15 MV, respectively. By comparing the coefficient of variation, the observed detectors displayed good short-term stability in clinical dose rate.

In Figure 2 (a,b), the detector response is plotted for two dosimeters as a function of dose rate for $10 \times 10 \text{ cm}^2$. Semiflex[®]3D and microdiamond dose rate dependence is 1.6% and 1%, respectively. Both detectors are low-dose-rate dependent and the response of examined detectors is reduced by increasing dose rate.

b) PDDs and profiles

Percentage of the depth dose curves and in-plan profiles were measured for field sizes from 0.6×0.6 to $5 \times 5 \text{ cm}^2$ (Figure 3 (a,b)) and

PDDs (Figure 3a) of both detectors (in both energies) are in good agreement with each other in all field sizes.

Observing profiles of microdiamond and Semiflex[®]3D (Figure 3b) presented no significant difference except for the high-dose gradient regions. In Table 2, the penumbra values (calculated as the distance in the profile between 20% and 80% dose) and measured field size in Table 3 are reported for two detectors for field sizes up to $5 \times 5 \text{ cm}^2$ at 10 cm depth in both energies. In comparison with Semiflex[®]3D, the microdiamond that has a smaller active volume, indicates a narrower penumbra. Semiflex[®]3D's penumbra values in 6 and 15 MV photon beams were compared and significant deviation was found (P -value < 0.05). In both examined depths, Semiflex[®]3D measured larger penumbra in 15 MV rather than 6 MV beam. In contrast, there was no significant difference in microdi-

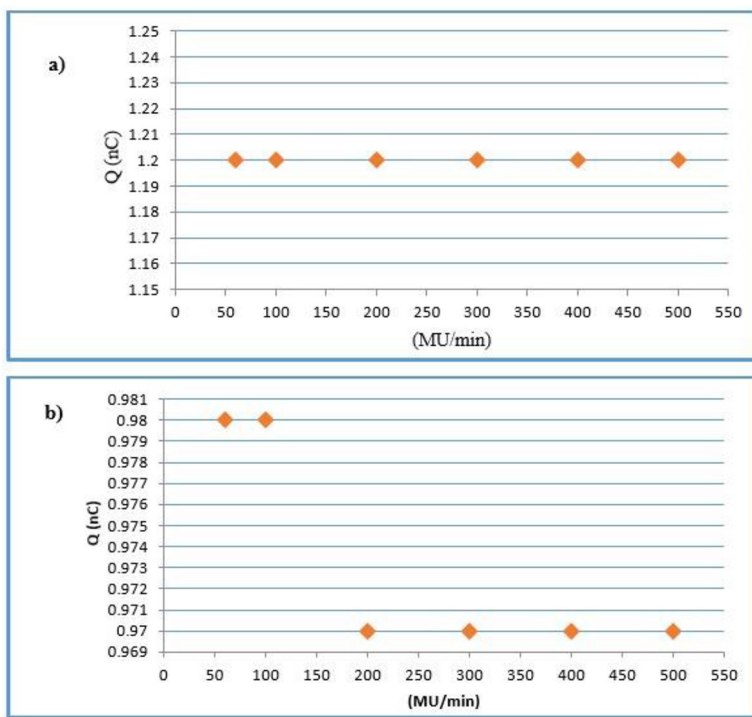


Figure 2: Dose rate dependence results in reference field $10 \times 10 \text{ cm}^2$ at 10 cm depth in 6 MV photon beams a) Microdiamond, b) Semiflex[®]3D

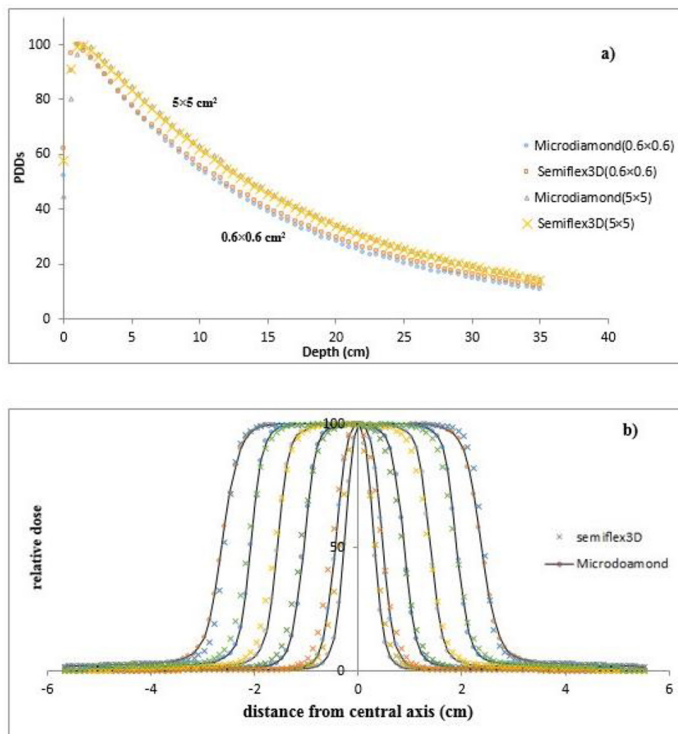


Figure 3: a) Percentage depth dose (PDDs) measured by two detectors in different field sizes in 6 MV photon beams, b) In-plane dose profiles at $d_{\text{max}} = 1.6 \text{ cm}$ with both detectors in 6 MV photon beams

Table 2: Measured penumbra at 10 cm depth for both photon beams

Field size (cm ²)	Measured penumbra at 6 MV (cm)		Measured penumbra at 15 MV (cm)	
	Microdiamond	Semiflex [®] 3D	Microdiamond	Semiflex [®] 3D
0.6×0.6	0.29	0.36	0.17	0.41
1×1	0.33	0.43	0.21	0.51
2×2	0.37	0.50	0.45	0.63
3×3	0.39	0.52	0.46	0.69
4×4	0.41	0.55	0.48	0.72
5×5	0.43	0.57	0.51	0.74

Table 3: Measured field size at 10 cm depth for both photon beams

Field size (cm ²)	Measured field's side size (cm) in 6 MV		Measured field's side size (cm) in 15 MV	
	Microdiamond	Semiflex [®] 3D	Microdiamond	Semiflex [®] 3D
	0.6×0.6	0.65	0.75	0.55
1×1	1.02	1.07	0.92	1.07
2×2	2.12	2.14	1.99	2.06
3×3	3.22	3.25	3.08	3.12
4×4	4.32	4.35	4.19	4.24
5×5	5.42	5.45	5.30	5.33

amond's penumbra values in the two energies.

According to Table 3, the present findings confirmed not only no significant difference between dosimetric field sizes and geometric ones but also no significant difference between two detectors' measured dosimetric field sizes. In terms of energy comparison, no significant deviation was seen for measured-field sizes by Semiflex[®]3D, but there was a significant deviation between microdiamond's measured field sizes in two energies at both depths.

c) The angular dependence

The angular dependence was examined by placing the detectors in the vertical direction at d_{\max} in a 3×3 cm² field size. The results are demonstrated in Figure 4 (a,b) as percent deviation from the response at 0 degree. Both dosimeters were rotated with respect to the

beam axis, ranging from 0 to 180° with 45° steps in two energies. The maximum deviation was 0.12% and 0.3%, respectively for microdiamond in 6 MV and Semiflex[®]3D in 15 MV in 180°.

d) Temperature dependence

The response of temperature dependence detectors was studied in the 21-30.5 °C range. For response stability and temperature equilibrium, each measurement was repeated three times (Figure 5 (a-c)). A maximum difference of 3.08% of uncorrected Semiflex[®]3D reading is derived at 15 MV in 30 °C, while microdiamond maximum deviation was 0.85% in 25.4 °C.

Discussion

In this work, some dosimetric properties of

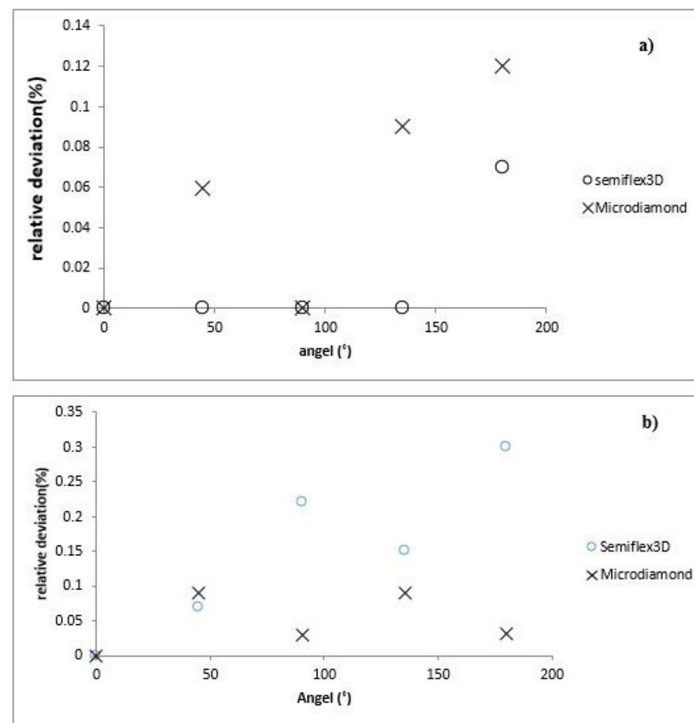


Figure 4: Angular dependence of Microdiamond and Semiflex[®]3D as normalized deviation from 0° value a) 6 MV, b) 15 MV photon beams

microdiamond and Semiflex[®]3D were evaluated, and their function in relative small-field dosimetry was compared. Both detectors were well performed in relative small field dosimetry.

In small photon beams, detector properties play a crucial role in accurately calculating dose distribution and monitor units [27-29]. Not only water equivalence but also active volume size of the detector is influencing dosimetric characteristic determinations [24]. By progressing small high-resolution detectors, some research was conducted for introducing proper detectors [2, 18, 22, 28, 30].

International dosimetry protocols recommended linear, stable, and dose rate independent radiation dosimeters for radiotherapy that linearity is determined by the type of dosimeter and its physical characteristics [31, 32]. The observed data showed linear behavior ($R^2=1.00$) with good short-term stability of both detectors in both energies.

Another promising finding was the low-dose-rate dependence of both detectors ($\leq 1.6\%$) in examined range. According to the literature, detector's linear deviation and dose rate dependence are recommended less than 1%, which our results indicated good agreement with this constraint; however, further dose rate dependence measurements are offered for Semiflex[®]3D [33]. LB. González et al. observed low-dose rate dependency in 6-8 Gy/min range and L. Gutiérrez et al. represented 0.2% dose rate dependence of microdiamond. Furthermore, G. Reggiori et al. reported linear deviation less than 0.8% for microdiamond [19, 34, 35]. Overall, our findings are in line with those reported by other authors, evaluating microdiamond and introducing it as a linear, stable, and low-dose-rate for dependent dosimeter. These three characteristics of Semiflex[®]3D have not been evaluated until now.

As seen in Figure 3(a), no significant devia-

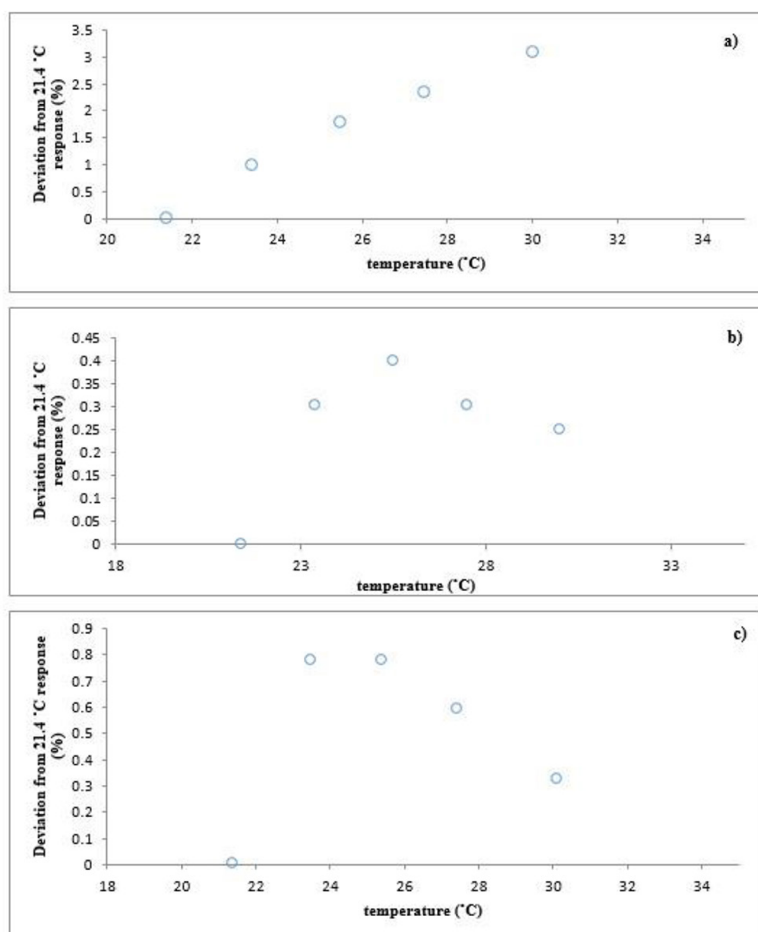


Figure 5: Temperature dependence of detectors response as normalized percentage deviation from 21.4 °C in 15 MV photon beams a) uncorrected response of Semiflex®3D, b) corrected response of Semiflex®3D (applied $K_{T,P}$), c) Microdiamond response

tion is between PDD curves attained by two detectors in 6 MV beams with the same result for 15 MV photon beams. Comparing the PDD curves at 6 and 15 MV energies demonstrated the field size dependence of PDD is less pronounced for the high energy due to increasing forward scattering beams for both detectors.

Measured penumbra is reported for field sizes ranging from 0.6-5 cm at depth of 10 cm, and 6 MV and 15 MV (Table 2). The outcomes of highlight significant deviation between penumbra widths are measured by Semiflex®3D and microdiamond (P -Value < 0.05 for both energies and depths), which measured narrower penumbra. The same result was attained from PM. Denia et al. by examining these two detectors in small fields that reported narrower pen-

umbra measured by microdiamond because of its smaller active volume [26] because of air low density and chamber wall non water-equival or inner electrode. Air-filled ionization chambers induced perturbation in particle fluence affecting the penumbra measurement in small fields. On the other hand, the mass density of diamond is much higher than that of the air in ionization chambers, resulting in smaller detector volumes with high sensitivity and spatial resolution of microdiamond, minimizing the volume effect and measuring narrower penumbra by microdiamond [36].

In terms of comparing penumbra width measured by Semiflex®3D in two energies 6 and 15, penumbra values in the 6 MV beam were narrower than 15 MV. In the range of megavolt

beams, incremental energy results in increasing the range of scattered electrons. The lateral dose variation is slower in the field's edge for larger penumbra measured in 15 MV beam by Semiflex[®]3D. In light of microdiamond's smaller active volume, no difference in measured penumbras and no effect of changing energy at 6,15 MV were found.

Comparing the detectors' measured field sizes are reported in Table 3, which displayed no significant deviation (P -Value >0.05). It should be noted that in the smallest field sizes 0.6×0.6 , 1×1 cm² Semiflex[®]3D overestimated field sizes for both energies and depths because of its larger active volume. PM. Denia et al. also compared these two detectors' field sizes and found Semiflex[®]3D overestimated the smallest field sizes compared to microdiamond and attributed to its active volume size [26].

According to Table 3, field sizes attained by microdiamond at 6 MV were larger than 15 MV. Notably, changing energy had no influence on measured-field sizes by Semiflex[®]3D with microdiamond.

Partial occlusion of photon source leads to loss lateral charged particle equilibrium and the congruence of geometric and dosimetric field size breaks down. Hence, apparent field widening occurs in small beams. It is worth discussing that there was no difference in geometric and dosimetric field size measured by the examined detectors in our results (P -Value >0.05) due to their small enough active volume.

Angular dependence was tested by placing the detector's axis parallel to the beam directions in both energies. The normalized data illustrated maximum variation in the full examined range occurred in 180°, 0.12%, and 0.3% for microdiamond and Semiflex[®]3D, respectively. As three dimensional Semiflex[®]3D structure, lower variation was expected; however, this small angular dependency of Semiflex[®]3D can be attributable to its structure (inner electrode) and larger active volume than microdiamond. B. Delfs et al. examined

dose-response in three-dimensional features of the Semiflex[®]3D by determining its dose-response function in three different chamber orientations and the same δ of three functions attained proved its three-dimensional behavior [37]. S. Kampfer et al. tested microdiamond angular dependence in the kV energy range in Small Animal Radiation Research Platform (SARRP) [38]. Their results demonstrated microdiamond maximum variation was 20% in 90° with a discrepancy in our results due to: a) differences in the energy, i.e. the more energy, more forwarded scatter, and b) measuring in the air without phantom. Note, the other research didn't measure in 180° but we did [38].

Based on the results of temperature dependence, low-temperature dependence of both detectors in the same conditions was achieved, and both detectors can be suitable devices for in vivo dosimetry. Maximum deviation from reference temperature in 6 MV photon beams (Figure 5) was 0.85% for microdiamond and 3.36% for uncorrected Semiflex[®]3D's readings, which reduced to 0.64% based on applying pressure and temperature correction factor ($k_{T,p}$) for ionization chamber and referring to the effect of water temperature on the density of air in the ion chamber at the collecting volume. The deviation in 15 MV photon beam was lower than 6 MV.

The maximum deviations occurred in 5.5 °C for both detectors and energies. The peak on this range was attained in NM. Islam et al. work on examining a Farmer-type ionization chamber explained by competing for two physical phenomena, increasing in transmitted photons in water with low density before the peak, and decreasing in scattering beams production beyond 26 °C [39].

Low-temperature dependence of microdiamond was found in the study of Y. Akinoo et al. (embedded in a plastic case filled with ice-cold water) in the 4-60 °C range and reported the temperature dependency within 0.7%, which was in agreement with our findings [40].

Detector positioning and field size setting are the causes of uncertainties in our study that uncertainty of detector positioning was dimensioned by using TRUFIX system and led to the accuracy of ± 1 mm in EPOM placement. The uncertainty of the field size due to the reproducibility of the machine jaw positioning was < 1 mm. Eventually, the estimated uncertainties of external beam radiation therapy were below 1.5% as recommended [33].

Conclusion

To sum up, both detectors behave linearly and stably in examined range, resulting in an improvement in low-dose-rate dependency in these detectors. Penumbra evaluation shows volume-averaging effect and perturbation caused by Semiflex[®]3D induced larger penumbra. In general, both examined detectors can be used for small field dosimetry. Additionally, the smallest active volume detector can be also used for penumbra measurement.

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Authors' Contribution

A. Nickfarjam and Z. Momeni developed the original idea, performed the experiments, and wrote the paper. N. Namiranian did the statistical analysis and MH. Larizadeh contributed to the development of the idea. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

Not applicable, because this article does not contain any studies with human or animal subjects.

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Conflict of Interest

None

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