IOP Publishing Phys. Med. Biol. 65 (2020) 01NT01 (6pp) https://doi.org/10.1088/1361-6560/ab6154

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

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RECEIVED
5 September 2019

REVISED
5 December 2019

ACCEPTED FOR PUBLICATION
12 December 2019

PUBLISHED
13 January 2020

NOTE

Small field dosimetry correction factors for circular and MLC shaped fields with the CyberKnife M6 System: evaluation of the PTW 60023 microSilicon detector

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Keywords: small field dosimetry, CyberKnife, robotic radiosurgery, microSilicon detector

Abstract

The PTW 60023 microSilicon is a new unshielded diode detector for small-field photon dosimetry. It provides improved water equivalence and a slightly larger sensitive region diameter in comparison to previous diode detectors in this range. In this study we evaluated the correction factors relevant to commissioning a CyberKnife System with this detector by Monte Carlo simulation and verified this data by multi-detector measurement comparison. The correction factors required for output factor determination were substantially closer to unity at small field sizes than for previous diode versions (e.g. $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = 0.981$ at 5 mm field size which compares with corrections of 5%–6% with other stereotactic diodes). Because of these differences we recommend that corrections to small field output factor measurements generated specifically for the microSilicon detector rather than generic data taken from other diode types should be used with this new detector. For depth-dose measurements the microSilicon is consistent with a microDiamond detector to $<1\%$ (global), except at depths <10 mm where the diode gives a significantly lower measurement, by 6%–8% at the surface. For profile measurements, the microSilicon requires negligible corrections except in the low dose region outside the beam, where it underestimates off-axis-ratio (OAR) for small fields and overestimates for large fields. Where this effect is most noticeable at the largest field size and depth (115 mm $\times$ 100 mm and 300 mm depth) the microSilicon overestimates OAR by 2.3% (global) in the profile tail. This is consistent with other unshielded diodes.

1. Introduction

Accurate beam data measurement, including output factor (OF), percent depth-dose (PDD), and off-axis ratio (OAR), is challenging for the small radiation fields employed in radiosurgery and SBRT (Aspradakis *et al* 2010). A recent formalism proposed the use of detector and treatment beam specific correction factors to convert measurement ratios into the corresponding dose ratios to define these beam data (Alfonso *et al* 2008, 2017). We have previously evaluated these corrections for the CyberKnife® Robotic Radiosurgery System (Accuray Incorporated, Sunnyvale, CA) as appropriate for stereotactic diodes, small-volume ionization chambers, synthetic microDiamond detectors, and point scintillation detectors (Francescon *et al* 2012, 2014a, 2014b, 2017). The most commonly used detector for CyberKnife commissioning is currently the PTW 60018 stereotactic diode (PTW-Frieburg, Germany), which the vendor has recently replaced with the 60023 microSilicon detector. Both are p-type silicon diodes designed for use in small photon fields and share the same external form factor. However, there are differences in their construction (table 1) that might affect the small field response. For unshielded diodes, field size dependent changes in the perturbation factor associated with detector encapsulation around the silicon, which is largely epoxy resin, contributes about 50% of the overall correction factor for small field OF measurements (Francescon *et al* 2014b), and therefore the lower density of the epoxy used in the microSilicon design might result in a correction factor closer to unity. In addition, the increased sensitive region diameter with

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Table 1. Key differences between the PTW 60018 stereotactic diode and its replacement the 60023 microSilicon diode (nominal values provided by vendor, except 60018 epoxy density from Francescon *et al* (2012)). The nominal 60023 sensitive region diameter is in good agreement with experimental determination (Poppinga *et al* 2019).

	Diode 60018	Diode 60023
Entrance window	0.3 mm RW3 (1.045 g cm^{-3})	0.3 mm RW3 (1.045 g cm^{-3})
	0.27 mm epoxy (1.4 g cm^{-3})	0.01 mm Al (2.71 g cm^{-3})
		0.48 mm epoxy (1.15 g cm^{-3})
Sensitive region diameter	1.1 mm	1.5 mm
Sensitive region thickness	250 μm	18 μm
Sensitive region volume	0.24 mm^3	0.03 mm^3

the microSilicon design will increase the geometric perturbation factor at small field sizes (it increases by about 1% for a CyberKnife 5 mm fixed field based on a volume averaging calculation). The purpose of this study was to investigate these differences, and to provide overall PTW 60023 correction factors for use with CyberKnife.

2. Method

We have previously reported Monte Carlo simulations to generate measurement correction factors, k_Ω, for the CyberKnife M6™ System with circular and MLC shaped fields, applied to multiple detector designs including the PTW 60018 (Francescon *et al* 2017),

$$k_\Omega\left(r, z, f, r_{ref}, z_{ref}, f_{ref}\right) = \frac{D(r,z,f)_w \big/ D(r,z,f)_{det}}{D(r_{ref},z_{ref},f_{ref})_w \big/ D(r_{ref},z_{ref},f_{ref})_{det}} \tag{1}$$

where $D(r,z,f)$ is the MC calculated absorbed dose per history at off-axis position r, depth z, and field aperture f. The subscript 'det' indicates that dose is scored within the sensitive volume of the detector placed within a water phantom, and 'w' indicates that dose is scored at the same position in the absence of the detector. With appropriate selection of geometric parameters this method was used to calculate correction factors for OF, PDD, and OAR. Further details are provided in Francescon *et al* (2017).

In this work a model of the microSilicon detector was constructed using details provided by the vendor. This model was used to calculate k_Ω for OF over the full range of fixed collimator and MLC field sizes in the manufacturers reference geometry of 785 mm SSD and 15 mm depth, relative to the 60 mm fixed collimator (which is the machine specific reference field). The correction factor k_Ω was also calculated for OAR measurements at 785 mm source-surface distance (SSD) for the 5 mm and 60 mm fixed collimators. In all simulations the detector was oriented with its stem parallel to the beam axis as per vendor recommendations, in a water phantom at 785 mm SSD.

A chain of multiple MC simulations was employed to evaluate the detector perturbations associated with OF correction. This method was first described for ionization chambers by Bouchard *et al* (2009). This was amended for use with diode detectors by Francescon *et al* (2014b), and the perturbation factor nomenclature from that paper are used here.

OF measurements were performed using a CyberKnife M6 system at the vendor's test facility. OF measurements were made with fixed collimators and an InCise™ 2 MLC (Asmerom *et al* 2016) using PTW 60023 and 60018 diodes, PTW 60019 synthetic microDiamond, and an Exradin A16 (Standard Imaging, Middleton WI, USA) microchamber. Measurements were performed at 785 mm SSD and 15 mm depth in water and were normalized to the 60 mm fixed collimator. PDD and OAR measurements were made in the same setup at multiple depths using the 60023 and 60019 detectors. The 60019 microDiamond was selected for this comparison since it has been previously shown to require significantly smaller corrections for PDD and OAR measurements (generally $<$ 1%) across this range of field sizes than any diode or microchamber (Francescon *et al* 2017). All detectors were mounted with their stems parallel to the beam axis. Further details of the measurement technique are in Francescon *et al* (2017). Note that all field sizes are defined at 800 mm distance from the source.

3. Results

Tables 2 and 3 show the k_Ω (0, 15 mm, f, 0, 15 mm, 60 mm fixed collimator) for the microSilicon detector. In this situation the reference is the machine specific reference field for CyberKnife, and k_Ω is identical to $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ as defined in (Alfonso *et al* 2008, 2017). Figure 1 shows small field OF measurements using multiple detectors before and after correction using $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ from this study for the microSilicon or from Francescon *et al* (2017) for the other detectors. Before correction the microSilicon measurement ratios are larger than the A16 microchamber in small fields (up to 9.4% at 5 mm field size) and smaller than the 60018 diode (up to 3.8%). After correction, the

Table 2. Monte Carlo calculated k_Ω for fixed circular collimator OF measurement correction, which correspond to $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ (Alfonso *et al* 2017), with the PTW 60023 microSilicon detector and the CyberKnife M6 System. The estimated total uncertainty in each factor is <0.75% ($k = 1$).

	$k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$					
	Field size (mm)					
Detector	5	7.5	10	12.5	15	20
PTW 60023	0.981	0.981	0.986	0.993	0.996	1.000

Table 3. Monte Carlo calculated k_Ω for MLC OF measurement correction, which correspond to $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ (Alfonso *et al* 2017), with the PTW 60023 microSilicon detector and the CyberKnife M6 System. The estimated total uncertainty in each factor is <0.75% ($k = 1$).

	$k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$					
	Field size (mm)					
Detector	7.6 × 7.7	15.4 × 15.4	23.0 × 23.1	53.8 × 53.9	84.6 × 84.7	115.0 × 100.1
PTW 60023	0.983	0.998	0.999	1.000	0.999	0.994

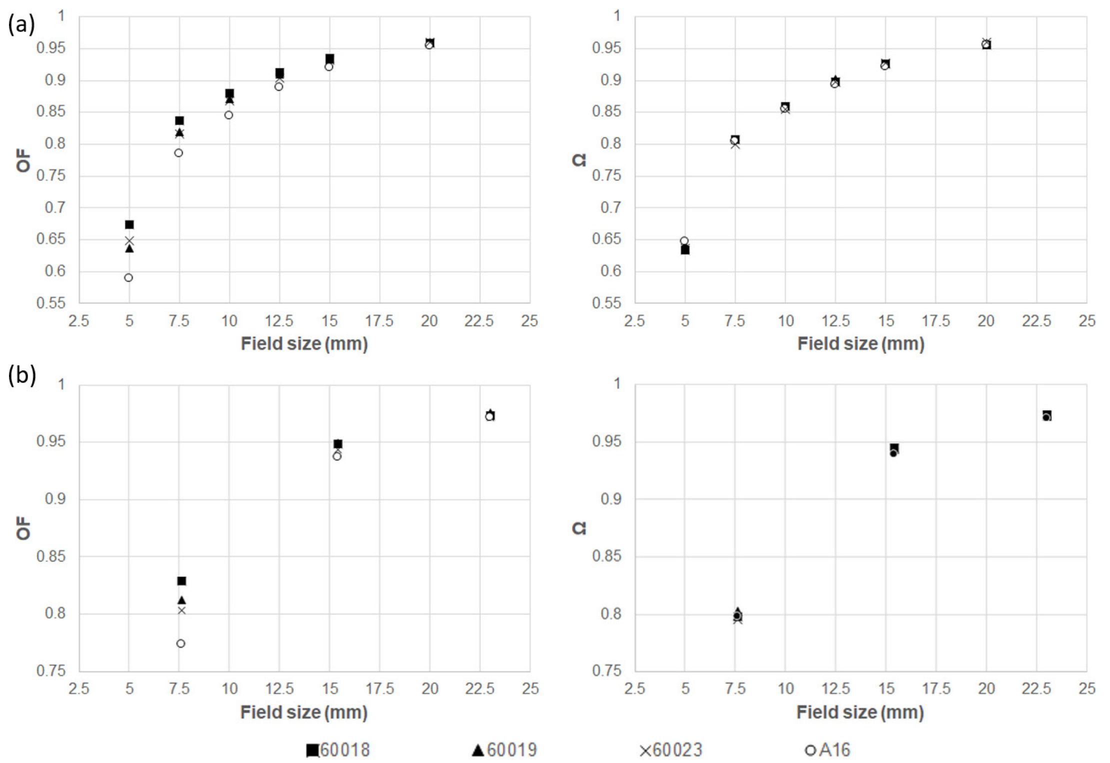

Figure 1. Measured output factors for the smallest CyberKnife System field sizes before ($\mathrm{OF}_{det}^{f_{clin},f_{msr}}$, abbreviated to OF in the axis title) and after ($\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, abbreviated to Ω in the axis title) correction using the $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ data from tables 2 and 3 for microSilicon and from Francescon *et al* (2017) for the other detectors. Data is shown for (a) fixed collimators and (b) MLC. Estimated total uncertainty in the measured $\mathrm{OF}_{det}^{f_{clin},f_{msr}}$ data is <0.55% ($k = 1$). Note the change in Y-scale between (a) and (b).

microSilicon OF's differ from the 60018 by ⩽0.9% at all field sizes, and from the A16 by ⩽1.6%. The microSilicon measurements are most similar to those of the 60019 microDiamond (raw measurement ratios agree to <1.8% at all field sizes, decreasing to ⩽1.0% after corrections are applied to both measurements). At all fields ⩾7.5 mm the raw microSilicon and microDiamond OF measurements agree to ⩽±0.7% which is within the combined uncertainty.

Table 4 shows the perturbation factors contributing to $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ for the microSilicon detector as a function of field size. All of the perturbations remain constant with field size to ⩽2%. The overall $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ correction is mainly influenced by the encapsulating material (P_{wall1}) and silicon surrounding the sensitive volume (P_{wall2})

Table 4. MicroSilicon perturbation factors at 15 mm depth on central axis for fixed circular collimators, normalized to the same perturbation factor at 60 mm field size.

Field size (mm)	P_{wall1}	P_{wall2}	$P_{fl}\left(^{L}/_{\rho}\right)^{w}_{\mathrm{det}}$	P_{ρ}	P_{geom}
5	0.991	0.980	0.999	0.997	1.013
7.5	0.989	0.990	1.001	0.998	1.002
10	0.991	0.994	1.001	0.999	1.000
12.5	0.993	0.997	1.002	0.999	1.002
15	0.994	0.999	1.002	0.999	1.001
20	0.997	1.001	1.002	1.00	0.999

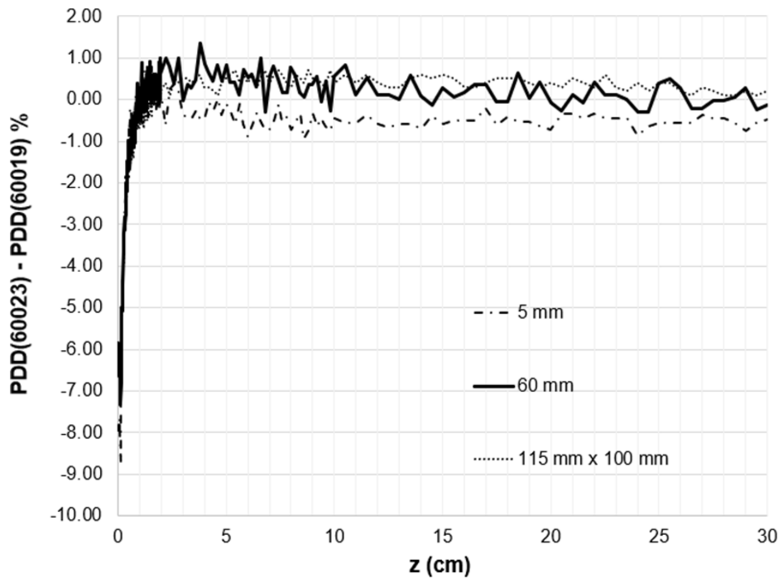

Figure 2. Percentage Depth Dose measurements with the microSilicon detector minus measurements using the PTW 60019 synthetic microDiamond detector at 785 mm SSD for the 5 mm and 60 mm fixed collimators and the maximum 115 mm × 100 mm MLC field size. For each field size the PDD were normalized at the depth of maximum dose determined using the microDiamond. Differences are <1% except within 10 mm of the water surface, where the microSilicon gives a significantly lower measurement.

which drive the measurement overestimation at small field sizes. These effects are partly offset at the very smallest field size by volume averaging (P_{geom}).

Figure 2 shows the difference between microSilicon and microDiamond PDD measurements over the full range of field sizes. For each field size the PDD were normalized at the depth of maximum dose determined using the microDiamond. At more than 10 mm depth the two measurements agree within 1% (normalized to d_{max} dose) for all field sizes. Closer to the surface the microSilicon detector gives a significantly lower measurement than the microDiamond in all field sizes, by up to 6%–8% at the water surface.

Figure 3 shows $k_{\Omega}(r,z,f,0,z,f)$ for OAR measurement. The corrections are <1% inside the field and immediately beyond the field edge. At larger off-axis distances the response is more complex. For small fields the microSilicon underestimates OAR and for larger fields it overestimates. The impact of this effect is shown in figure 4, which compares OAR measured at large field sizes and depths, where out-of-field OAR is largest, using the microSilicon, microDiamond, and 60018 diode detectors. Inside the beam and just outside the field edge all agree well so, for example, measurements of FWHM are consistent. Outside of the beam the 60023 measured OAR is typically 1.3% higher than the 60019 (normalised to central axis dose) at 60 mm field size, increasing to 2.3% at 115 mm × 100 mm. The 60023 and 60018 measurements are very similar at all positions.

4. Discussion

The purpose of this study was to evaluate the small field dosimetry characteristics of the microSilicon detector, and specifically to calculate and verify the correction factors required for the TRS-483 formalism (Alfonso *et al* 2017) with the CyberKnife system. The microSilicon is shown to overestimate output factors at field sizes smaller than 20 mm, to a degree that increases with decreasing field size. This trend is consistent with other stereotactic diode detectors. However, the correction factor magnitude is significantly smaller with the microSilicon. The largest measurement correction observed was about 2% ($k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ = 0.981 at 5 mm field size), which compares

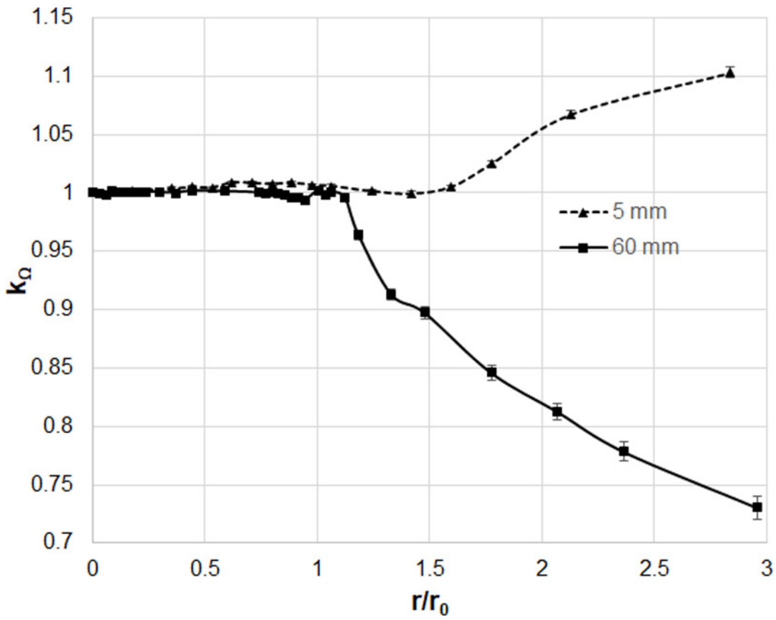

Figure 3. MC calculated correction factors for OAR measurement $k_\Omega(r,z = 100\,\text{mm},f,0,z = 100\,\text{mm},f)$, simplified to k_Ω in the figure, as a function of off-axis distance for the microSilicon detector at 785 mm SSD. Data is shown for the 5 mm and 60 mm fixed collimators at 100 mm depth. The *x*-axis shows the off-axis distance, *r*, as a proportion of the geometric field radius, r_0.

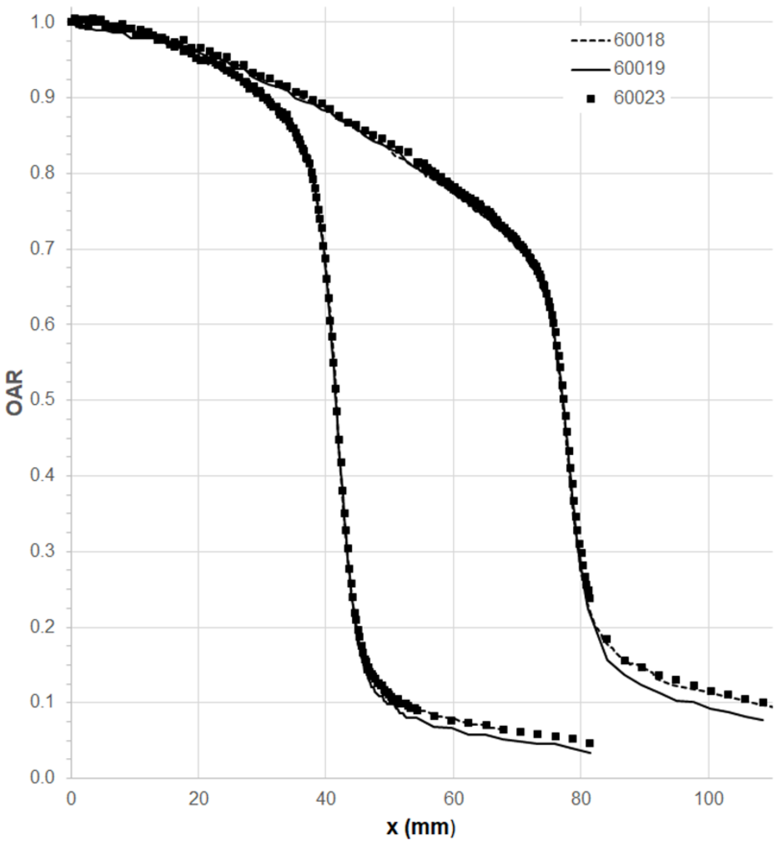

Figure 4. Measured OAR for the 60 mm fixed collimator and the 115 mm × 100 mm MLC field at 785 mm SSD and 300 mm depth. PTW 60023 microSilicon detector measurements are higher than PTW 60019 synthetic microDiamond measurements outside the beam by about 1.3% at 60 mm field size, and by 2.3% at 115 mm × 100 mm (normalized to central axis dose). The microSilicon measurements are very similar to the PTW 60018 diode measurements at all positions.

with corrections of 5%–6% for the same conditions with other stereotactic diodes (Francescon *et al* 2017). The microSilicon corrections are smaller (i.e. closer to unity) than those for the 60018 diode (Francescon *et al* 2017) by 1%–4% at field sizes $\leqslant 12.5$ mm. These $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ were confirmed by detector measurement comparison (figure 1).

Because of these significant correction factor differences between the microSilicon and other diode designs we recommend that $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ specific to the microSilicon detector is used (i.e. for CyberKnife measurements we recommend using the correction factors from this study rather than Francescon *et al* (2017) or CyberKnife data in TRS-483).

Schönfeld *et al* (2019) have recently evaluated microSilicon output factor corrections for a Siemens Artiste 6MV beam at 100 mm depth and square fields down to 5 mm × 5 mm, by measurement comparison with a point scintillation detector. That work also showed that the microSilicon overestimates OF at field sizes <20 mm, but to a much lesser degree than the unshielded PTW 60017 diode (their largest correction was 4% with the 60023 versus 7% with the 60017).

The PDD measurement comparison shows that the microSilicon is suitable for relative dose measurements along the central axis over the full range of CyberKnife fields without correction. Differences were observed between microSilicon and microDiamond detector measurements at depths <10 mm, rising to 6%–8% at zero depth. Stereotactic diodes have been previously shown to underestimate close to the surface, for example with the 5 mm fixed collimator the 60018 diode is associated with a depth-dose correction factor at zero depth of approximately 1.06 (Francescon *et al* 2014b). In addition the impact of experimental set-up uncertainties and inter-detector construction uncertainties is maximised in the very steep dose gradients near the surface. One repeat measurement on a separate occasion and using a different microSilicon detector found the zero depth PDD difference was decreased to 5%. These differences merit further investigation, but we do not consider them to affect the suitability of the detector for commissioning measurements.

For OAR measurements the microSilicon detector underestimates OAR in the low dose profile tail (i.e. outside the beam edge) at small field sizes and overestimates in this same region for larger field sizes, which is consistent with the behaviour of other unshielded diode detectors. A user should be aware of this when evaluating a beam model fit in the profile tail, and preference might be given to the synthetic microDiamond detector, if available, for OAR measurements.

On a practical note, the microSilicon detector produces a lower signal than the 60018 diode (about 10× lower) consistent with the smaller sensitive volume, although this is still 10× larger than the synthetic microDiamond. Other important detector characteristics such as response linearity and sensitivity to dose-per-pulse, temperature, and radiation history are not evaluated in this work. Some of these have been investigated recently by Schönfeld *et al* (2019). With that qualification we conclude that the microSilicon detector is suitable for small field dosimetry with CyberKnife. It requires smaller corrections for small field Output Factor measurements than the 60018 diode which it replaces.

Acknowledgments

The authors wish to thank Dr Jan Wuerfel and Dr Daniela Poppinga from PTW for loaning the 60023 microSilicon detector used in this study, helpful discussions on the new detector design, and their comments on this manuscript.

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