



Original paper

Multi-site evaluation of the Razor stereotactic diode for CyberKnife small field relative dosimetry



Serenella Russo^{a,*}, Laura Masi^b, Paolo Francescon^c, Paolo Dicarolo^d, Elena De Martin^e, Cristina Frassanito^f, Irene Redaelli^g, Sabrina Vigorito^h, Michele Stasi^{i,j}, Pietro Mancosu^k

^a Medical Physics Department, Azienda USL Toscana Centro, I-50012 Firenze, Italy

^b Department of Medical Physics and Radiation Oncology, IFCA, Radiotherapy, I-50139 Firenze, Italy

^c Department of Radiation Oncology, Ospedale Di Vicenza, I-36100 Vicenza, Italy

^d Medical Physics Unit, Meyer Children's University Hospital, I-50139 Firenze, Italy

^e Medical Physics Unit, Istituto Besta, Radiotherapy, I-20133 Milano, Italy

^f Radiotherapy Department, Mater Dei Hospital, Città di Bari Hospital spa, I-70125 Bari, Italy

^g Medical Physics Unit, C.D.I., Radiotherapy, I-20147 Milano, Italy

^h Unit of Medical Physics, I. E. O., Radiotherapy, I-20141 Milano, Italy

ⁱ Medical Physics Department, A.O. Ordine Mauriziano, I-10128 Torino, Italy

^j Medical Physics Department, Candiolo Cancer Institute – FPO, IRCCS, I-10060 Torino, Italy

^k Medical Physics Unit of Radiation Oncology Dept, Humanitas Clinical and Research Hospital, I-20089 Rozzano-Milano, Italy

ARTICLE INFO

Keywords:

Field output factors
CyberKnife
Silicon diode detector

ABSTRACT

Purpose: The aims of this study were: (i) to validate in a multi-site context the suitability of the IBA Razor silicon diode detector for CyberKnife relative dosimetry. (ii) to fit the multi-center experimental data into a function relating the field output factors to the effective field size (EFS).

Methods and materials: Ratio of detector readings in clinical and reference field (OF_{det}) and beam profiles were acquired on five CyberKnife units for fixed collimator diameters (range 5–60 mm), using both Razor and PTW 60017 diodes. Measured OF_{det} were corrected using published MonteCarlo correction factors to get field output factors $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$. Profiles were analyzed in terms of penumbra and EFS. $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ obtained in four centers were fitted as a function of EFS, while the data of the 5th center were used to validate the fitting curve.

Results: Differences between Razor and PTW60017 $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ were within 1.5% over all centers down to 7.5 mm aperture and within 3.5% for the 5 mm diameter. The fit showed a coefficient of determination $R^2 = 0.997$. The mean deviation of measured points from the predictive curve was within 0.5%. Data of the 5th center showed a mean deviation of 0.4% from the curve, with maximum differences within 2.5% for the 7.5 mm aperture.

Conclusions: The results confirmed the suitability of Razor detector for CyberKnife dosimetry by comparison to the PTW 60017 diode which has been well characterized and is in widespread use. The proposed mathematical relation between $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ and EFS is a robust predictive model applicable to different CyberKnife systems and detectors.

1. Introduction

Detector selection for small field dosimetry is not straightforward: high spatial resolution and water equivalence are the desirable attributes of a small field dosimeter [1,2], but most of the time the choice is the result of a compromise between different characteristics. Silicon diode detectors offer high resolution but exhibit a well-known over-response in small fields, due to having a higher density than water (2.3 g/cm^3) [3].

For small field sizes, however, unshielded diodes with small active areas appear to be a reasonable choice [4,5]. These devices have been the detector of choice in most centers to perform CyberKnife® (Accuray Inc., Sunnyvale USA) system dosimetric characterization and output factor measurements [6,7]. Recently, Francescon et al. [8] affirmed that preference should be given to a microDiamond or diode detector for small field output factor measurement because these have smaller corrections than microchambers and are also less sensitive to inter-unit variations in beam profiles. The over-response due to the high mass

* Corresponding author.

E-mail address: serenella.russo@uslcentro.toscana.it (S. Russo).

<https://doi.org/10.1016/j.ejmp.2019.07.027>

Received 21 May 2019; Received in revised form 22 July 2019; Accepted 30 July 2019

Available online 12 August 2019

1120-1797/ © 2019 Published by Elsevier Ltd on behalf of Associazione Italiana di Fisica Medica.

density of the active volume is the major reason for applying detector-specific correction factors $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ for silicon diodes in small fields [9–15].

An unshielded p-type silicon diode, the Razor, has been introduced by IBA (IBA Dosimetry, Schwarzenbruck, Germany) as a replacement of the IBA SFD diode. Compared to its predecessor, the Razor has been shown to be superior in its stability, dose linearity and radiation hardness [16]. The characterization of the response of the Razor diode in small fields generated by different models of linear accelerators (linacs) has been previously conducted [17]. Francescon et al. [18] presented the first set of correction factors for Razor detector obtained by MC simulation for output factor, PDD, and OAR measurements on the CyberKnife M6 system, including circular collimators and MLC, and validated by comparison to measurements. The Razor silicon diode exhibits a smaller correction factor when compared to other commercial silicon diodes: Razor and PTW 60017 correction factors to convert the ratio of detector readings in clinical and reference field to the corresponding point dose ratio with a 5 mm fixed collimator were -3.5% and -5.1% respectively and -1.8% and -3.7% in a $7.6 \text{ mm} \times 7.7 \text{ mm}$ MLC field.

The use of detectors requiring small correction factors is recommended in literature [3,19] since correction factors are valid only for the detector model and the specified beam they were calculated for. It is important to note that the need to apply large corrections may lead to serious errors directly on the dose delivered to the patient. Given the lower correction factor for Razor diode compared to PTW 60017 one, an evaluation of the Razor diode detector for CyberKnife relative beam dosimetry through the intercomparison between different institutions is recommended according to the methodology suggested by the TRS 483. The aims of the present study were:

- (i) to validate in a multi-site context the suitability of the Razor detector for CyberKnife relative small beam dosimetry as a possible alternative to PTW 60017 silicon diode, which is at the moment the most widely used detector for CyberKnife dosimetric characterization [6];
- (ii) to determine a mathematical function from multicentric experimental data and to evaluate its applicability in order to predict the field output factors as a function of effective field size for other systems.

This work was developed in the framework of the Italian Association of Medical Physics (AIFM) Stereotactic Body Radiation Therapy (SBRT) working group which was started in 2013 and dedicated to support the standardization of the involved procedures as well as to help the medical physicists to reach a high level of confidence in the accuracy of the entire treatment delivery process [20–33]. In particular, a sub-project was started aiming at the standardization of small beams dosimetry performing multi-institutional studies with different small field detectors [22,27–32]. The performance of a microdiamond and a plastic scintillator detector for CyberKnife output factor measurements has been previously validated [27,28], but this is the first multicenter study providing a complete dosimetric characterization of CyberKnife small beams, including output factor, field size and penumbra evaluation, by using the silicon diode Razor.

2. Methods

2.1. CyberKnife unit

The CyberKnife (Accuray Incorporated, Sunnyvale, CA, USA) is a radiosurgery system capable to delivery single or fractionated treatments with a 6 MV flattening-filter-free (FFF) beam mounted on a robotic manipulator (Kuka, Augsburg, Germany). CyberKnife VSI model operates in the latest version at 1000 MU/min dose rate, but the previous 800 MU/min G4 model is still in clinical use. Recently,

CyberKnife M6 series has been introduced where beam collimation is achieved by fixed cones, by Iris™ variable aperture collimator and by a multileaf collimator (MLC) [34]. The field size is always defined at a source detector distance of 80.0 cm.

The presented data were collected on five CyberKnife VSI systems operating all at 1000 MU/min dose rate, except for one working at 800 MU/min dose. The mean value and standard deviation over the enrolled linacs of beam quality factor $TPR_{20,10}$ measured for the 60 mm collimator was 0.637 ± 0.004 , showing negligible variation among the different linac designs.

The present study focused only on fixed collimators in order to rule out unwanted spurious effects due to the not perfect reproducibility of variable apertures (Iris™ or MLC).

2.2. Razor p-type silicon diode

The Razor detector (IBA Dosimetry, Schwarzenbruck, Germany) is an unshielded p-type silicon diode chip with a disk shaped active volume having the diameter of 0.6 mm and the thickness of about 0.02 mm. The Razor diode is encapsulated in a waterproof ABS plastic (acrylonitrile butadiene styrene) and epoxy resin. The active volume is located at a water equivalent depth of 0.4 mm below the detector surface. The detector works without any bias voltage.

The detector features a low dependence of sensitivity on dose and dose per pulse (overall variation in a range of 0.1–2.3 mGy is within 1%) [35].

2.3. Experimental measurements and data analysis

2.3.1. Output factors measurements

The participants were requested to perform output factors measurements with both Razor and PTW-60017 silicon diode for field sizes ranging from 5 to 60 mm defined by fixed circular collimators. The measurements were performed with the same Razor detector shared by the centers and with the PTW-60017 silicon diode used in daily practice in each center. Setup conditions were 80 cm source to detector distance and 1.5 cm depth in water and the normalization field was the circular field diameter of 60 mm. For detector centering, two orthogonal profiles were acquired in a 3D water scanner using step-by-step acquisition mode for the 5 mm diameter field with 0.1 mm steps by both the silicon diodes Razor and PTW 60017. Each detector was positioned where both profiles cross each other through the point of maximum detector signal. The dosimeters were used in parallel configuration, i.e. the detector axis parallel to the beam axis. The acquisition point was corrected for the active layer depth (i.e. 0.4 and 0.8 mm from the detector tip for Razor and PTW 60017 respectively). Measurements were averaged over 3 acquisitions using 200 monitor units (MU) exposures.

The CyberKnife measurements were analyzed in terms of detector readings ratio OF_{det} defined according to the formalism by Alfonso et al. [36] as the ratio of detector readings M in the clinical (f_{clin}) and in the machine specific reference field (f_{msr}):

$$OF_{det}^{f_{clin}, f_{msr}} = \left(\frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \right) \quad (1)$$

For the CyberKnife system, f_{msr} is defined by the fixed 60 mm collimator.

The field output factor $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ that converts the absorbed dose to water for f_{msr} to the absorbed dose to water for f_{clin} can be written as:

$$\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}} = OF_{det}^{f_{clin}, f_{msr}} \cdot k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}} \quad (2)$$

Where $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ is the correction factor accounting for the difference between detector response in the fields f_{clin} and f_{msr} . Monte Carlo (MC) simulations can be used to estimate $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$.

For PTW-60017 MC correction factors calculated for CyberKnife VSI and G4 systems were published in 2012 by Francescon et al. [12] for

Table 1

Razor and PTW 60017 field output factors ($\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$) mean values over the five CyberKnife centers for fixed circular apertures. Data standard deviations are reported in parentheses beneath each field size value. Percentage differences between Razor and PTW 60017 $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ are also shown.

Field Size (mm)	5	7.5	10	12.5	15	20	30	40	60
$\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ Razor	0.677 (0.007)	0.823 (0.004)	0.872 (0.003)	0.910 (0.003)	0.934 (0.003)	0.959 (0.003)	0.975 (0.003)	0.986 (0.004)	1.000
$\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ PTW60017	0.668 (0.014)	0.820 (0.005)	0.872 (0.002)	0.913 (0.001)	0.940 (0.001)	0.967 (0.003)	0.983 (0.002)	0.990 (0.001)	1.000
% Difference	1.3%	0.4%	0%	−0.3%	−0.6%	−0.8%	−0.8%	−0.4%	

600 and 800 MU/min models. Recently, Francescon et al. [18] have presented $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ for PTW-60017 and Razor detector obtained by MC simulation on the new CyberKnife M6 system operating at 1000 MU/min. In this work, OF_{det} measurements performed in each center by PTW-60017 and Razor detectors were corrected applying Monte Carlo correction factors published by Francescon et al. [18] for systems operating at 1000 MU/min and $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ published by Francescon et al. [12] for PTW-60017 data measured on the 800 MU/min model.

2.3.2. Profile acquisition and analysis

Crossplane and inplane dose profiles ranging from 5 to 60 mm fixed collimators were measured by Razor detector in a 3D water scanner at source-to-water surface distance equal to 70 cm and at depth of 10 cm using step-by-step acquisition mode (parameters: distance between points: 0.2 mm; measurement point acquisition time: 0.5 s). Profiles were acquired with a reference diode placed into the specific detector port supplied to the CyberKnife system.

No manipulation was performed before the analysis procedure, except a normalization of all profiles to the central axis. Nominal field size (NFS) was the nominal diameter of fixed collimators.

Then, the following parameters were determined:

- The effective field size (EFS), defined as $EFS = \sqrt{A \cdot B}$, where A and B correspond to the in- and cross-line FWHM [3].
- Left and Right values of penumbra in the region 20%-80%. The values were evaluated for crossplane and inplane dose profiles and then averaged.

The measurements of crossplane and inplane dose profiles were repeated with PTW-60017 only in one center. These data were acquired only in one center just to verify there were no differences between the measurements of EFS and penumbra performed by the two detectors.

2.3.3. $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ vs EFS

The field output factors $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ were reported as a function of EFS. Values measured by Razor diode in the first 4 centers were used to determine a fit of the empirical data, following the equation reported by Sauer et al. [4]:

$$\Omega(EFS) = P_{\infty} * \frac{EFS^n}{l^n + EFS^n} + S_{\infty} * (1 - \exp(-b * EFS)) \tag{3}$$

where P_{∞} , S_{∞} , l , b and n are fit coefficients. In detail, P_{∞} represents the maximum primary dose component; S_{∞} represents the maximum scatter component. The point ($\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}} = 1$, EFS = 60 mm) was considered as a boundary condition in the fit. However, an estimation of $M_{Q_{msr}}^{f_{msr}}$ is required as EFS (60 mm) could differ from 60 mm. In this study, $M_{Q_{msr}}^{f_{msr}}$ was derived for each center from the fit of data with the Sauer equation for each single center.

Moreover, measurements performed in the 5th center were used to test the fit by calculating the differences between fitted and measured $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$.

3. Results

3.1. $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ data

Razor OF_{det} measured for fixed collimators in the enrolled centers showed a data set spread ranging from 1.2% to 0.4% for field sizes from 7.5 to 60 mm and equal to 2.2% for the smallest cone. The variability obtained for OF_{det} measured by PTW-60017 was similar: the data set spread was less than 1% for field sizes from 7.5 to 60 mm and equal to 3.5% for the smallest diameter.

The statistical dispersion of repeated measurements of OF_{det} was less than 0.5% for all field sizes and less than 1% for the smallest one for each of the centers enrolled in the study.

Mean field output factors obtained applying the detector specific correction factor $k_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ to the corresponding reading ratios of Razor and PTW60017 are reported in Table 1. Standard deviations as well as percent differences between the corrected values of both diode models are also shown.

The agreement between mean field output factors measured with Razor and PTW 60017 silicon diodes was within 1% for all fixed circular collimators from 7.5 to 60 mm and equal to 1.3% for the smallest aperture.

Regarding the relative differences between Razor and PTW 60017 $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ for each of the enrolled centers, they were below 1.3% for field sizes from 7.5 to 60 mm and increased up to 3.5% for the 5 mm aperture. In Table 2 the percentage differences between Razor and PTW

Table 2

Relative percentage differences between Razor and PTW 60017 silicon diode field output factors $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ for fixed collimators for each center involved in the project.

Field Size (mm)	5	7.5	10	12.5	15	20	30	40
Center 1 (800 MU/min)	−0.4%	−0.4%	−0.6%	−0.7%	−0.9%	−0.9%	−0.8%	−0.3%
Center 2 (1000 MU/min)	3.5%	1.2%	0.8%	0.1%	−0.3%	−0.8%	−0.8%	−0.5%
Center 3 (1000 MU/min)	3.2%	1.3%	0.5%	−0.1%	−0.4%	−0.8%	−0.7%	−0.4%
Center 4 (1000 MU/min)	−1.1%	−0.4%	−0.4%	−0.3%	−0.4%	−0.7%	−0.5%	−0.2%
Center 5 (1000 MU/min)	1.7%	0.2%	−0.3%	−0.6%	−0.9%	−1.0%	−1.1%	−0.7%

Table 3

Nominal (NFS) and effective (EFS) field size for beams defined by fixed circular collimators. Penumbra values are also reported. Mean value over the five centers and one standard deviation are shown.

NFS (mm)	5	7.5	10	12.5	15	20	30	40	60
EFS (mm)	5.3 ± 0.1	7.7 ± 0.1	10.0 ± 0.1	12.5 ± 0.1	15.1 ± 0.1	20.3 ± 0.1	30.5 ± 0.1	40.9 ± 0.1	61.2 ± 0.1
P _{20%-80%}	2.1 ± 0.1	2.3 ± 0.1	2.7 ± 0.2	2.8 ± 0.2	2.9 ± 0.2	3.1 ± 0.1	3.3 ± 0.1	3.6 ± 0.2	6.3 ± 0.4

60017 field output factors for fixed collimators for each of the enrolled centers are reported.

3.2. Nominal and effective field size data

Nominal field size (NFS), effective field size (EFS) and penumbra values measured with the Razor detector and averaged over the five CyberKnife centers are reported in Table 3. Maximum difference between NFS and EFS was about 6% for 5 mm field size. Mean penumbra values were less than 3 mm for field sizes up to 15 mm.

The measurements of crossplane and inplane dose profiles with PTW-60017 performed in one center agreed with the Razor data within the mechanical tolerance of the water phantom.

3.3. $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ vs EFS

The $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ measured in the four centers with Razor with relative fit plotted as a function of EFS are reported in Fig. 1a. All data have been used for the fit. Experimental uncertainties scored are also shown whereas a detailed description of the uncertainty budget estimation is described in a specific following section.

The fit showed a coefficient of determination $R^2 = 0.997$. The mean deviation of measured points from the curve was within 0.5%, with a maximum value of 4.1% for the 5 mm field. In Fig. 1b the distribution of the residuals of $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ with respect to the fitted curve is shown for each center and each field size.

Table 4 reports the coefficients of the mathematical relation found for $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ as a function of EFS with the relative confidence interval. The value of P_∞ is determined by imposing that $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ for the reference collimator diameter (60 mm) was equal to 1.

The deviations between the fitted curve obtained by the first four centers and the $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ obtained from Razor measurements performed in the 5th center are reported in Fig. 2. The uncertainties of the differences between the fitted and the measured data were considered equal to measured $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ uncertainties.

The mean deviation was 0.4% confirming the good quality of the mathematical relation. The maximum differences of about 2.2% was

Table 4

Parameters in Eq. (1) describing the experimental relation between $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ and EFS for CyberKnife systems.

Fit parameters	S_∞	L	n	B
Coeff. Value	0.9532	38.79	2.266	0.2468
95% confidence bounds	0.9181/ 0.9882	25.78/ 51.81	-1.338/5.869	0.2272/ 0.2664

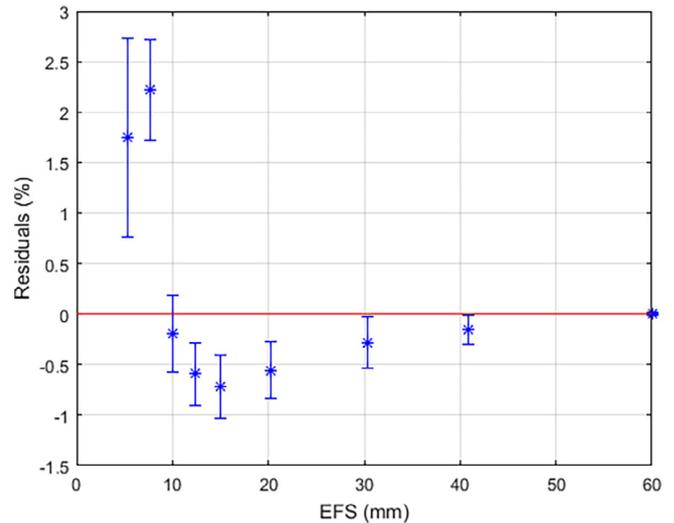


Fig. 2. Difference between theoretical fitted values and $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ obtained from corrected Razor measurements performed in the 5th center as a function of EFS.

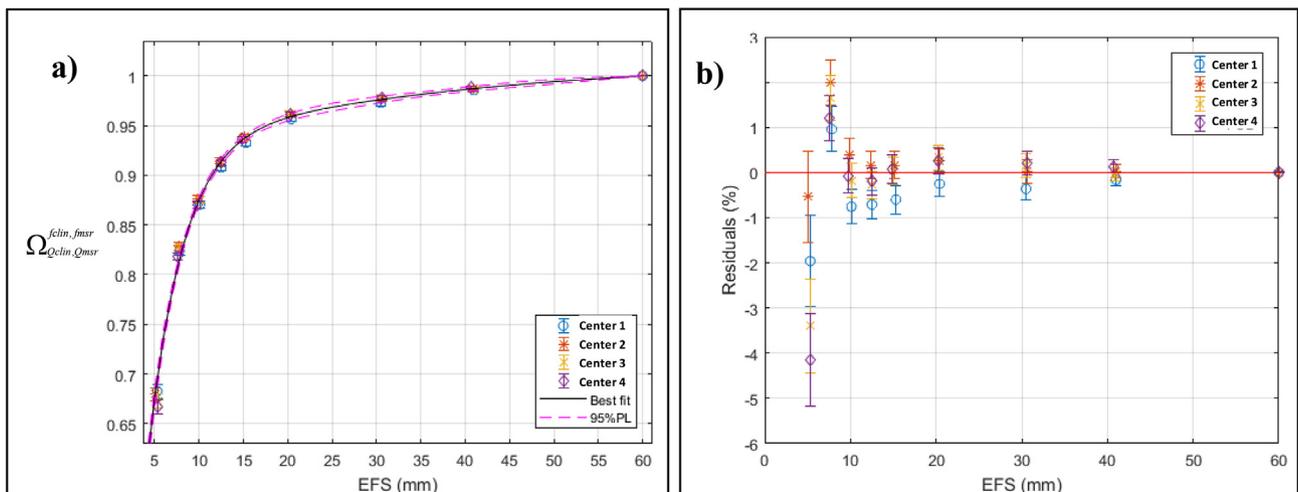


Fig. 1. (a) Field output factor $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ values with relative fit plotted as function of EFS and Prediction limits (PLs) with confidence interval of 95% are also reported. Error bars are also shown. (b) Residuals of $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ with respect to the fitted curve for each involved center.

observed for the 7.5 mm aperture.

3.4. Uncertainty budget estimation

The total uncertainty budget was estimated considering the measurement uncertainty and the MC correction factor uncertainty. Regarding the OF_{det} measurements, the uncertainties were calculated by the statistical dispersion of repeated measurements, the position uncertainty of the detector and the uncertainty related to the electrometer. The measurement readout uncertainties (calculated as one standard deviation of the mean of repeated measurements) ranged from 0.05% to 0.1%. The accuracy of the electrometer used, supplied by the manufacturer, was $\pm 0.2\%$. Positioning uncertainties were evaluated to be ± 0.2 mm: each center used its own water phantom but all phantoms had a certificated mechanical tolerance of ± 0.1 mm. This value was doubled to include possible uncertainties related to the method used to identify the center field. This positioning errors were estimated to contribute to the uncertainties on small field output factors evaluation between 0.1% and 1% for field size ranging from 12.5 mm to 5 mm respectively and negligible for field sizes larger than 12.5 mm [37]. Combined uncertainties for the OF_{det} measurements were estimated to be between 0.5% and 1.6% ranging from 60 mm to 5 mm respectively by using Gaussian error propagation.

The $k_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ uncertainty for silicon diode detectors was considered within 1% according to the evaluation made by Francescon et al. [18]

The combined uncertainties in $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ were within 2% for all fixed circular collimator.

4. Discussion

Dosimetric measurement uncertainties in small fields can be significant [38], leading to recommendations for the use of additional detectors and treatment unit specific corrections to increase accuracy [3,37]. In the framework of the Italian Association of Medical Physics (AIFM) Stereotactic Body Radiation Therapy (SBRT) working group, we previously measured output factors for CyberKnife fixed cones using a microdiamond and a plastic scintillator detector in a multi-site context [27,28]. Results obtained by these two dosimeters were compared with the measurements performed with the PTW 60017 diode corrected by published MC factors and considered in literature as the reference detector [6].

This study follows on from the previous multi-center experience and principally aims to evaluate the suitability of Razor silicon diode for relative small beams dosimetry for the CyberKnife system. The evaluation has been performed over many CyberKnife facilities and different systems. System-specific correction factors $k_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ available in the literature for this dosimeter have been applied.

The IAEA/AAPM TRS 483 Code of Practice listed output correction factors $k_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ for a number of diode detector including the PTW-60017 silicon diode but not for the Razor detector. This is why the correction factors applied to OF_{det} measurements performed in this study were those published by Francescon et al. respectively for the M6 CyberKnife system [18] and for the G4 model [12].

The differences in $k_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ for the PTW 60017 silicon diode between Francescon et al. [18] and IAEA/AAPM TRS 483 [3] are within 1% for all field sizes.

The IAEA/AAPM TRS 483 correction factors for CyberKnife systems are tabulated for field diameters equal to 6 mm and 8 mm, whereas the actual cone size for Cyberknife systems is 7.5 mm [39]. This forces interpolation to be used routinely, which is a potential source of error.

In this work a complete dosimetric characterization for small fields with CyberKnife machines was performed in accordance with ICRU Report 91 [40], which states that an output factor should always be accompanied by the measurement of the actual profile of the field. This includes output factor, beam profile, and penumbra measurements. The effective field size was thus evaluated in the same measuring session of

small field OF_{det} determination. The ICRU Report 91 recently stated that the measurement of an output factor should be always accompanied by a measurement of the actual profile of the field. A small variation of ± 0.1 mm on a field of 5 mm size can have an effect up to $\pm 5\%$ in the measured OF_{det} [12]. This effect is due to a combination of the phenomenon of source occlusion with the reduction in electron fluence received by the detector due to absence of photons near the edge of the field.

Fixed cones have the advantage that their dimension does not change, but there can be a difference between the nominal diameter and the actual diameter, and therefore, the measurement of an output factor must be always accompanied by a measurement of the actual profile of the field even if fixed cones were used [40].

Cranmer-Sargison et al. [5] suggested that the effective field size (EFS) should be considered to compare small field output factor data from different centers in a multi-site context.

A good agreement was observed between Razor and PTW-60017 field output factor values, with average differences within 1.3% for all field sizes. Results obtained for each of the enrolled centers showed relative differences within 1.3% for field sizes from 7.5 to 60 mm and equal to 3.5% for the 5 mm aperture: these results confirmed the agreement between field output factors measured by the two silicon diodes within the combined uncertainties of the measurements performed by the two detectors.

The $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ spread range among the involved centers was reasonable for both the detectors employed, even if three different models of CyberKnife devices were included in the study. The evaluation of EFS from dose profiles also showed a spread in the EFS data set within the mechanical tolerance of the water phantom.

The EFS values were significantly different with respect to the NFS ones, especially for the smallest field size where a 6% difference was observed.

The mathematical relation reported by Sauer et al. [4] was applied to describe the CyberKnife field output factors as a function of EFS. The function was initially proposed for standard linacs and has been successfully applied for a population of Varian Truebeams [22] allowing output factors to be calculated for arbitrary unmeasured field sizes. OF_{det} values measured by Razor silicon diode in four CyberKnife centers and corrected by applying $k_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ were used to determine a fit of the empirical data with this formula. The fit was tested using independent measurements acquired on another CyberKnife system. For all test centers and all beam sizes considered, $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ data deviated by less than 1% from the value predicted by the fit function for fixed collimator sizes ranging from 10 to 60 mm and the agreement was within 2.2% for the 7.5 mm field size. This difference is comparable to the overall uncertainties for $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$.

Therefore, the formula can be considered a robust reference mathematical function for CyberKnife systems to calculate $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ in function of EFS for fixed collimator sizes ranging from 10 to 60 mm and can be used to compare $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ values measured in any CyberKnife system regardless of the type of employed detector. More caution must be used for smaller diameters: for the smallest cone diameter of 5 mm, the value obtained from the fit function could be an estimate of the $\Omega_{Q_{clin,Qmsr}}^{f_{clin},f_{msr}}$ with an accuracy of about 4%.

These results confirmed the suitability of Razor silicon diode for relative small beams dosimetry for the CyberKnife system.

The consistency of measurements among different centres was checked in this work, adopting a crowd knowledge based community approach [41]. Following this approach, the sharing of small field dosimetric data allowed to improve the expertise of different radiotherapy centres.

5. Conclusions

Complex modern irradiation techniques are often challenging for dosimetry and the sharing of knowledge and reference data can reduce

dosimetric uncertainty. A common database of dosimetry data for CyberKnife centers has been provided in this work so that departments with less experience can cross-check their measured data. A mathematical relation able to calculate field output factors for fixed circular CyberKnife collimators has been determined for the first time.

A good agreement between field output factors evaluated by PTW60017 and Razor was found, showing Razor as a suitable detector for CyberKnife dosimetric characterization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Laud WU, Wong T. The volume effect of detectors in the dosimetry of small fields used in IMRT. *Med Phys* 2003;30:341–7.
- [2] Lecher W, Palmans H, Solkner L, Grochowska P, Georg D. Detector comparison for small field output factor measurements in flattening filter free photon beams. *Radiation Oncol* 2013;109:356–60.
- [3] INTERNATIONAL ATOMIC ENERGY AGENCY, Dosimetry of small static fields used in external beam radiotherapy, Technical Reports Series No. 483, IAEA, Vienna, 2017.
- [4] Sauer OA, Wilbert J. Measurement of output ratios for small photon fields. *Med Phys* 2007;34:1983–8.
- [5] Cranmer-Sargison G, Weston S, Sidhu NP, Thwaites DI. Experimental small field 6 MV output ratio analysis for various diode detector and accelerator combinations. *Radiation Oncol* 2011;100:429–35.
- [6] Dieterich S, Cavedon C, Chuang CF, Cohen AB, Garrett JA, Lee CL, et al. Report of AAPM TG 135: quality assurance for robotic radiosurgery. *Med Phys* 2011;38:2914–36.
- [7] Francescon P, Cora S, Cavedon C, Scalchi P, Stancanello J. CyberKnife dosimetric beam characteristics: comparison between experimental results and Monte Carlo simulation in robotic radiosurgery sunnyvale. CA: CyberKnife Society Press; 2005.
- [8] Francescon P, Kilby W, Satariano N, Orlandi C, Elshamndy S. The impact of inter-unit variations on small field dosimetry correction factors, with application to the CyberKnife system. *Phys Med Biol* 2019;64:13. <https://doi.org/10.1088/1361-6560/aaf971>.
- [9] Scott AJD, Kumar S, Nahum AE, Fenwick JD. Characterizing the influence of detector density on dosimeter response in non-equilibrium small photon fields. *Phys Med Biol* 2012;57:4461–76.
- [10] Underwood TSA, Winter HC, Hill MA, Fenwick JD. Detector density and small field dosimetry: integral versus point dose measurement schemes. *Med Phys* 2013;40:082102. <https://doi.org/10.1118/1.4812687>.
- [11] Bassinet C, Huet C, Derreumaux S, Brunet G, Chéa M, Baumann M, et al. Small fields output factor measurements and correction factors determination for several detectors for a CyberKnife and linear accelerators equipped with microMLC and circular cones. *Med Phys* 2013;40:071725.
- [12] Francescon P, Kilby W, Satariano N, Cora S. Monte Carlo simulated correction factors for machine specific reference field dose calibration and output factor measurement using fixed and iris collimators on the CyberKnife system. *Phys Med Biol* 2012;57:3741–58.
- [13] Morin J, Béliveau-Nadeau D, Chung E, Seuntjens EJ, Thériault D, Archambault L, et al. A comparative study of small field total scatter factors and dose profiles using plastic scintillation detectors and other stereotactic dosimeters: the case of the CyberKnife. *Med Phys* 2013;40:011719.
- [14] Pantelis E, Moutsatsos A, Zourari K, Petrokokkinos L, Sakellidou L, Kilby W, et al. On the output factor measurements of the CyberKnife iris collimator small fields: experimental determination of the k_{clin}, f_{msrQclin}, Q_{msr} correction factors for microchamber and diodes. *Med Phys* 2012;39:4875–85.
- [15] Moignier C, Huet C, Makovicka L. Determination of the k_{Qclin}, Q_{msr} f_{clin}, f_{msr} correction factors for detectors used with an 800 MU/min CyberKnife® system equipped with fixed collimators and a study of detector response to small photon beams using a Monte Carlo method. *Med Phys* 2014;41:071702.
- [16] Reggiori G, Mancosu P, Suchowerska N, Lobefalo F, Stravato A, Tomatis S, et al. Characterization of an unshielded diode for small field dosimetry under flattening filter free beams. *Phys Med* 2016;16:52–7.
- [17] Liu PZY, Reggiori G, Lobefalo F, Mancosu P, Tomatis S, McKenzie DR, et al. Small field correction factors for the IBA Razor. *Phys Med* 2016;32:1025–9.
- [18] Francescon P, Kilby W, Noll JM, Masi L, Satariano N, Russo S. Monte Carlo simulated corrections for beam commissioning measurements with circular and MLC shaped fields on the CyberKnife M6 System: a study including diode, microchamber, point scintillator, and synthetic microdiamond detectors. *Phys Med Biol* 2017;62(3):1076–95. <https://doi.org/10.1088/1361-6560/aa5610>.
- [19] Azangwe G, Grochowska P, Georg D, Izewska J, Hopfgartner J, Lechner W, et al. Detector to detector corrections: a comprehensive experimental study of detector specific correction factors for beam output measurements for small radiotherapy beams. *Med Phys* 2014;41:072103–16.
- [20] Veronese I, De Martin E, Martinotti AS, Fumagalli ML, Vite C, Redaelli I, et al. Multi-institutional application of Failure Mode and Effects Analysis (FMEA) to CyberKnife Stereotactic Body Radiation Therapy (SBRT). *Radiat Oncol* 2015;10:132. <https://doi.org/10.1186/s13014-015-0438-0>.
- [21] Clemente S, Nigro R, Oliviero C, Marchioni C, Esposito M, Giglioli FR, et al. Role of the technical aspects of hypofractionated radiation therapy treatment of prostate cancer: a review. *Int J Radiat Oncol Biol Phys* 2015;91(1):182–95.
- [22] Cagni E, Russo S, Reggiori G, Bresciani S, Fedele D, Iori M, et al. Technical note: multicenter study of TrueBeam FFF beams with a new stereotactic diode: can a common small field signal ratio curve be defined? *Med Phys* 2016;43(10):5570–7.
- [23] Marino C, Villaggi E, Maggi G, Esposito M, Strigari L, Bonanno E, et al. A feasibility dosimetric study on prostate cancer: are we ready for a multicenter clinical trial on SBRT? *Strahlenther Onkol* 2015;191(7):573–81. <https://doi.org/10.1007/s00066-015-0822-6>.
- [24] Esposito M, Maggi G, Marino C, Bottalico L, Cagni E, Carbonini C, et al. Multicenter treatment planning inter-comparison in a national context: the liver stereotactic ablative radiotherapy case. *Phys Med* 2016;32(1):277–83. <https://doi.org/10.1016/j.ejmp.2015.09.009>.
- [25] Giglioli FR, Strigari L, Ragona R, et al. Lung stereotactic ablative body radiotherapy: a large scale multi-institutional planning comparison for interpreting results of multi-institutional studies. *Phys Med* 2016;32(4):600–6. <https://doi.org/10.1016/j.ejmp.2016.03.015>.
- [26] Mancosu P, Clemente S, Landoni V, Ruggieri R, Alongi F, Scorsetti M, et al. SBRT for prostate cancer: challenges and features from a physicist perspective. *Phys Med* 2016;32(3):479–84. <https://doi.org/10.1016/j.ejmp.2016.03.011>.
- [27] Russo S, Masi L, Francescon P, Frassanito MC, Fumagalli ML, Marinelli M, et al. Multicenter evaluation of a synthetic single-crystal diamond detector for CyberKnife small field size output factors. *Phys Med* 2016;32(4):575–81.
- [28] Masi L, Russo S, Francescon P, Doro R, Frassanito MC, Fumagalli ML, et al. CyberKnife beam output factor measurements: a multi-site and multi-detector study. *Phys Med* 2016;32(12):1637–43.
- [29] Russo S, Reggiori G, Cagni E, Clemente S, Esposito M, Falco MD, et al. Small field output factors evaluation with a microDiamond detector over 30 Italian centers. *Phys Med* 2016;32(12):1644–50.
- [30] Mancosu P, Pasquino M, Reggiori G, Masi L, Russo S, Stasi M. Dosimetric characterization of small fields using a plastic scintillator detector: a large multicenter study. *Phys Med* 2017;S1120–1797(17):30082–90. <https://doi.org/10.1016/j.ejmp.2017.03.024>.
- [31] Clemente S, Masi L, Fiandra C, Cagni E, Villaggi E, Esposito M, et al. A multi-center output factor intercomparison to uncover systematic inaccuracies in small field dosimetry. *Phys Imag Radiat Oncol* 2018;5:93–6. <https://doi.org/10.1016/j.phro.2018.03.007>.
- [32] Talamonti C, Russo S, Pimpinella M, Falco MD, Cagni E, Pallotta S, et al. Community approach for reducing small field measurement errors: experience over 24 centers. *Radiation Oncol* 2019;132:218–22. <https://doi.org/10.1016/j.radonc.2018.10.012>.
- [33] Villaggi E, Hernandez V, Fusella M, Moretti E, Russo S, Vaccara EML, et al. Plan quality improvement by DVH sharing and planner's experience: results of a SBRT multicenter planning study on prostate. *Phys. Med.* 2019;62:73–82.
- [34] Asmeron G, Bourne D, Chappelou J, Goggin LM, Heitz R, Jordan P, et al. The design and physical characterization of a multileaf collimator for robotic radiosurgery. *Biomed Phys Eng Express* 2016;2:017003.
- [35] Iba – P-Razor Detector-510 01 User's Guide.
- [36] Alfonso R, Andreo P, Capote R, Saiful Huq M, Kilby W, Kjäll P, et al. A new formalism for reference dosimetry of small and nonstandard fields. *Med Phys* 2008;35:5179–86.
- [37] Bouchard E, Seuntjens J, Kawrakow I. A Monte Carlo method to evaluate the impact of positioning errors on detector response and quality correction factors in non-standard beams. *Phys Med Biol* 2011;56:2617–34.
- [38] Aspradakis MM, Byene JP, Palmans H, et al. Small field MV photon dosimetry. *IPEM Report 103*. York, UK; 2010.
- [39] Das IJ, Francescon P. Comments on the TRS-483 protocol on small field dosimetry. *Med Phys* 2018;45:5666–8.
- [40] Menzel HG. ICRU Report 91 prescribing, recording, and reporting of stereotactic treatments with small photon beams. *J Int Commis Radiat Units Measure* 2014;14:1–160.
- [41] Mancosu P, Baroni G, Alongi F, Esposito L, Stasi M, Strigari L. Crowd knowledge based community in radiotherapy: in response to Yartev et al. *Radiation Oncol* 2014;112:453.