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Short Communication

A multi-center output factor intercomparison to uncover systematic inaccuracies in small field dosimetry

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ABSTRACT

Large uncertainties in output factor (OF) small fields dosimetry motivated multicentric studies. The focus of the study was the determination of the OFs, for different linacs and radiosurgery units, using new-generation detectors. Intercomparison studies between radiotherapy centers improved quality dosimetry practices. Results confirmed the effectiveness of the studies to uncover large systematic inaccuracies in small field dosimetry.

1. Introduction

In recent years the number of machines capable of delivering cranial and extra-cranial stereotactic radiotherapy treatments (SBRT) has substantially increased. However, such developments have not been accompanied by dedicated training in terms of small field dosimetry. This may lead to a possible increase of those dosimetric uncertainties that represent the major features of small beams in comparison to wide fields [1–3]. Sharing of the measured data in terms of output factors (OF) for small fields, with regard to many different combinations of machines and dosimeters [4–8], was promoted with a specific working group focused on SBRT. Other had similar experiences [9,10], all with the aim to quantify systematic inaccuracies of small fields dosimetry.

Small field dosimetry must account for the lack of charged particle equilibrium (CPE) in the lateral direction. Moreover the dimension of the active volume and the material composition and density of the detector itself may influence the response in a different way when compared with non-small radiation fields [11,12]. In order to solve these issues, the International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM) proposed a new formalism for small field dosimetry in 2008 [13]. In this document, the concept of output correction factor k for obtaining the dose-to-water ratio between a clinical field (f_{clin}) and a machine-specific reference field (f_{msr}), based on the measured detector readings ratio (OF_{det}) has been introduced. The correction factors can be derived either by a direct calibration of the specific dosimeter in the two fields against a primary standard or against a passive dosimeter such as alanine, Thermoluminescent Dosimeters (TLDs) and radiochromic films, or by a Monte Carlo (MC) simulation [14,15]. Moreover, in small beams the positioning accuracy of the collimating devices is also important, since e.g. 1 mm error in a 1×1 cm^2 field setting can result in a 2–4% error in the measured dose or OF [6].

The main objective of this experience was to assess the consistency in small-field OF determination among a large number of centers, equipped with a wide variety of machines, using different new generation detectors. This multicenter study is a secondary quality assurance (QA) dataset and may be used as a robust baseline for a true audit focused on small-field dosimetry.

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2. Methods and materials

A total of thirty centers were enrolled in this study, twenty-four equipped with linacs of different manufactures and models (Varian and Elekta) and six with radiosurgery units, and focused on small-field OF determination using center-specific routine detectors and three new generation detectors: PTW 60019 microDiamond, Exradin W1 Plastic Scintillator (W1 PSD) and IBA new unshielded silicon Razor diode.

2.1. Linac study

Multi-centers studies were performed in four steps:

1. Twelve Varian and twelve Elekta centers performed measurements of the detector readings ratio (OF_{det}), using f_{clin} and f_{msr}, for nominal square field sizes (NFS) ranging from 0.6 cm to 10 cm, employing in-house routinely used detectors and the PTW 60019 microDiamond. A comparison of experimental data obtained with in-house and microDiamond detectors was performed [4];
2. The same centers measured $TPR_{20/10}$, in-plane and cross-plane dose profiles of $0.8 \times 0.8\,cm^2$ field and OF_{det} for NFS ranging from 0.8 cm to 10 cm, using W1 PSD and correcting for the Cerenkov effect as proposed by the manufacturer [5];
3. Each center was asked to measure in-plane and cross-plane dose profiles and OF_{det} for square field size ranging from 0.6 cm to 5 cm using Razor diodes [16]. According to Cranmer-Sargison [18], the effective field size (EFS) was calculated as: $EFS = \sqrt{A \cdot B}$ where A and B correspond to the in-plane and cross-plane FWHM values. OF_{det}, reported as a function of both NFS and EFS, were used to determine a fit of the empirical data, following the equation by Sauer [19]:

$$OF(FS)=P_{\infty}*\frac{FS^n}{l^n + FS^n} + S_{\infty}*(1-\exp(-b*FS)) \quad (1)$$

where OF is the detector signal ratio; FS is the field size (NFS or EFS); 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 (detector reading SR = 1; FS = 30 mm) was considered as a boundary condition.

4. Step 3 was repeated focusing on eight Varian TrueBeam centers [6].

The beam energy was 6 MV for steps 1–3, and 10 MV FFF (flattening filter free) for step 4, respectively. The set-up conditions were 10 cm depth in water phantom and SSD = 90 cm. The FS were defined only by the jaws with the MLC fully retracted for the Varian linacs and by both secondary jaws and MLC for the Elekta linacs. The f_{mrs} was $10 \times 10\,cm^2$ in the first two steps and $3 \times 3\,cm^2$ in the third one. The measurements were performed using two microDiamonds and two Razor diodes in order to speed up the process. The National Institute of Ionizing Radiation Metrology (INMRI) of the Italian institute for new technologies, energy and the environment (ENEA) carried out a complete characterization of both diamond dosimeters and Razor diodes to ensure the dosimetric equivalence of the detectors. Only one W1 detector was used.

Alfonso [13] correction factors $k^{fclin,fmsr}_{Qclin,Qmsr}$ were not considered for any of the studied detectors. Details on Linac models involved in the studies have been previously specified [4–6].

2.2. Radiosurgery units study

Eight radiosurgery units including all clinically available models were enrolled [7]. Inter-linac beam quality ($TPR_{20/10}$) variations were below 2%. For each unit, OF_{det} were measured for fixed cone diameters from 5 to 60 mm using PTW 60017 unshielded silicon diode (routine-used detector for all centers), PTW 60019 microDiamond, W1 PSD and IBA Razor diode. Measurements protocol has been previously described [9]. Published MC output correction factors specific for radiosurgery unit [9] were applied to PTW 60017 measured OF_{det} obtaining the field output factor for each cone size [13] as:

$$\Omega^{fclin,fmsr}_{Qclin,Qmsr} = OF^{fclin,fmsr}_{PTW\ 60017} \cdot k^{fclin,fmsr}_{Qclin,Qmsr}(PTW\ 60017) \quad (2)$$

For each radiosurgery unit, microDiamond, W1 PSD and Razor measured OF_{det}, were compared to PTW 60017 unshielded silicon diode MC corrected values [17]. The consistency of data over different units was evaluated calculating the ratio K_{det} for each cone size and detector [7] as:

$$K_{det} = \frac{OF^{fclin,fmsr}_{PTW\ 60017} \cdot k^{fclin,fmsr}_{Qclin,Qmsr}(PTW\ 60017)}{OF^{fclin,fmsr}_{det}} \quad (3)$$

Det = PTW 60019, W1 PSD, Razor.

K_{det} is an estimation of the correction factor $k^{fclin,fmsr}_{Qclin,Qmsr}$ needed for the specific detector. $k^{fclin,fmsr}_{Qclin,Qmsr}$ is expected to show small changes (< 2%) for the same detector among different radiosurgery units and models [20,21].

Since our first aim was to evaluate the different detectors performance in a multicentre context, complete results have been collected only for fixed collimators.

For IRIS variable aperture collimator, OF were measured also with PTW 60019 and PTW 60017 [8] but not with W1 PSD. Moreover, these data were not included in the final analysis due to the increased uncertainty in field size diameter defined with the IRIS collimator.

3. Results

3.1. Linac study

Deviations between routinely-used detectors and microDiamond were within 2.7% for FS > $2 \times 2\,cm^2$. For $1 \times 1\,cm^2$ FS, OF_{det} measured with micro-ion chambers were lower than microDiamond values, with differences up to 10%, while for silicon diodes a maximum overestimation of about 3% was found. MicroDiamond data standard deviation (SD) was within 2% in the range of investigated FS down to $1 \times 1\,cm^2$.

Beam quality characterization with W1 PSD showed an average $TPR_{20/10}$ value for 6 MV energy beam of 0.670 ± 0.01 (for Varian linacs) and 0.686 ± 0.01 (for Elekta linacs). The OF_{det} values for both Varian and Elekta linacs showed a limited spread of data for FS greater than $2 \times 2\,cm^2$, with a SD < 1.5%.

In the third step, when Razor OF_{det} data were reported as a function of EFS and clustered by linac model, the proposed analytical functions fit within 1% to the data for FS > $2 \times 2\,cm^2$.

For TrueBeam centers, the fit of OF_{det} determined using Razor with the EFS had $R^2 > 0.999$ with a mean and maximum deviation from the predicted OF_{det} of 0.5% and 1.9% (EFS = 0.6 cm), respectively. Fig. 1 shows the deviations between the fitted curve and the measured OF_{det} as a function of NFS (A) and EFS (B) for the eight centers analysed in step 4. The quality of the mathematical relation, quantified by the mean deviation between the fitted and the measured data, was3.4% for NFS and 0.5% for EFS. In both cases, the maximum differences were observed for the 0.6 cm aperture (5.0% for NFS and 1.9% for EFS).

3.2. Radiosurgery units study

K_{det} curves as a function of cone diameter for microDiamond (a), W1 PSD (b) and Razor diode (c) are shown in Fig. 2, averaged over all radiosurgery units. Good consistency was observed among different centers: inter-center variability (percentage range) was below 2% for diameters down to 0.75 cm and increased at 0.5 cm up to 2.1% for microDiamond, 4.5% for Razor and 4.9% for W1 PSD, respectively. The increased variability observed at 0.5 cm for Razor and W1 was partially

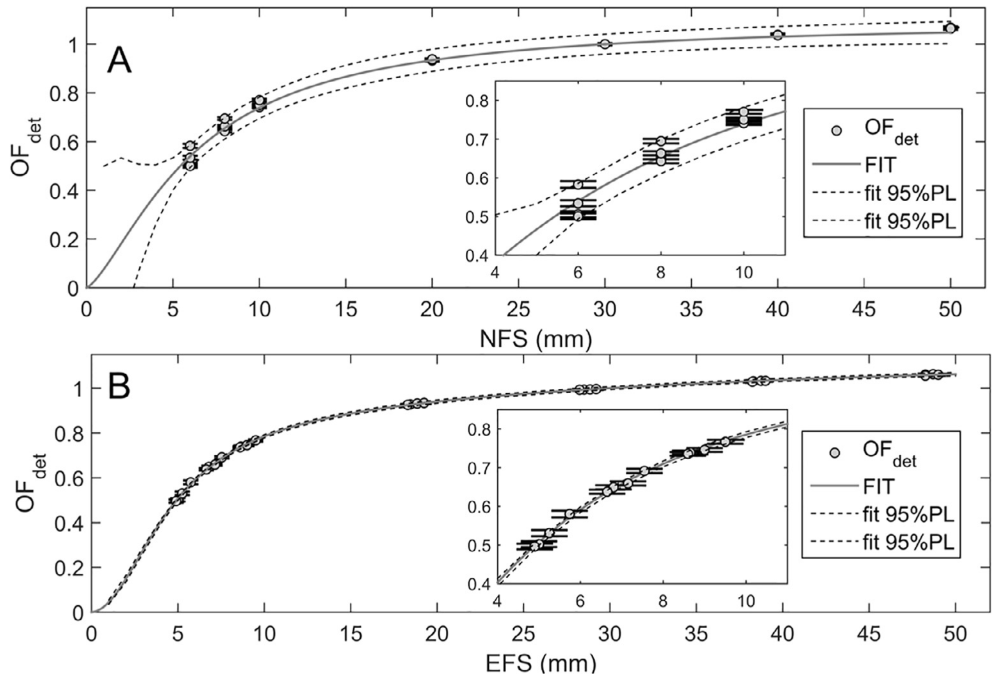

Fig. 1. Difference between theoretical values and OF_{det} measured with Razor plotted as function of (A) NFS and (B) EFS for Truebeam linacs with 10-FFF MV beam [7]. Prediction Limits (PL) with confidence interval of 95% for each fit are reported. Error bars are also shown. The coefficients of the mathematical relation has been reported by Cagni et al. [7].

due to the data measured in one center deviating from the mean K_{det} value for more than 2.5%. The determined semi-empirical output correction factors averaged over all centers remained within 2% for both microDiamond and W1 PSD, while for Razor the mean factor at 0.5 cm is 0.958.

4. Discussion

The lack of a national audit program for small-field dosimetry, performed by independent institutions on a regular basis, boosted the need for a multi-center dosimetric intercomparison to identify systematic dosimetric uncertainties.

In the context of a working group dedicated to small-field dosimetry, the main focus was the OF determination for different types of linac and radiosurgery systems, in a multi-site and multi-detector approach. Output corrections factors, to be applied to experimentally determined ratios of detectors readings, were used only for radiosurgery units diode results, for which well established published MC values were available [20]. The application of correction factors to linac results was not possible in consideration of the multiple models of linacs and the large variety of routinely-used detectors.

In a preliminary investigation [4], OF measurements with routinely used detectors and nominal FS were re-collected with deviations among centers up to 10% for the $1 \times 1\,cm^2$ field size. The use of microDiamond in the same condition reduced the SD of the OF by about 50%, being below 2% down to $1 \times 1\,cm^2$ FS, in good agreement with the results obtained by on-site quality audits performed by the Radiological Physics Center in the USA [10]. The use of plastic scintillator detector still yielded a large variability for FS below $2 \times 2\,cm^2$, with limited spread of data (SD < 1.5%) for FS greater than $2 \times 2\,cm^2$ [5]. Using the

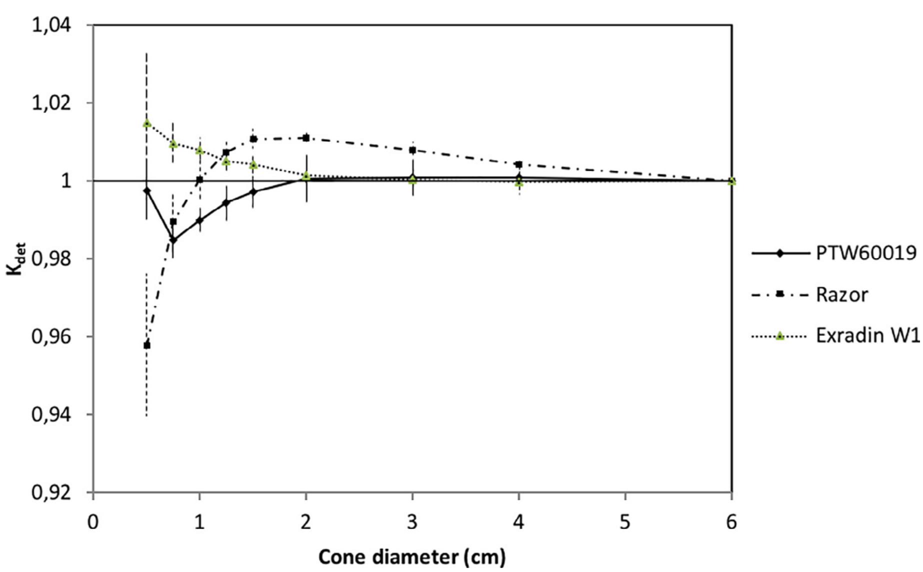

Fig. 2. K_{det} values obtained as the ratio between PTW 60,017 MC corrected values and the measured OF_{det} respectively for PTW 60019 microDiamond, Exradin W1 PSD and Razor diode. Mean values and standard deviations over the enrolled Cyberkinfe centers are shown.

NFS for data reporting, the comparison between OF measured by different detectors could be affected by differences in the calibration of the collimating devices performed at different times [4].

Regarding the average $TPR_{20/10}$ value for 6 MV beam measured with the PSD, the results were consistent with the reference value of 0.676 reported by the IAEA 398 [22].

This exploratory phase resulted in better defined guidelines on how to design our subsequent studies. A multicentric [6] study on small-field dosimetry was then performed using the 10 FFF MV beam on 8 TrueBeam linacs, with the awareness that EFS measurements were mandatory when comparing OF data over different centers. A strong relationship between OF_{det} and the EFS was obtained and its suitability in evaluating uncorrect OF was assessed indicating the Razor as a good detector for small-beam OF evaluation.

Furthermore, semi-empirical output correction factors, K_{det}, for microDiamond, plastic scintillator and Razor detectors relative to MC corrected silicon diode [7,8] were evaluated, in the setting of a multicentric study on radiosurgery systems. Radiosurgery K_{det} values determined by our multisite approach showed high consistency among centers. This uniformity in results emphasizes the value of a multicenter study as a useful tool to identify inaccurate data from a single center. This was probably the case for the single center showing deviating results for 0.5 cm cone size for two of the analysed detectors. The center was contacted to check the data but measurements could not be repeated because in the meantime the system had been uninstalled. Since we were not able to clarify the cause of this outlying result, it was not removed from the final analysis. The semi-empirical output correction factors were confirmed by MC calculated output correction factors within 1% for the radiosurgery unit M6 model, published after the completion of our study [21]. The agreement with independently calculate MC $k_{Qclin,Qmsr}^{fclin,fmsr}$ is a further validation of the adopted methodology.

In summary, a first step have been completed to develop a national dosimetry audit also in collaboration with ENEA. Our intercomparison studies supported the improvement of accuracy and safety in small-field dosimetry, in particular using extreme caution when selecting the dosimeter and its placement within the field essential to avoid gross errors in the determination of small-field OF data. As soon as, the national dosimetry audit will focus on determining small field OF, any challenges or difficulties in the proposed methodology will be addressed using the experience of this study.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.phro.2018.03.007.

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