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ORIGINAL ARTICLE

The influence of errors in small field dosimetry on the dosimetric accuracy of treatment plans

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ABSTRACT

Background: Dosimetric effects of inaccuracies of output factors (OFs) implemented in treatment planning systems (TPSs) were investigated.

Materials and methods: Modified beam models (MBM) for which the OFs of small fields (down to $1 \times 1\,cm^2$) were increased by up to 12% compared to the original beam models (OBM) were created for two TPSs. These beam models were used to recalculate treatment plans of different complexity. Treatment plans using stereotactic 3D-conformal (s3D-CRT) for brain metastasis as well as VMAT plans for head and neck and prostate cancer patients were generated. Dose distributions calculated with the MBM and the OBM were compared to measured dose distributions acquired using film dosimetry and a 2D-detector-array. For the s3D-CRT plans the calculated and measured dose at the isocenter was evaluated. For VMAT, gamma pass rates (GPRs) were calculated using global gamma index with 3%/3 mm, 2%/3 mm, 1%/3 mm and 2%/2 mm with a 20% threshold. Contribution of small fields to the total fluence was expressed as the ratio (F) of fluence trough leaf openings smaller than 2 cm to the total fluence.

Results: Using film dosimetry for the s3D-CRT plans, the average of the ratio of calculated dose to measured dose at the isocenter was 1.01 and 1.06 for the OBM and MBM model, respectively. A significantly lower GPR of the MBM compared to the OBM was only found for the localized prostate cases ($F = 12.4\%$) measured with the 2D-detector-array and an acceptance criterion of 1%/3 mm.

Conclusion: The effects of uncertainties in small field OFs implemented in TPSs are most pronounced for s3D-CRT cases and can be clearly identified using patient specific quality assurance. For VMAT these effects mainly remain undetected using standard patient specific quality assurance. Using tighter acceptance criteria combined with an analysis of the fluence generated by small fields can help identifying inaccuracies of OFs implemented in TPSs.

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Introduction

In current clinical practice, high-energy photon fields with dimensions of 2 cm and below are increasingly used, either for intensity-modulated radiotherapy with static (IMRT) or rotational gantry (VMAT) or for stereotactic radiotherapy (SRT). With next generation treatment concepts like dose painting even smaller fields might be commonly utilized.

While for SRT, the dose is delivered mainly using small fields, the situation is different for IMRT/VMAT where combinations of irregular shaped fields with various sizes are used to sculpture complex dose distributions. However, the utilization of small fields depends on the IMRT/VMAT sequencing algorithm and the degree of modulation. The latter is, on the one hand, related to the treatment site specific complexity and can, on the other hand, be limited by the user accessible sequencing parameters.

Dosimetric challenges when using small fields have been addressed by several groups. The specific issues encompass advancements of dosimetric concepts, detector-specific correction factors, beam modeling in the treatment planning systems (TPSs), or reference data sets for benchmarking own data [1–13]. Recently, the joint IAEA/AAPM code of practice on dosimetry of small and non-standard static fields has been published [14].

It has been shown that small field output factors (OFs) implemented in TPSs can deviate substantially from measured or reference OFs [15–17]. For IMRT/VMAT, patient-specific quality assurance (QA) is widespread clinical practice. The good dosimetric results reported in several studies and audits might lead to the conclusion that uncertainties in small field dosimetry do not largely impact the overall dosimetric accuracy in IMRT and VMAT. However, it has been

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Supplemental data for this article can be accessed here.

shown that many dosimetric tools and the current procedures for patient-specific IMRT QA are not ideal for detecting dosimetric errors [12,18–23]. Several studies have investigated the detecability of delivery errors such as MLC positioning errors [24–26], which are a composition of geometric errors and errors in OFs.

The aim of the present work was to perform a detailed study on the dosimetric impact of large discrepancies between OFs implemented in TPSs and actual OFs on advanced radiation therapy techniques. For that purpose, beam models of commercial TPSs were modified to resemble recently reported discrepancies in small field OFs calculated by TPSs with respect to reference data. Substantial differences between calculated and modeled OFs were found and related either to errors in measurements, incorrect beam modeling/commissioning or limitations of the beam models themselves [15–17]. The resulting treatment plans were experimentally benchmarked against plans calculated with beam models of highest accuracy in the small field region, i.e., for fields down to $1 \times 1\,cm^2$.

Material and methods

Linac

A Versa HD (Elekta AB, Stockholm, Sweden) medical linear accelerator (LINAC) with a nominal beam energy of 6 MV was used for all measurements. This LINAC is equipped with an Agility treatment head with 160 leafs with a width of 5 mm at the isocenter.

Beam models

Beam models of the Versa HD 6 MV beam were created for the TPSs Monaco (v5.0, Elekta AB, Stockholm, Sweden) using a Monte Carlo algorithm and iPlan (v4.5.3, Brianlab, Munich, Germany) using a pencil beam algorithm. Depth dose and lateral profiles as well as OFs were measured for field sizes ranging from $1 \times 1\,cm^2$ to $40 \times 40\,cm^2$ and served as basis for the clinically used beam models, henceforth denoted as original beam models (OBMs).

For each TPS, an additional beam model was created, where the same depth dose and lateral profiles as for the clinical beam model were used as input data, but the OFs for field sizes ranging from $1 \times 1\,cm^2$ to $7 \times 7\,cm^2$ were intentionally modified based on findings on discrepancies of small field OFs implemented in TPSs [15–17]. For this purpose, field size-dependent modification factors simulating the reported deviations were applied to the original OFs and are presented in Table 1. Note that these modification factors are not necessarily related to correction factors published in TRS-483 [14]. The beam model generated using these altered OFs are henceforth referred to as modified beam model (MBM).

The modified Monaco beam model was provided by the manufacturer while the generation of the modified iPlan beam was performed in-house. The OFs, depth dose profiles and lateral profiles of the modified beam models were verified by calculation of static square fields ranging from $1 \times 1\,cm^2$ to $40 \times 40\,cm^2$ on a digital $40 \times 40 \times 40\,cm^3$ water phantom. The Monaco beam models were used to create VMAT plans and the iPlan beam models were used to create stereotactic 3D-conformal radiotherapy (s3D-CRT) plans which is standard in our institution.

As presented in Table 1, the OFs of the modified beam models were different compared to the OFs used for the generation of the beam models. The modified iPlan beam model showed even higher OFs than expected. The OFs of the modified Monaco beam model were generally lower compared to the OFs used for modeling and also increased slower than expected. For field sizes down to $5 \times 5\,cm^2$, the OFs of the modified Monaco beam model remained unchanged or were even slightly lower compared to the OFs of the original beam model.

Investigated indications and treatment modalities

All patients were randomly selected from a set of patients treated between 2015 and 2016. For this work, 10 s3D-CRT treatments plans for brain metastasis, 10 VMAT plans for head and neck (HN) cancer patients and 10 VMAT plans for prostate cancer patients (with combined prostate and paraaortic lymph node irradiation (PR) as well as a subsequent boost plan (BP)) were used. As this study focused on the dosimetric uncertainties in small OFs for s3D-CRT and VMAT, a detailed description on contouring, PTV coverage and organ at risk sparing was deliberately omitted. A brief description of the investigated indications and modalities is provided as supplementary material.

Measurement and comparison of dose distributions

All investigated treatment plans were generated and optimized using the original beam models. In a subsequent step, these plans were recalculated on the phantom which was used for dose measurements using the original and the

Table 1. Summary of the actual modification factors applied to the input data for beam modeling and OF modification factors produced by the modified beam models after beam modeling.

	Field size (cm)						
	1 × 1	2 × 2	3 × 3	4 × 4	5 × 5	6 × 6	7 × 7
OF modification factors used for modeling	1.100	1.057	1.035	1.020	1.015	1.010	1.005
Monaco OF modification factors	1.093	1.033	1.007	1.014	0.996	0.994	1.000
iPlan OF modification factors	1.120	1.059	1.039	1.026	1.019	1.015	1.012

The modification factors were unity for field sizes larger than $7 \times 7\,cm^2$. The calculations were performed using the same beam and phantom geometry.

modified beam model. Treatment plans were measured with Gafchromic EBT3 films (Ashland, Covington, OH) and with the Delta^4 phantom (ScandiDos, Uppsala, Sweden). The measured dose distributions were compared to the dose distributions calculated by the original and modified beam model, respectively.

For the s3D-CRT plans the ratio of measured and calculated dose $R = D_{calc}/D_{meas}$ at the isocenter was analyzed. The dosimetric quality of VMAT plans was assessed using global gamma analysis with a dose threshold of 20% of the maximum dose, with combinations of dose difference and distance to agreement of 3%/3 mm, 2%/3 mm, 1%/3 mm, and 2%/2 mm. Note that the resolution of the Delta^4 phantom is not adequate for gamma analysis of treatment fields for the treatment of small lesions. However, the individual detectors have a sufficiently small diameter of 1 mm. Therefore, only the dose reported by the central detector was used for comparison. For gamma analysis using film measurements, the measured dose was normalized to the dose calculated by the original beam model in a high-dose/low-gradient area. It is important to mention that the same normalization factor was applied to both, the dose calculated by the original and the modified beam model. No normalization was applied for the Delta^4 measurements. Gamma pass rates (GPRs) larger than 90% were classified as acceptable for both phantoms. The s3D-CRT and VMAT plans were measured using the Delta^4 phantom and films. An Epson Perfection V700 scanner was utilized for scanning the EBT3 films according to previously defined protocols [27,28]. Film measurements of VMAT plans were performed using an octagonal slab phantom made of polystyrene with the film positioned in transversal orientation in the isocenter plane. This phantom was used for several years in our institution for clinical routine and research [29] before the Delta^4 phantom was available. Both phantoms are depicted in Figure S1 in the Supplementary material. For film measurements of the treatment plans generated using iPlan, all gantry angles were set to 0° and the film was placed in the coronal isocenter plane in 10 cm depth in a solid water phantom to reduce the influence of limitations of the pencil beam algorithm.

Fluence analysis

The DICOM files of all VMAT treatment plans were analyzed using an in-house developed Matlab script (version R2015a, MathWorks, Natick, MA). The proportion of the fluence delivered through leaf openings smaller or equal than 2 cm with respect to the total fluence was calculated. This fraction is henceforth denoted as small field fluence factor (F). As both phantoms have different orientation of their active volume, the selection of leafs contributing to the calculation of the small field fluence factor F was performed in two different ways. The measured film dose in the isocentric transversal plane is mainly determined by the central leaf pairs. Therefore, the calculation of F was restricted to the four central leaf pairs for film measurements. For the Delta^4 measurements, all involved leaf pairs were considered as the detector planes are perpendicular to the beams central axis.

Statistical analysis

Since the distribution of GPR results did not follow normal distribution, the differences between the dosimetric parameters of the original and modified beam model were analyzed using Wilcoxon paired signed-rank test assuming statistical significance for p-values smaller than 0.05. The statistical computation was performed in R (version 3.3.3, The R Foundation for Statistical Computing, Vienna, Austria). As four different gamma criteria were used to analyze the data, the results of the VMAT plans were corrected for multiple testing using Bonferroni correction with a factor of four.

Results

Before each measurement session a consistency check which consisted of a beam output check and the measurement of a frequently irradiated VMAT treatment plan verified that the dose applied by treatment machine was within 0.6% from unity. For the s3D-CRT cases, a statistically significant difference between the original and modified beam model was found for both detectors. The results of the experimental data of the s3D-CRT plans are summarized in Figure 1 and

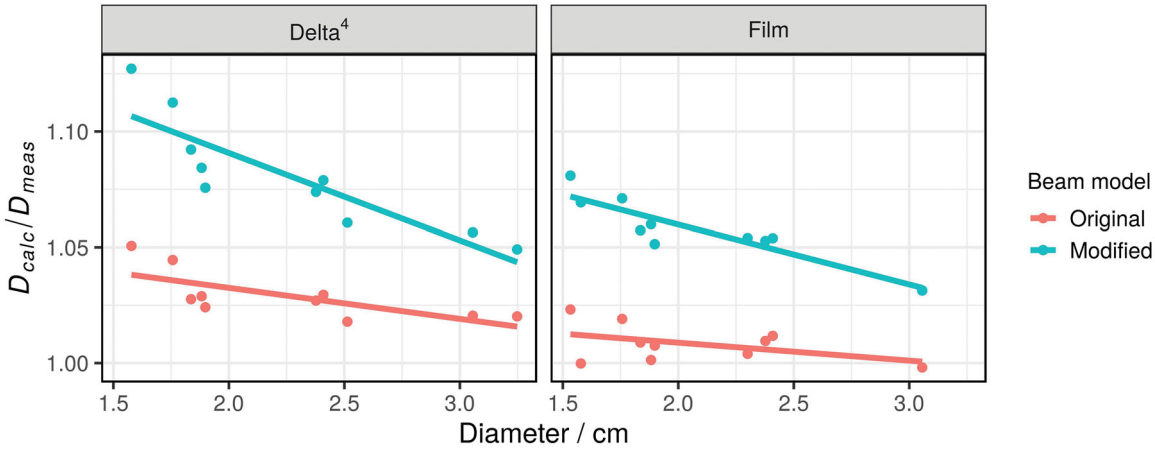

Figure 1. The ratio of calculated and measured dose at the isocenter of the s3D-CRT plans as a function of PTV diameter. Measurements performed with the Delta^4 phantom are depicted on the left and measurements performed using film dosimetry are depicted on the right.

Table 2. As depicted in Figure 1, the agreement between measured and calculated dose to the isocenter decreased with decreasing PTV diameter.

The results of the VMAT plans measured with two different detectors and evaluated with different acceptance criteria are illustrated in Figure 2 and Table S1 in the Supplementary material. For the 3%/3 mm criterion, a GPR higher than 90% was found for all investigated dose distributions irrespective of detector system and the beam models used for dose calculation. With more stringent evaluation criteria, also the GPRs decreased. The majority of significant differences between the beam models were found using the 1%/3 mm criterion. For the HN cases, F was 10.2% and 10.6%, for the PR cases 6.9% and 8.9% and for the BP cases 12.3% and 12.4% for the film measurements and the Delta^4 measurements, respectively. Statistically significant results indicating the modified beam model as the inferior one were only found for the BP cases measured with the Delta^4 phantom which also showed the highest fraction of small field fluence of 12.4%. Interestingly, for the HN and the PR cases, the GPR were higher for the modified beam model compared to the original beam model. Statistically significant differences of this effect were only found for the PR cases using film measurements with the 2%/3 mm, 1%/3 mm, and 2%/2 mm criteria. A summary of the fluence histograms of all VMAT treatment plans is depicted in the Supplementary material.

Table 2. Mean values and standard deviation of the ratio between calculated and measured dose of s3D-CRT plans generated with the original and modified beam models measured with two different detectors.

	D_{calc}/D_{meas}	
Detector	Original	Modified
Delta^4	1.03 ± 0.01	1.08 ± 0.02*
Film	1.01 ± 0.01	1.06 ± 0.01*

*p-value < 0.05.
The original beam model showed a closer agreement between the calculated and measured dose compared to the modified beam model.

Discussion

In this work, the OFs of small fields used in TPSs were systematically altered based on findings in [15–17] and the capability of dosimetry systems to detect these alterations was assessed. The main question was, whether the effects of these alterations on original treatment plans are detectable and can be attributed to errors in OF using commonly used dosimetry systems and evaluation criteria.

The most pronounced difference between the original and modified beam model was observed for s3D-CRT techniques since the plans are composed of several static beams using small fields only. The results of the s3D-CRT cases clearly indicate the modified beam model inadequate for clinical use for treatments involving small fields. Based on the findings of the film measurements depicted in Figure 1, lesions with a PTV diameter larger than 3 cm could be delivered with an accuracy better than 3% independent of the beam model. The artificially introduced deviations in OFs added up to a total difference between the two beam models which was detectable with film and the Delta^4 phantom. As expected, the difference increased with decreasing PTV size and consequently decreasing field size. Additionally, a systematic difference between the two detector types was observed. A possible reason for this can be that the gantry angle was not set to 0° as it was for the film measurements. This is the more challenging situation for accurate positioning of this detector for small fields as the radiological

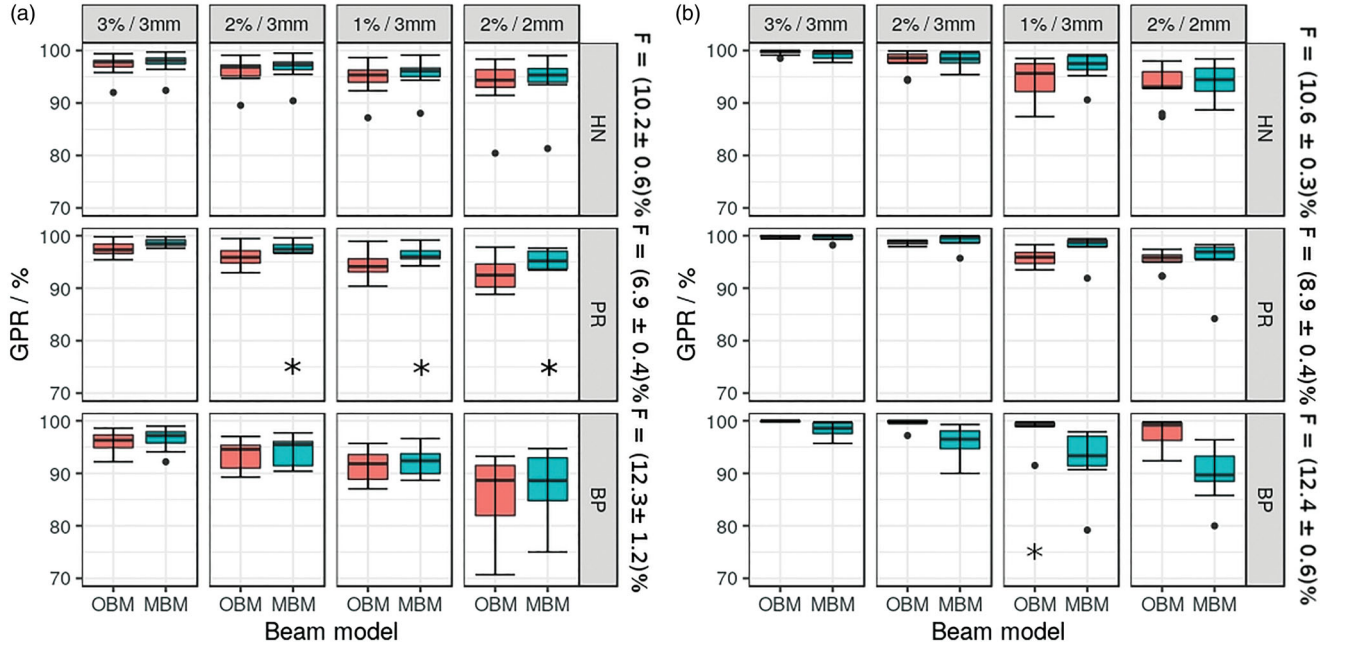

Figure 2. Boxplots of the GPRs for all investigated indications, acceptance criteria, and beam models. OBM is the original beam model and MBM is the modified beam model. The GPRs derived from the film measurements and from the Delta^4 phantom are shown in (a) and (b), respectively. The mean value of the proportion of the fluence delivered through leaf openings smaller than 2 cm (F) of the investigated treatment plans are depicted next to the box plots. Note that for the film measurements only the central four leaf pairs were considered for the calculation of F, while for the Delta^4 measurements all involved leaf pairs were considered. (*) p-value < 0.05 for comparison between original and modified beam model indicating the beam model with the higher GPR.

isocenter of the beam is moving as a function of gantry angle. The simplified setup for the film measurements of 3D-CRT plans was used to avoid other weaknesses of the pencil beam algorithm. The results of the Delta^4 measurements showed that the differences in output factors are also detectable with a clinically realistic setup.

VMAT plans which were dosimetrically verified using the Delta^4 phantom using an acceptance criterion of 3%/3 mm showed GPRs higher than 95% for all investigated treatment plans independent, of the beam model used for calculation. This acceptance criterion is clearly not sensitive enough to resolve differences between both beam models. By using more stringent criteria, larger differences between the two beam models become apparent. The BP cases measured with the Delta^4 phantom were the only cases where significant differences between the original and modified beam model were observed also indicating the modified beam model as the inferior one and also had the largest F-value.

The HN and PR cases showed, against the expected trend, higher GPRs for the modified beam model compared to the original beam model. This trend was visible for both detector types. An explanation for this could be the proportion of small fields to larger fields in these plan types as the only significant results were found for PR cases where the *F*-value was in the order of 6%. For the HN cases the *F*-values were approximately 10% and also the trend of the MBM having a higher GRP compared to the OBM is less pronounced. The higher GPR of the modified beam model compared to the original beam model can be explained by the lower contribution of small fields. As shown in Table 1, the OFs between the $3 \times 3\,cm^2$ and the $6 \times 6\,cm^2$ fields of the modified Monaco beam model were within 1.4% compared to the original beam model. These and other slight differences of the modified beam model compared to the original beam model could indeed lead to a better agreement of measured and calculated dose distributions compared to the original beam model. Evidently, even these large errors introduced to the beam model did not necessarily translate to an inferior dosimetric quality of the beam models, provided that the proportion of small fields was below 12%. While this threshold is dependent on the sequencing algorithm employed by the TPS and, therefore, might not be transferable to other TPSs, the method of analyzing the proportion of the fluence produced by small field can be generally applied.

The initial expectation was that the HN cases would be characterized by a high *F*-value and would also express the largest discrepancy between the OBM and MBM. Interestingly, the BP cases showed the highest *F*-values and also the largest differences between the two different beam models. A similar trend indicating also prostate cases as more sensitive to errors in small fields compared to HN cases was recently published by Wolfs et al. [30].

Considering the whole set of data reveals challenging aspects in patient specific QA. First, different detector systems might provide inconsistent data. Considering the BP cases, shows an example where no differences were observed using film dosimetry and significant differences were seen using the Delta^4 phantom. One possible explanation is the difference in measurement geometries, i.e., the location of the active volume of the detector system. In this work the film was positioned in the isocentric transverse plane while the Delta^4 phantom allows a quasi 3D dose acquisition. AAPM TG-218 now recommends an orientation of the detector plane in coronal or sagittal orientation is preferred over transversal orientation [31]. Note that this study was designed and performed before this recommendation was published.

Second, the choice of acceptance criteria for gamma-index analysis is critical. The commonly used 3%/3 mm criterion is too coarse for routine patient specific QA and for TPS commissioning. AAPM TG-218 recommends a standard acceptance criterion of 3%/2 mm and also recommends an adaptation of this criterion to the specific plan class and detector system [31]. As an effect in the dose deviation domain was expected, the dose deviation criterion was used varied in this work. The 1%/3 mm criterion was found to identify largest differences between the two investigated beam models. This acceptance criterion might be a good choice during the TPS commissioning process, provided that the uncertainty of the dosimetry system is low enough. In this work, the uncertainty of the Delta^4 and the film measurements were 0.9% and 1.3%, respectively, which is too large for this strict acceptance criterion. The propagation of uncertainties through gamma analysis is challenging to predict. The observed differences using the 1%/3 mm criterion might be due to the uncertainties of the detector system.

Third, considering one plan class alone (e.g., HN, PR, PB alone) is not sufficient for commissioning a beam model. As shown by the *F*-value, the fluence patterns can be very different for different plan classes. Re-modeling of beam models in TPSs might be worthwhile to improve the agreement of dose calculation of complex treatment plan with measured data for all plan classes used in clinical practice.

The methodology of calculating the small field fluence factor shown in this work can help to classify the specific treatment plans. Alternatively, complexity metrices for intensity modulated radiotherapy treatment plans, e.g., modulation complexity score [32], could be combined with uncertainties in small fields. The development of such an uncertainty weighted complexity score could be used to identify treatment plans sensitive to dosimetric uncertainties in small field OFs. This could be also implemented in modern TPSs to reduce the burden on individual institutions to program such a complexity score themselves.

Weaknesses of beam models could be identified by directly comparing doses calculated by a clinically used beam model to a modified beam model. Alternatively, for the identification of dosimetrically sensitive areas, the dose could be recalculated using a beam model based on reference machines (golden beam data). IROC-Houston QA Centre recently implemented a calculation system based on reference data capable of recalculating treatment plans. Recalculation of treatment plans which failed the experimental audit showed that 68% of these plans had errors already at the calculation stage [33].

It was not possible to achieve the desired OFs exactly for the modified beam model since this would have caused also an alteration of other beam parameters which would have introduced an additional uncertainty. However, the magnitude of the OF deviation for both beam models was still substantial enough to mimic the results reported in [15–17] on OFs calculated by several commercial TPSs which were compared to reference OFs for field sizes down to $2 \times 2\,cm^2$. In terms of experimental determination of OFs, the magnitude of the OF deviation in the $1 \times 1\,cm^2$ field would be equivalent to the use of an mini ionization chamber such as a PTW Semiflex or an IBA CC13 in this field without any correction. Note, that in that case the error would go in the other direction, i.e., the deviation factor would be smaller than unity. Similar differences were found in [34] where the output factors measured using an inappropriately aligned ionization chamber were compared to the results obtained using a well-positioned diode detector in small fields.

As outlined above, detecting deviations between the planned dose and delivered dose of complex treatment plans due to uncertainties in small field dosimetry is challenging and the fact that a treatment plan passes the patient-specific QA procedures does not mean that it is free of errors in dose delivery. In any case, output factors can always be calculated with the TPS and compared to measured output factors. If these calculated output factors show deviations to measured output factors, the beam model can be remodeled or the contribution of dose delivered through small fields can be limited for most sequencing algorithms. Patient specific QA as well as beam model commissioning for VMAT plans will benefit from time resolved dosimetry procedures as subfield can be investigated in more details.

In conclusion, large errors in OFs which can be present in TPSs are most pronounced in stereotactic treatment plans using small fields and can be identified also using patient specific QA. For intensity modulated treatment techniques, the effects of considerable deviations between measured and modeled OFs of small fields on total dose distributions of treatment plans can remain undetected using standard patient specific QA. Reasons for that are the limited contribution of dose through small fields to the total dose, a suboptimal position of the detector in areas unaffected by errors in OFs and the sensitivity of the detector system itself. Analyzing the fluence contribution of small fields can be useful for these investigations. The standard 3%/3 mm acceptance criterion for VMAT treatment plans is too coarse to be useful for analyzing treatment delivery with respect to small field dosimetry. Therefore, tighter dosimetric acceptance levels such as 2% or even 1% should be used but also the accuracy of the detector system needs to be considered.

Disclosure statement

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