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A multi-centre analytical study of small field output factor calculations in radiotherapy

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ABSTRACT

An audit methodology was developed and applied for output factor (OF) calculations in radiotherapy. The auditees were asked to calculate OFs for field sizes from $10 \times 10\,\text{cm}^2$ to $2 \times 2\,\text{cm}^2$. Sixty five beams were audited; missing reference OFs were interpolated. The calculated OFs were in 73% of cases higher than the reference data. The smaller the field size, the higher the overestimations which were observed in the higher fraction of cases. Treatment planning systems generally overestimated OFs for small fields. The reference dataset helped radiotherapy centres to identify discrepancies which were higher than typical.

1. Introduction

Appropriate calculation of output factors for small fields shaped by a multileaf collimator (MLC), performed in treatment planning systems (TPS), is essential for intensity-modulated radiation therapy (IMRT). Therefore, proper configuration of beam data and precise modelling of the MLC in the treatment planning system (TPS) are key factors that have to be verified prior to clinical use. Dosimetry for fields smaller than $3 \times 3\,\text{cm}^2$ is very difficult and has a high degree of uncertainty. This is caused both by the relatively large penumbra size, as well as by the changes in the energy spectrum [1–5] . The significant role of external dosimetry audits [6–8], including small field tests, in radiation therapy clinical trials, is often evoked [9]. Methodologies of audits of small field output performance were formerly proposed [8,10,11]. The Radiological Physics Center (RPC) at the MD Anderson Cancer Center (presently IROC-Houston QA Center) has prepared a set of data containing output factors depending on nominal beam energy, field sizes and accelerator models [12–14]. However, the published data do not cover all beam energies from the mega-voltage range used in photon-based radiotherapy. The RPC dataset and the interpolation functions proposed in this work were used to carry out a nationwide audit of small field OF calculations.

2. Material and methods

Participants were asked to calculate the output factors for beams formed by the multi-leaf collimator (MLC), using their planning software. The results of their calculations were compared with the reference published data. All 35 Polish radiotherapy departments were invited to take part in the study, and 32 of them responded and provided their results. The TPS calculations for medical accelerators of three vendors were evaluated: Elekta, Siemens and Varian, further denoted throughout the text as type A, B and C. In total, 65 beams were audited: 20 of type A, 15 of type B and 30 of type C accelerators. In seven centres the calculations were repeated for the same beams with two or three different TPSs or with alternative calculation algorithms. In total, 76 beam&TPS combinations were evaluated. Most of the results (90%) were obtained for beams with a nominal energy of either 6 MV (62%) or 15 MV (28%) (see Supplementary Tables S1–S3). The most commonly used beam energies (excluding FFF) for each of the vendors were used in the calculations. The participants had to calculate the number of monitor units (MU) for the delivery a dose of 10 Gy to water with five square, MLC-shaped fields ($10 \times 10\,\text{cm}^2$, $6 \times 6\,\text{cm}^2$, $4 \times 4\,\text{cm}^2$, $3 \times 3\,\text{cm}^2$ and $2 \times 2\,\text{cm}^2$), to a reference point at a depth of 10 cm on the central axis at a source-to-phantom distance (SPD) of 100 cm. The dose rates $DR_{(f,E)}$[Gy/MU] were calculated for a specific field size f [cm^2] and beam energy E [MV], and then divided by the $DR_{(10\times10,E)}$ calculated for a field size of $10 \times 10\,\text{cm}^2$ and for the same beam energy, thus providing a normalized output factor $OF_{(f,E)}$ (see Eq. (1)).

$$OF_{(f,E)} = \frac{DR_{(f,E)}}{DR_{(10\times10,E)}} \tag{1}$$

The discrepancies between the reference RPC data and the institution OF were analysed and compared with the criteria of acceptability provided by other authors [15,16]. Thus, when the 3% level of disagreement was exceeded, the authors expected institutions to consider

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Table 1
Treatment planning systems and related calculation algorithms used for the OF calculations.

Treatment planning system	Applied calculation algorithm	TPS/Algorithm abbreviation	Number of TPSs
Pinnacle	Collapsed Cone Convolution	PC/CC	2
Monaco	Monte Carlo	MO/MC	15
Prowess Panther	Collapsed Cone Convolution	PR/CC	13
CMS XiO	Superposition	XO/SP	3
	Convolution	XO/CV	1
Oncentra MasterPlan	Pencil Beam Convolution	ON/PB	3
	Collapsed Cone Convolution	ON/CC	8
Eclipse	Pencil Beam Convolution	EC/PB	1
	Analytical Anisotropic Alg.	EC/AA	29
	Acuros XB	EC/AX	2

this as problematic. The values of the OFs for beam energies E [MV], not present in the RPC data set, have been interpolated with a second degree polynomial (see Eq. (2))

$$OF_{(f,E)} = a(f)\cdot E^2 + b(f)\cdot E + c(f) \tag{2}$$

using the non-linear least-squares (NLLS) Marquardt-Levenberg algorithm [17–19]. Interpolated values of the reference OFs had to be used in 18% of cases. The clinically used TPSs and related calculation algorithms were examined (see Table 1).

The audit results for individual participants were grouped for accelerator types A, B and C.

3. Results

The *a(f)*, *b(f)* and *c(f)* parameters of the Eq. (2) were obtained in the procedure of fitting to the experimental data (see Supplementary Table S4 and Supplementary Figs. S1–S3). In any case of fitting, the final sum of the square residuals (WSSR) was not larger than 2.6×10^{-5}. The OFs calculated with TPSs were in 73% of cases higher than the published reference data. The smaller the field size, the higher the overestimations which were observed. Overestimations of OFs were observed in 69% calculations for $6 \times 6\,\text{cm}^2$ fields, in 70% for $4 \times 4\,\text{cm}^2$, in 75% for $3 \times 3\,\text{cm}^2$, and in 77% for $2 \times 2\,\text{cm}^2$ fields. The mean values ($\pm\sigma$) of the fraction of OFs calculated with TPS to the reference data were: 1.001 ($\pm$ 0.007) for $6 \times 6\,\text{cm}^2$, 1.004 ($\pm$ 0.010) for $4 \times 4\,\text{cm}^2$ 1.008 ($\pm$ 0.012) for $4 \times 4\,\text{cm}^2$, and 1.014 ($\pm$ 0.024) for $2 \times 2\,\text{cm}^2$ fields (see Supplementary Figs. S4–S7). For smaller field sizes, wider distributions and higher modal values of ratios of the institution OF to the reference OF were observed (see Fig. 1). The ratios of the audited institution mean OFs to the corresponding values reported by RPC, were generally within a range of 0.996–1.002. Only for type B accelerator 6 MV and field size $2 \times 2\,\text{cm}^2$, this ratio was as high as 1.04. For type A accelerators, all calculation results showed a deviation from the reference values lower than 3%. For type B and C accelerators, the resulting calculations for fields larger than $2 \times 2\,\text{cm}^2$ differed by less than 4%. For $2 \times 2\,\text{cm}^2$ fields formed by MLCs of B and C linacs, the differences between the calculated and measured output factors often exceeded 5% and were below 10%.

4. Discussion

This audit of small field calculation of OFs was performed in a significant number of institutions for a wide range of linac models and TPS. As reference data, OFs measured and published by other authors were used [12–14]. Interpolated OFs were generated for missing reference data. The universal formula derived from interpolation for the measurement data, was proposed here. This allowed calculation of the expected reference OF for most currently used models of accelerators for a wide range of nominal energies for beams modified with flattening filters.

The mean values (see Table 2) and the standard deviations of calculated relative output factors obtained in the audit were similar to the RPC values. Average absolute deviations from the mean values of calculated (institution) OFs acquired by RPC were 1.1%, 1.4% and 1.3% for A, B and C accelerators, respectively. The standard deviations of the calculated OFs were ≤ 0.04 in both audits. Previous results of Monte Carlo simulations [1,2] and investigations of the response of different detectors for radiation from narrow beams [3,4] were extensively exploited by the RPC in audits. The standard deviations of the RPC results are below 2.4%, which is comparable with the recommendations of 2% tolerance in comparisons between TPS-calculated and measured OFs for field sizes of $3 \times 3\,\text{cm}^2$ and larger [15]. The average standard deviations of measured OF within groups of the same accelerator type for different beam energies and field sizes were 0.9%, 0.7% and 0.6% for type A, B and C accelerator, respectively [14]. This means that the construction differences among classes available within the same accelerator type are minor and do not significantly influence the beam or the collimation sections. We consider that it is justified to refer to the published results of measurements performed for a large number of accelerators before referring to measurements performed for each specific unit installed at the audited institutions, because the OF measurements for TPS configurations are typically performed for field sizes $\geq 3 \times 3\,\text{cm}^2$, and because precise small field dosimetry in less advanced institutions is still limited. In the case of very small fields, the positioning or correction factor uncertainties would make the audit results confusing, if the measurements were carried out in different institutions with different equipment. The audit intended to highlight that institutions should compare their beam data and the TPS calculations also with the reference data. All audited institutions reported the commissioning measurements performed for small field sizes (as close as possible to $4 \times 4\,\text{cm}^2$). This is consistent with IAEA guidance [15,20] for small field calculation checks.

The aim of this study was not to repeat the whole on-site audit procedure performed by the RPC and, in our opinion, there is no need to repeat the measurements in future routine national audit programmes unless unresolved high discrepancies are observed by the auditee. The simple interpolation formula presented by the authors of this work needs further validation through carrying out and juxtaposing additional measurements and by means of Monte Carlo simulations. Similar work has been performed for electron and photon beams [21–23]. Reports presenting the ratios of the OF to the reference values calculated in institutions were sent back to the participants. Recalculated OFs showing improved results for five beams were obtained from four centres. In the first center (A/MO), the auditee performed new measurements and changed the beam modelling in the most advanced TPS used in the institution. In the second institution (C/EC), the PB calculation algorithm was replaced with an AA one. In the third institution (A/PC), the second alternative “small” beam model was created for the same beam, which was optimized and used only for field sizes from $1.5 \times 1.5\,\text{cm}^2$ up to $10 \times 10\,\text{cm}^2$. In the fourth institution, misunderstanding of the geometrical set-up from the audit instruction was reported. In one institution (B/PR), the OF factor value for field size $2 \times 2\,\text{cm}^2$ was set in TPS, as the same as for the $3 \times 3\,\text{cm}^2$ field. The institution did not change the TPS configuration, because $2 \times 2\,\text{cm}^2$ fields were not clinically used there. The results presented here include the corrected values of the OFs. It seems that there is a correlation between the results of the OF calculations and the type of the TPS calculation algorithm. For type B accelerators and ON/PB TPS, all results for the $2 \times 2\,\text{cm}^2$ field differ more than 5% from the reference data. For type C accelerators, upgrading TPS from EC/PB to EC/