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Dosimetric response of the Delta4 system for small fields and the impact on dose verification accuracy

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ABSTRACT

Background: This study investigates the dosimetric response of the Delta4 system to varying field sizes and assesses its accuracy in dose verification. ***Materials and Methods:*** Output factors for fields ranging from 1 × 1 cm² to 20 × 20 cm² were measured using PTW 60019 detector, PTW 60018 detector, and the Delta4 system. The PTW 60019 measurements were considered the gold standard and were compared with those from the other two detectors. Two test plans were developed to compare the dose verification results of the Delta4 system, both with and without output factor correction. ***Results:*** The PTW 60018 and IBA CC13 detector measurements, using the daisy-chaining method, demonstrated strong agreement with the gold standard. However, the Delta4 system showed an underestimation in the output factor of the 1×1 cm² field, with deviations of -2.259% for the 6 MV flattening filter (FF) beam and -3.343% for the 6 MV flattening filter free (FFF) beam. After correcting the output factor, the gamma passes rate (3%/2mm) for test plan 2 featuring 1 × 1 cm² sub-fields improved from 67.3% to 95.7% for the 6 MV FF beam. ***Conclusions:*** The Delta4 system exhibits a dosimetric response issue when managing small fields. Output factor corrections are recommended for Delta4 dose verification results when dealing with field sizes less than 4 cm and a high number of sub-fields.

INTRODUCTION

Intensity Modulated Radiation Therapy (IMRT) employs advanced techniques to precisely deliver radiation doses to tumors by modulating beam shape and intensity. This method yields dose distributions that are more heterogeneous compared to those generated by traditional three-dimensional (3D) planning, utilizing complex fields with varying degrees of modulation (1). Particularly with small fields, dosimetric errors in IMRT have increased significantly compared to conventional beams (2). To ensure radiotherapy's effectiveness and safety, ICRU Report 24 mandates that dose deviations should not exceed 5% (3). Due to these complexities, patient-specific dose verification has become imperative. Reports TG142 and TG218 from the American Association of Physicists in Medicine (AAPM) provide comprehensive guidelines for IMRT quality control and patient-specific quality assurance (QA) (1, 4).

For patient-specific QA, the equipment typically includes radiochromic film, ion chamber arrays, and semiconductor arrays, among others (5). Notably, radiochromic film is preferred for its high spatial resolution and minimal energy dependence, despite challenges such as film darkening and sensitivity to temperature variations (6-8). Accurate absorbed dose to water calibration is required for film readout procedures. Moreover, studies have indicated that the accuracy of dose verification can be impacted by unexposed film pixel values, which are not always readily available (9). The ion chamber, another commonly used device in radiotherapy dosimetry, faces limitations in areas with high dose gradients and nonuniform beam distributions. Furthermore, the large sensitive volume of ion chambers reduces the spatial resolution of ion chamber arrays. Semiconductor detectors, with their small sensitive volumes, are ideal for measuring small fields, enabling high spatial resolution depending on the distance between semiconductor detectors. However, it has been reported that semiconductor detectors have the problem of over-response to low-energy rays(10-11). When measuring large fields, the presence of scattered rays in the field increases with the field size, affecting measurement accuracy.

The Delta4, a 3D dose verification system featuring 1069 semiconductor detectors, enables rapid dose verification for IMRT plans. Numerous studies have highlighted the advantages of Delta4 and its successful application in dose verification for radiotherapy (10, 11). However, research has shown that Delta4's response varies with field size (12). The manufacturer of Delta4 has provided dose corrections for field sizes ranging from 5×5 cm^2 to 20×20 cm^2, but has not addressed fields smaller than 5×5 cm^2 (13).

In this study, we assessed the output factors for fields sized from 1 × 1 cm^2 to 20 × 20 cm^2 using diverse detectors on an Elekta linear accelerator (linac). Additionally, we investigated the influence of output factor discrepancies on dose verification by evaluating the gamma pass rates for two test plans with varying sub-field counts and dimensions, using the Delta4 system. This paper contributes by measuring the dose response of Delta4 for small fields from 1 × 1 cm^2 to 4 × 4 cm^2 and by attempting to correct the output factors of Delta4 for small fields, which enhances the accuracy of dose verification for small fields.

MATERIALS AND METHODS

Measurement of output ffactor

Measuring equipment

Four detectors were utilized in this study: Delta4, PTW 60018, PTW 60019, and IBA CC13. The Delta4, a 3D verification device manufactured by ScandiDos in Uppsala, Sweden, is cylindrical with two orthogonally arranged cross-shaped semiconductor matrices embedded at its center. It features a detection area of 20 × 20 cm^2 with 1069 semiconductor detectors, each having a sensitive diameter of 1 mm, a length of 0.05 mm, and a spacing of 5 mm within the central 5×5 cm^2 area, increasing to 1 cm in other regions (17). It is mainly composed of P-type semiconductor and polymethyl methacrylate (PMMA) material The PTW 60018 and PTW 60019 detectors, manufactured by PTW in Freiburg, Germany, were utilized. The PTW 60018 detector features a disc-shaped sensitive volume of 0.3 mm^3, with dimensions of 1.13 mm in diameter and 0.25 mm in thickness. Conversely, the PTW 60019 detector incorporates a diamond detector with a sensitive volume of 0.004 mm^3, measuring 2.2 mm in diameter and 0.001 mm in thickness. Furthermore, the IBA CC13 ionization chamber, produced by IBA in Louvain-La-Neuve, Belgium, holds a sensitive volume of 0.13 cm^3 and dimensions of 3.0 mm radius and 5.8 mm length. Output factor measurements for the PTW detectors were performed using a 3D water tank (IBA Blue Phantom2, also from IBA). The Elekta Infinity LINAC from Sweden was the machine employed in this study. The linac is equipped with 80 pairs of multi-leaf collimators (MLC) with a width of 5 mm. The maximum field area is 40 × 40 cm^2, with a maximum dose rate of 600 MU/min for the 6 MV flattening filter (FF) beam and 1600 MU/min for the 6 MV flattening filter-free (FFF) beam.

Quality control of linear accelerator before measurements

Quality control procedures were followed prior to the measurements as per the AAPM TG142 report (4). Checks included the absolute output dose, the consistency of the light and radiation fields, the accuracy of the laser and image guidance systems, and the mechanical precision of the linac components, such as the collimator, multi-leaf collimators (MLC), gantry, and treatment table. Calibrations of relative and absolute dose, as well as directional calibrations of the Delta4 system, were also performed prior to measurement.

Measurement process

All measurements took place at a source-skin distance (SSD) of 90 cm and a depth of 10 cm under the water surface. Before each measurement, the positioning of the detectors was confirmed with an image-guided device to align the detector center with the field center. The PTW 60019 and 60018 detectors were aligned parallel to the beam, facilitating vertical beam incidence on the disc-shaped sensitive volumes. It is crucial to acknowledge that the PTW 60018, a semiconductor detector, utilized the daisy chain method for data collection, as noted by Dieterich and Sherouse (15). Relative dose calibration, absolute dose calibration, and directional calibration of Delta4 system were also performed before measurement. A three-dimensional water tank (IBA blue phantom2, produced by IBA, Louvain-La-Neuve, Belgium) was used when measuring the output factors of the PTW 60019 and 60018 detectors. For fields smaller than 4×4 cm^2, measurements were conducted using the PTW 60018 detector, whereas for fields exceeding this size, the CC13 ionization chamber was utilized, with 4×4 cm^2 serving as the benchmark size. The CC13 chamber was oriented perpendicular to the beam's direction. Owing to the configuration of Delta4 detectors in a planar array, IBA solid water was substituted for the IBA Blue Phantom2, employing ten 1-cm thick layers of solid water. Beneath these layers, the Delta4 semiconductor array was positioned to align the central detector precisely with the field center. All detectors involved measured the output factors across a range from 1×1 cm^2 to 20×20 cm^2, with each measurement taken five times and normalized against the 10×10 cm^2 field value. Adjustments to the PTW 60018 and 60019 detectors' output factors were applied based on correction factors from the International Atomic Energy Agency (IAEA) TRS-483 report (16). The measurements of PTW 60019 were taken as the gold standard and compared with those of two other detectors.

Correction of output factor for Delta4

The output factors measured by the PTW 60019

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detector were considered the gold standard, and those for the Delta4 were corrected for small fields ranging from 1×1 cm^2 to 4×4 cm^2. Since the Delta4 software lacks a direct function to modify the output factor, manual adjustments were made to the output dose in the test plans based on the relative difference between the output factor of Delta4 and the gold standard.

Gamma pass rates of Delta4 in dose verification Test plans

To assess the impact of small field output factors on dose verification results for Delta4, two test plans were developed using the RayStation treatment planning system (RaySearch Laboratories, Stockholm, Sweden). Each plan included five beams at angles of 0°, 72°, 144°, 216°, and 288°. In Test Plan 1, each beam's field consisted of four sub-fields, depicted in figure 1 (a). Sub-fields of sizes 1×1 cm^2, 2×2 cm^2, 3×3 cm^2, and 4×4 cm^2 were employed, forming four sub-plans with varying sub-field sizes. The spacings between the sub-fields were 2 cm, 3 cm, 4 cm, and 5 cm, respectively. Figure 1 (b) shows the distribution of sub-fields in Test Plan 2. Similar to Test Plan 1, four types of sub-fields were used, but the number of sub-fields per beam increased to 121, with a sub-field spacing of 0.5 cm. Additionally, all sub-fields were centrally symmetric within the field, and the total field size of each beam was 6 cm, 7 cm, 8 cm, and 9 cm, respectively. The output factors obtained by the PTW 60019 detector were taken as the gold standard, and the output factors of Delta4 were modified to get the corrected gamma pass rate. Since there was no function in Delta4 software to directly modify the output factor, the output dose is manually increased or decreased for test plans according to the relative difference between the output factor of Delta4 and the gold standard.

Correction of gamma pass rates for Delta4

The gamma passes rates for both Test Plan 1 and Test Plan 2 under the 6 MV flattening filter (FF) and 6 MV flattening filter free (FFF) beams were evaluated using the Delta4 measurement system. The criteria for the gamma pass rate were 3mm/2%, 2mm/3%, and 3mm/3%, with a threshold set at 10%. The corrected gamma pass rates were achieved by manually adjusting the output dose in the Delta4 software for the two test plans.

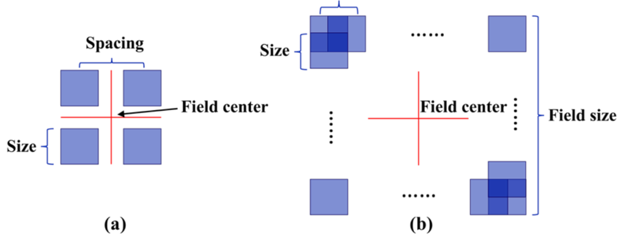

Figure 1. The distribution of sub-fields in the two test plans and four types of sub-fields and spacing were designed to calculate the gamma pass rates using Delta4. **(a)** Test plan 1 consist of 4 sub-fields, **(b)** Test plan 2 consist of 121 sub-fields.

RESULTS

Output factors of Delta4

The output factors of the PTW 60018 and IBA CC13 detectors, measured using the daisy-chaining method, are presented in table 1. Results for both the 6 MV FF and FFF beams were closely aligned with established standards. The greatest deviation observed with the 6 MV FF beam was -0.751%, and with the 6 MV FFF beam, it reached 1.744%. The Delta4 detector's output factors (table 2), demonstrated smaller values for field sizes under 10 × 10 cm^2 and larger for those above this threshold compared to the PTW 60019. Moreover, the relative deviations between Delta4's readings and the standard reference increased as field sizes diverged further from 10 cm. Notably, deviations exceeded 2% at a field size of 1×1 cm^2 and surpassed 1% at 20 × 20 cm^2 for the 6 MV FF beam. For the 6 MV FFF beam, deviations were more than 3% for a field size of 5 × 5 cm^2 and nearly 1% at 20×20 cm^2.

AAPM TG-198 stipulates that the tolerance for output factors of photon fields smaller than 4×4 cm^2 is a ±2% deviation from the output factors established at the time of commissioning, due to potential setup uncertainty. For photon fields 4×4 cm^2 or larger, the tolerance is ±1% deviation (17). The measurement results indicate that the output factors for Delta4 require correction for a field size of 1×1 cm^2.

Gamma pass rate of Delta4 in dose verification

Gamma pass rates for two distinct test plans are presented in Tables 3 and 4. In Test Plan 1, gamma pass rates for sub-plans with varied sub-field dimensions uniformly exceeded 95%, with higher rates observed under the 6 MV FFF beam compared to the 6 MV FF beam. In Test Plan 2, the gamma pass rate increased with larger sub-field sizes, and for the sub-plan with 4 × 4 cm^2 sub-fields, the rates surpassed 90% according to three different criteria. These results suggest that as the number of sub-fields increased and the sub-field spacing decreased, the gamma pass rate obtained by Delta4 deteriorated, particularly for small field irradiation, where the measurement error of Delta4 is significant.

Table 5 shows the gamma pass rates for Test Plan 2 following output factor correction, based on results from the PTW 60019 detector. Notably, the corrected gamma passes rates significantly improved, highlighting the importance of output factor correction when using Delta4 for dose verification in complex plans, particularly those involving many small sub-fields.

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Table 1. Output factors of fields ranging from 1 × 1 cm^2 to 20 × 20 cm^2 obtained by PTW 60018 and IBA CC13 detector using daisy-chashing method.

Beam	6 MV FF			6MV FFF		
Field size (cm^2)	PTW 60018+IBA CC13	PTW 60019	deviation (%)	PTW 60018+IBA CC13	PTW 60019	deviation (%)
1×1	0.003±0.662	0.002±0.664	-0.301	0.001±0.700	0.001±0.688	1.744
2×2	0.003±0.793	0.002±0.799	-0.751	0.001±0.830	0.001±0.827	0.363
3×3	0.003±0.841	0.002±0.845	-0.473	0.001±0.876	0.001±0.874	0.229
4×4	0.002±0.878	0.002±0.878	0.000	0.001±0.903	0.001±0.902	0.111
5×5	0.002±0.905	0.002±0.905	0.000	0.001±0.926	0.001±0.928	-0.216
7×7	0.003±0.950	0.002±0.950	0.000	0.001±0.962	0.001±0.961	0.104
10×10	1.000	1.000	0.000	1.000	1.000	0.000
15×15	0.002±1.059	0.002±1.057	0.189	0.001±1.041	0.002±1.039	0.192
20×20	0.002±1.097	0.003±1.095	0.183	0.002±1.065	0.001±1.063	0.188

Table 2. Output factors of fields ranging from 1 × 1 cm^2 to 20 × 20 cm^2 obtained by Delta4 detector.

Beam	6 MV FF			6MV FFF		
Field size (cm^2)	Delta4	PTW 60019	deviation (%)	Delta4	PTW 60019	deviation (%)
1×1	0.002±0.649	0.002±0.664	-2.259	0.001±0.665	0.001±0.688	-3.343
2×2	0.001±0.792	0.002±0.799	-0.876	0.001±0.815	0.001±0.827	-1.451
3×3	0.002±0.838	0.002±0.845	-0.828	0.001±0.864	0.001±0.874	-1.259
4×4	0.001±0.872	0.002±0.878	-0.683	0.001±0.895	0.001±0.902	-0.776
5×5	0.002±0.900	0.002±0.905	-0.552	0.002±0.919	0.001±0.928	-0.970
7×7	0.001±0.946	0.002±0.950	-0.421	0.001±0.959	0.001±0.961	-0.208
10×10	1.000	1.000	0.000	1.000	1.000	0.000
15×15	0.002±1.062	0.002±1.057	0.473	0.001±1.045	0.002±1.039	0.577
20×20	0.001±1.107	0.003±1.095	1.096	0.001±1.073	0.001±1.063	0.941

Table 3. Gamma pass rates of Test Plans 1 using Delta4 without output factor correction.

Beam	6 MV FF			6MV FFF		
Sub-field (cm^2)	2 3%/mm	3 2%/mm	3 3%/mm	2 3%/mm	3 2%/mm	3 3%/mm
1×1	97.6%	99.4%	99.4%	98.2%	100%	100%
2×2	97.1%	99.4%	99.4%	99.7%	100%	100%
3×3	97.2%	98.3%	99.4%	99.9%	100%	100%
4×4	98.8%	100%	100%	100%	100%	100%

Table 4. Gamma pass rates of Test Plans 2 using Delta4 without output factor correction.

Beam	6 MV FF			6MV FFF		
Sub-field (cm^2)	2 3%/mm	3 2%/mm	3 3%/mm	2 3%/mm	3 2%/mm	3 3%/mm
1×1	67.3%	67.6%	74.3%	79.9%	76.5%	83.4%
2×2	74.8%	77.3%	83.7%	98.9%	96.2%	99.8%
3×3	83.1%	84.3%	89.6%	99.2%	98.2%	99.8%
4×4	93.9%	93.9%	97.9%	93.1%	93.7%	96.6%

Table 5. Gamma pass rates of Test Plans 2 using Delta4 after output factor correction.

Beam	6 MV FF			6MV FFF		
Sub-field (cm^2)	2 3%/mm	3 2%/mm	3 3%/mm	2 3%/mm	3 2%/mm	3 3%/mm
1×1	95.7%	96.6%	99.3%	87.4%	83.8%	88.1%
2×2	83.2%	83.4%	89.5%	100%	100%	100%
3×3	87.6%	88.4%	93.1%	100%	99.8%	100%
4×4	97.5%	96.4%	99.8%	97.9%	97.9%	99.8%

DISCUSSION

The Delta4 system is widely utilized for clinical dose verification (18). The application of Intensity-Modulated Radiation Therapy has heightened the demand for patient-specific dose verification. Traditional two-dimensional matrices struggle to meet the dose verification needs of complex treatment plans. Although Delta4 offers high stability in IMRT plan verification and simplifies the measurement process, its semiconductor detectors exhibit an over-response to low-energy rays (19, 20).The Delta4 three-dimensional dose verification system consists of two orthogonal plates, and the semiconductor detectors on the plate can accurately measure the beam dose at any angle. Extensive research has been conducted using Delta4 for fields larger than 5 × 5 cm^2. Tani *et al.* explored optimal density scaling factors in Delta4 to enhance the accuracy of dose distributions in phantom materials (21). Zhang *et al.* analyzed gamma pass rates by comparing calculated and measured doses in nine lung cancer patients using Delta4 (22). Petrucci *et al.* assessed Delta4's ability to detect delivery errors through dose gamma index, MLC gamma index, and leaf position adjustments in 15 manually modified Volume Modulated Arc Therapy (VMAT) plans (12). In other studies, Delta4 is often regarded as the gold standard for dose verification, with its measurements compared to those from other detectors (23). However, there is a notable scarcity of analyses for fields smaller than 4×4 cm^2. The manufacturer made dose correction for fields larger than 5 × 5 cm^2 in Delta4 phantom, but did not mention the correction for fields smaller than 5 × 5 cm^2. In this study, three detectors (Delta4 semiconductor detector, PTW 60018 semiconductor detector, and PTW 60019 diamond detector) were used to measure dose for fields of varying sizes. The output factors were calculated using a 10 × 10 cm^2 field as the reference field, and the deviations between the output factors of the three detectors were compared. Two IMRT test plans were also designed in this study, and the gamma pass rate of the Delta4 was measured under both plans.

The manufacturer has provided dose corrections

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for fields larger than 5×5 cm^2 in the Delta4 phantom but has not addressed corrections for fields smaller than 5×5 cm^2. In this study, output factors for fields smaller than 5×5 cm^2 were measured, and the results from the PTW 60019 detector were used as the gold standard. Findings indicate that Delta4 consistently underperformed relative to the gold standard, with increased deviations for smaller fields. Although Borca *et al.* also measured field output factors using Delta4, they neither compared these results with those from other detectors nor corrected the measured output factors (24).

In subsequent gamma pass rate analysis, it was observed that Delta4 yielded lower results for IMRT plans with numerous small fields, necessitating corrections. Cho *et al*. assessed the global gamma pass rate of Delta4 in patient-specific dose verification across varying tumor sizes, discovering that smaller tumors resulted in higher gamma pass rates (25). The conclusions of their study seemed inconsistent with our findings, as smaller tumors generally involve smaller fields. However, their analysis primarily covered tumor sizes ranging from 3 to 15 cm, utilizing field sizes considerably larger than those typically classified as small. Additionally, the proportion of low-dose areas surrounding the tumor increases as tumor size decreases, and these areas were included in the global gamma pass rate calculation with Delta4. Consequently, gamma pass rates in these areas might elevate the overall rate. Results from Test Plan 1 also indicated that the influence of field size on gamma pass rate was negligible when the number of small fields was minimal. Therefore, the findings of Cho et al. do not contradict our study results.The results of this study showed that the output factors measured by PTW 60018 detector were consistent with the gold standard measured by PTW 60019 detector, and their deviations were within the tolerance suggested in AAPM TG-198 report. However, the measurement results of Delta4 detector were different from the gold standard. For the small field of 1 × 1 cm^2, the deviation exceeded the 2% tolerance recommended by the AAPM TG-198 report, and for the field of 20 × 20 cm^2, the deviation exceeded the 1% tolerance in the FF beam. Although the manufacturer of Delta4 claimed to have dose correction for fields ranging from 5 × 5 cm^2 to 20 × 20 cm^2, the accuracy of output factors for small fields was not mentioned. The results of this study suggested that the output factor error may lead to the inaccuracy of the gamma pass rate for those complex IMRT plans consists of a large number of small sub-fielLinac-based stereotactic radiosurgery (SRS) utilizes small fields to focus energy onto diseased tissues through non-coplanar irradiation and image-guided technology, which requires an accurate dose-verification method to provide quality assurance for clinical treatment(21, 22). To verify the dose validation accuracy of the Delta4 system for SRS, two IMRT test plans with different sub-field number and field size were designed. The dose verification results of Test Plans 1 showed that when the number of sub-fields was small, the gamma pass rates measured by Delta4 for all small fields were greater than 97% under the 3%/2mm criteria, meeting the universal tolerance limit of 95% recommend by AAPM TG-218 report. However, the dose verification results of Test Plans 2 showed that the gamma pass rate decreased sharply when the number of sub-fields increased, and the smaller the sub-field size, the smaller the gamma pass rate. In addition, the gamma pass rate of 6 MV FFF beam was higher than that of 6 MV FF beam, indicating that the 6 MV FFF beam was less affected by the number of sub-fields. Table 5 showed the gamma pass rates of Test Plans 2 were improved after the output factor correction, which pointed out that dose correction should be performed when using Delta4 for dose verification of complex plans, especially those with numerous small sub-fields. Although the gamma pass rates of some plans after the output factor correction were still lower than the action limit of 90% recommend by AAPM TG-218 report, the results of this study showed that Delta4 has the ability to perform dose-validation for IMRT plans less complex than Test Plans2 after dose correction.

The study's limitations include not considering the density correction for the IBA solid water used in measuring Delta4's output factors, which may have impacted the accuracy of measurements. Moreover, the two test plans implemented did not encompass complex-shaped fields, though the outcomes still illustrate the effectiveness of output factor correction in enhancing the dose validation accuracy of Delta4. The correction method for the output factor was also relatively straightforward, as the Delta4 system lacks a direct correction function for output factors, leading to adjustments being made based on the output factor discrepancies noted in this study.

CONCLUSION

This study quantified the dose response of the Delta4 system to small fields and implemented output factor corrections, significantly enhancing the accuracy of dose verification for small fields using Delta4. While the Delta4 system corrects the dose response for large fields, it encounters issues with small fields. When the sub-field size is less than 4 cm and there is a large number of sub-fields, it is necessary to apply a correction to the measured dose by Delta4 to ensure accurate dose verification.

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AI usage: No.

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