Original Article

Assessment of Imprecise Small Photon Beam Modeling by Two Treatment Planning System Algorithms

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Abstract

Background: Dosimetric accuracy in intensity-modulated radiation therapy (IMRT) is the main part of quality assurance program. Improper beam modeling of small fields by treatment planning system (TPS) can lead to inaccuracy in treatment delivery. This study aimed to evaluate of the dose delivery accuracy at small segments of IMRT technique using two-dimensional (2D) array as well as evaluate the capability of two TPSs algorithm in modeling of small fields. **Methods:** Irradiation were performed using 6 MV photon beam of Siemens Artiste linear accelerator. Dosimetric behaviors of two dose calculation algorithms, namely, collapsed cone convolution/superposition (CCCS) and full scatter convolution (FSC) in small segments of IMRT plans were analyzed using a 2D diode array and gamma evaluation. **Results:** Comparisons of measurements against TPSs calculations showed that percentage difference of output factors of small fields were 2% and 15% for CCCS and FSC algorithm, respectively. Gamma analysis of calculated dose distributions by TPSs against those measured by 2D array showed that in passing criteria of 3 mm/3%, the mean pass rate for all segment sizes is higher than 95% except for segment sizes below 3 cm × 3 cm optimized by TiGRT TPS. **Conclusions:** High pass rate of gamma index (95%) achieved in planned small segments by Prowess relative to results obtained with TiGRT. This study showed that the accuracy of small field modeling differs between two dose calculation algorithms.

Keywords: *Dose calculation algorithm, small-intensity modulated radiation therapy segment, two-dimensional array*

Introduction

Modern and complicated megavoltage photon treatments such as intensity-modulated radiation therapy (IMRT), image-guided radiation therapy (IGRT), and tomotherapy involve the delivery of multiple irregular and nonuniform beams using multileaf collimators (MLCs). The main goals of IMRT technique is to minimize the delivered dose to organs at risk located near the irradiated area and highly conformal dose to the target volume.[1] Implementation of IMRT treatment using small segments for head and neck cancers causes further maximizing tumor control probability and minimizing normal tissue complication. However, increase in number of monitor units (MU), number of segments, and complex segment configuration can cause complexity in treatment delivery.[2] To confirm accurate dose delivery to the patient, possible beam delivery errors should be determined before treatment. As a result, verification of dose distributions is a main part of the modulated radiation therapy.[3]

One of the important steps in complex modulated radiation therapy is verifying treatment plans with a process referred to as pretreatment patient-specific quality assurance (QA). The verification process includes validation of planar dose distribution and delivered absolute dose to a certain point in central axes of beam.[4] Dose distribution validation was done by comparison the planed and measured dose distribution.

This can be accomplished using radiochromic film[5-7] or two-dimensional (2D) arrays of ionization chamber or diode detectors.[8] Several studies have been performed in pretreatment patient-specific QA in standard segment size using both radiochromic films and 2D arrays of detectors. Limitations and advantages of each method were investigated.[9-11] When IMRT treatments are routinely accomplished, the usage of more reproducible QA device becomes very

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useful. Arrays of ionization chambers or diode detectors are now replacing instead of radiochromic films for routine IMRT QA because of simple application.[12] The number of studies showed that the performance of 2D detector arrays from different manufactures in terms of reproducibility, repeatability, linearity, and independency from the dose rate is excellent.[12-14] Dosimetry of small IMRT segments is a problematic issue, in particular for head and neck IMRT plans. These problems related to both dose measurements and small fields modeling with the TPS. In high gradient superimposed small (<4 cm × 4 cm) static or dynamic photon beams, lateral charge particles disequilibrium, partial blocking of the X-ray source by the collimators, and detector size cause inaccurate dose measurement.[15,16] In such conditions, output factor, surface dose, and penumbra dose measurements significantly depend on detector type and its active volume. Indeed, each TPS applies its specific extrapolation algorithm to obtain small fields dosimetric data, and therefore, incorrectly extrapolated data can result in systematic uncertainties in dose delivery. A number of works in assessing the suitability of the TPSs for step-and-shoot IMRT showed inaccuracy in small segments validation.[17,18] Accordingly, both improper modeling techniques and improper measurement can introduce significant errors in treatment delivery.[19]

As a result, dose delivery accuracy at small segments IMRT depend on to the dosimetric performance of instruments as well as capability of TPS algorithm in modeling of small fields. Moreover, pretreatment patient-specific QA of small IMRT segments requires particular dosimetry tools that ideally should be high spatial resolution, small volume, tissue equivalent, dose rate independent and have good reproducibility, linearity, and repeatability.[17] Therefore, the main goal of this study was to validate calculated dose distribution of small fields by two different dose calculation algorithms. The calculated dose distributions were compared against those measured by 2D array. Hence, first, two main characteristic of 2D array in small fields was evaluated.

Materials and Methods

All irradiations were made using 6 MV photon beams of Siemens Artiste (Siemens Medical Systems, Concord, CA, USA) linear accelerator. The artist single-focused MLCs are equipped to 160 tungsten leaves that mounted in two leaf banks. Each leaf project 0.5 cm width at isocenter and allows 20 cm traveling and interdigitization. The minimum field resolution at isocenter is 0.5 cm × 0.5 cm. The linac is calibrated to deliver 1 cGy/MU at depth of maximum dose for a field size of 10 cm × 10 cm at 100 cm source to surface distance (SSD).

Analyzing of reproducibility and linearity of two-dimensional array

Two-dimensional planar and absolute dose-measuring device in this work was MapCHECK 2. The 2D array contains 1527 n-type diodes (with 26.0 cm × 32.0 cm active area) arranged in a grid. The center-to-center distance between 2 adjacent detectors is 7.07 mm and acquisition rate is 50 ms. Their responses are instantly available in digital form.

Radiological buildup of 2 g/cm^2 is located above the reference point of the matrix detectors. Then 3 cm of water-equivalent slab added to array to measure absolute dose in 5 cm depth and 100 cm SSD [Figure 1]. To account backscatter radiation, same slabs placed under the 2D array. Errors in 2D array setup and linac output variations can affect the results. Therefore, all measurements was performed on the day of calibration and alignment of the 2D array was made with respect to a 10 cm × 10 cm field size.

6 MV photon beam was used to deliver 100 MU per reading. To evaluate the stability of the beam on the central axis, a pinpoint ion chamber (PTW-Freiburg, type 31016, Germany) with active volume of 0.015 cm^3 was placed in solid water at 1.5 cm under the 2D array. The performance of pinpoint ion chamber for characterization of small segments used in IMRT has already been investigated.[20]

To analyze the capability of the 2D array in dose verification, two sets of measurements were accomplished. First, the 2D array central diode dose value was used to evaluate the point dose reproducibility in high-gradient small fields. Ten consecutive measurements were performed in 1 cm × 1 cm to 10 cm × 10 cm field sizes. For each field size, the same MU delivered to 2D array in several measurements for the same delivered dose. Then, the percentage difference of measured dose value for each field size was calculated. Second, dose linearity response of 2D array was evaluated by performance different dose value measurements (1-400 cGy). For 1 cm × 1 cm to 10 cm × 10 cm field sizes, the regression coefficients between delivered dose values and responses of 2D array were calculated.

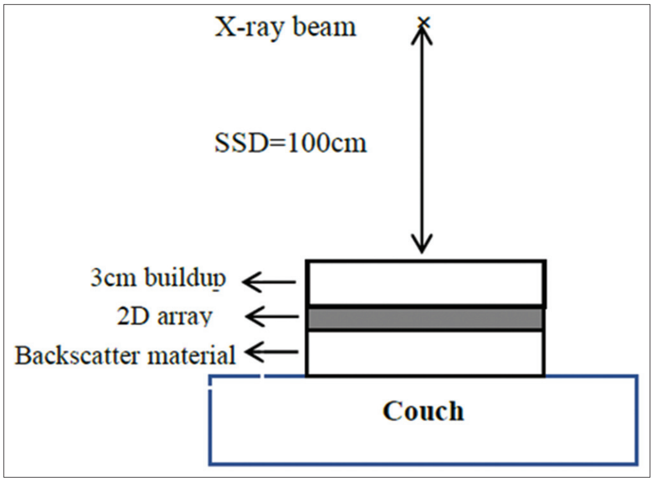

Figure 1: Measurement setup for 2D array

Validation of the 2D array in absolute dose measurements of small fields was made by comparing its measurements with an Edge diode[21] (Sun Nuclear Corp., Melbourne, 0.0019 cm^3 active volume) reading. Edge diode placed at the same position of central diode of 2D array in 5 cm depth of solid water phantom for field sizes from 1 × 1 to 10 × 10 cm^2.

Output factor

Measurement of output factor for field sizes 1 × 1, 2 × 2, 3 × 3, 4 × 4, 5 × 5, 6 × 6, 8 × 8 and 10 × 10 cm^2 were made using central diode of 2D array for 6 MV photon beams. All measurements were done in 5 cm depth and 100 cm SSD. For evaluation, the accuracy of dose calculation algorithms in modeling of small fields; the relative output factors derived from these measurements were compared to those calculated by each TPSs.

Planar dose evaluation

A total of 20 head and neck IMRT plans contain small target volumes (pituitary adenoma, cavernous sinus, and meningioma) were randomly selected.

All head and neck IMRT plans were static step-and-shoot with five beam or seven beam. Plans were designed with Prowess Panther (Version 5.4, Prowess Inc., Concord, CA, USA) and TiGRT (Sunnyvale, CA, USA) TPSs. Prowess Panther treatment planning system uses collapsed cone convolution/superposition algorithm (CCCS)[22] for external beam dose calculation and TiGRT uses a dose calculation algorithm based on full scatter convolution (FSC).[1] For comparison purposes, the same treatment plans have been taken using two different TPSs. Mean segment size of each field was between 1 cm × 1 cm to 5 cm × 5 cm. For plan validation, all plans were delivered to a flat QA phantom using 0° gantry angle.

In MapCHECK2 2D array relative sensitivity differences between the detectors performed by its analytical software component ("MapCHECK" version 5.2, Sun Nuclear Corporation of Melbourne). These individual correction factors can apply to subsequent diode measurements. The correction factors account different responses of the individual detectors. To simplify and reduce the QA process, both absolute and planar dose measurements were made simultaneously. All of the verification measurements were performed with a fixed 0° gantry angle and 100 cm SSD. Frequently, pretreatment patient-specific verification is done by comparing between measured and planned dose distribution (with a grid spacing of 2 mm) through the use of gamma evaluation. The gamma metric evaluates both the dose difference and the distance-to-agreement (DTA) criteria. DTA is the distance between a measured data point and the nearest point in the calculated dose distribution that exhibits the same dose.[23] The percentage of the points that pass the acceptance criteria is called gamma pass rate. In regions of low-dose gradient, dose difference criterion is applicable while in regions of high-dose gradient, the DTA criterion is more helpful. To remove dose points in the out-of-field region where a large relative dose difference can be estimated and deviate the gamma index outcome, it is common to set a lower dose threshold below which the gamma index result is ignored. Therefore, it is typical to limit the gamma index calculation to all points that are ≥10–20% of the maximum dose value within the dose distribution.[24] The gamma criteria of 3% dose difference and 3 mm DTA with 10% dose threshold was applied.

Results

Reproducibility and linearity in small fields

Table 1 represented the maximum standard deviation of central diode readings in 2D array for 10 consecutive similar measurements per each field size. It is shown that average reproducibility for small fields is <0.3%. The 2D array demonstrates excellent reproducibility in all field sizes. Table 1 also represents regression coefficients of readings for various field size under different dose values. These data show that the 2D array shows a high degree of linearity in 1–400 cGy dose values.

Output factor comparison of two-dimensional array and Edge diode

Figure 2 shows the output factors of 6 MV photon beam measured for different field sizes with Edge diode and 2D array central diode. The results were normalized to obtained readings in 10 cm × 10 cm field size.

From Figure 2, it can be seen that the percentage difference between output factor measured using Edge diode and 2D array for field sizes larger and smaller than 4 cm × 4 cm are, respectively, <1% and 1.5%. Because of these negligible differences, 2D array can also be used as absolute dosimeter for small field sizes.

Output factor comparison of two-dimensional array and treatment planning systems

For evaluation of TPSs in modeling of small fields, the results of comparison of the calculated output factors by two commercial TPSs with those measured by 2D array in same field sizes and SSD are illustrated in Figure 3. The percentage difference of output factors between Prowess and 2D array is <2% except in 2 cm × 2 cm and lower field sizes. However, this difference between TiGRT

Table 1: Reproducibility and linearity of two-dimensional array for different field sizes

Field size (cm^2)	1	2	3	4	6	8	10
Maximum SD (%)	0.243	0.201	0.111	0.209	0.123	0.157	0.186
Regression coefficients	0.9998	0.9989	0.9997	0.9997	0.9996	0.9998	0.9995

SD – Standard deviation

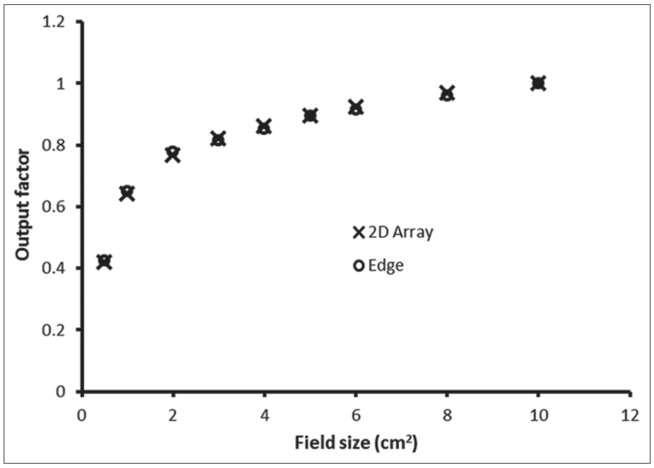

Figure 2: Output factor measured with Edge diode and central diode of two-dimensional array

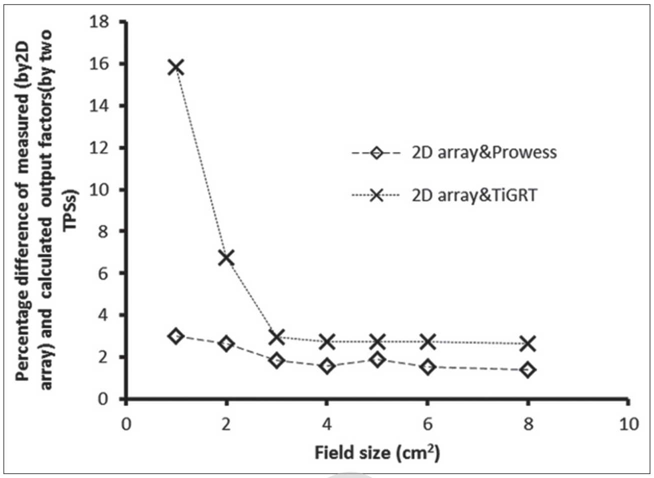

Figure 3: Percentage difference of output factors of 6 MV photon beams measured with 2D array and calculated with Prowess and TiGRT treatment planning system

and 2D array is higher than15% in field sizes below 3 cm × 3 cm and is <2.2% in field sizes above 4 cm × 4 cm.

Comparison of the gamma-analysis pass rate between treatment planning systems

Planar dose comparison between both TPSs and 2D array in small segments was performed and percentage of points that pass the acceptable gamma criteria was calculated. Table 2 demonstrates the overall results of gamma-analysis pass rate for Prowess TPS in various average segment size from 1 to 5 cm^2. The average pass rate of all beams of each plan is illustrated. The same calculation was provided for TiGRT TPS and summarized in Table 3. As this table showed, the mean pass rate for all segment sizes is higher than 95% except for segment sizes below 3 cm × 3 cm optimized by TiGRT. The percentage points with gamma >1 increase in smaller segment size and predominant in TiGRT with respect to Prowess.

Figure 4 shows the results of gamma passing rate derived from 2D array for two TPSs in average segment sizes ranging from 3 to 5 cm^2 with gamma passing criteria of 3mm/3%. These analyses show that for field size 5 cm^2, the pass rate for Prowess and TiGRT plans is similar, but for field size 3 cm^2, the gamma pass rate decrease for TiGRT more than Prowess. More than 70% of all segments have 98%–100% pass rate. About 10% of all segments with segment size above 3 cm2 have pass rate from 94%–96%. The average pass rate for two dose calculation algorithm is above 95% for segment sizes higher than 3 cm^2.

Table 2: Gamma analysis using passing criteria of 3 mm/3% and dose threshold 10% for small segments intensity modulated radiation therapy plans for head and neck cancers designed by Prowess treatment planning system

Average segment size (cm^2)	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Average	SD
5	98.82	98.77	98.54	97.16	96.89	98.03	0.83
4	97.91	98.11	97.42	99.15	98.75	98.26	0.61
3	98.15	96.6	98.15	96.95	97.31	97.43	0.62
2	96.5	97.5	95.5	95.65	96.74	96.37	0.73
1	96.27	96.55	95.17	95.19	96.27	95.89	0.58

SD – Standard deviation

Table 3: Gamma analysis using passing criteria of 3 mm/3% and dose threshold 10% for small segments intensity modulated radiation therapy plans for head and neck cancers designed by TiGRT treatment planning system

Average segment size (cm^2)	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Average	SD
5	98.5	98.62	98.33	96.76	96.80	97.80	0.83
4	97.3	98.15	97.08	96.46	96.75	97.148	0.57
3	96.15	96.6	95.15	96.95	92.31	95.432	1.67
2	94.25	93.22	92.78	91.87	90.25	92.474	1.35
1	90.51	89.12	88.10	90.51	91.35	89.91	1.15

SD – Standard deviation

Discussion

The performance of patient-specific QA process in terms of time-saving scheme as well as accuracy is a necessary issue that can be considered in routine clinical treatments. Before clinical use, characterization of detectors response are essential. Specifications of a good QA tool are that easy to implement in clinical proceeding and widely applicable. It can provide useful information at the shortest time.

Diode-based matrix arrays are known to have enough dose reproducibility and linearity in standard field sizes of megavoltage photon beams. Létourneau *et al*.[9] showed that MapCHECK diode array (including 445 n-type diodes) presents the required characteristics for carrying out dosimetry of conventional radiation therapy and IMRT QA. However, they eliminated small segments due to inaccurate

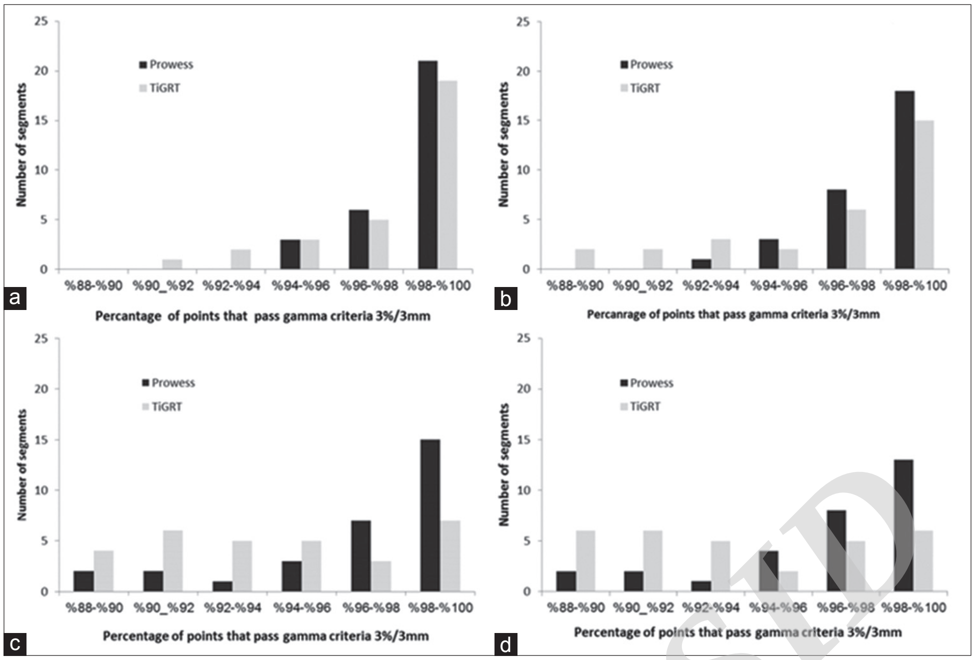

Figure 4: Gamma analysis comparison of all segment size between 2 and 5 cm^2 designed by two different TPSs (a) 5 cm^2 average segment size (b) 4 cm^2 average segment size (c) 3 cm^2 average segment size (d) 2 cm^2 average segment size

modeling of the penumbra in their TPS. Results of the current study [Table 1] showed that 2D array has excellent reproducibility and linearity in small fields which should be necessary for a dosimeter. Previous studies were reported large angular dependency in dose response of different 2D arrays[10,25,26] but it is acceptable to evaluate patient-specific QA process of all beams in the same angle of treatment plan in the TPS.[27] Therefore, all dose measurements in this work were carried out in gantry angle of 0°. The advantage of diode detector is small active volume that reduces the volume averaging effect and is suitable for dosimetry of small modulated photon beams.[18] The performance of Edge diode in small field dosimetry has already been investigated.[28] The results demonstrated that agreement between results of 2D array and Edge diode in small field measurement is in degree of 1.5%; consequently, 2D array can be used as absolute dosimeter in small segments point dose verification. The benefit of 2D array application is that both absolute point dose and relative planar dose evaluation can be done in a single measurement. The advantage of 2D array for absolute dose verification is the ability to measure several points in a single exposure.

Some studies have investigated the accuracy of TPS dose calculation algorithm in regular field sizes.[29-31] Accurate beam modeling of TPSs in small fields has significant effect on dose calculation. As Figure 4 demonstrated, in spite of good results of gamma index pass rate in small segments designed by Prowess, results obtained by TiGRT have significant difference in segment sizes below 3 cm × 3 cm. In 5 cm^2 average segment size, the 98% to 100% gamma pass rate of all planned fields with Prowess and TiGRT was 70% and 63%, respectively. By decreasing segment size to 2 cm^2, the 98% to 100% gamma pass rate reduces to 43 and 20% for Prowess and TiGRT, respectively. This may be due to inaccurate modeling of small fields by TiGRT. It can be understood from Figure 3 that changes more than 15% in output factor can lead to inappropriate planar dose distribution and fewer gamma index pass rate. In this study, the dependency of gamma passing rate to field size is similar to reported results of Wagner and Vorwerk.[11]

Small Beam modeling by TPSs is difficult due to nonequilibrium condition relative to standard size fields. In high-dose gradient regions, adequate accounting the scatter radiation is necessary in dose calculations. In CCCS algorithm used in Prowess, change of lateral transport of electrons is taken into account,[32] and optimized plans by this algorithm have better results in planar and point dose calculations. These results agree with previous analysis of Hasenbalg *et al*.[33] that compared CCCS algorithm with anisotropic analytic algorithm and Monte Carlo simulation. The results of this study are similar with results of the study which was done by Carrasco *et al*.[34] In mentioned study, differences between behavior of dose calculation algorithms for several field sizes were assessed and 24% difference between correction-based algorithms against monte carlo simulations in present of small low-density inhomogeneities was found. Based on internationally accepted guidelines, ICRU Report 24, the required inaccuracy level for treatment dose delivery is 5%.[35] Hence, the gamma pass rate in TiGRT is not sufficient to validate the calculated dose distribution compared to Prowess that satisfies 5% in all field sizes. In small segment size that dose gradient is great, large discrepancy between measured and calculated dose distributions was seen using FSC algorithm against the other segment sizes. This refers to inaccurate extrapolation of FSC algorithm for small fields.

Conclusions

In conclusion, the significant difference between CCCS and FSC dose calculation algorithms in nonequilibrium conditions of small fields were found. This study showed that the accuracy of small field modeling differs between two dose calculation algorithms. Furthermore, 2D diode array provides an overall accuracy when compared with single diode measurements and is suitable for dosimetry of small radiation field created by linac.

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Conflicts of interest

There are no conflicts of interest

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