A Practical Method to Optimize Quality Assurance Results of Arc Therapy Plans in Beam Modeling

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Abstract

Dosimetric accuracy of a volumetric modulated arc therapy (VMAT) plan is directly related to the beam model, particularly with multileaf collimator characterization. Inappropriate dosimetric leaf gap (DLG) value can lead to a suboptimal beam model, with significant failure in patient-specific quality assurance (PSQA) of VMAT plans. This study addressed the systematic issue of beam modeling and developed a practical method to determine the optimal DLG value for a beam model. Several complex VMAT plans were selected for the quality assurance analysis using the variable DLG values. The results of three-dimensional (3D) Gamma analysis as a function of the DLG at 3%/3 mm, 2%/2 mm, and 1%/1 mm criteria were fitted by a polynomial curve. The DLG value corresponding to the maximum Gamma passing rate for each polynomial fitting function was derived, and the average was calculated to be the optimal DLG value for each model. The 3D Gamma analysis was repeated with the optimal DLG value to verify the dosimetric accuracy of each VMAT case by PSQA. Gamma passing rates are seen to vary considerably with the DLG values and different analysis criteria (3%/3 mm, 2%/2 mm, and 1%/1 mm) for each case. The optimal DLG derived for each model was 1.16 mm and 1.10 mm, much larger than the measured value (about 0.3 mm). The beam models with the optimal DLG were able to produce an average Gamma passing rate of 97.1% (range, 94.6%–99.1%) at 3%/3 mm and 93.5% (range, 89.0%–96.5%) at 2%/2 mm for one beam model, and 97.1% (range, 94.8%–99.1%) at 3%/3 mm, and 93.3% (range, 88.8%–96.7%) at 2%/2 mm for another. The overall accuracy of dose calculation for VMAT plans should be optimized with a compromise of varied modulation complexities in a beam model. We have developed a practical method to derive the optimal DLG value for each beam model based on the Gamma passing criterion. This technique should be applicable in general for all beam energies and patient cases.

Keywords: Beam model, dosimetric leaf gap, quality assurance, treatment planning system, volumetric modulated arc therapy

INTRODUCTION

Stereotactic body radiation therapy (SBRT) can be a preferred choice of treatment for some small localized tumors because of the higher efficacy of tumor control and lower complication of normal tissues.[1] SBRT is often delivered on linear accelerator either using three-dimensional (3D) conformal radiation treatment, intensity modulated radiation therapy (IMRT) or volumetric modulated arc therapy (VMAT). Individual merits of each modality can be argued. However, a consensus is appearing in favor of VMAT.[2-9] VMAT plans, in general, are more conformal and less radiation dose with shorter treatment time that can be advantageous for SBRT. The SBRT treatments can be demanding of a high gradient, fast dose fall-off to achieve planning target volume coverage and sparing of adjacent normal tissues. To achieve this goal, optimal beam modeling is essential for accurate dose calculation, in particular, for complex plans such as IMRT/VMAT.

Treatment planning systems (TPS) employ a sophisticated inverse optimization algorithm to create the desired VMAT treatment plan by modulating gantry speed, leaf speed, and dose rate.[10] The TPS has to be commissioned with an optimized beam model before it can be used for clinical dose calculation. Most modern TPS are analytical in nature and processed based on measured data.[11-13] The commissioning process involves accurate beam data measurement, dose

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calculation modeling, and extensive validation tests. Beam modeling of a modern dose calculation algorithm is usually performed by fitting the measured beam data with the calculation for a given dose algorithm. A VMAT plan is generated by many irregularly shaped, often with small multileaf collimator (MLC) segments. It is particularly critical of beam data for small fields and the modeling of MLC dose profile among many factors affecting the dosimetric accuracy of a beam model. Some commercial planning systems allow for users to adjust a number of beam parameters to optimize the model. Others provide very limited tuning of parameters for beam data configurations thus possibly compromising in beam modeling.

It has been shown that dose calculation of VMAT plans is subtly related to the modeling of small field penumbra and tails as well as the rounded MLC leaf ends. In Eclipse TPS (Varian Medical System, Palo Alto, USA), penumbra can be adjusted by effective target spot size in X/Y direction, but a discrepancy often exists if the measurement was less accurate, for example, inappropriately designed is used for small fields. For MLC leaf ends, Eclipse provides one simplified parameter, the dosimetric leaf gap (DLG), to model the dose profile of the rounded leaf ends (Eclipse Algorithms Reference guide). The DLG is defined as the width of transmitted dose profile through closed leaf ends. Apparently, the value of DLG would be a function of beam energy, leaf position (distance from central axis) due to beam divergence, segment size, and possibly leaf motion for a given MLC configuration of leaf thickness and radius of MLC leaf curvature. It has shown that DLG is insensitive to variations in SSD (following correction for geometric projection), depth of measurement, dose rate, and ionization chamber.

LoSasso et al. provided a method to measure the DLG. Effect of MLC leaf gap has been extensively studied in respect to its effect in treatment planning. Vendor-specific guidelines are also available such as Eclipse (Varian Medical System, Eclipse reference guideline) and Pinnacle (Philips Medical System reference guideline). Using sliding slit technique recommended by Varian, a single DLG value can be measured. When the measured value is used in the beam model, there are controversial points of views: some studies have shown a good agreement of calculated and delivered plans for VMAT, whereas others have pointed out a significant discrepancies. As a result, those highly modulated VMAT plans would likely experience a low Gamma passing rate in quality assurance for verification of dose calculation. It is argued that the value of DLG used in the beam model has to be optimized with clinical VMAT plans instead of the measured value. We believe that the different findings reported might be related to the variations of the beam model each user-generated as well as the validation tests they performed.

The quality of a beam model should be the combined effect of the beam data used, and the fitting parameters applied. This study explored the beam model generated by two different sets of beam data in association of varied DLGs used in the model. We attempted to validate a beam model by examining the accuracy of dose calculation of VMAT plans, particularly for SBRT. We investigated two beam models for 6 MV flattening filter free (FFF) photon beam because it is a preferred choice of beam for the SBRT. In addition, FFF beams can be operated at very high dose rate (6MV-1400 MU/min) on a Varian TrueBeam.

**Materials and Methods**

The anisotropic analytical algorithm (AAA) is modeled in Eclipse TPS version 13.7 for 6 MV FFF on Varian TrueBeam Edge. The Edge machine is equipped with Varian high definition 120 MLC leaves, which consists of 40 pairs of leaves at 2.5 mm width each and 20 pairs of leaves at 5.0 mm width, all with a 16 cm radius of curvature. TrueBeam Edge is designed, especially for SBRT treatment due to its sharper beam penumbra and higher mechanical accuracy.

Two complete sets of beam data were collected independently for 6 MV FFF beam, with the open field output factors shared. The MLC transmission used the measured value of 1% and 1.1%, respectively. One set of PDD and profiles were measured with IBA CC13 scanning chamber (0.13 cm³, effective volume) for all field sizes from 2 × 2 up to 40 × 40 cm. Other sets of data were scanned with small volume (0.07 cm³, effective volume) PTW (PTW, Freiburg, Germany) ionization chamber 31021 for field sizes from 2 × 2 to 40 cm × 40 cm. The AAA dose calculation models were generated by fitting PDD and profiles to the beam data, following the standard beam data configurations in Eclipse TPS version 13.7 (Varian Medical Systems, Palo, Alto, CA, USA). All the fitting parameters were calculated by the modeling software in the system. A few parameters are made available for users to tweak the optimization, one being effective target spot size and another DLG or MLC transmission.

Summarized in Table 1 is the comparison of the beam data configuration for these two models under study. Based on the Gamma errors (Eclipse beam model reference guide), both models have a reasonably good quality, but a subtle difference can be observed in penumbra region for small MLC fields. The detailed modeling and validation process for a high energy

| Table 1: Summary of some dosimetric parameters for two models |
|-----------------------------------------------|
| **Average Gamma error (mm)** | **Model #1** | **Model #2** |
| Depth dose curves | 0.25 | 0.24 |
| Depth dose curves after D<sub>max</sub> | 0.15 | 0.16 |
| Profiles inside field | 0.20 | 0.09 |
| Profiles in penumbra region | 0.70 | 0.54 |
| Profiles outside field | 0.49 | 0.60 |
| MLC transmission (%) | 1.0 | 1.1 |

MLC: Multileaf collimator
photon beam is described elsewhere. This study is focused on the dosimetric accuracy of VMAT plans in relation to the quality of a beam model.

Several clinical SBRT cases were selected for VMAT planning, including lung and spine. It usually requires a high degree of modulation to produce a good VMAT plan for SBRT cases because of the tight dose constraints. Each VMAT plan was optimized in Eclipse 13.7 with 6 MVFFF beam and jaw tracking to minimize the impact of MLC transmission, and the dose was calculated with the AAA model. Table 2 shows the results of characteristics for these VMAT plans. The measurement was performed using a commercial QA device, ArcCHECK (Sun Nuclear, Melbourne, FL). Verification plans for each case were calculated with the fixed MU from the same optimization plan to ArcCHECK phantom with varied DLGs from 0.1 mm to 2.0 mm (an increment of 0.2 mm to 0.5 mm) in each model. The 3D Gamma analysis was performed using ArcCHECK patient QA software to evaluate the agreement of the measured dose with the calculated dose from each verification plan. All the analysis is based on absolute dose, DTA, 10% threshold and global maximum setting. An optimal DLG is generated from the maximum passing rate of Gamma analysis, for which a polynomial fitting function was employed.

Results

For each case under study, verification plans were calculated for seven different DLGs (range: 0.1 mm to 2.0 mm) and then compared with the measurement. Table 3 presents the Gamma passing rate at 3%/3 mm, 2%/2 mm, 1%/1 mm criteria for case #1. Plotted in Figure 1 are the Gamma analysis results for four lung cases on the same model. Figure 2 compares the Gamma analysis results for the same case with different models. The Gamma passing rate apparently varies with lower percentage toward both small and large DLGs.

A polynomial function up to the 3rd degree was found to fit well for each set of 7 plotted points representing the varied DLG values. Table 4 provides the example of polynomial functions for one of the lung cases ($Y$ denotes Gamma passing rate in percentage and $X$ denotes the variable of DLG in mm).

Median $R^2$ value of all fitting curves was 0.990 (range, 0.920–0.999) and 0.972 (range, 0.902–0.999) for model #1 and model #2, respectively. We derived DLG that gives the maximum passing rate by solving each of the polynomial function. Table 5 presents those DLGs for each case. We determined the optimal DLG for each beam model to be the average, 1.16 mm for model #1 and 1.10 mm for model #2. When the optimal DLG is applied back to each model, the average Gamma passing rate would be 97.1% (range, 94.6%–99.1%) for model #1 and 97.1% (range, 94.8%–99.1%) for model #2 at 3%/3 mm, and 93.5% (range, 89.0%–96.5%) for model #1 and 93.3% (range, 88.8%–96.7%) for model #2 at 2%/2 mm.

**Table 2: Summary of volumetric modulated arc therapy plans**

| Clinical VMAT cases | Dose/fraction (cGy) | Number of arc | Total (MU) | MU/Gy |
|---------------------|---------------------|---------------|------------|-------|
| Case #1: Right lung SBRT | 1000 | 4 | 4265 | 427 |
| Case #2: Left lung SBRT | 1200 | 3 | 3133 | 261 |
| Case #3: Left lung SBRT | 1000 | 3 | 2790 | 279 |
| Case #4: Left lung SBRT | 1000 | 4 | 2829 | 283 |
| Case #5: Spine SBRT | 700 | 3 | 1998 | 285 |
| Case #6: Spine SBRT | 800 | 2 | 2395 | 299 |

VMAT: Volumetric modulated arc therapy, SBRT: Stereotactic body radiation therapy
DISCUSSION

The dosimetric accuracy of VMAT plans has shown considerable dependence on the DLG with a polynomial relationship, which is less dependent on beam models. The optimal DLG that leads to the maximum agreement in patient-specific QA between the calculation and the measurement can vary to the extent of a few tenth millimeters from plan to plan. The beam modeling software in Eclipse is designed to have a minimum variation in beam data configurations. Therefore, DLG plays a significant role for those highly modulated dose plans. The DLG in Eclipse system is truly a factor of dose modulation. It is also noted that the optimal DLG is not site specific as other studies have suggested. However, an average value can be derived and applied to a particular beam model. The optimal DLG values determined in this study were based on all SBRT cases, which had small field sizes from 5 cm to 8 cm, so plans were all segmented by central MLC leaves of 2.5 mm width only.

The measured DLG value following the vendor’s sliding slit technique would not generate an optimum beam model because of the complexity of beam modulation in clinical plans, particularly VMAT plans for SBRT. The results of this study support other publications that DLG should be a fitting parameter in the beam modeling of Eclipse AAA dose calculation algorithm. The optimal DLG value can be simply determined for a model using several clinical VMAT cases, which preferably are modulated to different degrees of complexity. Nevertheless, small uncertainty as demonstrated by the standard deviation of six cases should have justified the validity of the proposed method. This DLG value is truly a single simplified parameter to achieve the best yet compromised fitting for the beam model in general.

We used Gamma analysis of VMAT plans delivered to an ArcCHECK device that is a widely available QA device to verify the dosimetric accuracy of IMRT or VMAT plans. It uses helical diode array to measure dose distribution projected to a circular phantom with the machine delivering the same treatment as for a patient. This QA tool is among one of the instrumentations recommended by the recently published MPPG 9.a. Guideline for patient‑specific QA.

Table 3: Numeric Gamma passing rate in percentage for case #1

| DLG (mm) | Model #1 | Model #2 |
|----------|----------|----------|
|          | 3%/3 mm  | 2%/2 mm  | 1%/1 mm  | 3%/3 mm  | 2%/2 mm  | 1%/1 mm  |
| 0.1      | 88.9     | 78.9     | 59.6     | 87.3     | 78.7     | 64.3     |
| 0.3      | 93.9     | 86.7     | 70.4     | 94.8     | 90.1     | 73.8     |
| 0.5      | 96.7     | 92.8     | 79.6     | 97.5     | 93.1     | 82.4     |
| 0.7      | 98.9     | 95.3     | 84.3     | 99.2     | 95.6     | 85.4     |
| 1.0      | 98.6     | 95.9     | 86.3     | 98.4     | 95.3     | 84.7     |
| 1.5      | 95.1     | 85.8     | 65.2     | 92.9     | 84.1     | 61.1     |
| 2.0      | 82.3     | 70.0     | 44.1     | 80.4     | 67.3     | 41.7     |

DLG: Dosimetric leaf gap

Table 4: Example of polynomial fit to the data

| Gamma index | Polynomial function |
|-------------|---------------------|
| 3%/3 mm     | \( y = -0.0317x^3 - 4.4131x^2 + 12.477x + 90.643 \) |
| 2%/2 mm     | \( y = -6.8504x^2 + 18.64x + 84.102 \) |
| 1%/1 mm     | \( y = -2.1105x^3 - 8.5744x^2 + 32.819x + 65.434 \) |

Table 5: Dosimetric leaf gap (mm) for the maximum Gamma passing rate of each test set with the average and the standard deviation

| Gamma     | Model #1 | Model #2 |
|-----------|----------|----------|
|           | 3%/3 mm  | 2%/2 mm  | 1%/1 mm  | Average | STD     | 3%/3 mm  | 2%/2 mm  | 1%/1 mm  | Average | SD      |
| Case #1   | 0.93     | 0.93     | 0.80     | 0.89     | 0.08    | 0.82     | 0.78     | 0.82     | 0.81    | 0.02    |
| Case #2   | 1.39     | 1.36     | 1.29     | 1.35     | 0.05    | 1.35     | 1.36     | 1.10     | 1.27    | 0.15    |
| Case #3   | 1.37     | 1.33     | 1.34     | 1.35     | 0.02    | 1.30     | 1.25     | 1.21     | 1.25    | 0.05    |
| Case #4   | 1.38     | 1.34     | 1.35     | 1.36     | 0.02    | 1.32     | 1.30     | 1.22     | 1.28    | 0.05    |
| Case #5   | 0.84     | 1.12     | 1.19     | 1.05     | 0.18    | 0.83     | 1.11     | 1.10     | 1.01    | 0.16    |
| Case #6   | 0.98     | 0.79     | 1.19     | 0.99     | 0.20    | 1.02     | 0.83     | 1.05     | 0.97    | 0.12    |
| Average   | 1.15     | 1.15     | 1.19     | 1.16     | 0.21    | 1.11     | 1.10     | 1.08     | 1.10    |         |
| SD        | 0.26     | 0.24     | 0.20     | 0.21     |         | 0.25     | 0.25     | 0.15     | 0.20    |         |

SD: Standard deviation

Figure 2: Gamma passing rate for the same lung volumetric modulated arc therapy case at 3%/3 mm, 2%/2 mm and 1%/1 mm for both models #1 and #2, respectively. Solid circles (blue) for model #1, diamond (orange) for model #2. Solid line for 3%/3 mm, dash for 2%/2 mm, dotted for 1%/1 mm
resolution of ArcCHECK device is not as high as other QA tools, such as film and amorphous silicon electronic portal imaging device, its sensitivity is proven reliable. It is beyond the scope of this study but would be interesting to cross-check our method using different QA tools. We believe that the optimal DLG value as derived by the proposed method should have a minimum variation with QA tools used, a sample size of plans selected and treatment sites.

Several studies\cite{26,27} have shown that the measured DLG value used for the beam model is acceptable for VMAT plans. However, one of these studies\cite{26} did not specify what kind of VMAT cases were used for the validation tests. Nevertheless, their measured DLGs were already way larger than the nominal ones, e.g., 0.71 mm and 0.89 mm for 6XFFF and 10XFFF beams, respectively. One possible reason was that they had an older version of TrueBeam software before 2.0 when Varian changed the MLC calibration technique, which led to lower DLG values. In addition, their results were based on less tight Gamma analysis (90% passing rate at 3%/3 mm and 5% threshold). Another study\cite{28} used TG-119 test cases but did not provide the DLG values for the beam model. We also demonstrated that a single optimal DLG value can be determined for a beam model, regardless of treatment sites. The fitting function of Gamma passing rate has shown different curvatures and maximum passing rates for each patient case and each Gamma criterion. There is no simple metrics found to provide a meaningful correlation with the complexity of modulation. The curve can be quite flat for less modulated plans so less sensitive to the variation in the DLG value. Data seem to converge reasonably to one average optimal DLG value, which would generate the desired model for each beam energy.

The dosimetric accuracy of a beam model in Eclipse TPS appears insensitive to the beam data measurement, but quite sensitive to the DLG parameter. The sliding slit technique suggested by Varian for the measurement of DLG has an apparent deficiency to produce the optimal value for an accurate beam model. Dosimetric effect of the rounded leaf ends can be complex, especially for those modulated beams, which varies with leaf position, segment size, beam energy, and possibly leaf speed. Some TPS (e.g., Pinnacle) employs a leaf offset calibration table to model the variation effect of the rounded leaf ends. Eclipse uses DLG as a single parameter to fit the beam model. As demonstrated, an optimal DLG should be used in the beam model for the best overall dosimetric accuracy achievable.

**CONCLUSION**

Dosimetric accuracy of VMAT plans is associated with the quality of a beam model. For highly modulated VMAT plans, for example, most SBRT cases, the dosimetric effect of rounded leaf ends becomes critical to determine the dose distribution achievable, particularly for high dose gradient regions. The modeling of AAA dose calculation algorithm is relatively straightforward in Eclipse TPS with a few fitting parameters available for users to adjust. However, the DLG plays an important role in the dosimetric accuracy of a beam model. The measured DLG would not provide the best model for VMAT plans. The study revealed a simple yet practical method to derive the optimal DLG for each beam model. This single DLG value should be valid to plan VMAT cases of different treatment sites with the expectation of high dosimetric accuracy.

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**Conflicts of interest**

There are no conflicts of interest.

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