Technical Note

Monte Carlo Dose Calculation – A QA Method for SRT and SBRT Plans in Treating Multiple and Small Metastatic Lesions

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Abstract

To provide accurate and fast 3-D dose verification for hypofractionated stereotactic radiotherapy (SRT/SBRT) of small and multi targets calculated with a Varian Eclipse treatment planning system (TPS) delivered on a Varian accelerator. Ten brain and lung hypofractionated SRT/SBRT linac-based and CyberKnife plans were generated by the Eclipse system for delivery on the accelerator with the Millenium-120 leaf multileaf collimator (MLC) and Multiplan for the CyberKnife machine. These clinical SRT/SBRT plans required accurate quality assurance measurements to obtain absolute point dose and 3-D dose distributions due to the low number of fractions and high fraction doses. For small-field and multi-target plans, the EGS4/MCSIM code was used to calculate the dose distribution. A 0.125 cc ion chamber, a 0.016 cc pin-point chamber and Kodak EDR2 film were used for the measurements and the results were compared with Monte Carlo (MC) calculations. The dosimetry for small-field and multi-target treatment plans is challenging due to the comparable range of secondary electrons and the field sizes defined by SRT/SBRT MLC segments. Our MC simulations can accurately reproduce the linac dose distributions (within 1%/1 mm) three dimensionally. For the clinical SRT/SBRT plans investigated in this work, the MC doses agreed within 3% with ion chamber measurements and within 2%/2 mm with film measurements. The doses calculated by the Eclipse AAA algorithm and Multiplan differed by no more than 5% from MC calculations for small (4–40 cc) Planning Target Volumes (PTVs). MC dose calculation provides accurate and fast 3-D dose verification for hypofractionated SRT for small and multi-target treatment plans generated by a Varian Eclipse TPS on a Varian accelerator and Multiplan treatment planning on the CyberKnife System.

Keywords: Monte Carlo, quality assurance, radiation treatment, SRT/SBRT

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Introduction

Quality assurance for stereotactic radiotherapy has been of interest to clinical researchers.[1-4] Due to the low number of fractions and large fractional doses, stereotactic (body) radiotherapy (SRT/SBRT) are high precision technique for delivering a highly conformal dose to a stereotactically localized target. It is crucial to provide accurate and fast 3D dose verification for hypofractionated SRT for small and multi-target treatment plans. However, the dosimetry of small-field treatment is challenging due to the comparable range of secondary electrons and the field sizes defined by the SRT multileaf collimator (MLC) segments. MLC leaf scattering, transmission, and also, the lowered photon fluence induced by the small field sizes[5,6] make direct dose measurements at the target(s) difficult. Quality assurance with film measurements due to better resolution could be one of the methods adopted in clinics to verify the delivered dose for SRT/SBRT plans.[7]

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SRT/SBRT plans with small or multi-target dose distribution, on the other hand, also have practical verification issues due to the closeness and relative location between individual targets three-dimensionally that may not be easily measured by single film. Film measurements also require absolute dosimetry calibration. It could be tricky if more films are utilized. Using specific film H-D curves with a varying dose range is necessary for treatment plan dose verification. However, it made QA for small or multi-target SRT/SBRT plans time-consuming and possibly less precise. Therefore, an accurate and fast 3D dose quality assurance procedure is desirable for SRT/SBRT with small and multiple targets.

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Numerous publications have reported the Monte Carlo (MC) method to be a useful tool for radiation therapy dose calculation.[8-10] Considering all of the beam data, including the energy and the phase space distribution,[11-15] the MC method can accurately calculate the dose distributions in heterogeneous patient anatomy.[16-22] From the various publications, it is suggested that the MC method has the potential to be a dominant quality assurance tool in radiotherapy for treatment planning dose verification. The MC method has recently been adopted as an independent dose calculation check.[23,24] In our institution, we have already commissioned the Varian Eclipse SRT/SBRT treatment planning system (TPS) for the Varian accelerators with a Millennium MLC. Plan delivery measurements and Varian Eclipse calculations are both verified with our in-house EGS4/MCSIM MC code simulation.[25] CyberKnife beam models are also verified by the same method.[26] For patient-specific hypofractionated SRT/SBRT quality assurance, MC dose calculation has been chosen to compare to ion chamber and film measurements to minimize the dosimetry uncertainties mentioned above. The MC method can be an accurate and fast 3D dose quality assurance tool following proper commissioning and validation.

This study investigated the possibility of performing accurate and fast 3D QAs on small and multi-target SRT/SBRT treatment plans by analyzing the dose from the MC method with measurements on 10 SRT/SBRT plans.

Materials and Methods

Treatment plans

A total of 10 brain, spine, and lung hypofractionated SRT/SBRT plans were generated by a Varian Eclipse TPS on the Varian linear accelerators with the Millenium-120 leaf MLC and Accuray (Accuray Inc., Sunnyvale, California) Multiplan treatment planning on CyberKnife system. Varian Eclipse TPS uses AAA (Analytical Anisotropic Algorithm) and Multiplan uses both pencil beam convolution and the MC methods as the calculation algorithms. More than 1 target area exists for brain cases. All 10 plans have a small target size (smaller than 3.5 cm in diameter). These clinical SRS/SBRT plans [details listed in Table 1] required thorough quality assurance measurements to obtain absolute point dose and 2-D dose distributions due to the low number of fractions and high fraction doses.

Table 1: Details of each patient plan

Patient number	Site	Target number	Average target diameter (cm)	TPS
1	Spine	1	3.5	Eclipse
2	Lung	1	2	Eclipse
3	Lung	1	2	Eclipse
4	Lung	1	2	Eclipse
5	Brain	5	1.5	Eclipse
6	Brain	4	1.5	Eclipse
7	Brain	2	1.5	Eclipse
8	Lung	1	2.9	Multiplan
9	Lung	1	2.4	Multiplan
10	Lung	1	3.3	Multiplan

TPS: Treatment planning system

Monte Carlo simulation

We used an MC code, MCSIM,[25] developed at Fox Chase Cancer Center to simulate plan delivery on different machines. MCSIM has been used as a dose calculation tool for radiotherapy and treatment verification studies. MCSIM is an EGS4[27] user code, which can be used to perform patient dose calculations for both conventional photon/electron treatment and intensity-modulated radiotherapy (IMRT). MCSIM uses a multiple-source model to reconstruct the beam phase space. The source model parameters are derived directly from a set of measured beam data. Beam modifiers such as jaws, physical and dynamic wedges, blocks, electron cutouts and bolus can be simulated in MCSIM together with 3D patient geometry built from computed tomography data. MCSIM can simulate different machine geometries and MLC segmented fields based on the information provided by the RTP file exported from Eclipse. For the Cyberknife system MC simulation, MCSIM dose calculation was commissioned with single-source model due to Cyberknife does not have a flattening filter.[26] Cyberknife plan XML files exported from the Multiplan system are used in MCSIM phantom calculations.

Ion chamber and film measurements

This study used a 0.125 cc ion chamber and a 0.016 cc pin-point chamber for point measurements. The 2D ionization chamber array I'mRT MatriXX (IBA Dosimetry, Bartlett, TN, USA) was also used for 2D dose delivery verification. Kodak EDR2 film (Eastern Kodak Company, Rochester, NY, USA) was used to verify the dose distribution. The chamber measurements were to be made with all fields irradiating the phantom using the planned gantry and collimator angles. For all of the tests, measurements were to be made in the target. Conversion of chamber reading to dose was to be done by irradiating the phantom with a 10 cm by 10 cm field to establish the ratio of reading to planned dose in that geometry followed the recommendation from IAEA technical reports series No. 483.[28,29] This could reduce the effects of daily linac output variations and differences between the phantom and liquid water. For film measurements, in each test, films were placed at the level of target positions which could be a coronal or axial plane but definitely exposed to all fields irradiating the phantom with the planned gantry and collimator angles. Noted there is about 1% uncertainty with absolute film dosimetry and about 0.5% uncertainties with relative dosimetry. Dose distributions were analyzed using gamma criteria 3%/3 mm distance to agreement criteria referenced from TG119,[30] TG218.[31] The planar dose distributions obtained with the film could be normalized to the dose measured with the chamber at a high dose and low gradient region. Radiological Imaging Technology, Inc. software was used for film analyses. The gamma analysis was set to have a threshold at 50% maximum dose. For small field and multi-target plans, MC

dose calculations were performed and the results compared with ion chamber and film measurements.

Results

Our MC code was commissioned to accurately reproduce the Varian linacs and CyberKnife dose distributions (within 1%/1 mm at various depths, square field sizes, and different material densities). Figure 1 demonstrates the agreement between the Eclipse and MC dose distributions on a target measuring about 10 cm in diameter. For SRT and SBRT conditions, our group has several publications on the MC simulation results matching the machine commissioning data.[32-34] In this study, comparisons on clinically used patient plans are reported as a routine QA method. The average time consumed for MC calculations is 24 min with under 1% calculation uncertainty. The maximum dose differences in the SRT/SBRT plans [Table 2] between the Eclipse AAA, Multiplan pencil beam algorithm and MC are within 5% (average 2.7%) for small targets (4–40 cc). Patient-specific measurement results are listed in Table 2. An average of 1.66% (up to 3.66%) of difference between ion chamber measurements and MC calculations is recorded. 2D measurements with films also agree with TPS calculations to within 3 mm, shown in Figures 2 and 3. These results are within the TG119 and TG218 3%/3 mm IMRT QA criteria above 95% with 50%

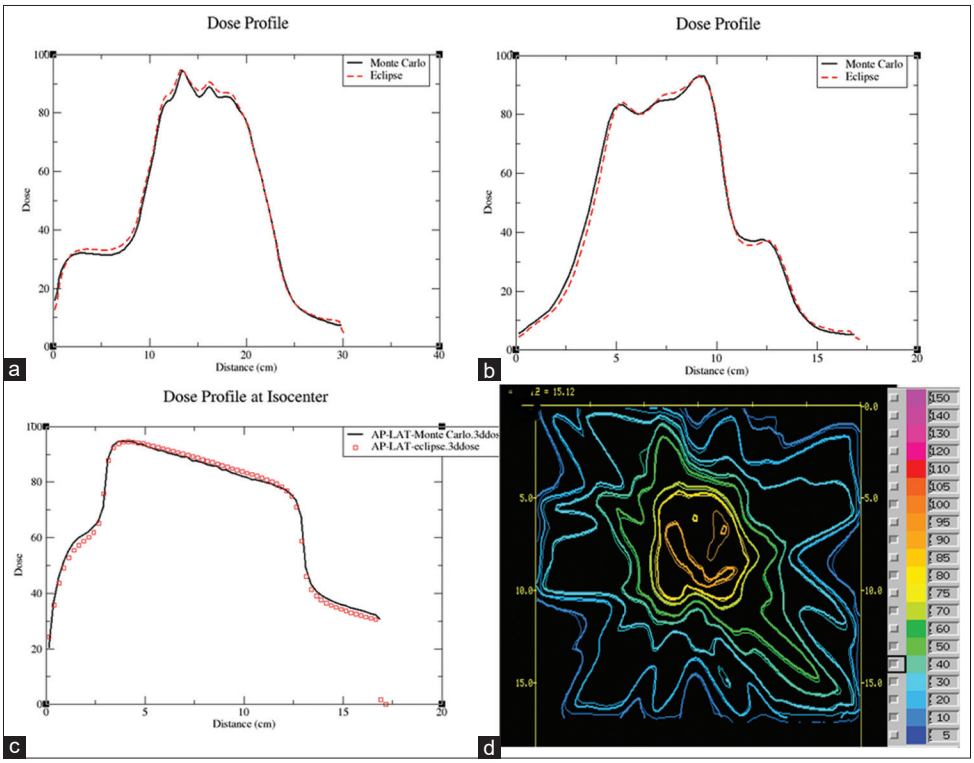

Figure 1: (a-c) show 1D comparisons of Monte Carlo and Eclipse AAA algorithm at the directions of anterior-posterior, superior-inferior and left-right respectively. (d) shows a 2D comparison of Monte Carlo (thin lines) and Eclipse AAA algorithm (thick lines)

Table 2: Patient-specific ion chamber measurement results

Patient	Eclipse/multiplan (TPS) (cGy)	MC (cGy) (%)	Measurement (cGy) (%)	Measurement-MC/MC (%)	TPS-MC/MC (%)
1	587.3	560.8±0.5	581.3±1.5	3.66	4.73
2	673.0	662.9±0.7	659.5±1.5	−0.51	1.52
3	1729.4	1679.0±0.5	1688.0±1.5	0.54	3.00
4	582.0	573.3±0.5	584.9±1.5	2.02	1.52
5	579.0	555.8±1.0	573.5±1.5	3.18	4.17
6	650.0	627.3±1.0	629.5±1.5	0.35	3.62
7	681.0	654.8±0.7	661.0±1.5	0.95	4.00
8	1060.3	1031.8±1.0	1069.4±1.5	3.65	2.76
9	2033.5	2004.8±1.0	2051.8±1.5	2.34	1.43
10	1177.0	1173.9±1.0	1179.3±1.5	0.46	0.26
Ave				1.66	2.70

TPS: Treatment planning system, MC: Monte Carlo

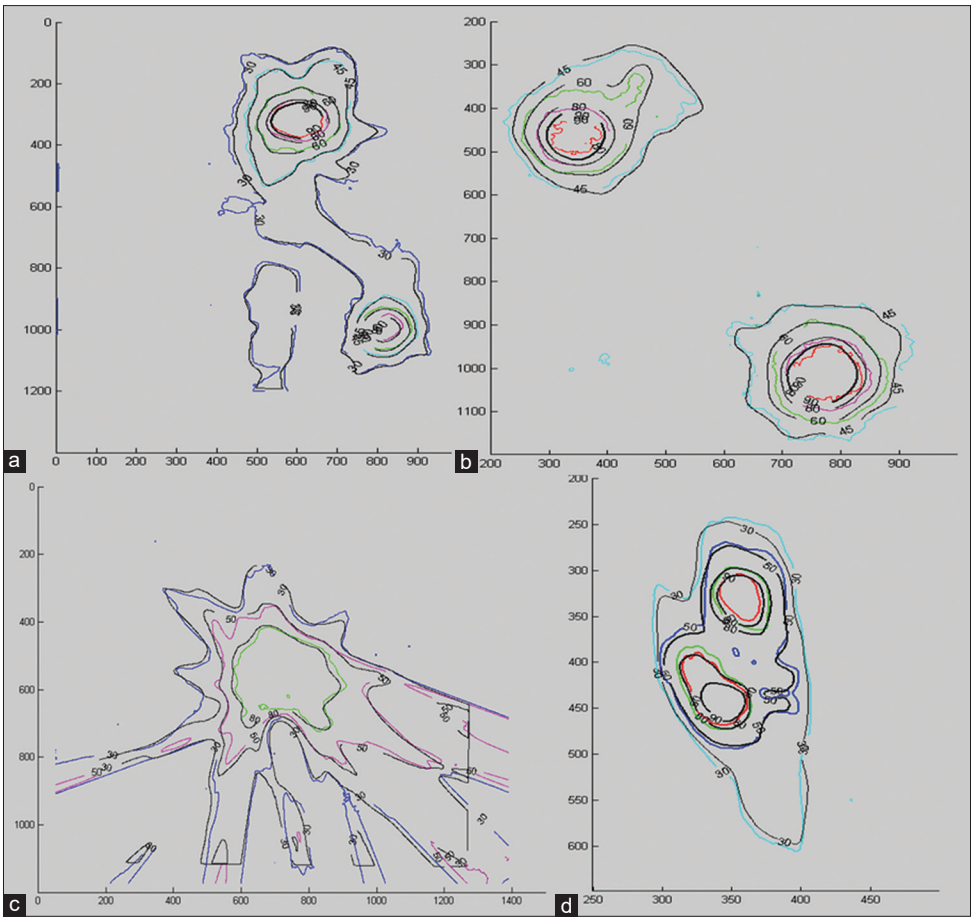

Figure 2: This figure shows the overlay of Eclipse/Multiplan export (in Black) and EDR2 film measurements (in colors). (a and b) are from case #5 [Table 1] brain case; (c) is case #1 [Table 1]; (d) is a brain case #7 [Table 1]. The figure scale is in 1/10 of mm

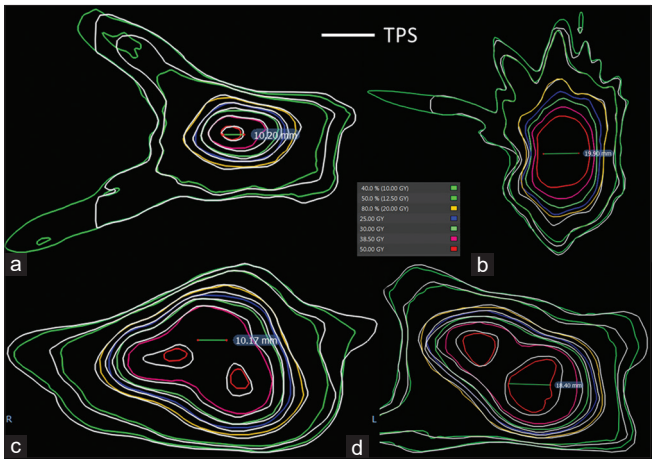

Figure 3: This figure shows the overlay of TPS (in white) and Monte Carlo calculations (in colors). (a) is from case #9 [Table 1] lung case; (b) is case #10 [Table 1] lung case; (c and d) is a brain case #6 [Table 1]

threshold. Figure 2 shows film measurement results with TPS comparison on 2 brain cases (a, b, d) and 1 spine case (c). Gamma passing rates above the 50% dose line for (a) is 96.54% and 95.02% for (b); for (c) is 96.80%; (d) is a brain case with two lesions 1.2 cm apart. Gamma passing rates above the 50% dose line is 97.85%. Figure 3 shows dose calculations with TPS comparison using MC calculations. Gamma passing rates above the 50% dose line from (a) to (d) are 96.78%, 98.02%, 95.85%, and 95.37%, respectively.

Discussion

A major advantage of MC dose computation algorithms is the ability to accurately compute dose in complex geometry. While MC dose calculations do not require the approximation of radiation equilibrium conditions, the calculations can truthfully reflect the delivered dose for small treatment field sizes or for treatment plans with multiple treatment targets in one treatment session, such as those found in brain cancer patients. These advantages make the MC dose calculation method the premier independent checking technique for the current commercial TPSs which usually utilizes non-MC algorithms to estimate doses. Currently, medical physicists will deliver patient plans on ion chamber-based 2-D dose measurements as an independent patient-specific IMRT QA method. However, for the SRT/SBRT treatment scheme, ion chamber-based QA devices provide lower spatial resolution which is crucial for small targets or multi-target treatments

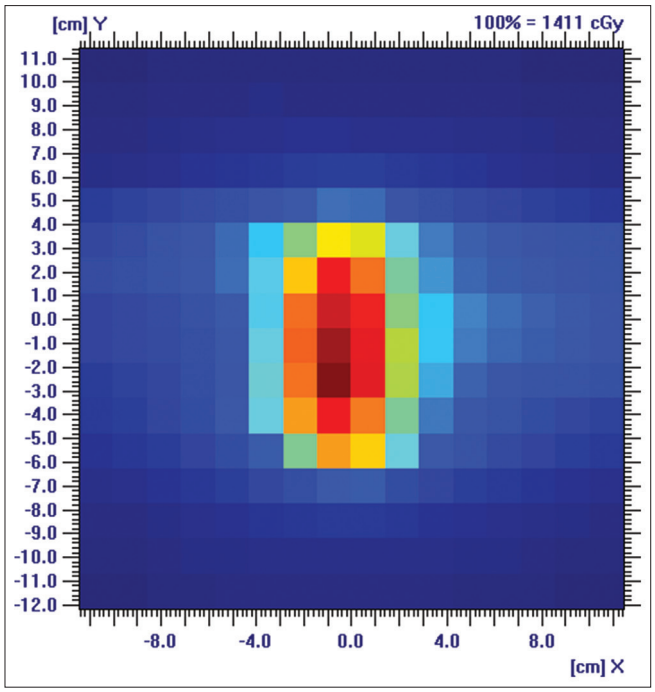

Figure 4: Ion chamber-based 2D measurements on case #2

with small separations. Figure 4 illustrates the difficulties when comparing the dose distribution with ~2.5 cm target area with few measurement points. One can observe that it is difficult to incorporate the doses between the chambers when the chamber size is large. In the meantime, the uncertainty comes from the ion chamber correction with electron disequilibrium for small field measurements will affect dramatically for the QA results. This created a disadvantage allowing medical physicists only be able to perform QA on SRT/SBRT IMRT plans using film measurement. However, film dosimetry is very complex and time-consuming. With a large number of SRT/SBRT patients, it is also challenging to perform QA on each patient using films for absolute dose comparison. Moreover, when treatment plans involve multiple targets, it is difficult to choose the location of the film placement. Very often, multiple films are needed for only 1 QA validation. The differences of density between films, solid water, and simulated human tissue became significant on dose calculations which contained scatterings from the film material with various incident gantry angles of radiation beams. Film measurements also involve film processing and film sensitivity issues. Take Figure 2 as an example, the isodose line below 50% of the prescription dose can be very noisy and this problem can evolve from an inadequate film processing and handling procedure or the sensitivity of the film active level. Dose comparisons and isodose line overlay challenges are also major drawbacks of film dosimetry which is described in AAPM TG-218.[28] These two major difficulties, chamber sizes and film dosimetry complexity, make practical SRT/SBRT QA measurements lack accuracy and efficiency. As for the MC calculation time, it depends on the target numbers, treatment beam selection, and desired calculation uncertainties. The longest calculation time for this study is 59 min with 0.7% uncertainty; the shortest time is 9 min with 1% uncertainty. The average calculation time of the 10 cases is 24 min which is much shorter than the ion chamber and film measurements. MC dose calculations, being able to truly simulate how each photon enters into patient geometry, make a proper tool to be an SRT/SBRT QA method and succeed both in accuracy and efficiency.

Table 2 shows the comparison results of this 10-patients study. Pinpoint chambers are used for measurements with target volume of 3 cm diameter or less. Pinpoint chambers have up to 5% measurement uncertainties with these conditions.[32] Based on our results shown in Table 2, both comparisons between measurement to MC calculations (average 1.66%) and TPS to MC calculations (average 2.7%) are all within 5% uncertainties. We could say that our MC calculations, TPS calculations and measurements are very close to each other and are practically used clinically. It is also confirmed on gamma analyses shown in Figures 2 and 3.

This study also provides confidence to the community of implementing adaptive radiation therapy. For example, the ViewRay system (ViewRay, Inc, Cleveland, OH, USA) uses a MC dose computation engine that can be accessed at the treatment console to perform an on-the-fly QA for the adaptive IMRT plans. With their MC algorithm, owing to efficient variance reduction techniques, a 3D dose calculation can be completed in under a minute. Our study can provide a strong validation of the accuracy and efficiency of MC calculations on the re-plans with adaptive target volumes.

Conclusions

MC dose calculation provides accurate, thorough, and fast dose verification for hypofractionated SRT for small and multi-target treatment plans generated by a Varian Eclipse TPS on a Varian Trilogy accelerator.

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Conflicts of interest

There are no conflicts of interest.

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