Published in final edited form as:

Int J Radiat Oncol Biol Phys. 2012 October 1; 84(2): 508–513. doi:10.1016/j.ijrobp.2011.12.005.

Dosimetric Verification Using Monte Carlo Calculations for Tissue Heterogeneity-corrected Conformal Treatment Plans Following RTOG 0813 Dosimetric Criteria for Lung Cancer Stereotactic Body Radiotherapy

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Abstract

Purpose—The recently activated RTOG studies on stereotactic body radiation therapy (SBRT) of non-small cell lung cancer (NSCLC) require tissue density heterogeneity correction, where the high and intermediate dose compliance criteria were established based on superposition-algorithm dose calculations. The study was aimed to compare superposition-algorithm dose calculations with Monte Carlo (MC) dose calculations for SBRT NSCLC treatment and to evaluate whether compliance criteria need to be adjusted for MC dose calculations.

Materials and Methods—Fifteen RTOG 0236 study sets were used. The PTV volumes range from 10.7 to 117.1 cm³. SBRT conformal treatment plans were generated using CMS XiO treatment planning software with superposition algorithm to meet the dosimetric high and intermediate compliance criteria recommended by the RTOG 0813 protocol. The plans were recalculated using the MC algorithm of a CMS Monaco treatment planning system. Tissue density heterogeneity correction was applied in both calculations.

Results—Overall, the dosimetric quantities of the MC calculations have larger magnitudes than those of the superposition calculations. On average, $R_{100\%}$ (ratio of prescription isodose volume to PTV), $R_{50\%}$ (ratio of 50% prescription isodose volume to PTV), $D_{2\text{cm}}$ (maximal dose 2 cm from PTV in any direction in percentage of prescription dose), and V_{20} (percentage of lung receiving dose equal to or larger than 20 Gy) increased by 9%, 12%, 7%, and 18%, respectively. In the superposition plans, 3 cases did not meet the criteria for $R_{50\%}$ or $D_{2\text{cm}}$. In the MC recalculated plans, 8 cases did not meet the criteria for $R_{100\%}$, $R_{50\%}$, or $D_{2\text{cm}}$. After re-optimization with MC calculations, 5 cases did not meet the criteria for $R_{50\%}$ or $D_{2\text{cm}}$.

Conclusions—The results indicate that the dosimetric criteria, e.g., the criteria for $R_{50\%}$, recommended by RTOG 0813 protocol, may need to be adjusted when MC dose calculation algorithm is employed.

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Conflict of interest: none.

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Keywords

RTOG; stereotactic body radiation therapy; non-small-cell lung cancer; heterogeneity correction; Monte Carlo

INTRODUCTION

Lung cancer is the second most common cancer in both men and women. It accounts for about 15% of all new cancers. According to the American Cancer Society's most recent estimates (1), about 222,520 new cases of lung cancer will be diagnosed in the United States for 2010, and there will be an estimated 157,300 deaths from lung cancer, accounting for about 28% of all cancer deaths. The most common types of lung cancer, affecting 75%–80% of patients with lung cancer, are "non-small cell lung cancer (NSCLC)". Approximately 15–20% of NSCLC patients present with early or localized disease, with the primary tumor in the lung, and no nodal involvement, or metastases elsewhere (2). Primary radiotherapy for early stage non-small lung cancer is considered reasonable non-surgical therapy for patients who cannot tolerate the rigors of surgery or the postoperative recovery period. Reported five-year survival rates range from 10–30% (3–7).

Stereotactic body radiotherapy (SBRT), which uses multiple co-planar and non-coplanar beams and stereotactic localization, and incorporates a variety of systems for decreasing the effects of lung and other organ motion, can substantially improve local control of lung cancer treatment. SBRT allows for dramatic reduction of treatment volumes, facilitating oligofractionation using markedly increased daily doses and significantly reduced overall treatment time. A study of toxicity and efficacy of SBRT in a high-risk population of patients with early stage but medically inoperable lung cancer was reported recently (8).

Clinical trials have been conducted to study SBRT for NSCLC treatment, such as Radiation Therapy Oncology Group (RTOG) protocols 0236 and 0618 (9). Both of these trials did not allow heterogeneity density corrections for calculating monitor unit settings for actual patient treatment, i.e., all tissues within the body, including lung, are assumed to have unit (water) density. Studies have reported that dose calculations with and without heterogeneity density corrections showed remarkable differences in the calculated doses and dose distributions in the thoracic region (10–12). Schuring *et al.* studied the influence of heterogeneity corrections on dose calculations for SBRT NSCLC treatment and showed significant differences in the dosimetric data between calculations with and without heterogeneity (13). Xiao *et al.* evaluated treatment plans with and without heterogeneity corrections submitted from multiple institutions accruing patients to RTOG protocol 0236, and proposed dosimetric objectives for RTOG SBRT NSCLC study with heterogeneity corrections (14). The currently enrolling RTOG protocol 0813 (9), which was designed for phase I/II study of SBRT for early stage centrally located NSCLC in medically inoperable patients, requires heterogeneity corrections in dose calculations and has included dosimetric objectives for treatment planning with heterogeneity corrections.

Ideally, treatment plans with heterogeneity corrections would predict more accurate dose distributions, compared to those without heterogeneity corrections. However, the prediction relies on the accuracy of dose calculation algorithms. Studies have shown that different algorithms have different accuracies in dose calculations with heterogeneity corrections in lung treatments (10,15,16). Monte Carlo (MC) algorithms have been considered as a more accurate method for dose calculations although they have not been widely available in commercially available treatment planning platforms. Convolution/superposition algorithms

have been considered having accuracies close to MC algorithms and have been used for dose calculations in SBRT NSCLC treatments (13, 14).

The dose compliance criteria for current protocols, e.g., RTOG 0813, were established in order to create conformal plans with steep dose gradients in all directions away from the target. The aim of this study was to compare superposition-algorithm dose calculations with MC dose calculations for SBRT NSCLC treatment to evaluate whether the compliance criteria can be achieved using available MC dose calculations.

METHODS AND MATERIALS

Validation of MC calculation

In the study, MC dose calculations were performed using the MC algorithm of a Monaco treatment planning system (CMS Inc., St. Louis, MO). To validate the MC algorithm dose calculation with heterogeneity correction for SBRT lung cancer treatment, a phantom study was conducted. An anthropomorphic inhomogeneous thoracic Rando phantom was used and EDR2 films were applied to measure dose distributions generated by SBRT beams. The film was placed in a transverse plane in the phantom. Five beams with field sizes of $\sim 4 \times 2 \text{ cm}^2$ were delivered. Dose distributions measured with the film were compared with MC calculations. Analysis was performed with Omni-Pro ImRT software (Version 1.4.0.1).

Comparison of superposition-algorithm dose calculations with Monte Carlo dose calculations for SBRT lung cancer treatment

Fifteen RTOG 0236 study sets from RTOG database with CT images and structures were used as input data for this study. The PTV volumes of the 15 cases varied from 10.7 to 117.1 cm^3 . Conformal SBRT treatment plans were generated in an XiO treatment planning system (CMS Inc., St. Louis, MO) with a superposition algorithm with heterogeneity corrections, which were optimized to meet the dosimetric objectives proposed by RTOG protocol 0813. The multigrid superposition method of XiO treatment planning system uses kernels represented in spherical coordinates in dose calculation. The kernels are modified according to the density changes in the irradiated medium with the use of a varying resolution for the calculation grid, depending on the potential dose gradients (e.g., at high density gradients, a finer grid is used). In the plans using the superposition algorithm (superposition plans), the doses were scaled such that the prescription dose covered 95% of the planning target volume (PTV). Dose normalization influences dose profiles. The superposition plans were re-calculated with the MC algorithm of the Monaco treatment planning system, with identical beam settings (number of beams, beam energy, angles, field sizes, and monitor units). The beam energy used was 6 MV and all the calculations were based on the same linear accelerator beam data.

The dosimetric parameters (defined in RTOG protocol 0813) of the superposition plans and the MC recalculated plans were calculated and compared. The parameters included: ratio of prescription isodose volume to PTV ($R_{100\%}$), ratio of 50% prescription isodose volume to PTV ($R_{50\%}$), maximal dose 2 cm from PTV in any direction in percentage of prescription dose ($D_{2\text{cm}}$) and percentage of lung receiving dose equal to or larger than 20 Gy (V_{20}).

Further, the MC plans were re-optimized by adjusting the beam weights to meet the criteria recommended by RTOG protocol 0813. In the re-optimization, the beams (number of beams, incident angles) were kept the same and only the beam weights were optimized. The dosimetric parameters of the final optimized MC plans were evaluated.

RESULTS

Validation of MC calculation

Figure 1 shows the isodose comparison between the MC calculation and the film measurement in the phantom study. The MC calculation had good agreement with the measurement: the gamma-analysis pass rate of the absolute dose comparison was 97.6% for the criteria of 3%/3mm. The gamma criteria of 3%/3mm were recommended by AAPM Task Group Report TG-119 for quality assurance (QA) of intensity modulated radiation therapy (IMRT) (17), which usually includes small segmented treatment fields. The criteria have been widely used in clinics (18) for QA of treatments including SBRT. We have been using the criteria in our clinic. In the gamma analysis, the dose difference term is defined as: the dose at a point minus the reference dose at the same point then divided by the reference dose at that point.

Comparison of superposition plans with MC recalculated plans

The dosimetric parameters of the superposition plans and those of the MC recalculated plans are compared in Fig. 2(a)-(d). Figure 2(a) shows the ratios of $R_{100\%}$ between the superposition plans and the MC recalculated plans, as functions of PTV volume. $R_{100\%}$ is a quantity measuring high dose conformity. The results do not show observable PTV volume dependence. Overall, the ratios of $R_{100\%}$ are less than 1.0. Since the PTVs are identical in both sets, the prescription isodose volumes of the MC recalculated plans are larger than those of the superposition plans, which on average increased by 9% (minimum, -8%; maximum, 29%; standard deviation, 9%).

Figure 2(b) shows the ratios of $R_{50\%}$ between the superposition plans and the MC recalculated plans, as functions of PTV volume. $R_{50\%}$ is a quantity measuring intermediate dose spillage. Similar to that of $R_{100\%}$, the variation of $R_{50\%}$ does not show observable PTV volume dependence. On average, the $R_{50\%}$ of the MC recalculated plans are larger than those of the superposition plans, which increased by 12% (minimum, 0; maximum, 28%; standard deviation, 5%).

Figure 2(c) shows the ratios of D_{2cm} , which is another quantity measuring low dose spillage. Figure 2(d) shows the ratios of V_{20} . These two quantities in the MC recalculated plans also increased, with average increases of 7% (minimum, 3%; maximum, 13%; standard deviation, 3%) and 18% (minimum, 11%; maximum, 29%; standard deviation, 6%), respectively.

Minimum tumor coverages were also compared. The ratios of D_{90} (the dose that 90% of the PTV receives) between the superposition plans and the MC recalculated plans were calculated. Compared to the quantities presented in Fig. 2(a)-(d), the differences in D_{90} between the superposition plans and the MC recalculated plans are smaller. The D_{90} in the MC recalculated plans increased by 1% (minimum, -5%; maximum, 6%; standard deviation, 3%).

Evaluation of the dosimetric parameters against the criteria of RTOG protocol 0813

The dosimetric parameters of the superposition plans, the MC recalculated plans, and the MC optimized plans are listed in Tables 1–4. The criteria of minor deviations of RTOG protocol 0813 are also listed in the tables. The parameters which have major deviations from RTOG protocol 0813 are highlighted.

In the superposition plans, all fifteen cases meet the minor deviation criteria for $R_{100\%}$ and V_{20} , i.e., no major deviations from the protocol criteria. Three cases have major deviations

in $R_{50\%}$ and two cases have major deviations in D_{2cm} . The pass rates (i.e., the percentage of the cases that have no major deviations) of $R_{100\%}$, $R_{50\%}$, D_{2cm} , and V_{20} are: 100%, 80%, 87%, and 100%, respectively.

In the MC recalculated plans, cases that violate the criteria are increased: Three cases have major deviations in $R_{100\%}$, eight cases have major deviations in $R_{50\%}$, and four cases have major deviations in D_{2cm} . The pass rates of $R_{100\%}$, $R_{50\%}$, and D_{2cm} decreased to 80%, 47%, and 73%, respectively. Although the pass rate of V_{20} still remains 100%, the V_{20} are actually remarkably increased.

In the optimized MC plans, there are still five cases having major deviations in $R_{50\%}$ and three cases having major deviations in D_{2cm} . The pass rates of $R_{100\%}$, $R_{50\%}$, D_{2cm} , and V_{20} are 100%, 67%, 80%, and 100%, respectively. The pass rates of $R_{50\%}$ and D_{2cm} are lower than those of superposition plans. It is noted that the pass rate of $R_{50\%}$ is lower, which is less than 80%.

DISCUSSION

The results showed the differences of the dosimetric parameters calculated respectively with superposition and MC algorithms. On average, the superposition calculations underestimated the magnitudes of those dosimetric parameters, i.e., underestimated the high dose spillage, the low dose spillage, and the dose to lung. The differences in $R_{50\%}$ and V_{20} between superposition and MC calculations were relatively larger, compared to those in $R_{100\%}$ and D_{2cm} . These dosimetric differences can be attributed to the differences of MC and superposition algorithms in modeling electronic disequilibrium. The regions described by $R_{50\%}$, which were farther away from the targets, compared to those described by $R_{100\%}$, might include air volumes that led to significant electronic disequilibrium. The differences in $R_{50\%}$ between MC and superposition calculations were thus more remarkable than those in $R_{100\%}$. Figure 2(e)-(f) show isodose distribution comparison between superposition and MC calculations in one of the cases, where PTV structure, 100% isodose line, and 50% isodose line are shown. Hurkmans *et al.*'s study (19), though it did not specify the differences between MC and superposition calculations, did show observable differences in $R_{50\%}$ between the advanced algorithms and the non-advanced algorithms. The latter did not model lateral electronic disequilibrium very well. Fogliata *et al.*'s phantom study (20) showed larger differences between XiO superposition algorithm and MC calculations in light lung (lower density lung region) than in normal lung, though the trend of their single-phantom study result is different from the result of our multiple-case clinical study.

Our study showed that because of the differences of MC and superposition calculations, in some cases, the superposition plans met the criteria while the MC recalculated plans did not meet the criteria. Even after re-optimizing, there were still a few MC plans which could not meet the criteria. Current protocol criteria were established based on superposition-algorithm dose calculations. According to the results, some of the criteria (e.g., those for $R_{50\%}$) may be too strict for MC dose calculations. Although it is limited, the use of MC-based treatment planning systems is increasing in nowadays. During this transition period, the protocol criteria may need to be adjusted for MC dose calculations to ensure patient accrual. The study here is a preliminary study, which could provide references for future studies. Comprehensive studies with larger case volumes, involving multiple treatment planning systems from major manufacturers, are expected to develop dosimetric criteria to accommodate the use of MC calculation technique. The results of the study were generated based on the comparison of XiO superposition algorithm and MC. For different dose calculation algorithms, the differences of the dosimetric parameters relative to MC results

may vary. If one wishes to realize more accurate dose prediction, MC method needs to be used and a protocol needs to be generated.

CONCLUSION

The results of our particular study showed average differences of 9% (minimum, -8%; maximum, 29%), 12% (minimum, 0; maximum, 28%), 7% (minimum, 3%; maximum, 13%), and 18% (minimum, 11%; maximum, 29%) in $R_{100\%}$, $R_{50\%}$, D_{2cm} , and V_{20} , respectively, between superposition and MC calculations, and indicate that the dosimetric criteria, e.g., the criteria for $R_{50\%}$, recommended by RTOG 0813 protocol, may need to be adjusted for MC dose calculations. Further studies are expected to establish protocol criteria for MC dose calculations.

Acknowledgments

This project was supported by RTOG grant U10 CA21661, CCOP grant U10 CA37422, and ATC grant U24 CA81647 from the National Cancer Institute (NCI). This manuscript's contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Cancer Institute.

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Summary

RTOG 0813 protocol for stereotactic body radiation therapy (SBRT) of non-small cell lung cancer (NSCLC) requires tissue density heterogeneity correction, where the dosimetric compliance criteria were established based on superposition-algorithm dose calculations. The study compared superposition-algorithm dose calculations with Monte Carlo dose calculations in fifteen SBRT NSCLC cases and evaluated the dosimetric compliance criteria for MC dose calculations. Results indicate that the compliance criteria of RTOG 0813 protocol may need to be adjusted when MC dose calculation is employed.

Fig. 1.

Experimental validation of MC calculation: isodose comparison between MC calculation (dashed line) and EDR2 film measurement (solid line). The pass rate of gamma analysis of the absolute dose comparison (criteria of 3% and 3mm) is 97.6%.

Fig. 2.

(a)–(d): Comparison of the dosimetric parameters between superposition plans and Monte Carlo recalculated plans (MC_{recal}). (a) ratio of $R_{100\%}$, (b) ratio of $R_{50\%}$, (c) ratio of D_{2cm} , and (d) ratio of V_{20} . (e)–(f): Isodose distributions of (e) superposition and (f) MC calculations in one case. The lines indicate PTV (the most inner one), 100% isodose line, and 50% isodose line (the outmost one), respectively.

Comparison of $R_{100\%}$. RTOG 0813 criteria, results of superposition plans, MC recalculated plans, and MC optimized plans, are listed. The data which have major deviations from the RTOG 0813 criteria are highlighted.

Table 1

Case No.	PTV Vol. (cm ³)	$R_{100\%}$			
		RTOG 0813 Minor deviation	Superposition plans	MC recalculated plans	MC optimized plans
1	43.3	1.2-1.5	1.2	1.7	1.2
2	30.7	1.2-1.5	1.2	1.3	1.2
3	48.2	1.2-1.5	1.4	1.5	1.4
4	29.0	1.2-1.5	1.2	1.4	1.3
5	12.0	1.2-1.5	1.1	1.3	1.3
6	71.6	1.2-1.5	1.3	1.2	1.2
7	68.8	1.2-1.5	1.1	1.3	1.3
8	51.2	1.2-1.5	1.2	1.3	1.3
9	43.9	1.2-1.5	1.2	1.2	1.2
10	22.3	1.2-1.5	1.3	1.4	1.3
11	91.1	1.2-1.5	1.2	1.3	1.3
12	10.7	1.2-1.5	1.2	1.2	1.2
13	39.3	1.2-1.5	1.2	1.3	1.3
14	22.9	1.2-1.5	1.4	1.6	1.4
15	117.1	1.2-1.5	1.2	1.2	1.2

Table 2

Comparison of $R_{50\%}$. RTOG 0813 criteria, results of superposition plans, MC recalculated plans, and MC optimized plans, are listed. The data which have major deviations from the RTOG 0813 criteria are highlighted.

Case No.	PTV Vol. (cm ³)	$R_{50\%}$			
		RTOG 0813 Minor deviation	Superposition plans	MC recalculated plans	MC optimized plans
1	43.3	4.1-5.1	3.9	5.4	4.5
2	30.7	4.4-5.4	4.0	4.5	4.4
3	48.2	4.0-5.0	4.5	5.0	4.8
4	29.0	4.4-5.4	4.8	5.3	5.1
5	12.0	4.8-5.8	4.6	5.1	5.1
6	71.6	3.5-4.8	4.4	4.9	4.9
7	68.8	3.5-4.8	3.3	3.7	3.7
8	51.2	4.0-5.0	4.2	4.8	4.8
9	43.9	4.1-5.1	4.5	5.1	5.1
10	22.3	4.5-5.5	4.7	5.5	5.3
11	91.1	3.3-4.5	3.5	4.0	4.0
12	10.7	4.9-5.9	4.8	4.8	4.8
13	39.3	4.2-5.2	7.4	8.4	8.4
14	22.9	4.5-5.5	9.2	10.6	10.0
15	117.1	3.2-4.1	4.9	5.8	5.6

Table 3

Comparison of D_{2cm} . RTOG 0813 criteria, results of superposition plans, MC recalculated plans, and MC optimized plans, are listed. The data which have major deviations from the RTOG 0813 criteria are highlighted.

Case No.	PTV Vol. (cm ³)	D_{2cm}			
		RTOG 0813 Minor deviation	Superposition plans	MC recalculated plans	MC optimized plans
1	43.3	60.3-73.2	51.7	59.5	56.6
2	30.7	56.9-66.6	52.9	57.4	56.0
3	48.2	61.5-76.0	74.0	76.4	74.0
4	29.0	56.3-65.9	60.2	63.7	62.2
5	12.0	50.0-58.0	47.0	51.7	51.7
6	71.6	66.3-86.2	66.7	74.7	74.7
7	68.8	65.8-85.5	55.0	58.8	58.8
8	51.2	62.2-77.5	58.8	61.9	61.9
9	43.9	60.5-73.6	66.4	70.4	70.4
10	22.3	54.1-63.1	52.1	56.8	55.4
11	91.1	69.4-88.5	64.6	67.9	67.9
12	10.7	50.0-58.0	46.9	49.5	49.5
13	39.3	59.3-71.0	80.8	84.8	84.8
14	22.9	54.3-63.4	61.1	67.7	66.1
15	117.1	72.1-90.4	92.4	99.4	97.6

Table 4

Comparison of V_{20} . RTOG 0813 criteria, results of superposition plans, MC recalculated plans, and MC optimized plans, are listed.

Case No.	PTV Vol. (cm ³)	V_{20}			
		RTOG 0813 Minor deviation	Superposition plans	MC recalculated plans	MC optimized plans
1	43.3	10-15	4.9	6.4	6.4
2	30.7	10-15	5.9	6.7	6.5
3	48.2	10-15	4.1	4.8	4.8
4	29.0	10-15	3.2	3.8	3.8
5	12.0	10-15	2.3	2.6	2.6
6	71.6	10-15	10.2	11.9	11.9
7	68.8	10-15	5.0	5.8	5.8
8	51.2	10-15	6.6	7.6	7.6
9	43.9	10-15	6.0	7.1	7.1
10	22.3	10-15	4.9	6.4	6.4
11	91.1	10-15	10.4	14.7	14.7
12	10.7	10-15	1.6	1.9	1.9
13	39.3	10-15	5.9	8.0	8.0
14	22.9	10-15	2.9	3.5	3.3
15	117.1	10-15	7.7	10.9	10.6