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Original research article

Characterization of robust optimization for VMAT plan for liver cancer

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ABSTRACT

Purpose: We investigated the feasibility of robust optimization for volumetric modulated arc therapy (VMAT) stereotactic body radiation therapy (SBRT) for liver cancer in comparison with planning target volume (PTV)-based optimized plans. Treatment plan quality, robustness, complexity, and accuracy of dose delivery were assessed.

Methods: Ten liver cancer patients were selected for this study. PTV-based optimized plans with an 8-mm PTV margin and robust optimized plans with an 8-mm setup uncertainty were generated. Plan perturbed doses were evaluated using a setup error of 8 mm in all directions from the isocenter. The dosimetric comparison parameters were clinical target volume (CTV) doses ($D_{98\%}$, $D_{50\%}$, and $D_{2\%}$), liver doses, and monitor unit (MU). Plan complexity was evaluated using the modulation complexity score for VMAT (MCSv).

Results: There was no significant difference between the two optimizations with respect to CTV doses and MUs. Robust optimized plans had a higher liver dose than did PTV-based optimized plans. Plan perturbed dose evaluations showed that doses to the CTV for the robust optimized plans had small variations. Robust optimized plans were less complex than PTV-based optimized plans. Robust optimized plans had statistically significant fewer leaf position errors than did PTV-based optimized plans.

Conclusions: Comparison of treatment plan quality, robustness, and plan complexity of both optimizations showed that robust optimization could be feasibile for VMAT of liver cancer.

1. Introduction

Surgical resection is the standard therapy for liver malignancies, hepatocellular carcinoma (HCC), and liver metastases. Radiofrequency ablation, percutaneous ethanol injection therapy, and transarterial chemoembolization are alternative procedures used in medically inoperable patients.[1] Stereotactic body radiation therapy (SBRT) has recently been used as a curative rather than a palliative modality. Because the liver is an organ that moves, managing respiratory motion is important. The management of respiratory motion and a comprehensive review of different methods that do so are found in the Report of AAPM Task Group 76.[2] Among the techniques discussed, breath-hold is a noninvasive and cost-effective approach for minimizing respiratory motion. It has the potential to minimize the internal target volume (ITV) and, thus, the planning target volume (PTV). Expiratory breath-holding has been shown to be reliably stable, making it clinically applicable for liver tumors. Moreover, the variable gantry speed, dose rate, and rapid dynamic multileaf collimator (MLC) motion of volumetric modulated arc therapy (VMAT) can significantly decrease treatment times. Therefore, many institutions use the expiratory breath-hold with VMAT for treating liver tumors.

Currently, two main types of optimization methods are available: PTV-based optimization and robust optimization. PTV-based optimization is generally used for VMAT plans that provide certain doses to the PTV while minimizing the doses to the organs-at-risk (OARs). Robust optimization, an alternative method that could replace PTV-based optimization, directly uses the clinical target volume (CTV) as the primary target during plan optimization.[3–13] Photon robust optimization also facilitates a significantly more robust dose distribution to targets and OARs than PTV-based optimization. It is useful for the build-up region, electron density, and location problems. One study has shown that robust optimization provided a better homogeneous dose distribution to peripheral targets than did conventional PTV-based plans using partial-arc VMAT techniques,[9] that is, robust optimization of VMAT can be

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Table 1
Patient characteristics.

Patient	Male/female	Age (y)	Tumor location	CTV volume (cc)	PTV volume (cc)
1	M	70	S4	7.2	50.2
2	F	66	S6	1.1	14.0
3	M	90	S8	3.4	23.2
4	M	85	S8	0.9	12.7
5	M	82	S4	2.7	21.8
6	M	80	S7	2.4	20.2
7	M	73	S6	3.3	21.7
8	M	57	S3	3.9	24.2
9	M	87	S2	4.4	28.9
10	M	63	S7	4.3	29.7
Mean	–	75	–	3.4	24.6

M; male, F; female, CTV; clinical target volume, PTV; planning target volume.

adapted for use with liver cancer because of its peripheral location. SBRT dose prescriptions for liver cancer are often low isodoses (e.g., 80% isodose line) and increase dose heterogeneity within the target, compared with traditional radiation therapy. Hot spots within the target volumes are generally considered clinically acceptable. However, robust optimization with dose heterogeneities should be carefully introduced because of normal tissue, such as liver, that is near the target.

Verification of the accuracy of dose delivery before the introduction of a new technique into clinical practice is very important to ensure that the treatment is correct. The modulation complexity score for VMAT (MCSv) is used to assess the variability of leaf positions and aperture areas between segments, which are indexed to the complexity of the treatment plan.[14,15] VMAT patient-specific quality assurance (QA) is used to verify the treatment planning system (TPS)-calculated dose via several detectors such as an ionization chamber, 3D diode arrays, and radiochromic or radiographic films. VMAT patient-specific QA can use a log file to analyze the accuracies of leaf position, dose rate, and gantry speed control during gantry rotation.

The purpose of the present study was to compare robust optimized plans for liver cancer patients with PTV-based optimized plans. First, we created treatment plans and evaluated their robustness with shifted positions. The perturbed dose was calculated with respect to the localization offset of the patient for both optimization plans. Second, the complexity of both optimization plans was investigated. Third, the QA of both optimization plans were compared using an ionization chamber, 3D diode arrays, and log files.

2. Materials and methods

2.1. Treatment planning

This study was approved by the Institutional Review Board of Hiroshima University (E-1223). Ten liver cancer patients who had previously been treated in our clinic were selected. The patient characteristics are provided in Table 1. The reproducibility of the tumor position was confirmed within 5 mm using an X-ray fluoroscopy simulator (VersiFlex VISTA, Hitachi Medical Corporation, Kashiwa, Japan). The respiration-monitoring Abches system (Apex Medical Inc., Tokyo, Japan) was used to monitor patient control of respiratory motion as well as tumor displacement. Images for radiation treatment planning were acquired using an Optima computed tomography (CT) 580W (GE Healthcare, Milwaukee, WI, USA) instrument with a tube potential of 120 kV, a gantry rotation time of 0.5 s, a slice thickness of 1.25 mm, and a tube current of 350 mA. Radiation treatment plans were created using the RayStation TPS ver. 6.2.0 (RaySearch Medical Laboratories AB, Stockholm, Sweden) commissioned with a TrueBeam STx (Varian Medical Systems, Palo Alto, CA, USA) linear accelerator. The gross tumor volume (GTV) and the liver were delineated by a radiation oncologist. No additional margin was added for the definition of the CTV. The PTV was created by expanding the CTV by 8 mm in all directions to account for breath-hold uncertainty, setup uncertainty, and mechanical inaccuracy. The CTV was 3.4 ± 1.7 cc (0.9–7.2 cc) and the PTV was 24.6 ± 10.0 cc (12.7–50.2 cc). A PTV plus a 3-mm ring was created to conform the dose to the PTV, and a PTV plus an 8-mm ring was used to reduce the dose to healthy tissues.

Two types of VMAT plans were prepared for each patient: PTV-based and robust optimizations. The partial-arc range was chosen in a rotating manner ipsilateral to the target to avoid contralateral normal tissue. Robust optimized plans were created using the same arc range as that used for the PTV-based optimized plans. The robust optimization function of the RayStation TPS is based on minimax optimization, as described by Fredriksson et al.[12] We defined robust optimization as the administration of a directly optimized dose to the CTV under a maximum-uncertainties setup of 8 mm in the left–right (LR), anterior–posterior (AP), and superior–inferior (SI) directions. The isocenter was placed at the center of the target. The selected beam energy was 10 MV flattening filter free (FFF) (dose rate = 2400 MU/min) because liver tumors are small targets, so a sharp dose is needed in the center of the beam profile to reduce the dose outside the field. The collimator angle was fixed at 5°. The PTV-based optimized plans were normalized so that the prescribed dose of 40 Gy (80% isodose line), administered in four fractions, was administered to 95% of the PTV ($D_{95\%}$). Robust optimized plans were normalized so that 98% (relative volume) of the GTV received 100% of the prescribed dose ($D_{98}\%$). Because the concept of PTV is not used in the ITV-based robust planning, the dose normalization was prescribed an equivalent dose to the CTV after analyzing PTV-based optimized plans. The $D_{95\%}$ of 40 Gy to the PTV obtained using PTV-based optimization plans was delivered as the $D_{98\%}$ of 49 Gy to the CTV (Table 2). Therefore, the prescribed dose for the CTV for robust optimized plans was 49 Gy. The maximum dose to the CTV and PTV from 125% to 130%. VMAT treatment plans were calculated using the collapsed cone convolution superposition (CCCS)-based algorithm. The TPS dose grid size was $2.0 \times 2.0 \times 2.0\ mm^3$. The final calculated dose, a dose–volume histogram (DVH), and dose statistics were recorded for each patient. The dosimetric parameters of the PTV-based and robust optimized plans were compared. The delivered dose to the CTV, liver dose, and monitor unit (MU) were investigated. The dosimetric parameters were computed to evaluate the $D_{98\%}$, $D_{50\%}$, and $D_{2\%}$ (close to the maximum dose) to the CTV. For the OARs, the mean dose, $D_{2\%}$, and the volumes of the liver treated with doses of at least 20 Gy (V_{20Gy}) were investigated.

2.2. Perturbed dose evaluation

The following method was used to investigate the variation in dose indices caused by setup errors. For setup uncertainties, the isocenter of the patient was rigidly shifted in the LR, AP, and SI directions from the nominal position to the maximum-uncertainties

Table 2
Dosimetric comparisons between the PTV-based and robust optimizations for the nominal plan.

	PTV-based optimized plans	Robust optimized plans	*p*-Value
CTV: $D_{98\%}$ (cGy)	4913.7 ± 78.8 (4717.0–4992.0)	4900.0 ± 0.0 (4900–4900)	0.375
CTV: $D_{50\%}$ (cGy)	5037.3 ± 63.4 (4891.0–5092.0)	5044.8 ± 26.3 (4982.0–5071.0)	0.922
CTV: $D_{2\%}$ (cGy)	5113.8 ± 65.9 (4986.0–5211.0)	5169.5 ± 38.6 (5105.0–5219.0)	0.193
Liver-CTV: mean dose (cGy)	491.7 ± 179.4 (205.0–756.0)	505.6 ± 181.4 (213.0–786.0)	0.023*
Liver-CTV: $D_{2\%}$ (cGy)	3407.6 ± 637.1 (2118.0–4464.0)	3611.8 ± 699.7 (2228.0–4669.0)	0.002*
Liver-CTV: V_{20Gy} (%)	5.6 ± 2.2 (2.2–9.3)	5.8 ± 2.3 (2.4–9.8)	0.004*
MU	1702.2 ± 176.2 (1385.4–1944.0)	1688.1 ± 162.7 (1438.6–1917.7)	0.160

Data are presented as group averages with ranges in parentheses ($n = 10$).
CTV, clinical target volume; MU, monitor unit.
* Wilcoxon signed-rank test resulted in a statistically significant difference ($p < 0.05$).

setup of 8 mm, yielding six dose distributions. For the CTV, the evaluation metrics included perturbed doses of $D_{98\%}$, $D_{50\%}$, and $D_{2\%}$. For the liver doses, the mean dose, $D_{2\%}$, and V_{20Gy} were evaluated.

2.3. Plan complexity

We used the MCSv to assess the plan complexities for the PTV-based and robust optimizations.[14] MCSv was calculated using the variability of leaf positions and the aperture area between control points, as originally proposed by McNiven et al.[15] MCSv is a single metric ranging from 0 to 1.0 such that an open rectangular field with no complexity has an MCS of 1.0. The value of MCSv decreases with increasing MLC sequence modulation. In our study, MCSv was calculated using the Digital Information and Communication in Medicine Radiation Therapy (DICOM-RT) files and Microsoft Visual C#.

2.4. Quality assurance

Pretreatment VMAT QA was performed using the 3D diode array ArcCHECK (Sun Nuclear Corporation, Melbourne, FL, USA), which consists of 1386 *n*-type solid-state diode detectors at a spacing of 10 mm. An acrylic plug, a 15-cm-diameter cylinder with a hole for an ionization chamber to measure absolute dose, was inserted into the ArcCHECK phantom. All plans were mapped onto the CT data of the ArcCHECK device and the DICOM dose data were obtained. The measurement isocenter of the plan was placed at the center of the cylindrical phantom. The dose was calibrated before measurement using the nominal dose. SunCHECK Patient v. 6.2.1 (Sun Nuclear Corporation) was used to measure the two-dimensional (2D) percentage gamma passing rate for the dosimetric differences between the dose delivered to the ArcCHECK and the dose calculated from the TPS by comparing the 2D distributions from the cylindrical surface. Gamma analysis using the acceptance criteria of 3%/3 mm, 2%/2 mm, and 10% lower dose threshold was applied. The ionization chamber (PTW31016 pinpoint chamber; PTW GmbH, Freiburg, Germany) was used for absolute dose comparison at the isocenter. The acceptance level of the gamma agreement index was at least 95%.

A log file was used to assess the leaf position error. The expected and actual leaf positions of the TrueBeam STx (Varian) during beam delivery are recorded at an update rate of 20 ms in a single binary trajectory log file on a Linac computer. We developed an in-house program to extract beam delivery data as well as the expected and actual positions of the leaves from the log file every 20 ms using Microsoft Visual C#. The leaf position error was calculated by subtracting the expected leaf position from the actual leaf position for each delivery time. It is the root mean square error (RMSE) of an individual leaf. The RMSE was the mean of the individual leaf RMSEs of a given A or B bank. The RMSEs and 95th percentile errors of the PTV-based and robust optimizations were compared. In addition, the delivery times were investigated to compare the efficiency of the delivery.

2.5. Data analysis

Data were analyzed using Wilcoxon signed-rank tests and R ver. 3.5.1 (www.r-project.org), with the statistical significance set at $p < 0.05$.

3. Results

3.1. Treatment planning

Fig. 1 shows one example of the dose distributions and DVHs of PTV-based and robust optimized plans for the same patient. CTV doses ($D_{98\%}$, $D_{50\%}$, and $D_{2\%}$), liver doses, and MU of the PTV-based and robust optimized plans are presented in Table 2, with the data presented as group averages and with ranges for all directions. There were no statistically significant differences between the doses to the CTV for the PTV-based and robust optimizations. The mean dose, $D_{2\%}$, and V_{20Gy} to the liver using robust optimization were, on average, 2.8%, 5.7%, and 4.7% higher than those using PTV-based optimization, respectively ($p < 0.05$). The MU values obtained by both optimized plans were similar, although the MU for robust optimized plans trended lower ($p > 0.05$).

3.2. Perturbed dose evaluation

Table 3 compares the doses to the CTV and the liver dose obtained from the rigidly shifted plans for PTV-based and robust optimized plans for overall perturbation, with data presented as group averages and ranges for all directions. $D_{98\%}$ to the CTV using the robust optimized plans was 5.8% higher on average than that using the PTV-based optimized plans ($p < 0.05$). The CTV $D_{98\%}$ perturbed doses for the PTV-based and robust optimized plans were covered by more than a minimum of 3721 and 4347 cGy of the prescribed dose for all patients. The mean dose, $D_{2\%}$, and V_{20Gy} dose to the liver of the robust optimized plans were 2.9%, 6.0%, and 4.5% higher than those of the PTV-based optimized plans, respectively ($p < 0.05$). The CTV doses for robust optimized plans showed small variations compared to those for the PTV-based optimized plans (see Fig. 2). The variations in $D_{98\%}$, $D_{50\%}$, and $D_{2\%}$ to the CTV were 235.1 versus 83.6 cGy, 97.0 versus 44.7 cGy, and 96.8 versus 69.5 cGy for the PTV-based and robust optimized plans, respectively. The variations in the mean dose, $D_{2\%}$, and V_{20Gy} dose to the liver were 181.5 versus 183.6 cGy, 684.6 versus 751.6 cGy, and 2.2% versus 2.4% for the PTV-based and robust optimized plans, respectively.

3.3. Comparison between the nominal plan and perturbed dose evaluation

Fig. 3shows the $D_{98\%}$ dose reduction to the CTV, from the nominal plan to the perturbed evaluation, for all patients. The average (range) perturbed $D_{98\%}$ doses to the CTV against the nominal plan for the PTV-based and robust optimized plans decreased by 13.7%

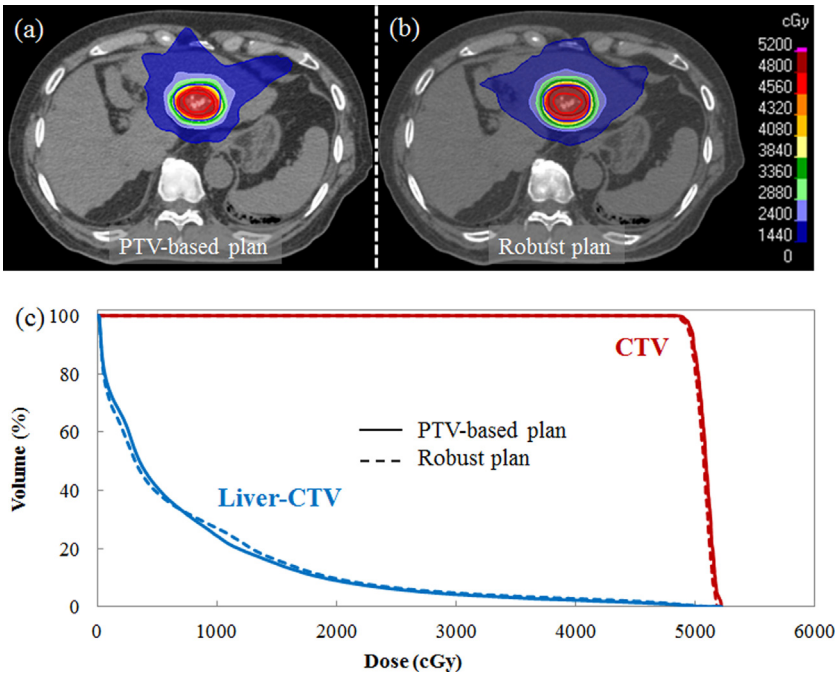

Fig. 1. Dose distributions for a patient with liver cancer calculated using (a) PTV-based optimization and (b) robust optimization. (c) Comparison of DVHs of PTV-based optimization (solid line) and robust optimization (dashed line) for the same patient. The CTV curves were nearly identical for both optimizations. However, the liver-CTV curves were slightly different.

Table 3
Dosimetric comparisons between the PTV-based and robust optimizations at offset locations.

	PTV-based optimized plans	Robust optimized plans	*p*-Value
CTV: $D_{98\%}$ (cGy)	4327.1 ± 235.1 (3721.0–4977.0)	4577.6 ± 83.6 (4347.0–4809.0)	<0.001*
CTV: $D_{50\%}$ (cGy)	4941.4 ± 97.0 (4708.0–5137.0)	4976.0 ± 44.7 (4868.0–5070.0)	0.013*
CTV: $D_{2\%}$ (cGy)	5101.4 ± 96.8 (4881.0–5354.0)	5136.8 ± 69.5 (4987.0–5279.0)	0.016*
Liver-CTV: mean dose (cGy)	486.0 ± 181.5 (130.0–821.0)	499.0 ± 183.6 (138.0–854.0)	<0.001*
Liver-CTV: $D_{2\%}$ (cGy)	3333.2 ± 684.6 (1667.0–4537.0)	3531.7 ± 751.6 (1734.0–4732.0)	<0.001*
Liver-CTV: V_{20Gy} (%)	5.5 ± 2.2 (1.5–11.0)	5.7 ± 2.4 (1.5–11.4)	<0.001*

Data are presented as group averages with ranges in parentheses ($n = 10$).
CTV, clinical target volume.
* Wilcoxon signed-rank test resulted in a statistically significant difference ($p < 0.05$).

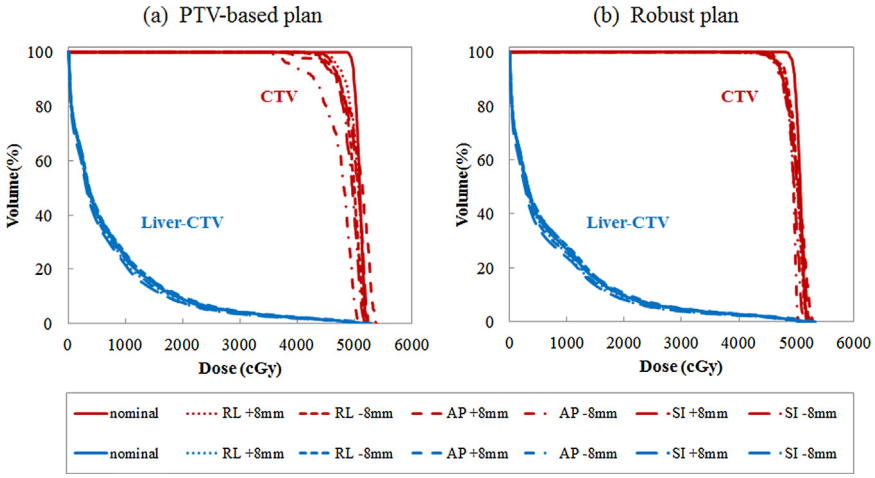

Fig. 2. Variation in DVHs recalculated in the left–right (LR), anterior–posterior (AP), and superior–inferior (SI) directions using (a) PTV-based optimized and (b) robust optimized VMAT plans for liver cancer. The robust optimized plan shows a more certain dose to the CTV than does the PTV-based optimized plan.

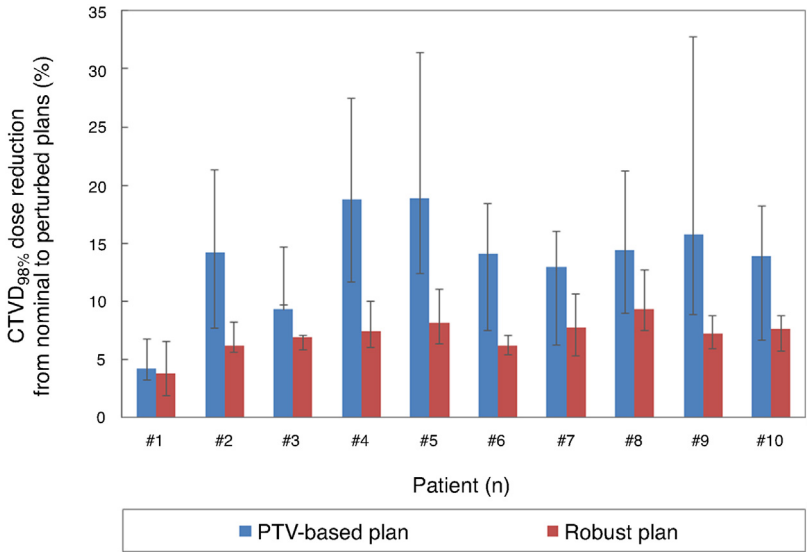

Fig. 3. Reduction rate of the CTV dose from the nominal to perturbed plans of the PTV-based and robust optimizations. The bars indicate the average values: the upper and lower whiskers indicate the maximum and minimum values, respectively.

Table 4
Comparison of the delivery parameters between PTV-based and robust optimizations.

	PTV-based optimized plans	Robust optimized plans
Chamber results (%)	−0.95 ± 0.27 (−1.43 to −0.44)	−0.82 ± 0.34 (−1.20 to −0.14)
ArcCHECK results (%): criteria 3 mm/3%	99.8 ± 0.2 (99.4–100.0)	99.7 ± 0.3 (99.1–100.0)
ArcCHECK results (%): criteria 2 mm/2%	97.7 ± 1.2 (95.8–99.4)	98.1 ± 0.6 (97.2–99.4)
Log file MLC: RMSE (mm)	0.016 ± 0.001 (0.015–0.017)	0.014 ± 0.001 (0.013–0.018)
Log file MLC: 95% tile (mm)	0.037 ± 0.001 (0.035–0.039)	0.035 ± 0.003 (0.031–0.040)
Delivery time (s)	44.7 ± 4.2 (38.5–50.9)	44.6 ± 3.3 (39.3–49.0)

MLC, multileaf collimator; RMSE, root mean square error.

(3.2–27.5%) and 7.1% (1.9–12.7%), respectively. The robust optimized plans achieved higher ITV dose certainties compared with the PTV-based optimized plans.

3.4. Plan complexity

The mean ± standard deviation MCSv for the PTV-based and robust optimized plans were 0.299 ± 0.037 (0.237–0.340) and 0.354 ± 0.073 (0.220–0.488), respectively ($p = 0.037$).

3.5. Quality assurance

Table 4 compares the ionization chamber and ArcCHECK measurements and MLC position errors for the PTV-based and robust optimized plans. The absolute doses measured at the isocenter for both optimizations were within 3%. The gamma passing rate (3%/3 mm) for both optimizations was approximately 100%. Both optimizations achieved a >95% gamma passing rate using stricter gamma criteria (2%/2 mm). The average MLC RMSE and 95% tile errors for all patients were 0.016 mm and 0.014 mm for the PTV-based optimized plans and 0.037 mm and 0.035 mm for the robust optimized plan, respectively ($p < 0.05$). The delivery time for both optimizations was approximately 45 s ($p > 0.05$).

4. Discussion

We investigated the robust optimization of VMAT for liver cancer patients and evaluated the robustness of the treatment plan with perturbed doses shifted from the isocenter, before introducing the plan into the clinical. Robust optimization was compared with PTV-based optimization with respect to CTV dose coverage, liver doses, and MU. In addition, plan complexity, dosimetric measurements, and log file analysis were investigated. Based on the VMAT optimization constraint in the target, the dose to the CTV using robust optimization was shown to be equivalent to that using PTV-based optimizations. In this study, the prescribed dose for robust optimization was defined after analyzing data from PTV-based optimization, that is, the CTV dose was equivalent at each optimization. Doses to the liver for robust optimization were worse than those for the PTV-based optimizations. The MU value was similar for both optimizations due to the same conditions, such as the prescribed dose and number of arcs.

Tumor position errors during beam delivery, including patient setup error and inter- and intrafractional tumor motion, may lead to a delivered dose distribution that deviates from the planned dose distribution. Robust optimization has been used to address this issue for lung cancer patients. It depends on the low density of the area around the target in SBRT for lung cancer. Archibald-Heeren et al.[7] reported that robust optimization can significantly improve dose stability in the treatment of lung cancer where there are large motion and density variations in the surrounding tissue, whereas for smaller tumor motion of <1 cm, the effect of robust optimization is less significant. Liang et al.[10] showed that robust optimization of the ITV accounts for setup uncertainty and is a possible new method for planning SBRT with VMAT. In our study, robust optimization yielded stable CTV doses for all position errors compared to the PTV-based optimization. The dose prescription strategy (e.g., 80% isodose line) includes using a higher dose at the center of the PTV and a somewhat lower dose close to the edges of the PTV. Variations in the doses to the CTV when using PTV-based optimization cause inhomogeneous dose distributions. On the other hand, robust optimization provides greater stability in

the dose to the CTV with respect to setup position errors. The clinical parameter CTV $D_{98\%}$ is commonly defined as the minimum dose to the clinical target. It is expected to withstand positioning errors throughout the course of treatment. However, compared to PTV-based optimization, robust optimization delivers a worse liver dose to compensate the CTV dose. The volume of normal tissue receiving high doses outside the target needs to be minimized to limit the risk of treatment toxicity. Some researchers have reported on hepatic tolerance to SBRT.[16,17] The median tolerance doses for Child-Pugh A and B patients are 30.5 and 25.2 Gy in five fractions, respectively.[16] The total liver volume that receives <18 Gy in a total dose of 36 Gy in three fractions should be greater than 800 cm^3 to reduce the risk of causing deteriorating hepatic function.[17] Our study showed that the dose to the liver was very small. The most important goal is that the prescribed dose for the tumor is received. If the dose to the liver is acceptable, robust optimization should be used to accurately deliver the target dose. We applied a setup error of 8 mm and obtained different $D_{98\%}$ doses to the CTV for the PTV-based and robust optimized plans, which were approximately 13.7% and 7.1% as compared to the nominal plan, respectively. In addition, the CTV $D_{98\%}$ dose variation for the robust optimized plan was less than that of the PTV-based optimized plan.

Even if robust optimization is a useful method, accurate dose delivery to the target is requisite. Our study confirmed the plan complexity and dose delivery accuracy of robust optimization in liver cancer treatment. The average MCSv for the PTV-based and robust optimizations was 0.30 and 0.35, respectively. In addition, the complexity of the MLC sequence differed slightly between both optimized plans, whereby robust optimization was less complex than PTV-based optimization. The absolute ion chamber dose measurements showed that there was good agreement in the QA verifications of the PTV-based and robust optimizations. Both optimizations achieved a >95% gamma passing rate using ArcCHECK devices compared to that of the TPS-calculated dose at the 2%/2 mm criterion.[18] On average, robust optimized plan had fewer leaf position errors than did PTV-based optimized plan ($p < 0.05$). The average leaf position errors of both optimizations were negligible, i.e., <0.020 mm. The differences between the optimizations with respect to leaf RMSE and 95% tile error were significant ($p = 0.03$), but only a small difference between the means (0.002 mm) was observed. The delivery times for the PTV-based and robust optimized plans were also similar.

In this study, treatment planning and perturbed dose were calculated from the CT data originally acquired for treatment planning. This study considered a maximum dose variation in the worst-case scenario. Day-to-day variations in the setup should be considered when determining the number of dose fractions. Future studies will calculate the perturbed dose using cone-beam computed tomography (CBCT) data and deformed anatomical structures.

5. Conclusions

We compared robust optimization with a corresponding PTV-based optimization for VMAT to treat liver cancer patients. The CTV dose of the robust optimization for VMAT to treat liver cancer was almost the same as that of the PTV-based optimization. In addition, the MUs of the robust optimization were almost the same compared to those of the PTV-based optimization. With respect to the perturbed dose evaluation, robust optimization for VMAT for liver cancer treatment had fewer CTV dose variations compared to PTV-based optimization. Not only did robust optimization have stable target coverage with shifted locations, it also contributed to a slight reduction in plan complexity. Dosimetric measurements of both optimizations showed good agreement. Robust optimization for VMAT could be useful in liver cancer patients.

Conflict of interest

None declared.

Financial disclosure

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Presentation

None.

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