Original Article

Dosimetric impact of systematic spot position errors in spot scanning proton therapy of head and neck tumor

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ABSTRACT

Purpose: The spot position is an important beam parameter in the quality assurance of scanning proton therapy. In this study, we investigated dosimetric impact of systematic 15 spot position errors (SSPE) in spot scanning proton therapy using three types of optimization methods of head and neck tumor.

Materials and Methods: The planning simulation was performed with ± 2 mm model SSPE in the X and Y directions. Treatment plans were created using intensity-modulated proton therapy (IMPT) and single-field uniform dose (SFUD). IMPT plans were created by two optimization methods: with worst-case optimization (WCO-IMPT) and without (IMPT). For clinical target volume (CTV), D95%, D50%, and D2cc were used for analysis. For organs at risk (OAR), D_{mean} was used to analyze the brain, cochlea, and parotid, and D_{max} was used to analyze brainsetem, chiasm, optic nerve, and cord.

Results: For CTV, the variation (1 standard deviation) of D95% was ± 0.88%, 0.97% and 0.97% to WCO-IMPT, IMPT, and SFUD plan. The variation of D50% and D2cc of CTV showed <0.5% variation in all plans. The dose variation due to SSPE was larger in OAR, and worst-case optimization reduced the dose variation, especially in D_{max}. The analysis results showed that SSPE has little impact on SFUD.

Conclusions: We clarified the impact of SSPE on dose distribution for three optimization methods. SFUD was shown to be a robust treatment plan for OARs, and the WCO can be used to increase robustness to SSPE in IMPT.

KEY WORDS: Intensity-modulated proton therapy, proton therapy, robust planning, single-field uniform dose, spot position error

INTRODUCTION

In recent years, the scanning proton beam has become widely used in the radiotherapy. The ideal dose distribution to the target volume can be achieved by optimizing the weights and positions of individual spots with different energies. To optimize beams, an inverse planning process is used.[1] There are two optimization methods for scanning irradiation: single-field optimization (SFO)[2,3] and multi-field optimization (MFO).[1,4-6] Single-field uniform dose (SFUD) is an optimization method that aims to irradiate a target uniformly with a single field and is a concept of SFO.[7,8] SFUD is superior to the conventional passive method in that it can optimize not only distal but also proximal dose distribution. MFO is commonly known as intensity-modulated proton therapy (IMPT). In IMPT, there is no requirement to make a uniform dose in an individual field, and the ideal dose distribution is achieved in all fields based on dose constraints to critical structures and targets.[9]

There are various uncertainties in scanning beam parameters: setup for image guidance, anatomical variations, organ motion, and beam parameter such as spot position, spot size, energy, and output of the individual spot.[10] The sensitivity of the treatment plan to uncertainties is referred to as robustness, and increased robustness is important for achieving high-precision treatment. When dealing with uncertainty in SFUD, range margin is often added on clinical target volume (CTV) to make a beam-specific planning target volume (bs-PTV) in proton therapy.[11] In the case of IMPT, robust

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Table 1: Plan information with fields, gantry angle, prescribed dose and CTV volume of WCO-IMPT/IMPT

	WCO-IMPT/IMPT				
ID	Gantry angle (°)	Field aperture/all	Beam range (cm)	Prescribed dose (GyE)	CTV volume (cc)
1	105, 240, 350	2/3	1.6–21.5	70.2	216.8
2	0, 105, 240	2/3	0.5–20.5	70.2	265.4
3	0, 105, 245	2/3	0.5–2.0	70.2	440.9
4	20, 80, 135	3/3	4.5–17.6	70.2	179.6
5	0, 40, 80, 120, 260, 310	5/6	0.5–19.0	70.2	122.3
6	45, 85, 250, 305	4/4	0.5–15.0	70.2	315.5
7	0, 115, 265	2/3	0.8–18.1	70.2	216.8
8	0, 90, 290	3/3	1.2–15.0	60.8	83.6
9	0, 85, 255	2/3	1.3–15.0	60.8	106.4
10	160, 230, 315	3/3	0.6–14.5	74.0	211.5

optimization is widely used to increase the robustness.[12,13] There exists a variety of methods for robust optimization, and all approaches have in common that they require a model of uncertainties. In many cases, uncertainties of the setup and the beam range are taken into account for optimization.[14,15] Many studies have examined the impacts of uncertainties and beam parameters on dose distributions.[16-20]

In relation to the beam parameter, quality assurance (QA) programs to be implemented are proposed.[21] One of the important parameters is spot position, and many studies recommend the management of the spot position in periodic QA.[21-23] In these previous studies, a range of 1–2 mm, and absolute 1 mm or relative 0.5 mm, were proposed as tolerances for daily and annual QA, respectively. Spot position errors are divided into systematic errors and random errors.[24] Random error is the uncertainty of the position of each spot, which may show statistical variation or unpredictable variation; systematic error is caused by imperfections in the equipment, including discrepancies between the origin and spot positions during commissioning. Random errors are partially canceled out and have little impact, while systematic errors are not partially canceled out and have a large impact on the dose distribution.[25] Yu *et al*. revealed the dosimetric impacts induced by spot position error as a function of spot spacing on IMPT used brain tumors, and for small spot size, the impact of systematic error is 2–3 times larger than random error.[25] However, to the best of our knowledge, there is no report that quantitatively evaluates the impact of systematic spot position error (SSPE) in head and neck scanning proton therapy for the various optimization algorithms. In this study, we clarify the impact of SSPE in spot scanning proton therapy of head and neck tumor using three optimization methods: worst-case optimize (WCO)-IMPT, IMPT, and SFUD.

MATERIALS AND METHODS

Treatment planning and patient selection

The treatment planning system (TPS) used in this study was VQA version 3.0.1, a commercially available TPS in Japan. The VQA uses a triple Gaussian kernel model for accurate dose calculation[26] and a worst-case optimization (WCO) for dose optimization to obtain a robust plan.[12] Ten cases of head and neck tumors treated with WCO-IMPT and eight cases treated with SFUD were examined. Patient-specific collimators were used when possible to create an optimal dose distribution.[27-29] The tumor volume, dose, and numbers of irradiated ports are shown in Tables 1 and 2. The collimator margin was computed by the expanded maximum outline of the target from the beam's eye view and set to the same value as the spot spacing. The spot spacing was dependent on the spot size and was 7.2–11.6 mm in this study. This value was also applied to the collimator margin when a collimator was used. The minimum spot diameter was 4.9 mm at the highest energy/nonshort-range absorber (in-air, isocenter, 1 σ), and the maximum was 26.7 mm at the lowest energy with a short-range absorber.[30] Spot sizes vary depending on the energy/short-range absorber type. Penumbra is known to worsen with distance from the patient, four types of short-range absorber are used depending on the distance from the patient's surface and field size. The normal IMPT plan, i.e., not WCO-IMPT, was created by changing only the optimization method, with the same gantry angle and number of fields as WCO-IMPT. Parameters of the WCO were 3 mm for three-dimensional direction and 3.5% for range uncertainty and thus optimized based on nine independent scenarios for each of the range and setup errors. The value of 3 mm was set based on the setup error and the machine variability in NPTC. For SFUD, bs-PTV was used with the same uncertainty as for the WCO parameters. CT images were acquired and reconstructed with 1 mm slices.

Model errors and plan evaluation

Ninety-five energies can be extracted from the synchrotron for scanning beam applications from the Hitachi ProBeat III operating in the NPTC. Water equivalent penetration depths from 4 to 30.6 g/cm^2 can be irradiated using the 95 energies, and $<$4 g/cm^2 can be irradiated by attaching an absorber. A patient-specific collimator can be attached to the 4 g/cm^2 energy absorber and used for shallow tumors of 15 g/cm^2 or less. Similar to other scanning systems, the NPTC's scanning system uses spot position monitors to monitor beam parameters such as spot position and spot size. Spot positions were verified in daily, monthly, and annual QA and in each treatment field QA in the NPTC.

Based on the tolerance level of QA, the model SSPE in this study was ± 2 mm in the X and Y directions, respectively.

Table 2: Plan information with fields, gantry angle, prescribed dose and CTV volume of SFUD

	SFUD				
ID	Gantry angle (°)	Field aperture/all	Beam range (cm)	Prescribed dose (GyE)	CTV volume (cc)
1	120, 230, 270, 310	2/4	0.9–21.5	70.2	138.8
2	0, 140, 180, 220, 300	2/5	0.5–22.0	70.2	50.2
3	30, 65, 100, 195	3/4	0.7–21.5	70.2	14.3
4	0, 50, 100, 230	3/4	0.5–21	70.2	260.2
5	0, 40, 115, 245, 320	5/6	0.5–20.0	70.2	211.9
6	0, 50, 100, 300	4/4	0.5–15.0	70.2	103.3
7	40, 325	2/2	4.5–11.0	60.8	19.7
8	10, 140, 270	2/3	0.5–15.5	60.8	33.7

In this study, we added a systematic error of 2 mm as the worst case, based on the results of previous studies showing that the dosimetric impact of systematic error is larger than random error.[25] While the error in the Y direction is synonymous with the patient setup error, the error in the X direction is an uncertainty that cannot be considered a setup error because the direction of the error changes with the patient at each gantry angle. Lin *et al*. also showed that there was variation in the spot position for each gantry angle, although they concluded that the impact was negligible.[31] Therefore, the same value (±2 mm) of spot position error for each gantry angle was used in this study. We added a model SSPE of ±2 mm spot position to each plan spot files and analyzed the changes in dose distribution for each optimized plan. A total of 140 plans (WCO-IMPT: 50, IMPT: 50, SFUD: 40) were analyzed using 10 IMPT patients and 8 SFUD patients with four model errors. We used the relative changes of some dose indexes, such as dose receiving 95% volume, 50% volume, and 2 cc to the CTV (D98%, D50%, and D2cc). For organs at risk (OAR), mean dose (D_{mean}) was used to analyze brain, cochlea, and parotid, and maximum dose (D_{max}) was used to analyze brainstem, chiasm, optic nerve, and cord.

RESULTS

Figure 1 and Table 3 show the impact of SSPE on WCO-IMPT and IMPT plans. For CTV, the variation (1 standard deviation) of D95% was ± 0.88% and 0.97% to WCO-IMPT and IMPT plan. The variation of D50% and D2cc of CTV showed <0.5% variation in all plans. Figure 2 and Table 4 show the impact of SSPE to SFUD plans. The variation of D95%, D50%, and D2cc was 0.97%, 0.30%, and 0.26% to SFUD plan. Note that the outliers of Figures 1 and 2 are out of the upper and lower limits of the following equation: third quartile ± 1.5 × interquartile range. The dose variation due to SSPE was larger in OAR, and worst-case optimization reduced the dose variation, especially in D_{max}. SSPE was in a different direction from the patient setup error assumed in WCO, and also in a different direction for each gantry angle; however, the robustness was improved using WCO. The analysis results showed that SSPE has little impact on SFUD. The dose-volume histogram (DVH) calculated by the three optimization methods is shown in Figures 3 and 4.

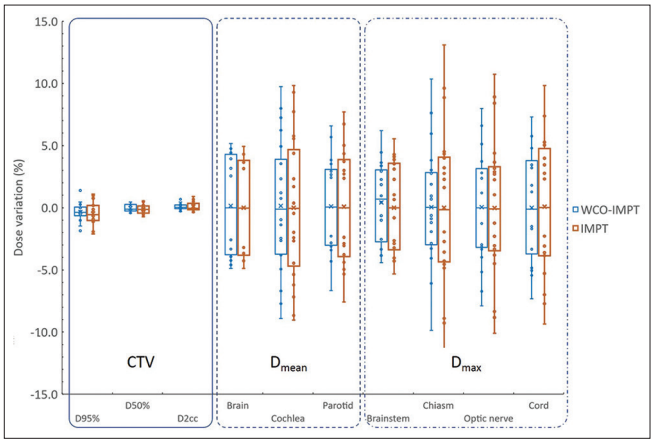

Figure 1: Dosimetric impact of systematic spot position error of WCO-IMPT and IMPT. The outliers are out of the upper and lower limits of the following equation: third quartile ± 1.5 × IQR (interquartile range)

For each optimization method, three typical examples are shown. DVHs of WCO-IMPT and IMPT were the same cases. All elements are marked with one solid line and four dashed lines. The dashed lines were the results for spot position errors of X ± 2 mm and Y ± 2 mm, respectively. In most OARs, there were symmetrical dotted lines across the solid line. The narrowness of this width indicates a high degree of robustness. WCO-IMPT had a smaller bandwidth than IMPT in all plans; SFUD had many plans with smaller bandwidths, especially OAR's bandwidth was smaller.

DISCUSSION

In this study, we showed the dosimetric impact of SSPE in spot scanning proton therapy of head and neck tumor. Periodic QA of spot position error is performed with various devices; however, it is very complicated to detect the origin correctly, and it is practical to manage spot position by absolute and relative position.[21] Among the errors, it is important to understand the impact of SSPE on treatment planning to perform proper QA. The impact on treatment planning is also highly dependent on the optimization method, so in this study, we evaluated the impact of three types of optimization: WCO-IMPT, IMPT, and SFUD. In IMPT, the WCO can be used to increase robustness to SSPE. In the present study, however, the impact of range error is not verified because we evaluate

the results in terms of QA of the spot position. The robustness of WCO-IMPT to range and setup errors has been evaluated in previous studies,[16,32,33] and it is necessary to refer to them in the evaluation of optimization methods. It is also known that the spot position error depends on the spot pattern and gantry angle.[31] In this study, the impact of SSPE was evaluated with regard to various optimization algorithms, and the dosimetric impact was close to that of the previous studies. The log file is useful for detecting spot position errors that vary with the gantry angle, irradiation position, and energy. The results of previous studies using log files show that spot position errors are within ± 2 mm at a maximum and ± 1 mm on average.[34,35] However, log file spot position data are acquired with limited resolution, and projecting them to an isocenter introduces uncertainty.[35] Furthermore, in the commissioning process, SSPE are unavoidable, and the impact of SSPE should be considered. Systematic and random errors lead to large changes in dose distribution in complex heterogeneous head and neck treatments. For this purpose, the spot position should be guaranteed by QA. Although under limited conditions, the results of this study, which investigated the impact of SSPE, is useful to set an

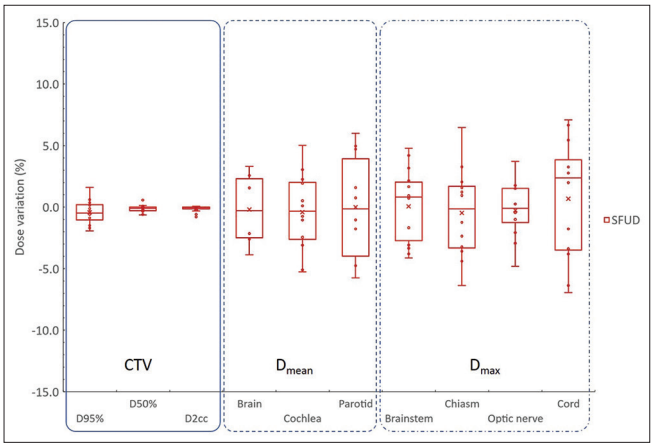

Figure 2: Dosimetric impact of systematic spot position error of SFUD. The outliers are out of the upper and lower limits of the following equation: third quartile ± 1.5 x IQR (interquartile range)

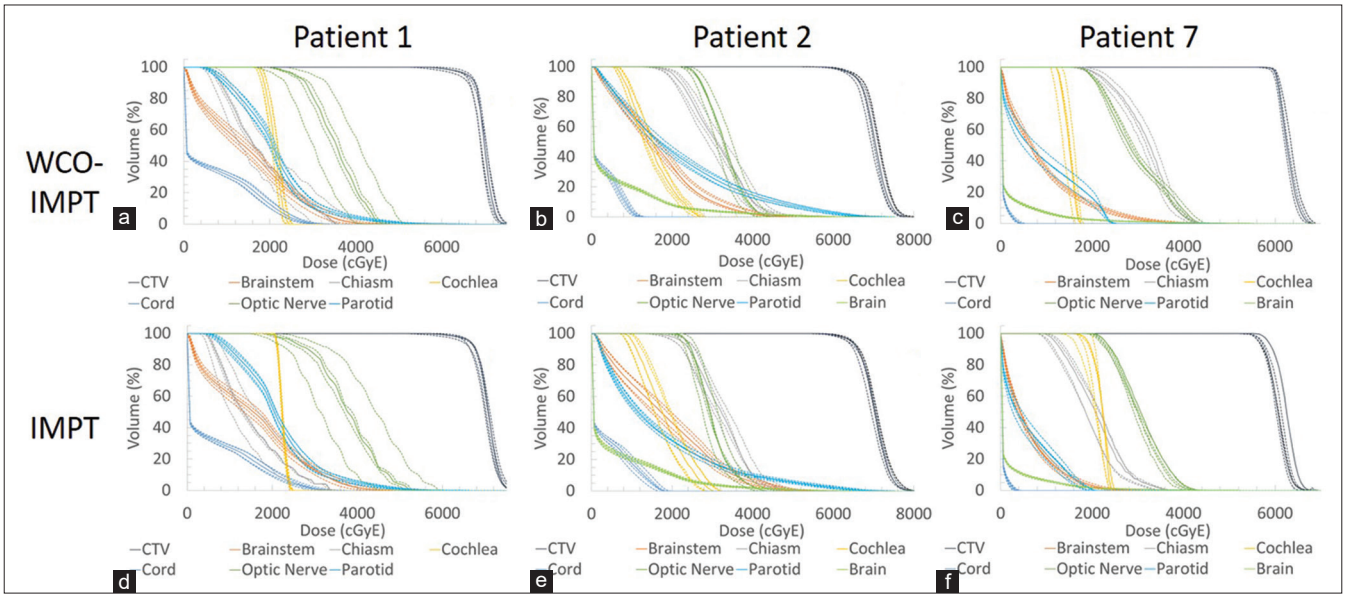

Figure 3: Calculated DVHs for CTV and OARs. The dotted lines are the DVH with model errors and the solid lines are the DVH without model error. (a-c) is WCO-IMPT, (d-f) is IMPT

Table 3. Variation in dose index SSPE plans in comparison with nominal plans of WCO-IMPT/IMPT

		WCO-IMPT		IMPT	
		Maximum difference (%)	Std Dev (%)	Maximum difference (%)	Std Dev (%)
PTV	D95%	1.85	0.88	2.11	0.97
	D50%	0.46	0.30	0.73	0.36
	D2cc	0.68	0.27	0.91	0.40
Brain	Dmean	5.17	4.20	4.92	4.34
Choclea	Dmean	9.75	5.39	9.83	5.85
Parotid	Dmean	6.66	4.05	7.70	4.84
Brainstem	Dmax	6.20	3.22	5.55	3.60
Chiasm	Dmax	10.35	4.86	13.09	6.56
Optic nerve	Dmax	7.96	4.51	10.74	5.85
Cord	Dmax	7.33	4.61	9.84	5.85

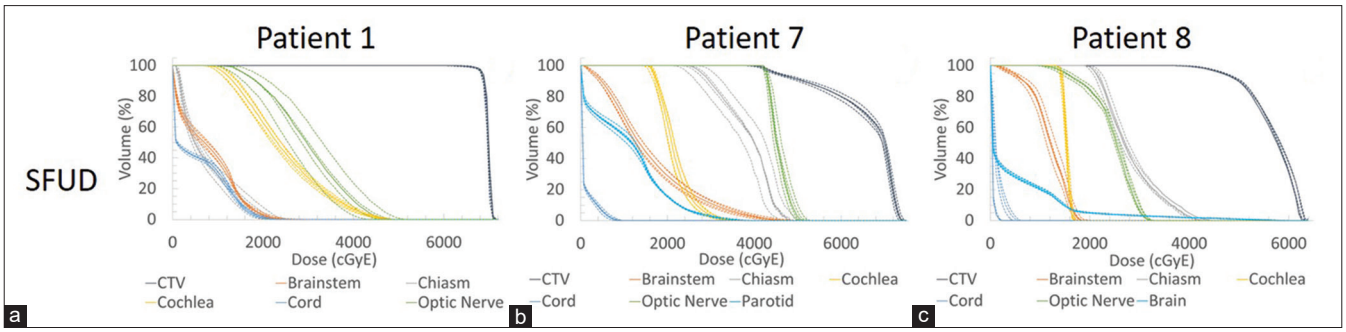

Figure 4: Calculated DVHs for CTV and OARs. The dotted lines are the DVH with model errors and the solid lines are the DVH without model error. (a-c) is SFUD for each patient case

Table 4. Variation in dose index SSPE plans in comparison with nominal plans of SFUD

		SFUD	
		Maximum difference (%)	Std Dev (%)
PTV	D95%	1.94	0.97
	D50%	0.63	0.30
	D2cc	0.79	0.26
Brain	Dmean	3.88	3.04
Choclea	Dmean	5.26	3.20
Parotid	Dmean	6.01	4.32
Brainstem	Dmax	4.78	3.01
Chiasm	Dmax	6.47	3.68
Optic nerve	Dmax	4.81	2.32
Cord	Dmax	7.08	4.95

appropriate tolerance and frequency of spot position QA. In the current study, we used data from a group of patients who were treated with either IMPT or SFUD based on clinical decision. Therefore, the patient groups were different, and it was not possible to directly compare the WCO-IMPT/IMPT and SFUD methods. However, we showed that SFUD tended to be robust against OAR under the condition that SSPE was added, and furthermore, WCO was able to provide sufficiently robust planning.

CONCLUSIONS

SFUD was shown to be the most robust for OARs, and the WCO can be used to increase the robustness of IMPT to spot position error. Due to the different directions of shifts between fields, existing optimization methods cannot account for this impact, and the results of this study are useful as a method for evaluating the impact of QA. Such an analysis could provide useful data for setting the frequency and tolerance of periodic QA of the spot position. The results are greatly impacted by spot size, energy used, planning parameters, and irradiation site, so it is necessary to accumulate data in various combinations.

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Conflicts of interest

There are no conflicts of interest.

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