


A Comprehensive Evaluation of the Application of the Halcyon(2.0) IMRT Technique in Long-Course Radiotherapy for Rectal Cancer

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Abstract

Objective: To evaluate if the Halcyon(2.0) Intensity Modulation Radiotherapy (IMRT) technique has an advantage in the long-course rectal cancer radiotherapy. **Methods:** A total of 20 clinical IMRT plans of Halcyon(2.0) for long-course (2Gy in 25 fractions) rectal cancer radiotherapy were randomly selected. Based on the parameters of these plans, 20 TrueBeam (with the Millennium 120 MLC) plans were redesigned, respectively. The dosimetry indexes, field complexity parameters, the Gamma Passing Rates (GPR), and the delivery time of the 2 groups of plans were obtained as measures of the plan quality, the modulation complexity, the delivery accuracy, and the delivery efficiency. The differences between the 2 groups of parameters were analyzed, with $P < .05$ means statistically significant. **Results:** In terms of dosimetry, there was no significant or clinical difference between the 2 groups in critical dosimetry parameters. The Monitor Unit of the Halcyon(2.0) fields is lower than the TrueBeam fields by 26.39, while the modulation complexity score (MCS), the mean aperture area variability (AAV), and the mean leaf sequence variability (LSV) of the Halcyon(2.0) fields were 23.8%, 20%, and 2.3% larger than those of the TrueBeam fields, respectively. Neither the ArcCheck-based GPRs nor the portal-dosimetry-based GPRs in both 3%/3 mm and 2%/2 mm criteria showed the difference between the Halcyon(2.0) fields and the TrueBeam fields. The Pearson correlation coefficient between GPR(2%/2 mm) and MCS of the Halcyon(2.0) fields was 0.335, while that of the TrueBeam fields was 0.502. The mean total delivery time of the TrueBeam plans was 195.55 ± 22.86 s, while that of Halcyon(2.0) was 124.25 ± 10.42 s ($P < .001$), which was reduced approximatively by 36%. **Conclusion:** For long-course rectal cancer radiotherapy, the Halcyon(2.0) IMRT plans behave almost the same in dosimetry and delivery accuracy as the TrueBeam plans. However, the lower MU and the field modulation complexity, combined with the higher delivery efficiency, make Halcyon(2.0) a feasible and reliable platform in long-course radiotherapy for the rectal cancer.

Keywords

Rectal cancer, IMRT, Halcyon(2.0), TrueBeam, dosimetry, modulation complexity, delivery accuracy, delivery efficiency

Abbreviations

IMRT, intensity modulation radiotherapy; VMAT, volume modulation arc radiotherapy; MLC, multi-leaf collimator; CBCT, cone beam CT; DVH, dose-volume histogram; HI, homogeneity index; CI, conformity index; GI, gradient index; OAR, organ at risks; MU, monitor unit; MCS, modulation complexity score; AAV, aperture area variability; LSV, leaf sequence variability; ESAPI, eclipse scripting application programming interface; GPR, gamma passing rate; PDIP, portal dose image prediction.

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Introduction

The incidence rate of rectal cancer in Asia is high and there is an increasing trend in the Asian population.^{1,2} Long-course preoperative radiotherapy of 1.8 to 2.0 Gy in 25 to 28 fractions with concurrent chemotherapy has been widely practiced in the last 15 years and still proves to be superior to the short-course radiotherapy in tumor control and recurrence reduction.³⁻⁵ However, the large fractionation number of the long-course radiotherapy

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combined with the high rectal cancer incidences results in a heavy workload for the radiotherapy departments.

In 2017, Varian Medical System introduced an O-ring radiotherapy platform, Halcyon(1.0), aiming to offer a more efficient and effective clinical workflow for radiotherapy departments.⁶ The Halcyon platform has 2 times faster leaf speed (5 cm/s), 4 times faster collimator rotation (2.5 rpm), and 4 times faster gantry speed (4 rpm) as compared to the TrueBeam platform. The dual-layer MLC (each has a resolution of 10 mm) has a stacked and staggered design (SX1) with ultralow dose leakage and transmission of <0.5%.⁷ Besides, this Linac is designed for a “one-step” patient setup that automatically applies couch shifts after an image-guidance procedure. These features, combined with the 6 MV-FFF (flattening filter-free) photon beam of 800 MU/min dose rate, largely simplify and streamline the image-guided radiotherapy practices. Several researchers studied the Halcyon(1.0) IMRT/VMAT plans of the H&N cancer (compared to TrueBeam) and cervical carcinoma (compared to Trilogy) in plan quality, delivery accuracy, and delivery efficiency.^{8,9} These studies have shown that the Halcyon(1.0) improved the efficiency of treatment workflow and shortened the delivery time of treatment plans on the basis of ensuring the plan quality. However, Halcyon(1.0) uses the distal layer of SX1 to modulate the beam and the proximal layer, as a slaving layer, to track the distal layer, resulting in a 10-mm resolution MLC. Therefore, Halcyon(1.0) may have a lower ability to generate optimal plans compared with TrueBeam, which is equipped with the Millennium 120 MLC and has a resolution of 5 mm in the range of 20 cm in the *y*-axis under machine coordinate system.^{10,11} In 2018, Halcyon(2.0) was introduced by Varian and one of the upgrades is that the new dual-layer MLC (SX2) offers the independent movement of both layers. In this way, a resolution of 5 mm can be achieved for beam modulation.^{12,13} In addition, the Halcyon(2.0) platform is equipped with a fast 15-s kV cone-beam CT (kV-CBCT) imaging system that includes a high-quality iterative CBCT reconstruction algorithm (iCBCT),¹⁴ which further improves the fluency of the workflows.

The long-course radiotherapy for the rectal cancer places a heavy burden on radiotherapy departments due to the high incidence of the rectal cancer and the large fraction number. Since the Halcyon(2.0) platform is developed declaring streamlined clinical radiotherapy workflow and simplified steps, it may be more feasible than other machines such as TrueBeam in long-course radiotherapy for rectal cancer, especially for large cancer hospitals. However, systematic evaluation about the Halcyon(2.0)-based IMRT/VMAT plans in the foundation of multiple points need be provided. Normally, critical points for a planning technique or platform adopted include plan quality, modulation complexity, delivery accuracy, and delivery efficiency. The plan quality is described by the target coverage and the normal tissue sparing of the plan which is directly relative to the treatment outcomes. The complexity metric measures the degree of the modulation (through well-designed motions of the MLC leaves and other components) and is supposed to reflect the agreement between expected and delivered dose distributions.^{15,16} The delivery accuracy of an IMRT/VMAT plan is always the goal to pursue in

radiotherapy practices and the Gamma Passing Rate (GPR) offers a common and overall evaluation of the accuracy to a certain extent. The delivery efficiency is another critical metric and short treatment time is deemed to improve the patient comfort and reduce the intrafraction motion during the delivery.

However, studies on the systematic evaluation of the Halcyon(2.0)-based plans are relatively few. Petrocchia et al¹⁷ investigated the differences of spine SBRT VMAT plans between Halcyon(2.0) and TrueBeam in the plan quality, the modulation complexity, the GPR-based delivery accuracy, and the delivery speed. Pokhrel et al^{18,19} also investigated the prostate and lung SBRT VMAT plans in the 4 aspects. These researches have shown a reliable and fast delivery is possible using Halcyon(2.0) for SBRT VMAT plans. Nevertheless, for other treatment sites (different target types in geometry and OARs) or conventionally fractionation numbers, whether or not Halcyon(2.0) has a comparable or superior performance compared with TrueBeam has not been clear yet. Besides treatment sites and therapeutic schedules, all these researches use a single complexity metric in an attempt to describe the modulation degree, which may be a lack of comprehensiveness. Failure to reveal correlations between the delivery accuracy and the calculated modulation complexity may be another limitation, since these correlations may be more significant than the indexes on their own. In this study, we performed an overall evaluation about the Halcyon(2.0)-based IMRT plans for rectal cancer long-course radiotherapy (with a typical C-type target) in the plan quality, the field complexity, the delivery accuracy, and the delivery efficiency taking the TrueBeam platform as a benchmark. Four complexity metrics were calculated in order to describe the modulation complexity from different views. Furthermore, correlations between the delivery accuracy and above 4 field complexity metrics were also compared between Halcyon(2.0) and TrueBeam plans, which has not been investigated up to now.

Materials and Methods

Patient Selection

Since this was a planning study without any delivery to any patient, there was no ethical approval required for this study. A total of 20 out of 73 patients with rectal cancer receiving long-course radiotherapy in our department from March to December in 2020 were randomly selected. The age ranged from 49 to 74 years old (median of 64 years old). The dose prescriptions were 2Gy in 25 fractions. There were no contraindications to radiotherapy in all cases. All patients provided written informed consent prior to enrollment in the study for the research use and publishing of their clinical data. The treatment plans were planned using Eclipse 15.6 (Varian Medical System, USA) and delivered on the Halcyon(2.0) platform.

Halcyon(2.0) & TrueBeam Plans

All patient orientations were head-first prone. Each Halcyon(2.0) plan contained 7 IMRT fields with identical isocenter defined approximately by the geometric center of PTV

(uniformly expanded by 5 mm from CTV). Gantry angles were fixed as 210°, 260°, 310°, 0°, 50°, 100°, and 150°, while collimator angles were manually optimized, respectively. Photo energy was Halcyon 6 MV-FFF and the dose rate was 800 MU/min. The segment number of each IMRT field was 165. The optimization algorithm was the photon optimization (PO) algorithm in Halcyon(2.0) version, and the dose calculation algorithm was anisotropic analytical algorithm (AAA) in Halcyon(2.0) version with a grid of 2.5 mm. The normalization method was that 100% prescription dose covered 95% of the target volume. All dosimetry metrics of these plans meet clinical requirements.

A total of 20 TrueBeam plans were designed taking parameters of the above Halcyon(2.0) plans as references. Field geometry, photon energy (6 MV-FFF, 800 MU/min), algorithms (PO and AAA in TrueBeam version), and optimization objectives remained identical to corresponding Halcyon(2.0) plans. All TrueBeam plans were implemented in Jaw-tracking mode which differed from these of Halcyon(2.0).²⁰

Plan Quality

Several common dosimetry metrics were selected for plan quality comparison. Target-coverage indexes included $D_{98\%}$ and $D_{2\%}$ of PTV. The mean doses (D_m) of the left femoral head (FH_L), the right femoral head (FH_R), and bladder were adopted to represent the OAR sparing of plans of rectal cancer. V_{45Gy} of the small bowel (SB) was another metric for dosimetry evaluation. Besides, homogeneity index (HI), conformity index (CI), and gradient index (GI) were also analyzed as complements for a comprehensive comparison. In this study, HI is defined by

$$HI = \frac{OA^2}{IA * AA}$$

where IA is the area under the ideal PTV DVH curve, AA is the area under the actual PTV DVH curve, and OA is the overlapping area between IA and AA.²¹ CI is defined as the ratio of the volume covered by the 100% prescription dose to the volume of PTV. Similarly, GI is the ratio of the volume covered by the 50% prescription dose to the volume of PTV, which is a measure of dose fall-off in the volume of the normal tissue.

Field Complexity

Four common indexes measuring modulation complexity of the IMRT field were selected:

1. Monitor unit (MU).
2. Modulation complexity score (MCS).²²
3. The mean aperture area variability (AAV_m), the average of AAV (an intermediate parameter for MCS calculation) over all segments of the IMRT field.

4. The mean leaf sequence variability (LSV_m), the average of LSV (the other intermediate parameter for MCS calculation) over all segments of the IMRT field.

The closer to 1 the value of MCS means the lower the modulation complexity of the IMRT field. Similarly, values of AAV_m and LSV_m not only indicate the modulation complexity of an IMRT field, but also disclose it in 2 aspects: AAV_m measures the proportions of the segment areas in the total area that the MLC scans, while LSV_m measures irregularity, in other words, the deviation from rectangle, of the segment shapes of a given IMRT field.

For the Halcyon(2.0) plans, MCS, AAV_m , and LSV_m were calculated based on the effective apertures formed by the stacked and staggered dual-layer MLC, as shown in Figure 1c. All above parameters are calculated by an in-house ESAPI-based C# program.²³

Delivery Accuracy

Delivery accuracy was evaluated based on the GPR data obtained in 2 ways:

1. *ArcCheck-based (Sun Nuclear, Melbourne) GPR:* ArcCheck-based GPR was used to evaluate the overall delivery accuracy of each plan. Before the deliveries of plans, Machine Performance Check (MPC) was performed on both machines to ensure the accuracy and consistency of the beam and mechanical properties.²⁴ Each plan was delivered to the ArcCheck phantom as an automated sequence in QA mode. The AAA was used to obtain the TPS-calculated dose distribution of each plan. GPRs in both criteria of 3%/3 mm and 2%/2 mm with a threshold of 10% were extracted using the dedicated software.
2. *Portal-dosimetry (PD)-based (Varian, Palo Alto) GPR:* PD-based GPR was used to evaluate the delivery accuracy of each single field of a given IMRT plan. Distances of the source to imager were all set to 154 cm and all gantry angles were set to 0 for both machines. Recently, AAA has been feasible for PD of the 6MV-FFF beam of TrueBeam. Therefore, AAA was selected for PD of the TrueBeam plans in order to be identical to the Halcyon(2.0) plans. Before the deliveries of the verification plans, Machine Performance Check (MPC) was performed on both machines. After delivery of each verification plan, GPR data in both criteria of 3%/3 mm and 2%/2 mm with a threshold of 10% were extracted using the PD data analysis tool.

Delivery Efficiency

To evaluate if the Halcyon platform has an advantage over the TrueBeam platform in delivery efficiency for long-course rectal cancer, the total delivery time was recorded for each IMRT plan. The total delivery time was defined as the duration time

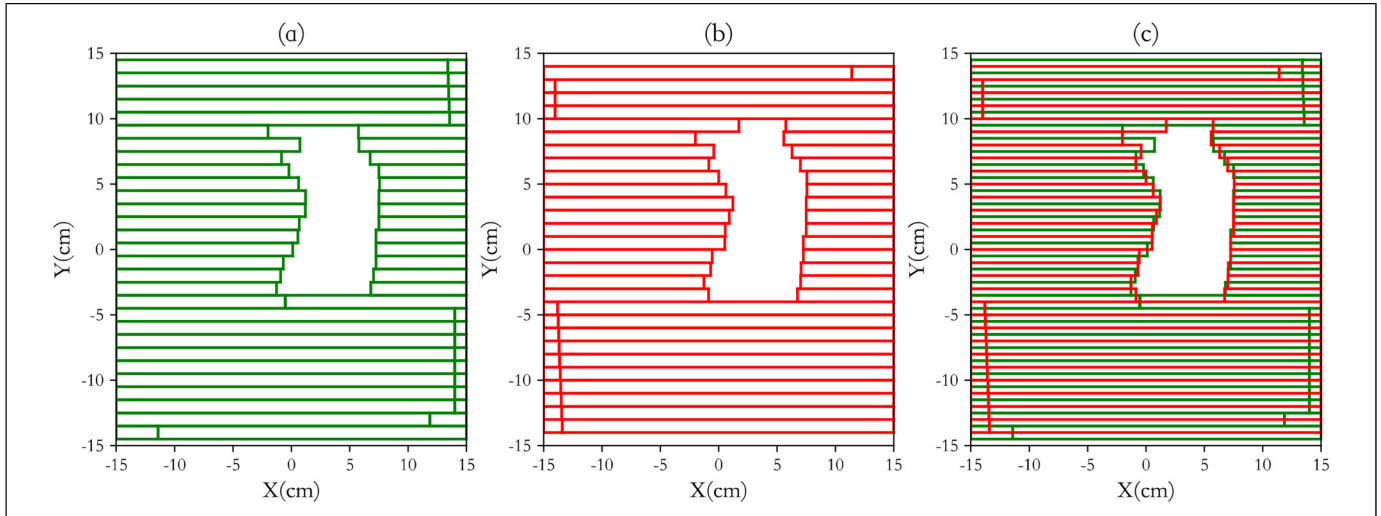


Figure 1. Schematic diagram of a segment aperture of a Halcyon (2.0) plan: (a) aperture formed by the proximal layer of SX2 with 10 mm resolution; (b) aperture formed by the distal layer of SX2 with 10 mm resolution; (c) effective aperture formed by the stacked and staggered dual-layer MLC (SX2) with 5 mm resolution.

from the moment that the “beam-on” button was pressed to the beam-off time of the last field in the ArcCheck-based data acquisition.

Statistics

All parameters were analyzed by the *scipy.stats* tool using the paired *t*-test method and $P < .05$ was regarded as statistically significant. In addition, analysis of Pearson correlations between GPR(2%/2 mm) and 4 complexity parameters was performed using the *scipy.pearsonr* tool.

Results

Plan Quality

The dosimetric indexes of the IMRT plans of both machines are given in Table 1. $D_{2\%}$ (PTV), D_m (FH_L), D_m (FH_R), HI, and GI of the TrueBeam plans are slightly better than those of Halcyon(2.0) by 0.28 Gy, 0.01, and 0.05, respectively. There

was no significant difference in $D_{98\%}$ (PTV), D_m (bladder), $V_{45\text{Gy}}$ (SB), and CI. Figure 2 gives the DVH plots of the Halcyon(2.0) and TrueBeam plans of patient #1 as an example. The DVH curves of PTV and OARs suggest Halcyon(2.0) provides dosimetrically comparable plans with slightly different (but clinically insignificant) normal tissue sparing relative to the TrueBeam Linac. Figure 3 gives isolines in the cross-section at the isocenter of both plans, which are similar with each other in both conformity and homogeneity.

Field Complexity

Parameters about the modulation complexity of the TrueBeam and Halcyon(2.0) fields are shown in Table 2. MUs of the Halcyon(2.0) fields are significantly lower than those of TrueBeam, while the other 3 parameters represent just the reverse. The difference of MU is 26.39. MCSs of the TrueBeam and Halcyon(2.0) fields are 0.21 ± 0.08 and 0.26 ± 0.08 , respectively (difference of 23.8% relative to TrueBeam), stating that fields of both machines have relatively high-modulation segments. Specifically, AAV_m of the Halcyon(2.0) fields is nearly 20% larger than the TrueBeam fields, while LSV_m of the Halcyon(2.0) fields is 2.3% larger than the other one. Figure 4 shows the apertures of 4 segments (segment number of 30, 60, 90, and 120) of a TrueBeam field with gantry angle of 260° (upper) and corresponding Halcyon(2.0) apertures (lower) of patient #1. The displaying range of the TrueBeam apertures are limited in $15 \times 15 \text{ cm}^2$ to keep the identification between 2 machines.

Delivery Accuracy

The overall ArcCheck-based GPRs of the TrueBeam plans were $(99.81 \pm 0.17)\%$ (3%/3 mm) and $(97.35 \pm 0.95)\%$ (2%/2 mm),

Table 1. Dosimetric comparison of the TrueBeam and Halcyon(2.0) IMRT plans for long-course rectal cancer radiotherapy (mean \pm standard deviation).

Metric	TrueBeam	Halcyon(2.0)	<i>P</i> value
$D_{98\%}$ (PTV) (Gy)	49.7 ± 0.06	49.67 ± 0.04	.05
$D_{2\%}$ (PTV) (Gy)	51.19 ± 0.18	51.48 ± 0.22	<.001
D_m (FH_L) (Gy)	20.15 ± 5.04	20.74 ± 4.98	.01
D_m (FH_R) (Gy)	20.07 ± 4.79	20.69 ± 4.82	<.001
D_m (bladder) (Gy)	29.28 ± 5.46	28.67 ± 5.73	.05
$V_{45\text{Gy}}$ (SB) (%)	3.09 ± 3.33	3.05 ± 3.36	.26
HI	0.99 ± 0	0.98 ± 0	<.001
CI	0.97 ± 0.01	0.97 ± 0.01	.06
GI	3.55 ± 0.51	3.65 ± 0.5	<.001

while those of the Halcyon(2.0) plans were $(99.78 \pm 0.31)\%$ (3%/3 mm) and $(97.05 \pm 1.26)\%$ (2%/2 mm). As for the field-relevant delivery efficiency, the PD-based GPRs of the TrueBeam plans were $(99.9 \pm 0.26)\%$ (3%/3 mm) and $(96.48 \pm 4.59)\%$ (2%/2 mm), while those of the Halcyon(2.0) plans were $(99.93 \pm 0.24)\%$ (3%/3 mm) and $(96.75 \pm 4.34)\%$ (2%/2 mm). The corresponding P values range from 0.32 to 0.59, stating no difference of GPRs existed between the 2 platforms. Moreover, the IMRT fields of both machines can be delivered with enough accuracy taking 95% as the passing threshold in the criterion of 3%/3 mm.

Since the GPR(2%/2 mm) of part of fields of both machines failed to pass the 95% threshold, correlations between GPR(2%/2 mm) and complexity parameters were analyzed. Correlations of Halcyon(2.0) were lower than those of TrueBeam. The correlation coefficient between GPR(2%/2 mm) and MCS was 0.502 for the TrueBeam fields and 0.335 for the Halcyon(2.0) fields. GPR(2%/2 mm)s of the Halcyon(2.0) fields with MCS exceeding 0.36 passed the 95% threshold without exceptions in terms of plans of study (see Figure 5b). The correlation of GPR and AAV_m was similar to MCS. As to the other 2, GPR negatively correlated with MU and weakly with LSV_m . The scatter plots and specific values of correlation coefficients were given in Figure 5.

Delivery Efficiency

The mean total delivery time of 20 plans at TrueBeam was 195.55 ± 22.86 s, while that at Halcyon(2.0) was 124.25 ± 10.42 s ($P < .001$), which was reduced approximatively by 36%.

Discussion

In this study, the dosimetric comparisons were firstly performed between the Halcyon(2.0) and TrueBeam plans. There were no significant or clinical differences between the 2 groups in critical parameters of $D_{98\%}(PTV)$, $D_{2\%}(PTV)$, $D_m(FH_L)$, $D_m(FH_R)$, $D_m(\text{bladder})$, and $V_{45Gy}(SB)$. Petrocchia et al¹⁷ reported that the Halcyon(2.0) plans had similar HI and CI

with the TrueBeam plans for spine SBRT, but the dose-off outside the target volume of TrueBeam plans was more tight than those of Halcyon(2.0). In this study, the difference of HI between the 2 groups was only 0.01, and there is no significant difference in CI. GI of the Halcyon(2.0) plans was slightly greater than that of the TrueBeam plans by 0.1, indicating that the doses of the TrueBeam plans dropped faster, which is similar to the study of Petrocchia et al. We also found that the difference of $D_{2\%}(PTV)$ of the 2 groups was lack of clinical significance. Therefore, the Halcyon(2.0) IMRT plans have comparable quality with the TrueBeam plans for long-course radiotherapy of rectal cancer. Through the stacked and staggered design and independent movements of 2 layers, STX2 achieves a resolution of 5 mm in the range of 28×28 cm² for the beam modulation, which is equivalent to the Millennium 120 MLC of TrueBeam in the range of 40×20 cm² in the Y-axis (as shown in Figure 4). In addition, the Jaw-Tracking of TrueBeam can also reduce the dose leakage to a relatively low level like STX2 of Halcyon(2.0).^{7,20} These factors may be the reason why there were no differences in the OAR sparing between the 2 machines.

Tamura et al²⁵ calculated the MCS of 15 VMAT plans for prostate cancer based on the effective 5-mm resolution aperture of STX2 and the reported value was 0.297 ± 0.021 . Considering the difference of the treatment sites and techniques, the deviation from the value of 0.26 ± 0.08 in this study is acceptable. Petrocchia et al¹⁷ reported that MCS of the Halcyon(2.0) fields was higher than that of the TrueBeam fields, which were 0.28 ± 0.03 and 0.18 ± 0.04 , respectively. In our study, MCS of the Halcyon(2.0) and TrueBeam fields were 0.26 ± 0.08 and 0.21 ± 0.08 , respectively, showing that the modulation complexity of the Halcyon(2.0) field was lower than that of TrueBeam, which is similar to Petrocchia's study. We further analyzed the mean AAV of these plans and found that AAV_m of the Halcyon(2.0) field was 20% higher than that of TrueBeam while LSV_m of the Halcyon(2.0) field was only 2.3% higher than that of TrueBeam (as shown in Table 2). That means area proportion of the segment aperture in the whole scanning area of the Halcyon (2.0) field was greater than that of the TrueBeam field, while the difference of irregularity of the segment aperture was quite small. The reason of this may result from the weakened modulation ability of the "effective" 5-mm width (actually 1 cm width) leaf of the Halcyon(2.0) MLC compared with the actual 5-mm width leaf of the TrueBeam Millennium 120 MLC. In the leaf sequence calculation after the fluence optimization of the Halcyon(2.0) plans, each 5-mm width effective leaf may be lagged by the adjacent effective 5-mm width leaf affiliated to the same actual 1-cm width leaf since the target coverage should be always satisfied in prior. As a result, the segment apertures of the Halcyon(2.0) were larger than those of the TrueBeam MLC. The larger AAV_m and GI (suggesting larger irradiation volume) of the Halcyon(2.0) plans may be supposed to agree with the above analysis. As for the MU number, the delivered photon amount was designed to match the leave movements to finish the modulation. Since the leaf speed of

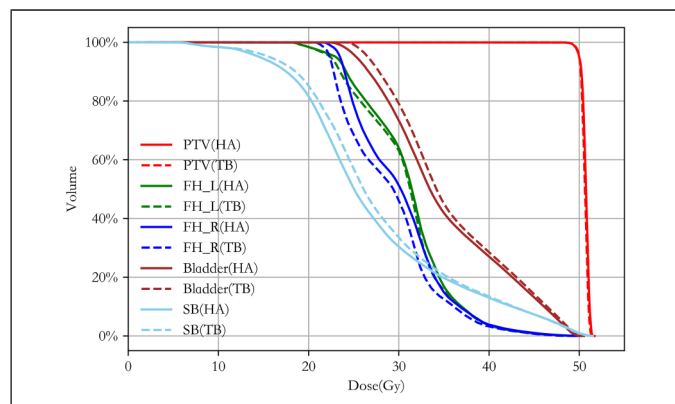


Figure 2. DVH plots of the Halcyon(2.0) and TrueBeam plans of patient #1.

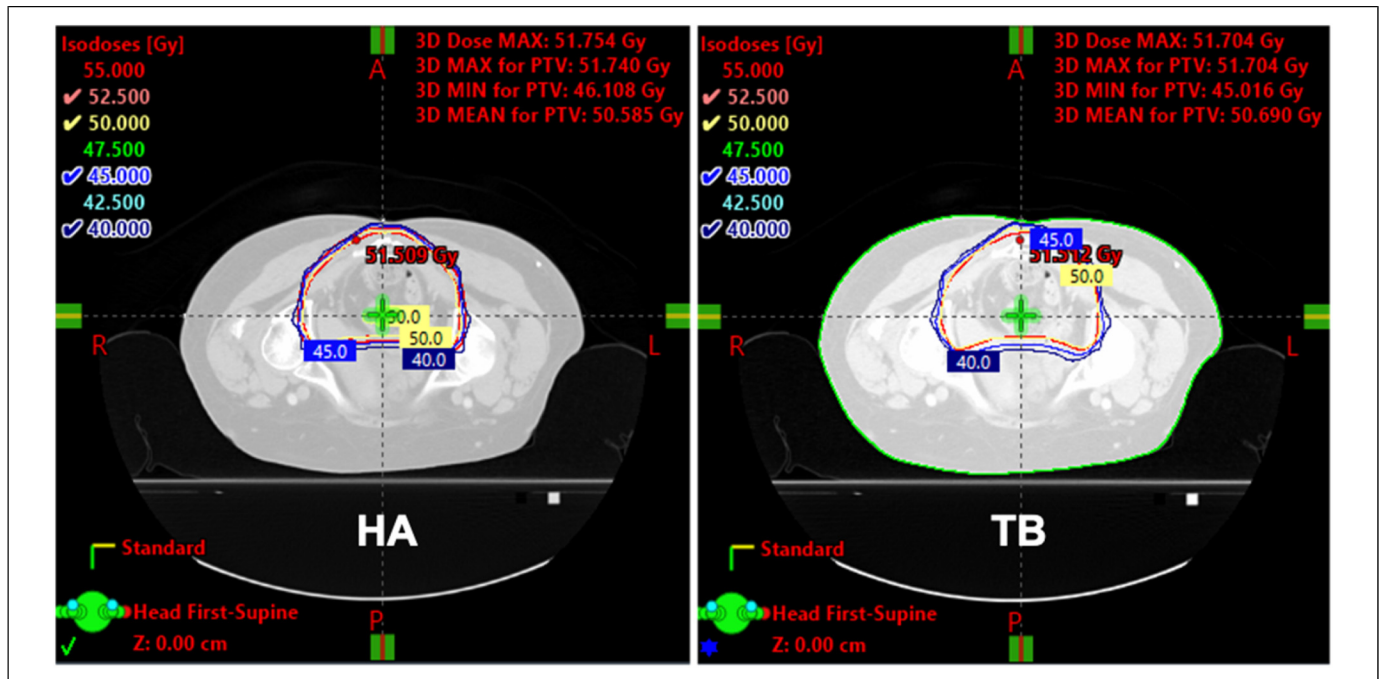


Figure 3. Isolines in the cross-section at the isocenter of the Halcyon(2.0) and TrueBeam plans of patient #1 (left: Halcyon[2.0]; right: TrueBeam).

the Halcyon(2.0) MLC is 2 times faster than that of the TrueBeam MLC, lower MU is needed for achieving identical optimization goals.

Petrocchia et al¹⁷ reported there was no difference in ArcCheck-based GPR between the Halcyon(2.0) and TrueBeam fields for prostate cancer, which is in agreement with results in this study. Pokhrel et al reported there was no difference in the PD-based GPR in the criterion of 2%/2 mm of the prostate SBRT VMAT plans between both machines, while that of the lung SBRT VMAT plans of Halcyon(2.0) was 1.4% lightly larger than that of TrueBeam. However, the algorithm used to obtain the calculated PD-based dose distributions was not mentioned in Pokhrel's tests. In this study, AAA, rather than the portal dose image prediction (PDIP) algorithm, was selected for TrueBeam to eliminate the error induced by algorithm difference. The differences of GPRs of the 2 groups in our study were insignificant in both criteria, suggesting comparable abilities in delivery accuracy.

Table 2. Comparisons of 4 modulation complexity metrics (MU, MCS, AAV_m, and LSV_m) between the TrueBeam and Halcyon(2.0) IMRT fields for long-course rectal cancer radiotherapy (mean ± standard deviation).

Metric	TrueBeam	Halcyon(2.0)	P
MU	185.37 ± 37.88	158.98 ± 25.15	<.001
MCS	0.21 ± 0.08	0.26 ± 0.08	<.001
AAV _m	0.25 ± 0.1	0.3 ± 0.1	<.001
LSV _m	0.84 ± 0.03	0.86 ± 0.02	<.001

Several studies have shown that there is a moderate correlation between GPR and MCS of TrueBeam.^{15,16,22} Correlations can be used to limit the complexity of field in the process of plan optimization and predict the result of dose verification without delivery. Tamura et al²⁵ studied 45 VMAT plans (15 for prostate, 15 for head and neck, and 15 for other sites) and showed that GPR(2%/2 mm) of the Halcyon(2.0) fields had little correlation with MCS (correlation coefficient was -0.06). However, there are few reports on the comparison of the correlation of GPR and modulation complexity between Halcyon(2.0) and TrueBeam. In this study, the correlation coefficient between GPR(2%/2 mm) and MCS of the Halcyon(2.0) fields for long-course rectal cancer radiotherapy was 0.335, which was less than 0.502 of TrueBeam, implying that the delivery accuracy of the Halcyon(2.0) field was weakly related to MCS and thus MCS may not be a sensitive predictor of deliverability for the Halcyon(2.0) field as it does to TrueBeam. Nevertheless, as shown in Figure 5b, for the Halcyon(2.0) fields, GPR(2%/2 mm)s of the fields with MCS exceeding 0.36 (black dotted line) passed the 95% threshold. Therefore, 0.36 can be used as the MCS threshold and the fields with MCS of 0.36 or above can be free of verification, which can further reduce the workload resulting from patients with rectal cancer of the radiotherapy departments.

There were also limitations in this study. Deeper insights about the dosimetry deviations induced by rotational setup errors of patients need to be given due to the lack of the rotational correction function of the Halcyon(2.0). Daily CBCT before treatments and a relative large number of fractions (25-28 for long-course radiotherapy of rectal cancer) may blur

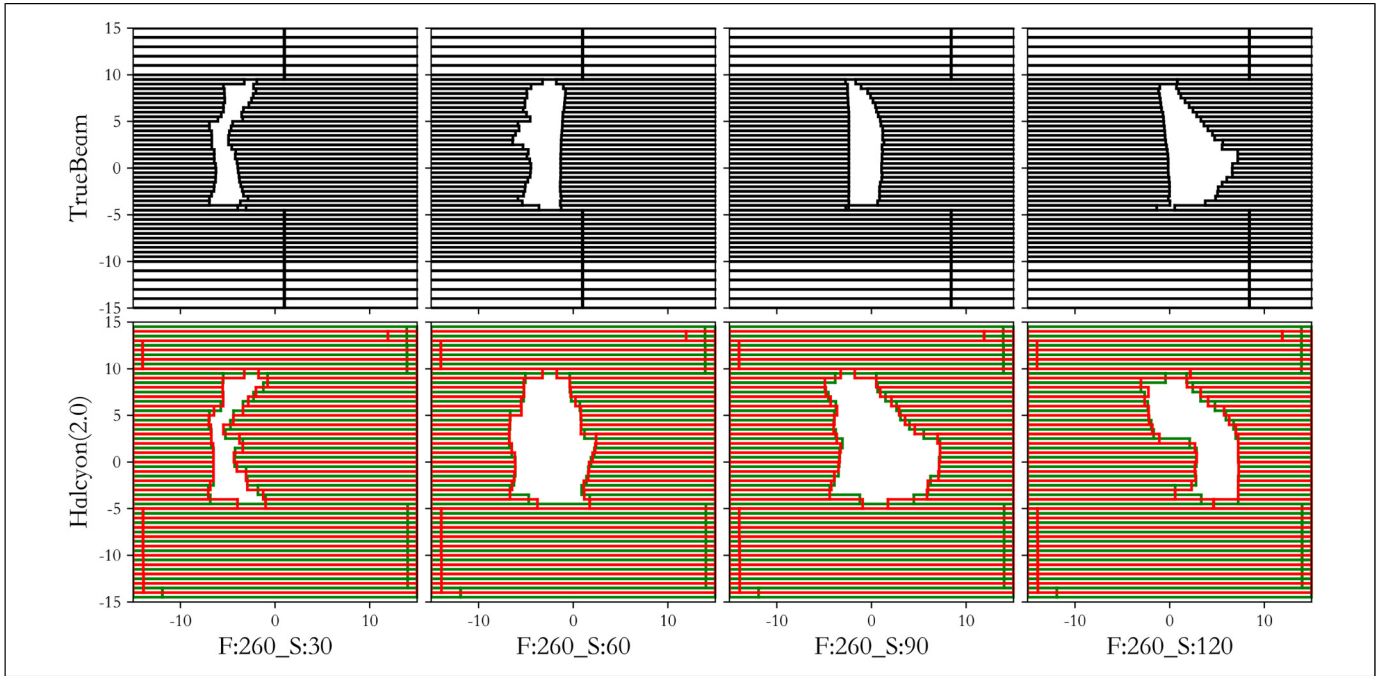


Figure 4. Apertures of 4 segments (segment number of 30, 60, 90, and 120) of a TrueBeam field with gantry angle of 260° (upper) and corresponding apertures of Halcyon(2.0) (lower) of patient #1.

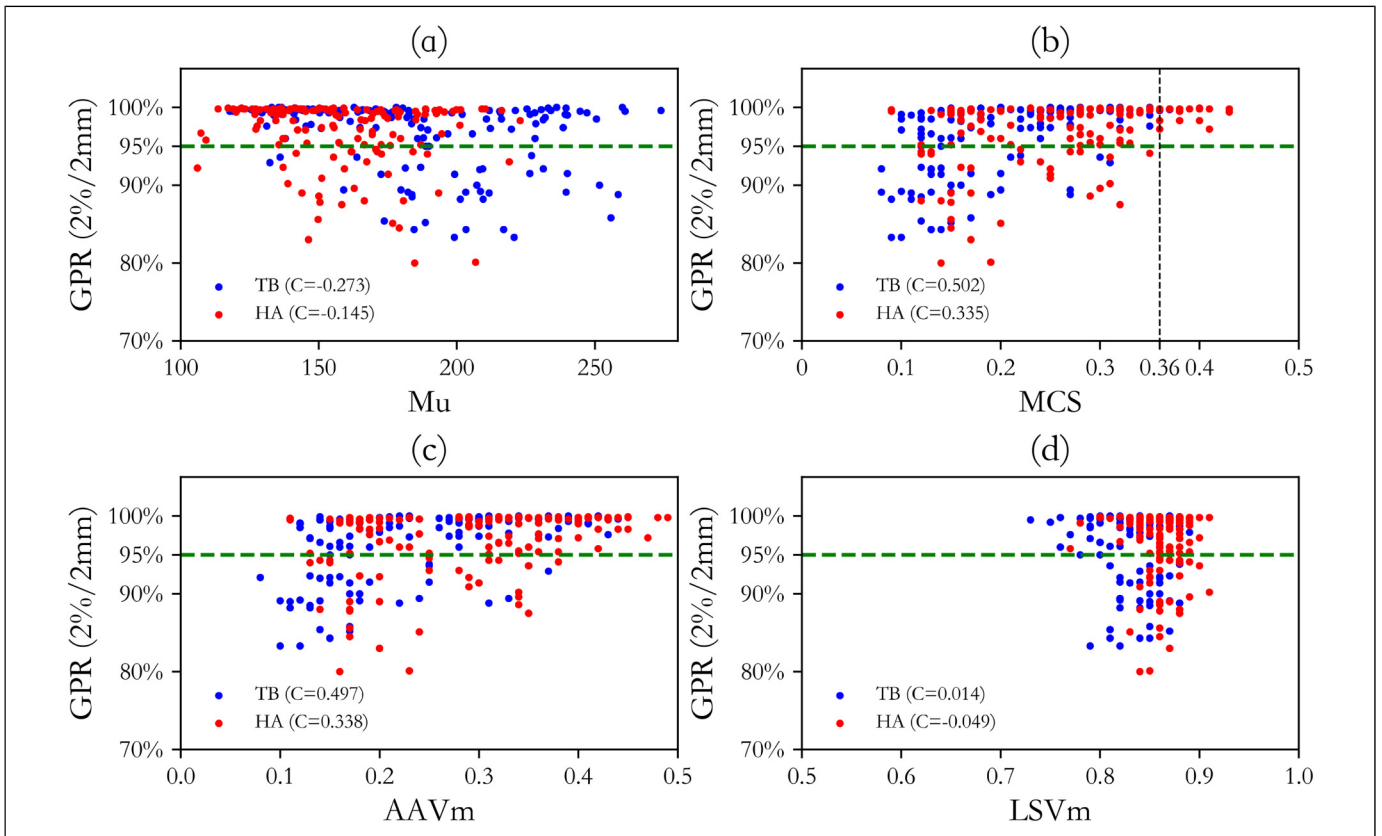


Figure 5. Scatter plots of PD-based GPR(2%/2 mm) and (a) MU, (b) MCS, (c) AAV_m, and (d) LSV_m of the TrueBeam and Halcyon(2.0) IMRT fields for the long-course radiotherapy of the rectal cancer (TB: TrueBeam; HA: Halcyon[2.0]; green dotted line: 95% threshold; black dotted line: recommended MCS threshold; C: correlation coefficient).

negative dosimetry effects from setup errors (the latter may be in the foundation of the central-limit theory in statistics). However, the radiotherapy society needs more dedicated studies and data about this aspect. Moreover, Halcyon(2.0) comes equipped with a Varian aSi-1200 digital megavoltage imaging panel,^{26,27} which is different from the Varian aSi-1000 imager of TrueBeam in our department.²⁸ According to Mhatre's study, the aSi-1200 detector showed a significant dosimetric improvement when compared with the aSi-1000 hence providing more accurate measurements.²⁹ To what extent does the effect have on the comparison of delivery accuracy between the 2 machines need further investigation. In addition, the quality of the Halcyon(2.0) 6MV-FFF beam is slightly different from that of the TrueBeam machine. Typically, the PDD(10 cm) is 63% for Halcyon(2.0) while that is 63.3% for TrueBeam.^{30,31} Thus, the impact of response of EPID resulting from energy deviation can be ignored for delivery accuracy verification.

Conclusion

In this study, we investigated the comprehensive performance of the Halcyon(2.0) IMRT plans for the long-course rectal cancer radiotherapy. Results showed the Halcyon (2.0) plans were almost the same in dosimetry and delivery accuracy compared with the TrueBeam plans. However, the Halcyon(2.0) fields have lower MU and modulation complexity (mainly the larger proportions of the aperture areas in the whole scanning area). Combined with the ultrahigh delivery efficiency, Halcyon(2.0) is reliable and feasible in long-course radiotherapy for the rectal cancer and is highly recommended especially in large medical centers. To be further, the correlations between the field-relevant GPR and MCS reported in this study may help further reduce the workload resulting from the patient QA tasks using proven MCS thresholds.

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Declaration of Conflicting Interests

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Ethical Statement

Since this was a planning study without any delivery to any patient, there was no ethical approval required for this study.

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Supplemental Material

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