Evaluation of dose robustness to SPR variations for different beam orientations in carbon-ion radiotherapy for pancreatic cancer

Terufumi Kusunoki, PhD; Yoshiki Takayama, PhD; Shogo Kurokawa, MSc; Junya Nagata, MSc; Yohsuke Kusano PhD
Kanagawa Cancer Center

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ABSTRACT

[Purpose] To evaluate the effect of beam orientation on dose distribution robustness in carbon-ion radiotherapy for pancreatic cancer, focusing on stopping power ratio (SPR) variations and their impact on delivered dose accuracy.

[Methods] A total of 90 treatment beams used for carbon-ion radiotherapy of pancreatic cancer between February 2022 and January 2025 were analyzed. The dataset included head-first supine vertical beams (virtual gantry angle [GA] = 0°, n = 30), head-first prone vertical beams (GA = 165°, n = 30), and head-first prone horizontal beams (GA = 255°, n = 30). The SPR differences within patients were calculated by comparing the planning CT with CT images acquired during the treatment course. The dose distribution calculated from the planning CT was used as the reference, and dose distributions during treatment were recalculated accordingly. Gamma analysis was then performed between the planned and the recalculated dose distributions. The Pearson's correlation coefficients (CCs) between the mean SPR difference within the 20% isodose region and the gamma pass rate (GPR) with the criteria of 3%/2mm were evaluated for each beam orientation.

[Results] The mean GPRs for GA = 0°, 165°, and 255° were 86.8%, 96.0%, and 91.0%, respectively, with corresponding CCs of -0.790, -0.337, and -0.828. A negative correlation was found between the mean SPR difference and the GPR, indicating reduced agreement between dose distributions with increasing SPR variation. The primary contributors to SPR variation were changes in patient body contour and positional variations of gastrointestinal gas, both of which strongly depended on beam orientation.

[Conclusion] The robustness of dose distributions with respect to SPR variation and beam orientation was quantitatively evaluated. These results suggest that both beam arrangement and dose delivery accuracy during treatment should be carefully managed in carbon-ion radiotherapy for pancreatic cancer.

CONTACT

[name] Terufumi Kusunoki
[organization] Kanagawa Cancer Center
[address] 2-3-2, Nakao, Asahi-ku, Yokohama, Kanagawa, Japan
[email] rt.kusunoki@gmail.com
[phone] 81-45-520-2222

INTRODUCTION

Carbon-ion radiotherapy (CIRT) takes advantage of the **Bragg peak**, enabling highly conformal dose delivery to the tumor while reducing the dose to adjacent normal tissues. However, in CIRT, treatment-day anatomical changes can shift the beam range, potentially reducing the tumor dose and increasing unexpected irradiation of surrounding organ at risk (**Figure 1**). The beam range is affected by changes in the stopping power ratio (**SPR**), which may influence irradiation accuracy.

In this study, we evaluated treatment-day changes in SPR and their impact on dosimetric accuracy for each beam direction clinically used in CIRT for pancreatic cancer at our institution.

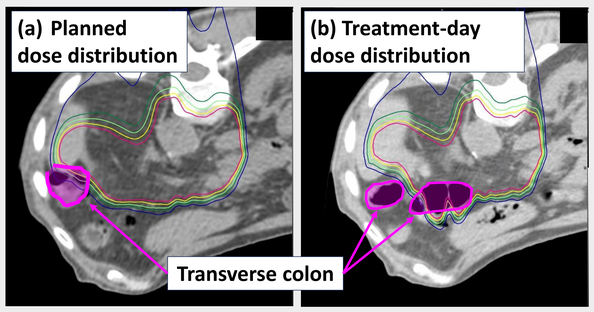

Figure 1. Dose distribution changes caused by gastrointestinal gas variation. (a) Planned dose distribution avoiding the transverse colon. (b) Treatment-day dose perturbation due to displacement of the transverse colon and colonic gas.

METHODS AND MATERIALS

A total of 90 beams from 25 patients who underwent CIRT for pancreatic cancer at our institution were randomly selected and analyzed. Planned dose distributions were optimized using Carbon for Monaco (Elekta AB) for three beam directions: **virtual gantry angle [GA] = 0°, GA = 165°, and GA = 255°**. The prescribed dose was 4.6 Gy(RBE) per beam. Treatment-day CT images were acquired using an in-room CT system (Canon Medical Systems Corporation), and treatment-day dose distributions were recalculated on these CT images using the original treatment plan parameters.

SPR difference images were generated by converting the planning and treatment-day CT images into relative SPR images using a CT-to-SPR table and subtracting them (**Figure 2**). **The mean SPR difference (ΔSPR)** was calculated within the 20% isodose region of the planned dose distribution. **The gamma passing rate (GPR)** between the planned and treatment-day dose distributions was calculated using 3%/2 mm criteria with a 20% threshold (**Figure 2**). **Pearson's correlation coefficients (CC)** between ΔSPR and GPR were evaluated for each beam direction.

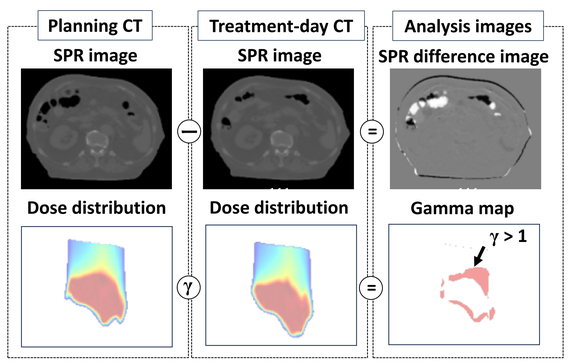

Figure 2. Overview of the image and dose analysis workflow. The γ symbol represents the 3D gamma analysis.

RESULTS

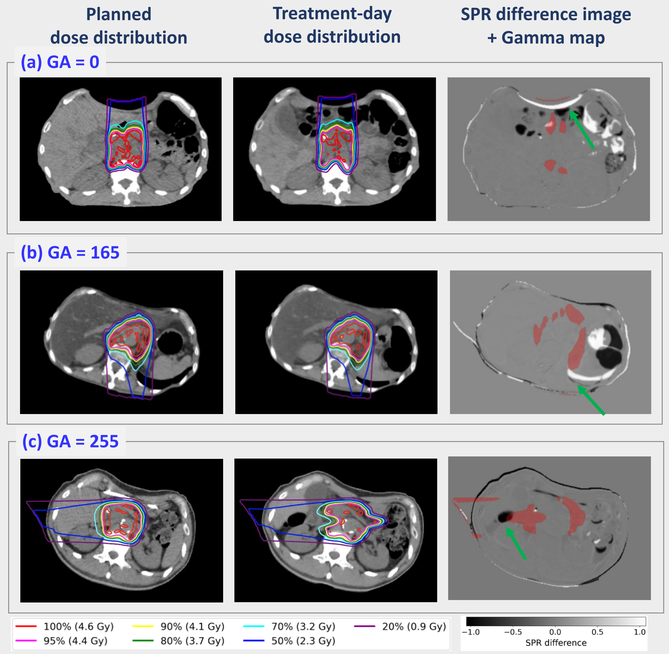

Figure 3. Representative example of factors influencing changes in the treatment-day dose distribution for each gantry angle. **The green arrows** indicate regions of SPR difference that contributed to dose variation.

Figure 3 shows representative cases in which the treatment-day dose distribution varied for each gantry angle. Variations in the treatment-day dose distribution were mainly attributed to changes in the **body surface** (case (a)), displacement of **the diaphragmatic dome** (case (b)), and changes in the location and volume of **gastrointestinal gas** (cases (a) and (c)).

Table 1. Mean ± SD, range (min – max), and CC between ΔSPR and GPR

	GA = 0 (n = 30)	GA = 165 (n = 30)	GA = 255 (n = 30)
ΔSPR	0.064 ± 0.031 (0.019 – 0.152)	0.029 ± 0.009 (0.014 – 0.046)	0.045 ± 0.015 (0.020 – 0.070)
GPR (%)	86.8 ± 8.1 (67.2 – 98.7)	96.0 ± 3.2 (88.2 – 99.8)	91.0 ± 5.0 (78.5 – 98.8)
CC	−0.790	−0.337	− 0.828

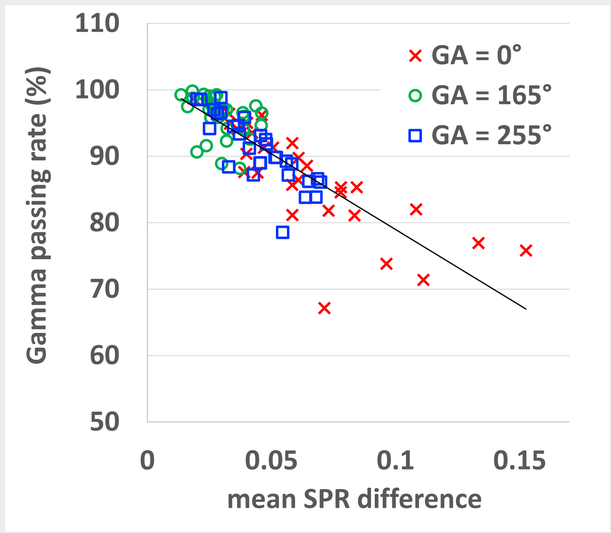

Figure 4. Correlation between the mean SPR difference and gamma passing rate

Table 1 shows the statistical values of the ΔSPR and the GPR for the each gantry angle. The GPR was highest at GA = 165°, followed by GA = 255°, and was lowest at GA = 0°. The GPR tended to decrease as the ΔSPR increased (**Figure 4**). The correlation between the ΔSPR and the GPR was strong for GA = 0° and GA = 255°, and very weak correlation was observed for GA = 165° (**Table 1**).

DISCUSSION

The GPR for GA = 165° was higher than those for GA = 0° and GA = 255°, indicating that the dose distribution was relatively robust for this beam direction. This may be because the posterior beam path includes fewer gastrointestinal structures and is less affected by changes in body surface. However, as shown in **Figure 3(b)**, caution is required when the diaphragmatic dome is included in the posterior beam path. In contrast, the treatment-day dose distributions for GA = 0° and GA = 255° showed larger variations due to the effects of gastrointestinal gas and changes in body surface. The GPR for GA = 0° was lower than that for GA = 255°, probably because of differences in the irradiated gastrointestinal region. Although the GA = 255° beam partially passes through the liver, the GA = 0° beam passes through the stomach, duodenum, small intestine, and large intestine. Therefore, the lower GPR for GA = 0° may be attributed to the greater influence of physiological changes in these organs.

In this study, treatment-day anatomical changes were represented by ΔSPR. The ΔSPR increased in the order of GA = 165°, GA = 255°, and GA = 0°, which was consistent with the anatomical interpretation described above. ΔSPR corresponded well with variations in the dose distribution; as shown in **Figure 4**, higher ΔSPR values tended to be associated with lower GPR values. **These findings suggest that dose distribution variations may be predicted before irradiation by acquiring treatment-day CT images and calculating ΔSPR.** Kawashima et al.[1] discussed the usefulness of beam angle selection in CIRT for pancreatic cancer, and **our results suggest that ΔSPR may help support beam angle selection and decision-making.**

CONCLUSIONS

In this study, the robustness of dose distributions was quantitatively evaluated for each gantry angle. The magnitude of ΔSPR differed among gantry angles and strongly affected treatment-day dose distribution variations. In particular, ΔSPR for GA = 0° was larger than those for the other gantry angles, mainly because this beam passed through the gastrointestinal tract. **These results suggest that both beam arrangement and dose delivery accuracy during treatment should be carefully managed in CIRT for pancreatic cancer.**

In addition, ΔSPR was correlated with GPR, suggesting that ΔSPR may serve as an indicator for predicting GPR. These findings suggest that ΔSPR can be used to evaluate the robustness of treatment-day dose distributions and may support clinical decision-making, such as beam angle selection or modification. **Pre-treatment evaluation of ΔSPR using image analysis may therefore be an important clinical QA process for accurate dose delivery in CIRT for pancreatic cancer.**

ACKNOWLEGMENTS

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