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学 位 論 文 の 内 容 の 要 旨

Dissertation Abstract

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（学位論文のタイトル） Title

Robust Beam Selection Based on Water Equivalent Thickness Analysis in Passive Scattering Carbon-Ion Radiotherapy for Pancreatic Cancer.

（膵癌における受動散乱型炭素イオン放射線治療における水当量厚さ解析に基づく最適なビーム選択）

（学位論文の要旨）2,000字程度、A4判 （approx.800 Words in English /A4 size）

Carbon-ion radiotherapy (CIRT) provides a more effective treatment for pancreatic cancer compared with photon RT. However, it is challenging to maintain a good dose coverage in CIRT for pancreatic cancer, even if maintaining good tumor reproducibility. The main reason for coverage reduction is the variation in carbon ion beam range caused by anatomical changes in the field, with the water equivalent thickness (WET) variation being a crucial parameter determining the beam range. Thus, this study aimed to investigate the angular dependency of WET variation in the supine and prone positions for pancreatic cancer and to evaluate the robustness of accumulated doses with WET-based beam configurations (BCs) under two matching methods (bone matching (BC) and tumor matching (TM)).

This retrospective study evaluated eight patients with pancreatic cancer who underwent passive scattering CIRT. A total of 110 CT images that included 15 for treatment planning (CT_plan) and 95 on every treatment day (CT_daily) were studied. On each of the 12 treatment days, CT_daily images corresponding to the treatment position were taken after treatment irradiation under the same conditions as CT_plan. Original treatment planning involved four-box fields at 0°, 90°, 180°, and 270° angles, delivering 55.2 Gy (RBE) over 12 fractions. The clinical target volume (CTV) for the initial nine fractions (CTV1) was delineated by an experienced radiation oncologist expanding the gross tumor volume (GTV) by at least 5 mm. As CTV2, the GTV was expanded by only 5 mm for three boost irradiations, excluding the GI tract. The planning target volumes (PTV1 and PTV2) were expanded by a 3 mm margin to the CTVs and were adjusted to avoid the GI tract. Dose constraints were set for CTV V95% (>95%), D2cc of the stomach/duodenum (<44 Gy), Dmean of the ipsilateral kidney (<15 Gy), and Dmax to the spinal cord (<30 Gy). An in-house program was developed to calculate WETs from the body surface to the distal edge of the CTVs. ΔWET was WET change between CT_plan and CT_daily. ΔWET analysis was performed for each 5° of 360° coplanar directions. ΔWET-based beam configurations (BCs) were defined: rotating gantry (BC_gantry) and fixed port (BC_fixed). These BCs were designed to protect OARs and included both supine and prone positions. For BC_fixed, angles within ±20° of specific directions

(355°, 110°, 255° in the supine position and 180° in the prone position) were selected to consider the couch-rotation limit and dose constraints for OARs. BC_gantry angles (210°, 150°, and 345° in the supine position and 0° in the prone positions) were chosen based on minimal ΔWET with tumor matching and avoidance of critical structures. A total of 69 planned doses and 552 daily doses of BM or TM with three BCs were evaluated. To assess the robustness of the treatment plan, we calculated dose reduction, which is the difference between the planned and daily doses. To calculate the accumulated dose distribution, the daily dose distributions (4.6 Gy (RBE) per fraction) on each CT_daily were warped and transferred to the corresponding CT_plan by hybrid-DIR using MIM Maestro. Dose differences were evaluated for various parameters including CTV V95%, GTV V95%, CTV D95%, GTV D95%, D2ccs of duodenum and stomach, and Dmax of the spinal cord with the three beam configurations.

The study findings indicated that posterior oblique (120- 240°) beams in the supine position and anteroposterior (0° and 180°) beams in the prone position were the most robust to WET variation. For daily dose, the dose reduction for CTVs with both proposed BCs was significantly lower than for those with BC_original, especially for TM. For OARs, the difference in the dose variation with the three BCs is very slight in the supine position. In the prone position, the dose variation of D2cc of the stomach with BC_gantry with TM was significantly better than BC_original/BC_fixeds. The analysis of the homogeneity of variation showed that in the supine position, only those in both kidneys were significant. For the prone position, the variance of the dose variation with BC_gantrys in D2cc of the stomach is significantly smaller (more robust) than with BC_original. As for accumulated dose, we also found the mean CTV V95% reductions with TM were -3.8% and -5.2% with the BC for gantry and the BC for fixed ports, respectively. For OARs, the D2ccs of the stomach and duodenum and the Dmax of the spinal cord with both proposed BCs were higher than those of the BC_original in some patients. However, the difference was due to the planned dose distribution, and there was no statistical difference in the magnitude of variation or its deviation, which indicates robustness.

In summary, we investigated anatomically robust BCs based on WET variations for pancreatic cancer treatment with CIRT. A significant angle dependency on interfractional change was observed. For most of the patients, posterior oblique beams (120- 240°) in the supine position and anteroposterior (0° and 180°) beams in the prone position were more accurate for minimizing the interfractional change than the other beams. Additionally, treatment plans with WET-based BCs were the most robust in the majority of patients. However, the improvement in robustness with BM was limited owing to significant tumor movement in some patients.