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Respiratory gating of pancreatic cancer

Programmable segmented volumetric modulated arc therapy for respiratory coordination in pancreatic cancer

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ABSTRACT

We programmably divided long-arc volumetric modulated arc therapy (VMAT) into split short arcs, each taking less than 30 s for respiratory coordination. The VMAT plans of five pancreatic cancer patients were modified; the short-arc plans had negligible dose differences and satisfied the 3%/3-mm gamma index on a MapCHECK-2 device.

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The recently developed and clinically adopted technique known as volumetric modulated arc therapy (VMAT) improves target conformity and organ sparing by use of rotational intensity modulated radiation therapy (IMRT) and more control points (gantry locations) for intensity optimization [1,2]. There has not been a gating solution to respiratory coordination for the dynamic delivery of the Elekta VMAT system (Elekta Oncology System Ltd., Crawley, West Sussex, UK). In contrast, respiratory-gated VMAT by Varian TrueBeam™ (Varian Medical Systems, Palo Alto, CA, USA) has been tested [3]. Some commercially available planning systems, such as the Pinnacle^3 planning system (ADAC Laboratories, Philips Medical Systems, Milpitas, CA, USA), do not allow the partial-arc design with less than 90° of gantry rotation. Therefore, the delivery of each arc of VMAT usually takes more than 1–2 min, longer than a single tolerable breath hold. We designed a solution to divide the long arc from the original VMAT plan into split short arcs, with each short-arc delivery taking less than 30 s. This study aimed to programmably modify the VMAT plan with a segmented short-arc design, and test this method in the VMAT plans of five pancreatic cancer patients for accuracy of dose delivery.

Materials and methods

VMAT plan modification

Five pancreatic cancer patients whose VMAT plans were originally designed by the SmartArc module version 9.0 of the Pinnacle^3 planning system were included in this study. The original VMAT plans with either full arcs or partial arcs taking longer than one breath hold for delivery were modified to use split short arcs of less than 30 s each. Because the original VMAT designs used the relatively constant gantry rate (1–5°/s), the cut-edge control points of split short arcs were selected every 30–50°. The end gantry angle of each short arc was the starting gantry angle of the next short arc. The monitor units (MUs) of arcs in the RTP files of the record-and-verify system, MOSAIQ version 1.6 (IMPAC Medical Systems, Inc, Sunnyvale, CA, USA), were reassigned between the short arcs. In the case of an original VMAT arc coming from sequenced static fields, the MUs of the control points between two adjacent segments of arc are considered as half-weighted, while the MUs of the control points at the edge are considered for their whole value. The originally designed half-MUs of the control point at the edge between the split short arcs were added from the next short arc to the previous short arc, because zero MU is required for the beginning control point of the arc by the Pinnacle^3 planning system. The algorithm of the split-arc modification is shown in Fig. 1A. The program of the RTP file in the record-and-verify system for each short-arc VMAT delivery was modified with the revised number of control points, MU weight at each control point, as well as the starting and end gantry angles.

The dose grid resolution was 0.4 cm for inverse planning, primarily based on the calculation and storage capacity of our planning system. Pinnacle plans were transferred in DICOM export protocols through the MOSAIQ system to the linear accelerator. Continuous gantry motion, dose-rate variation, and multi-leaf collimator (MLC) motion were approximated by optimizing individual

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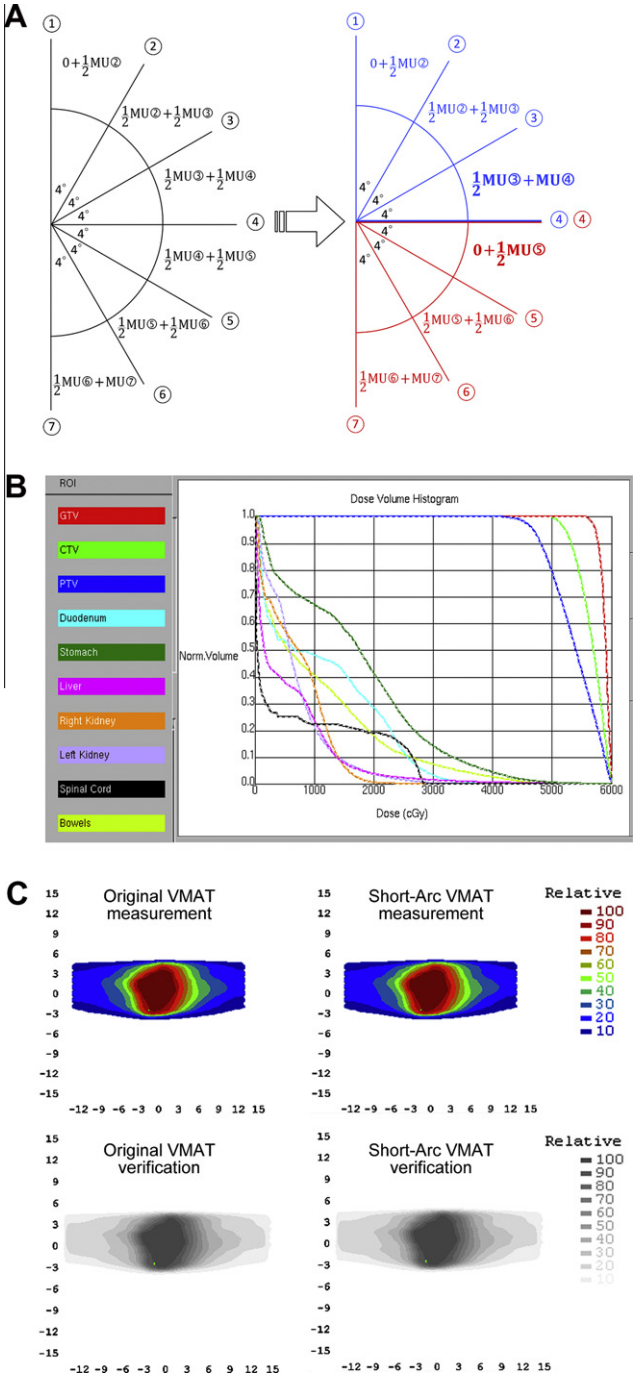

Fig. 1. (A) The simplified algorithm of modifying the original long-arc volumetric modulated arc therapy (VMAT) (black color) with the segmented short-arc VMAT (blue and red colors) for the split delivery. (B) Dose-volume histogram (DVH) of gross tumor volume (GTV), clinical target volume (CTV), planning target volume (PTV), and organs at risk between original long-arc volumetric modulated arc therapy (VMAT) (solid line on DVH) and modified short-arc VMAT (thin dashed line on DVH) and (C) the 2-dimensional dose verification on coronal section for original long-arc VMAT and modified short-arc VMAT of a representative patient (No. 2).

beams at 4° gantry angle increments with MLC leaf positions varying by up to 4.6 mm for every 1° of gantry rotation.

Plan studies for pancreatic cancer patients

The original VMAT plans of five pancreatic cancer patients, with passive abdominal compression for respiratory control, were archived from the Pinnacle[3] system, and were modified with the split short arcs of less than 30 s each. The modified short-arc VMAT plans were recalculated with the reassigned MUs of short arcs for the summated doses. All patients were planned with 10-MV photon beams in supine position. The minimum doses prescribed to the gross tumor volume (GTV), clinical target volume (CTV), and 95% planning target volume (PTV) were 55 Gy, 45 Gy, and 45 Gy in 25 fractions, respectively.

VMAT delivery and dose verification

The original long-arc and modified short-arc VMAT plans were delivered by an Elekta Synergy® linear accelerator. The Elekta VMAT delivery was basically by MU-based servo control. The accelerator used automatic dose-rate selection, which ensures that the maximal possible dose rate was chosen for each individual segment of the arc. The possible dose rates were 440, 222, 112, and 57 MU/min. The delivery time of each long/short arc was recorded from the MOSAIQ system.

Doses were verified using the MapCHECK 2 device version 5.02.00.02 (Sun Nuclear Corporation, Melbourne, FL, USA). The differences between the planned and measured doses were analyzed by gamma tests for the original long-arc plans. Besides, gamma tests were taken for the differences between the planned doses of the original long-arc plans and the measured doses of the modified short-arc plans. The criteria of gamma evaluation were 3% dose difference and 3-mm distance to agreement. $\Gamma \leqq 1$ was defined as the verification passing the criteria and satisfying ≧95% of points.

Results

One patient had original VMAT plans with three arcs, three with two arcs, and one with one arc. The median and mean (± standard deviation) delivery times of each arc in the original VMAT plans were 122.5 s and 123.7 ± 21.5 s, with a range from 95 to 168 s. After the programmed segmentation of long arcs, one patient had modified VMAT plans with 24 short arcs, three with 16 short arcs, and one with eight short arcs. The median and mean delivery times of each short arc in the modified VMAT plans were 20.0 s and 20.1 ± 3.6 s, with a range from 13 to 30 s (Table 1).

The recalculated dose-volume data with the summation of segmented short arcs showed negligible difference from the original VMAT plans. The average dose differences in minimum dose between the original and modified plans for GTV (55 Gy), CTV (45 Gy), and 95% PTV (45 Gy) were 1.3 ± 0.8 cGy, 3.0 ± 4.6 cGy, and 1.4 ± 1.5 cGy, respectively. The dose-volume histogram for targets and organs at risk of a representative patient is shown in Fig. 1B.

The average passing rates of 3%/3-mm gamma index for accuracy of dose delivery were not different, 99.1% ± 1.6% for the original VMAT plans, and 98.8% ± 2.1% for the modified VMAT plans ($p = 0.24$ by paired Student t test). The 2-dimensional dose verifications on the MapCHECK 2 device of a representative patient's original and modified VMAT plans were shown in Fig. 1C.

Discussion

In this study we proposed a practical algorithm to split the long arc into a few short arcs tolerable for actively coordinated breath hold in VMAT delivery. We tested this method in five pancreatic cancer patients' VMAT plans, and demonstrated a minimal dose difference and accurate dose delivery by 3%/3-mm criteria with the modified short-arc VMAT plans. The short-arc VMAT delivery took an additional 26–31% beam-on time to the original long-arc