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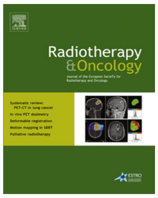

Original article

Fully automatic volumetric modulated arc therapy plan generation for rectal cancer

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ABSTRACT

Background and purpose: To develop and evaluate a fully automatic rectal planning optimizer (ARPO) for volumetric modulated arc therapy (VMAT) treatment planning without human interaction.

Materials and methods: The ARPO was developed using inherent Pinnacle^3 script language; it was designed to perform the whole planning process including planning structure generation, beam placement, doseline setting and treatment planning. The automatic scheme adjusts the objectives of the objective function simulating the operation of dosimetrists based on our clinical experience. A total of 29 planned rectal cancer patients were retrospectively replanned using the ARPO (VMAT$_{auto}$) under the same constraints.

Results: With the ARPO, the hands-on time required for the whole planning process was significantly reduced to <1 min. All VMAT$_{auto}$ plans were recognized as clinically acceptable and 69% as clinically improved; 3% of VMAT$_{auto}$ plans were marked equal and 28% inferior to manually generated VMAT$_{man}$ plans when reviewed in a single-blind study by one experienced radiation oncologist. Without any planning workload the VMAT$_{auto}$ plans had similar planning target volume dose coverage to the VMAT$_{man}$ plans and statistically better organ-at-risk sparing, especially regarding lower small intestine irradiation.

Conclusions: The ARPO is robust and dramatically efficient in clinical application and provides improved planning quality.

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Treatment planning for rectal cancer radiotherapy is a complicated task because of the irregular shape of the target volume and multiple involved organs at risk (OARs) such as the bladder, small intestine and femoral heads [1]. The commonly used radiotherapy (RT) technique intensity modulated radiation therapy (IMRT) has obvious advantages over three-dimensional conformal radiotherapy concerning target coverage and OAR sparing; it is used routinely for rectal cancer patient treatment [2,3]. However, the deficiencies in IMRT are also obvious, such as the long delivery time. Volumetric modulated arc therapy (VMAT) [4–8] is an emerging technique increasingly used as an effective and time-efficient alternative. During VMAT treatment, the intensity-modulated dose is delivered using a dynamic multileaf collimator (MLC) and variable dose rate, while the gantry continuously rotates. With its advanced features, VMAT provides better conformal dose distributions, higher treatment delivery efficiency and an obvious reduction in monitor units (MU) in rectal radiotherapy [9,10].

However, during the VMAT planning, dosimetrists have to complete the planning process manually, some of which involves repetitive operations. In most cases, the optimization parameters need to be further modified manually in a trial-and-error process to obtain a high-quality treatment plan.

Thus, there is on-going research to establish more efficient schemes for VMAT planning and automated tools are promising solutions. Fully automated VMAT plans for lung cancer [11] and prostate cancer [12,13] have been successfully generated without manual interference. However such studies were undertaken with in-house developed optimizers or third-party coding languages [14–16], which are not available for other dosimetrists in the broader community.

With the VMAT technique, which is increasingly available to primary-level hospitals, it is becoming progressively harder to ensure plan quality; this is because similar to the IMRT plan, the VMAT plan quality heavily depends on the experience of dosimetrists. There is a long learning curve involving considerable human, physical and financial resources for individuals who lack sufficient knowledge and experience regarding IMRT planning. Qualified automated tools can be used to confirm the consistency of plan quality among different radiotherapy facilities.

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We developed a fully automatic rectal planning optimizer (ARPO) that aims to save labor resources and meet the requirement for high planning quality. The ARPO is generated using the Pinnacle^3 planning script, which is imbedded with the treatment planning system (Pinnacle^3: Philips Radiation Oncology, Fitchburg, WI, USA). The ARPO runs without any interaction, leaving the dosimetrists free for other tasks, and minimizes the time spent on the whole process. The objective of our study was to demonstrate the ARPO and present an initial evaluation of its performance.

Methods and materials

Patient and CT simulation

In our study, 29 patients with pathologically proven rectal cancer treated from July 2014 to April 2015 at our institution were randomly selected. There were five (17%) females and 24 (83%) males. The radiotherapy plans were retrospectively replanned using the ARPO for analysis purposes. Therefore, each patient had two VMAT plans, one involving trial-and-error planning after full discussion and communication between dosimetrists and oncologists (VMAT$_{man}$) and another involving the ARPO (VMAT$_{auto}$).

All the patients were immobilized in the supine position using a thermoplastic mask. Planning CT scanning was performed in the treatment position, using a slice distance of 3 mm.

Target volume definition and dose constraints

The clinical target volume (CTV) and OARs including bladder, small intestine, and femoral heads were delineated by experienced radiation oncologists. The planning target volume (PTV) was generated with margins around the CTV, namely 0.5 cm in lateral, 1 cm in superior-inferior and 0.5 cm in anterior–posterior directions. Bladder and femoral heads were fully outlined and the regions 3 cm above and below the PTV were taken into consideration in the case of small intestine contouring.

The prescription dose to the PTV and the OAR dose constraints were as follows: $\geqslant$95% of PTV received 100% of the prescription dose, Dprescription = 50.4 Gy in 28 fractions; for the bladder a V50 < 50% (V50 = percentage of the volume receiving 50 Gy); for the small intestine a V50 < 5%; and for the left and right femoral heads a V50 < 5%. These regions were the only input parameters for the ARPO.

Automatic VMAT plan generation

Overview

All the planning was conducted on the Pinnacle^3 9.2 workstation with the model for the Elekta Synergy accelerator. In the ARPO, VMAT plans were generated using 6-MV photon dynamic arc beams with two 360° coplanar arcs (A1 and A2) consisting of 91 CPs respectively sharing the same isocenter. A fixed collimator angle of 0° was used and the maximum field size was 40 × 40 cm^2 with dynamic MLCs and automatically tracking collimator jaws for each CP. The dose rate was set at 510 MU/min. The SmartArc algorithm provided by Pinnacle^3 was chosen as the calculation engine and the calculation grid resolution was set as $4 \times 4 \times 4$ mm^3. All the settings were the same as those for the VMAT$_{man}$ plans.

The ARPO is capable of completing the whole planning process without manual interaction. The workflow of the ARPO is illustrated in Fig. 1.

Additional contour generation

The additional contours generated by the ARPO were as follows: (1) PTV-3 mm, shrinkage from the PTV by 3 mm; (2) Ring 1 and Ring 2, the 5-mm-wide rings at 5 mm and 10 mm distance, respectively, from the PTV; (3) Fan up and Fan down (Supplemental file S2), the fan volumes in the superior and inferior directions, respectively, of the PTV at a distance of 10 mm; (4) NT 1 and NT 2, the whole CT volumes excluding the PTV expanded by 20 mm and 30 mm, respectively; and (5) BladderAvoid/SmalIntAvoid, the whole bladder/small intestine excluding the volume PTV expanded by 5 mm.

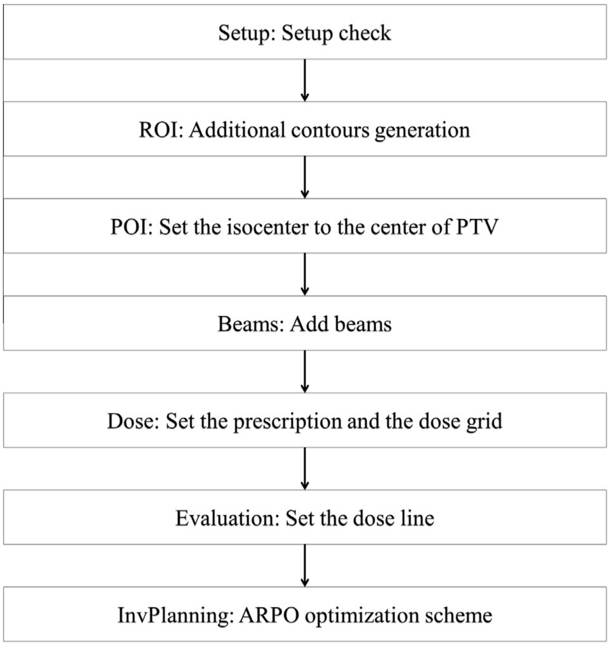

Fig. 1. Workflow of ARPO.

The automatic ARPO optimization scheme

There were three steps in the ARPO optimization scheme: initial optimization (step 1), main optimization (step 2) and final optimization (step 3).

In the initial optimization step, a set of 25 pre-designed initial VMAT optimization objective items, denoted as $I_i (i = 1, \ldots, 25)$, was loaded by the Pinnacle^3 protocol tool as illustrated in Table 1. There were six types of optimization applied in the ARPO including maximum dose, minimum dose, minimum dose volume histogram (DVH), uniform dose, maximum generalized equivalent uniform dose (gEUD) and maximum DVH. The optimization types together with the corresponding target dose (T_i) and weight (W_i) affecting the specific volume at the i^{th} objective item comprised an effective optimization objective set verified by our clinical experience derived from the radiotherapy planning for over 300 rectal patients and a large number of repeating experiments for typical rectal planning cases. When optimization type gEUD was adopted, the estimated parameter $gEUD_i (i = 11, 13, \ldots, 25)$ [17] provided by Pinnacle^3 was used as an indicator for target dose (T_i) value updating. The parameter $OV_i (i = 1, \ldots, 25)$ [18] represents the optimization objective value of each $I_i (i = 1, \ldots, 25)$, which is proportional to the difference between the computed dose and the dose target T_i of the corresponding region of interest (ROI), and the composite objective value *COV* [19] computed as the sum of all weighted optimization objectives serves as an indicator for the iteration stopping criterion of the optimization scheme. During each optimization iteration, Pinnacle^3 provides real-time updates on *OV* and *COV*, which can be directly read out. The initial optimization step prepared an optimal starting point for step 2, which was thus set to produce the best possible dose coverage of the PTV, temporarily neglecting OARs. This is why the highest weights were given to

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