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Original paper

Evaluation of optimization workflow using design of experiment (DoE) for various field configurations in volumetric-modulated arc therapy

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ABSTRACT

Purpose: In volumetric-modulated arc therapy (VMAT), field configurations such as couch or arc angles are defined manually or using a template. A field configuration is reselected through trial-and-error in the case of undesirable resultant planning. To efficiently plan for desirable quality, configurations should be assessed before dose calculation. Design of experiments (DoE) is an optimization technique that efficiently reveals the influence of inputs on outputs. We developed an original tool using DoE to determine the field configuration selection and evaluated the efficacy of this workflow for clinical practice.

Methods: Computed-tomography scans of 17 patients and target structures were acquired retrospectively from a brain tumor treated using a dual-arc VMAT plan. The configurations of the couch, arc, collimator angles, field sizes, and beam energy were determined using DoE. The resultant dose distributions obtained using the DoE-selected configuration were compared with the clinical plan.

Results: The averaged differences between the DoE and clinical plan for 17 patients of doses to 50% of the planning target volume (PTV-D50%), Brain-D60%, Brain-D30%, Brain stem-D1%, Left eye-D1%, Right eye-D1%, Optic nerve-D1%, and Chiasm-D1% were 0.2 ± 0.5%, −1.0 ± 4.6%, 1.7 ± 3.5%, −2.5 ± 6.7%, −0.2 ± 4.9%, −1.2 ± 3.6%, −2.8 ± 7.3%, and −2.1 ± 5.7%, respectively.

Conclusions: Our optimization workflow obtained using DoE for various field configurations provided the same or slightly superior plan quality compared with that created by experts. This process is feasible for clinical practice and will efficiently improve treatment quality while removing the influence of the planner's experience.

1. Introduction

Intensity-modulated radiation therapy (IMRT) was developed in the 1980s [1–4] as a technique to generate a conformal dose distribution, especially for complex target shapes, while sparing the organs at risk (OARs). It has been applied to several tumor sites—such as the prostate, head and neck, and brain—and been found to show superior dose distribution compared to conventional three-dimensional conformal radiation therapy (3D-CRT) [5,6]. Recently, volumetric-modulated arc therapy (VMAT) was developed to provide continuous irradiation during gantry rotation with multiple field shapes formed by a multileaf collimator (MLC). This method affords additional degrees of freedom through the continuous variation of the MLC, gantry speed, and dose rate; furthermore, compared with conventional IMRT, it provides higher beam delivery efficiency and higher dose conformity [7,8]. In VMAT treatment planning, typical field arrangement parameters include the isocenter position, couch angle, number of arcs, arc angles, collimator angles, field size, and beam energy. These parameters are often selected manually via trial-and-error according to the planner's experience for the particular patient. The MLC modulation or dose rate is then optimized by the treatment planning system (TPS) using an inverse planning process to obtain an appropriate dose distribution. Several commercial optimization systems are available for clinical applications, such as RapidArc (Varian Medical Systems, Palo Alto, CA) and SmartArc (Philips Healthcare, Eindhoven, Netherlands) [9–12]. Optimization requires considerable facility resources because treatment planning of IMRT or VMAT is more complex than that of 3D-CRT. In addition, planners may need to reselect field configurations when the resultant dose distribution is clinically unacceptable. For adequate and efficient planning, field configurations should be determined before

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dose-distribution optimization. Although optimization algorithms such as RapidArc and SmartArc are widely used, they do not provide any suggestions for field-configuration selection. Therefore, the plan quality, which is related to the field-configuration selection, depends strongly on the planner's experience. Several studies have investigated beam-angle optimization in IMRT planning [13–15], but few have investigated field-configuration optimization for VMAT. In this regard, one of the challenges is the large number of choices that makes it unrealistic to determine the optimal field arrangement for each patient.

Design of experiments (DoE) is a popular optimization technique. In general, to investigate the output variance with different input selections or combinations, trials must be performed one-by-one by varying only one input. However, with an increasing number of inputs, the number of trials quickly increases greatly. Efficient experimental design must be planned before studying input selection. Experimental design methods using basic statistics were first introduced in the 1920s [16]; they have since been applied to several fields such as biology, mechanical engineering, and radiology [17–19]. Such methods identify the few factors among many that greatly impact the results and then obtain the optimized result by using the best combination of inputs. DoE is a multivariate optimization method that is used for performing effective optimization. To determine the adequate dose distribution for each patient, the DoE method was used and modified for implementation in clinical practice.

In this study, we developed the optimization workflow using DoE of field configurations for VMAT and verified its effectiveness. First, we introduce our workflow that uses computed-tomography (CT) images of treated patients as well as the corresponding structures in our facility. Then, we confirm the efficacy of the proposed method in clinical practice, especially when applied to brain tumors.

2. Materials and methods

2.1. Patient data acquisition

Initially, we selected patient datasets with head and neck cancer or brain tumors to develop the optimization workflow using DoE. Then, to confirm the efficacy of this tool, we retrospectively studied 17 patients with brain tumors who were scheduled to receive VMAT radiation treatment at our facility from 2014 to 2017. The patients were nine men and eight women with a mean age of 41.3 ± 19.7 years (range: 7–69 years). Prescribed doses of 60.0 Gy/30 fractions (8 cases), 54.0 Gy/27 fractions (2 cases), or 50.4 Gy/28 fractions (7 cases) were administered, and 100% doses to 95% of the PTV volume (PTV-D95%) were planned. The Institutional Review Board in our hospital reviewed and approved this study.

CT images were acquired using a 16-slice CT scanner (Light Speed® 16-slice; GE Healthcare, Waukesha WI, USA) and imported into the TPS (Eclipse, Varian Medical Systems, Palo Alto, CA). Scans were performed with tube voltage of 120 kV, tube current of 210 mA, and slice thickness of 2.5 mm. The tube current was modified or used auto-exposure control (AEC) if necessary. Radiation oncologists contoured the gross tumor volume (GTV); clinical target volume (CTV), which included 2–10 mm expansion of the GTV; and planning target volume (PTV), which included 3–5 mm expansion of the CTV. These target volumes were manually modified if necessary. The delineated structures for the brain, brain stem, eyes, optic nerve, and chiasm were focused upon as the OARs. To reduce positional uncertainty, most clinical planning used the planning organ at risk volume (PRV) with 1–3 mm expansion for each OAR [20,21]. The margin size was clinically determined for each case; therefore, different margin sizes were defined for each patient. To eliminate interpatient differences, we used the OAR for analysis instead of the PRV. Data files for the radiation therapy treatment plan (RT-plan), target structures (RT-structure), and CT images were exported from the TPS in the Digital Image and COmmunications in Medicine (DICOM) format.

2.2. Dose-distribution calculation

In the DoE, dose distributions have to be calculated repeatedly by changing the field configuration. However, most commercial TPSs cannot add user-developed functions freely. Because manual calculations are unrealistic when using a TPS for all trials required in the DoE, we originally developed a VMAT dose-distribution simulator using MATLAB (version 9.2, The MathWorks Inc., Natick, MA). By using this dose calculator instead of the TPS, we could automatically determine the field configuration in the DoE. Because the dose simulator is simple, the dose distribution has to be less detailed. Nonetheless, to only determine the combination of best field configurations, it is sufficient to find the dose distribution response for different field configurations. To use the dose simulator instead of the TPS for DoE workflow, the TPS and dose simulator should have high correlation. To verify the simulator function, the resultant dose distribution was compared with that generated by the TPS (Acuros XB algorithm) by using the dose volume histogram (DVH) for several field-configuration selections.

The patient body and other structures were imported from the RT-structure file into the voxel space. The voxel size was 512, and the pixel spacing was 0.977 mm for each axis. As the voxel spacing in the superior–inferior direction of the RT-structure was 2.5 mm, the acquired insufficient data were interpolated using adjacent voxel values. The distance from the patient surface to each objective voxel was calculated along each beam ray line (depth map). The X-ray source was placed 1000 mm from the isocenter. Each voxel on the depth map was multiplied by the percentage depth dose (PDD) obtained using the measured data for our facility (depth-dose map). The depth-dose map was shifted to fit the center voxel position to the isocenter of the RT-plan and was then rotated to designate an arc angle or a couch angle using a rotation matrix. Voxel values on the outside of the collimator window, which was placed toward the body structure, were set to 0. The depth-dose maps of each gantry angle were summed to generate the depth-dose distribution. Finally, the DVH was calculated using the number of voxel values and the volume of each structure (Fig. 1).

2.3. DoE

The optimization factors for field configurations in this study were the couch angle, rotating range of gantry angle (arc angle), collimator angle, field size, and beam energy. We focused on the planning of two fields: one coplanar field and one noncoplanar field. Because both the couch angle and the arc angle are related to the irradiation field trajectory, it is difficult to determine the main factor affecting the dose distribution as an independent value simultaneously (i.e., they interact strongly with each other). To avoid this interaction effect, we used a two-step DoE. In the first step (DoE 1), dose distributions were calculated repeatedly while the couch angle was changed in 15° steps. For the coordinate system, the definition of the International Electrotechnical Commission was used [22], where the positive couch angle direction is defined as the patient's right-hand side when the patient faces vertically upward. Other factors were kept the same. To avoid the collision of the gantry head, a partial angle (200°) was used for the rotating range. In the second step (DoE 2), the arc angle, collimator angle, field size, and energy were determined. For the arc angle, the angle count was started from vertically upward in the clockwise direction of the gantry. For the collimator angle, the pair of 10° and 85° was used as the default setting in this study; this angle set has been used in our facility. Three levels were adopted for the arc angle, collimator angle, and field size, and two were adopted for the energy. Thus, $3 \times 3 \times 3 \times 2 = 54$ trials were required for each field to determine the main effect on the DoE 2. To reduce the number of trials, an L_9 (3^4)-type orthogonal table with four columns and nine rows was used [23]. By using this technique, we reduced the number of trials from 54 to 9 (Table 1) for each field. In the trial list in Table 1, trials of the same level are equally included three times for each row. For example, the