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Implementation of a volumetric modulated arc therapy treatment planning solution for kidney and adrenal stereotactic body radiation therapy

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ABSTRACT

To develop a volumetric modulated arc therapy (VMAT) treatment planning solution in the treatment of primary renal cell carcinoma and oligometastatic adrenal lesions with stereotactic body radiation therapy. Single-arc VMAT plans ($n = 5$) were compared with clinically delivered step-and-shoot intensity-modulated radiotherapy (IMRT) with planning target volume coverage normalized between techniques. Target volume conformity, organ-at-risk (OAR) dose, treatment time, and monitor units were compared. A VMAT planning solution, created from a combination of arc settings and optimization constraints, auto-generated treatment plans in a single optimization. The treatment planning solution was evaluated on 15 consecutive patients receiving kidney and adrenal stereotactic body radiation therapy. Treatment time was reduced from 13.0 ± 2.6 to 4.0 ± 0.9 minutes for IMRT and VMAT, respectively. The VMAT planning solution generated treatment plans with increased target homogeneity, improved 95% conformity index, and a reduced maximum point dose to nearby OARs but with increased intermediate dose to distant OARs. The conformity of the 95% isodose improved from 1.32 ± 0.39 to 1.12 ± 0.05 for IMRT and VMAT treatment plans, respectively. Evaluation of the planning solution showed clinically acceptable dose distributions for 13 of 15 cases with tight conformity of the prescription isodose to the planning target volume of 1.07 ± 0.04, delivering minimal dose to OARs. The introduction of a stereotactic body radiation therapy VMAT treatment planning solution improves the efficiency of planning and delivery time, producing treatment plans of comparable or superior quality to IMRT in the case of primary renal cell carcinoma and oligometastatic adrenal lesions.

Introduction

Stereotactic body radiation therapy (SBRT) is an emerging treatment modality for the treatment of primary renal cell carcinoma and oligometastatic adrenal lesions. Traditionally, kidney cancer has been considered radioresistant owing to poor local control rates attained with conventional radiotherapy fractionation schemes (*i.e.*, 2 Gy per fraction).[1] Surgery has been and continues to be the standard treatment option for primary localized kidney cancer. Similarly, some patients have surgical resection of solitary adrenal metastases. This approach, however, is not suitable for patients with medical comorbidities, which preclude them from surgery.[2]

SBRT uses a high dose per fraction treatment protocol to aggressively target malignant disease. The high daily dose of $\geq$6 Gy typically used in SBRT is thought to overcome the inherent radioresistance of the cancer and lead to higher local control of the tumor.[1] Various studies in the literature report local control rates ranging from 44% to as high as 93% at 1 year and 27% to 44% at 2 years.[1-4] In addition to tumor control, SBRT provides improved sparing of adjacent normal tissues through the use of advanced image guidance techniques such as 4D computed tomography (4DCT) and kilovoltage cone beam CT (kV-CBCT), highly conformal dose distributions with steep dose gradients, sophisticated

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immobilization techniques to minimize breathing motion, and the use of a robotic couch to correct for setup misalignments in 6 degrees of freedom.[5,6] The use of advanced diagnostic imaging facilitates accurate target delineation by physicians and accounts for internal organ motion, whereas the application of immobilization tools and online imaging with automatic position correction permits a reduction in treatment margins owing to interfraction and intrafraction motions. Further benefits from the use of SBRT with concomitant chemotherapy have also been suggested via the induction of an abscopal effect.[7] Here, immunologic processes become stimulated to provide a natural systemic therapy supplementing the prescribed treatment regimen to improve tumor response.

Given the advancement of radiotherapy treatment techniques, multiple delivery methods of SBRT have been proposed: 3D conformal static fields, intensity-modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), and intensity-modulated proton therapy.[8] IMRT or VMAT is recommended as the first option for patients not suitable for surgery, if proton therapy is not available. Given the proposed benefits provided with SBRT, we sought to develop a radical radiotherapy treatment protocol for primary renal cell carcinoma and oligometastatic adrenal lesions. The specific aims of this study are twofold: (1) to evaluate the quality of VMAT when compared with clinically delivered IMRT treatment plans and (2) to develop a generalized treatment planning solution to improve planning efficiency regardless of tumor laterality.

Methods and Materials

This study was approved by the institutional ethics committee. The treatment planning process and plan quality were retrospectively evaluated by analyzing 4DCT image data sets.

Overall, 15 SBRT patients were immobilized in the Elekta BodyFIX system and treated on an Elekta Synergy beam modulator with a 4-mm multileaf collimator leaf width equipped with kV-CBCT and a hexapod robotic couch capable of correcting in 6 degrees of freedom. CT simulation was performed using a helical 4DCT with the gross tumor volume delineated on the inhale, exhale, and average projection phases.[9] No margins were added to generate the clinical target volume, and the internal target volume (ITV) was a fusion of the 3 clinical target volume contours from the imaging phases. A 5-mm isotropic planning target volume (PTV) margin was applied to the ITV based on our institutional experience, producing PTV volumes ranging from 14.4 cm^3 to 281.3 cm^3 (102.2 $\pm$ 69.0 cm^3). IMRT and VMAT treatment plans were generated using Pinnacle v9.2 (Philips, Andover, MA). Dose was prescribed to the ITV to 35–40 Gy and to the PTV to 95% of the ITV prescription, depending on target proximity to organs-at-risk (OARs), in 5 fractions delivered every second day.

IMRT and VMAT plan quality comparison and evaluation

The first 5 patients were treated with step-and-shoot IMRT and were replanned with VMAT, based on their unique clinical scenario, for comparison purposes only to verify that VMAT plans were equivalent or superior to IMRT treatments. The clinical scenario of these 5 patients varied based on the type of lesion (3 adrenal metastases *vs* 2 primary renal cell carcinoma), laterality (2 left *vs* 3 right), and the presence of a solitary kidney ($n = 1$). The IMRT plans delivered clinically consisted of coplanar beams of 7 to 9 6 MV with various collimator rotations and 1 to 2 noncoplanar beams for maximum OAR sparing, whereas the VMAT plans were restricted to a single 360° arc to allow for the subsequent VMAT planning solution to be applicable to all tumors regardless of laterality. Both treatment techniques were developed by multiple planners to meet the same OAR constraints with identical optimization structures used to constrain the delivered dose. The VMAT plans were reviewed by a medical physicist and radiation oncologist for target coverage, conformity, and dose to OARs. The settings used to define the beam parameters (multileaf collimator motion, gantry spacing, and treatment time) and dose calculation (dose algorithm, calculation grid size, total and conversion to machine iterations, and intermediate dose calculation at conversion iteration) were then varied to determine their effect on the dose distribution and dose-volume histogram (DVH) results to acquire a collection of settings that produced a clinically acceptable dose distribution with an efficient optimization calculation and high degree of accuracy. Table 1 illustrates the final parameters established for VMAT. The collapsed cone algorithm is a convolution-superposition technique and is the most accurate option for dose calculation in Pinnacle; however, the extended treatment time of 1000 seconds, compared with the default of 90 seconds, is for optimization purposes and does not translate into actual beam delivery time. Shorter beam delivery parameters used during optimization unnecessarily restrict the direct machine parameter optimization to larger segments, higher dose rates, and faster gantry motion resulting in a suboptimal treatment plan that does not translate to a clinically significant decrease in beam delivery time. As a result, a time that was large enough to avoid placing additional limitations on the optimization algorithm was selected. Comparatively, the 4° gantry spacing used for the VMAT plans resulted in 91 control points for a single arc, whereas the IMRT plans were constrained to $\leq$30 control points across all beams with minimum segment area $\geq$8 cm^2 and minimum monitor units (MUs) $\geq$10. Plan comparison was then achieved by normalizing the VMAT PTV coverage of the prescription isodose, 95% isodose, to the PTV coverage in the IMRT plans delivered clinically. Plan quality was then assessed through OAR sparing and the calculated conformity index (CI) of the gradient and prescription isodose to the PTV (50% and 95% isodoses, respectively) using the ICRU definition:[10]

Table 1
VMAT beam and optimization parameters

Parameter	Setting
Beam	360° Single arc
Collimator	15°
MLC leaf motion	$\leq$0.45 cm/°
Gantry spacing	4°
Treatment time	1000 s
Dose algorithm	Collapsed cone convolution
Calculation grid size	2.5 × 2.5 × 2.5 mm^3
Total optimization iterations	100
Conversion iterations to machine specifications	25
Intermediate dose calculation	Yes

$$CI_x = \frac{\text{Volume encompassed by the } x\% \text{ isodose}}{\text{PTV volume}}$$

with a desired CI of the prescription isodose less than 1.20 for both IMRT and VMAT treatment techniques, whereas a CI of less than 1.40 is acceptable for cases of increased complexity. Each of the 5 VMAT plans then underwent quality assurance (QA) using a cylindrical diode array adopting the global percent difference gamma pass criteria of 3%/3 mm for low/high-dose gradients and a threshold of 10% for disregarding low dose comparisons with a pass defined as agreement between $\geq$95% of the points. Total MUs and treatment delivery time were also compared between the treatment techniques by measuring the time from initial beam start to completion of treatment delivery for both IMRT and VMAT plans during the QA measurements.

Generation of a VMAT treatment planning solution

With the VMAT beam parameters set, a list of dose constraints that produced clinically acceptable treatment plans after a single optimization was generated. This was achieved by investigating the constraints used for each individual plan and compiling a list of the OARs that most affected the plan's dose distribution. The dose constraints and respective weightings for these selected contours were then taken as an approximate average across all plans to determine the starting point for the optimization. Selected contours included the following: ITV, PTV hollow (PTV-ITV), small bowel, large bowel, spinal cord, spinal cord + 5 mm, kidneys-PTV, a 1-cm thick ring structure surrounding the PTV and acting as an avoidance structure to improve the conformity of the high isodoses and normal tissue sparing, and a tissue contour encompassing all normal tissue beyond the boundaries of the 1-cm ring for the purposes of constraining the dose gradient. Through an iterative process, a collection of optimization constraints were created that, together with the VMAT beam parameters given in Table 1, constituted the VMAT planning solution. This solution was then tested on 15 consecutive patients treated to date to evaluate the quality of treatment plans produced following one optimization. The quality of these plans was assessed using recommended OAR SBRT constraints found in the report of AAPM Task Group 101 and a spine SBRT consensus guidance study for probabilities of radiation myelopathy with healthy kidney mean dose values scaled from conventional fractionation, and target coverage goals provided in Table 2 (*i.e.*, the volume of the ITV and PTV receiving 100% and 95% of the dose, respectively, with the CI of the prescription isodose to the PTV less than 1.20).[11,12]

Results

First, comparison between step-and-shoot IMRT and single-arc VMAT plans displayed no reduction in the MUs required for treatment for the 5 patients planned with both techniques—an