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Feasibility study of volumetric modulated arc therapy with constant dose rate for endometrial cancer

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ABSTRACT

To investigate the feasibility, efficiency, and delivery accuracy of volumetric modulated arc therapy with constant dose rate (VMAT-CDR) for whole-pelvic radiotherapy (WPRT) of endometrial cancer. The nine-field intensity-modulated radiotherapy (IMRT), VMAT with variable dose-rate (VMAT-VDR), and VMAT-CDR plans were created for 9 patients with endometrial cancer undergoing WPRT. The dose distribution of planning target volume (PTV), organs at risk (OARs), and normal tissue (NT) were compared. The monitor units (MUs) and treatment delivery time were also evaluated. For each VMAT-CDR plan, a dry run was performed to assess the dosimetric accuracy with MatriXX from IBA. Compared with IMRT, the VMAT-CDR plans delivered a slightly greater V_{20} of the bowel, bladder, pelvis bone, and NT, but significantly decreased the dose to the high-dose region of the rectum and pelvis bone. The MUs decreased from 1105 with IMRT to 628 with VMAT-CDR. The delivery time also decreased from 9.5 to 3.2 minutes. The average gamma pass rate was 95.6% at the 3%/3 mm criteria with MatriXX pretreatment verification for 9 patients. VMAT-CDR can achieve comparable plan quality with significant shorter delivery time and smaller number of MUs compared with IMRT for patients with endometrial cancer undergoing WPRT. It can be accurately delivered and be an alternative to IMRT on the linear accelerator without VDR capability.

Introduction

With the recent development of planning and delivery techniques, volumetric modulated arc therapy (VMAT) has been shown to give better or equivalent plan quality, but much higher delivery efficiency compared with conventional intensity-modulated radiation therapy (IMRT).[1-6] Cilla *et al.*[7] reported the feasibility of VMAT in the postoperative irradiation of the vaginal vault alone, as an alternative to high dose-rate brachytherapy, considering the brachytherapy unit, theater, and dose limitation for deeply seated or irregular targets. They found that VMAT plans can be planned and carried out with high quality and efficiency for the irradiation of vaginal vault alone, providing similar or better sparing of organs at risk (OARs) than fixed-field IMRT and resulting in the most efficient treatment option. In multiarc VMAT, intensity modulations are achieved by superimposing multiple overlapping arcs at multiple beam angles, whereas single-arc VMAT techniques deliver conformal dose distributions to the target in 1 single gantry rotation. The segments in single-arc VMAT are evenly distributed within an arc and have different monitor unit (MU) weightings. Therefore, a variable dose-rate (VDR)–capable linac is required for delivery, in which the radiation dose varies by changing the dose rate during gantry rotation. The VDR VMAT capability is not available for the low- or intermediate-end linacs without upgrade, such as Precise from Elekta, or 2100EX or 21EX from Varian. VDR requires complicated software and hardware control and expensive equipment, not all institutions have the facilities and personnel for VMAT-VDR, especially in the underdeveloped countries and regions. The purpose of this study was to explore the feasibility, efficiency, and delivery accuracy of an alternative technique for VMAT using constant dose-rate (CDR) delivery for the whole-pelvic radiotherapy (WPRT) of endometrial cancer.

Methods and Materials

Patient selection and simulation

Nine consecutive patients who had been treated with postoperative WPRT for endometrial cancer were retrospectively selected for this study. All patients had undergone total abdominal hysterectomy and bilateral salpingo-oophorectomy and pelvic or para-aortic lymph node dissection/sampling or both, with no gross

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residual disease. Of the 9 patients, 7 were simulated and treated in the supine position and 2 patients in the prone position on the belly board. A vaginal marker was inserted to indicate the position of the vaginal apex, carefully not to distort the vagina. All patients were instructed to drink 1500 mL of water 1 hour before simulation and treatment, they were then immobilized using thermoplastic mask and scanned with oral and intravenous contrast from the T12 vertebrate to midthigh, with the slice thickness of 5 mm. The image sets were transferred to the Pinnacle planning system for contouring and planning.

Definition and contour of targets

The clinical target volume (CTV) was delineated according to the consensus guidelines of Radiation Therapy Oncology Group.[8] The CTV included pelvic lymph node regions (common, internal, and external iliacs), the proximal 3.0 cm of the vagina, and paravaginal tissues for all the patients. For patients with cervical stromal invasion, the presacral lymph node region was also contoured to the inferior border of S2. A margin of 0.7 cm was added to the "vessels" contour in all dimensions and modified by anatomic boundaries (as clinically indicated for individual patients) to create the nodal CTV, from which the pelvic bones, femoral heads, and vertebral bodies were excluded. The CTV was expanded by 1 cm to create the planning target volume (PTV).

Definition and contour of OARs and normal tissue (NT)

The OARs contoured include the bladder, rectum, small intestine, colon, and pelvic bones. The superior and inferior extents of OARs were outlined on all computed tomography slices in which portions of the PTV existed, as well as at an additional 2-cm superior and inferior to the limits of the PTV. The rectum was defined from the rectosigmoid flexure to anus. The small intestine and colon were contoured together as 1 structure referred to as the "bowel." The pelvic bones were defined and contoured according to previous publication.[9] The external contour of all bones within the pelvis was delineated for each patient. The entire bony contour was divided into 3 subsites: ilium, lower pelvis, and lumbosacral spine. No expansion of all these OARs was made to account for the organ's motion and setup error. The whole body was contoured as the entire volume of all slices where PTV existed, as well as at an additional 2-cm superior and inferior to PTV. The NT is defined as the whole body within the skin surface minus the PTV.

Treatment planning

The IMRT, VMAT-VDR, and VMAT-CDR plans were created with 6-MV photon beams for each patient using Pinnacle planning system, version 9.2 (Philips Radiation Oncology Systems, Fitchburg, WI), for delivery using a Varian Trilogy linear accelerator equipped with the Millennium MLC. The linear accelerator was calibrated to deliver 1 cGy/MU for 10 cm × 10 cm field at depth of 1.5 cm and 101.5 cm from source. All plans were generated for IMRT, VMAT-VDR, and VMAT-CDR using the same plan objectives (Table 1). The dose-volume objectives and constraints used in this study were defined in our department protocol with the literature[10] as reference, with a little adjustment.

The IMRT plan optimization was performed by utilization of the Direct Machine Parameter Optimization algorithm in the Pinnacle[3] treatment planning system. Some studies[11,12] show that Direct Machine Parameter Optimization achieved better overall plan quality with less MUs than fluence modulation with subsequent leaf sequencing algorithm. Based on the findings of previous studies,[13,14] 9 coplanar beams were used. Fields were set with equal space of 40° and the starting angle of 0°. The minimum segment area was set to 5 cm^2 and minimum segment MU was 5 MUs.

The VMAT-VDR and VMAT-CDR plans were optimized using the SmartArc module in Pinnacle.[3] The details about the SmartArc planning algorithm have been described by Bzdusek *et al.*[15] All VMAT-VDR plans were generated using 1 dual arc, the first clockwise from 181° to 179° and the second counterclockwise from 179° to 181°, with a final control points resolution of 2°. To allow maximal modulation per arc, no limitation on the delivery time was used during the optimization. Continuous gantry motion, dose-rate variation, and MLC motion were approximated by optimizing individual beams at 2° gantry angle increments. The choice of this resolution was based on preliminary planning exercises to get better plan quality utilizing the higher degree of modulation. A fixed collimator angle of 10° and 350° were used in the VMAT-VDR and VMAT-CDR plans to minimize the tongue-and-groove effects. Other planning parameters were MLC motion speed 0 to 2.5 cm/s, gantry rotation speed 0.5 to 4.8 degrees/s, and dose rate 0 to 600 MU/min. Different from the VDR in VMAT-VDR, CDR of 200 MU/min was used in the VMAT-CDR plans. In addition to that, the delivery time limit of 90 seconds per arc was set in the VMAT-CDR plans. A collapsed-cone convolution superposition algorithm was used to calculate the dose distribution for the IMRT, VMAT-VDR, and VMAT-CDR plans, with a dose grid resolution of 4 mm.

Table 1
The dose-volume objectives and constraints used in IMRT, VMAT-VDR, and VMAT-CDR

Structures	Objectives and constraints	Penalty factors
PTV	Minimal dose, 47.5 Gy; maximal dose 55 Gy	90
	≥95% of PTV receiving 50 Gy;	90
Bowel	≤35% of bowel receiving ≥35 Gy	30
Bladder	≤40% of bladder receiving ≥40 Gy	30
Rectum	≤60% of rectum receiving ≥40 Gy	50

Dosimetric comparison

For the convenience of comparison, all plans were normalized to deliver 50 Gy in 25 fractions to 95% of the PTV. The dose-volume histograms (DVHs) of the IMRT, VMAT-VDR, and VMAT-CDR plans were compared for the PTV coverage, OARs, and NT sparing. The parameters analyzed included the percentage of PTV receiving 95%, 100%, 105%, and 110% of the prescription dose (PTV_{95}, PTV_{100}, PTV_{105}, and PTV_{110}); the homogeneity index (HI); and conformity index (CI). The HI was defined as D5%/D95% (minimum dose in 5% of the PTV/minimum dose in 95% of the PTV). The lower (closer to 1) the HI is, the better the dose homogeneity. Because not all parts of the PTV were covered by the prescribed dose, the CI was calculated as follows: CI = CF (cover factor) × SF (spill factor), where the CF was defined as the percentage of the PTV volume receiving at least the prescribed dose and the SF as the volume of the PTV receiving at least prescription dose relative to the total prescription dose volume.[16] The closer the CI value is to 1, the better the dose conformity. To quantify the dose distribution of OARs and NT in different dose levels, the percentage volume of the OARs and NT receiving a dose of 2 Gy, 5 Gy, 10 Gy, 20 Gy, 30 Gy, 40 Gy, and 50 Gy (V_2, V_5, V_{10}, V_{20}, V_{30}, V_{40}, and V_{50}) were evaluated and compared for IMRT, VMAT-VDR, and VMAT-CDR plans. The mean dose and integral dose (ID) to OARs and NT were also compared. The ID is equal to the mean dose times the volume of each structure.

MU and treatment delivery time

For comparison of the efficiency of IMRT, VMAT-VDR, and VMAT-CDR, the MUs and treatment delivery time were also recorded and evaluated. In this study, the treatment delivery time was defined as the time from first beam-on until the last beam is turned off.

Treatment plan verification

For deliverability checks and dosimetric verification purposes, each of the VMAT-CDR plans was delivered to the MattriXX/Multicube phantom (IBA Corporations, Belgium). The MattriXX/Multicube phantom was placed on the treatment couch for measurements. The VMAT-CDR plans were delivered with the Varian Trilogy linear accelerator. The 2D dose distributions at the coronal plane were measured with MattriXX and compared with predictions by the Pinnacle planning system. The measurements and calculations were analyzed using the Omnipro IMRT software. A gantry angle correction was applied considering the angular dependency of the MatriXX detectors. A gamma evaluation was performed with inclusion of the points with a dose of at least 10% of the maximum dose. The dose criterion was 3% of the global maximum absolute dose and the distance criterion was 3 mm. It was considered acceptable clinically if more than 95% of the evaluated points passed the gamma criteria.

Statistics

The dosimetric differences of VMAT-CDR were compared with those of IMRT and VMAT-VDR. The significance of differences was tested using a paired 2-tailed Student t-test. A 2-tailed p value < 0.05 was considered statistically significant. Analyses were performed using Statistical Package for Social Science, version 13.0, software (SPSS, Chicago, IL).

Results

PTV coverage

The volumes of PTV, bowel, and bladder were 1035 (901 to 1179) cc, 889.0 (526.0 to 1136.3) cc, and 321.1 (51.7 to 90.3) cc, respectively. For all 9 cases, clinically acceptable plans could be generated for IMRT, VMAT-VDR and VMAT-CDR. The typical isodose distribution and the DVH comparison were given in Figs. 1 and 2. The data for PTV coverage are summarized in Table 2. Both VMAT-VDR and VMAT-CDR significantly improved the PTV dose homogeneity compared with IMRT. No significant difference was found in plans between VMAT-VDR and VMAT-CDR. The average HI was 1.10, 1.06, and 1.07 for IMRT, VMAT-VDR, and VMAT-CDR plans. The mean CI was 0.87, 0.89, and 0.87 for IMRT,