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Modeling the target dose fall-off in IMRT and VMAT planning techniques for cervical SBRT

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ABSTRACT

There has been growing interest in the use of stereotactic body radiotherapy (SBRT) technique for the treatment of cervical cancer. The purpose of this study was to characterize dose distributions as well as model the target dose fall-off for intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) delivery techniques using 6 and 10 MV photon beam energies. Fifteen (n = 15) patients with non-bulky cervical tumors were planned in Pinnacle[3] with a Varian Novalis Tx (HD120 MLC) using 6 and 10 MV photons with the following techniques: (1) IMRT with 10 non-coplanar beams (2) dual, coplanar 358° VMAT arcs (4° spacing), and (3) triple, non-coplanar VMAT arcs. Treatment volumes and dose prescriptions were segmented according to University of Texas Southwestern (UTSW) Phase II study. All plans were normalized such that 98% of the planning target volume (PTV) received 28 Gy (4 fractions). For the PTV, the following metrics were evaluated: homogeneity index, conformity index, D_{2cc}, D_{mean}, D_{max}, and dose fall-off parameters. For the organs at risk (OARs), D_{2cc}, D_{15cc}, $D_{0.01cc}$, V_{20}, V_{40}, V_{50}, V_{60}, and V_{80} were evaluated for the bladder, bowel, femoral heads, rectum, and sigmoid. Statistical differences were evaluated using a Friedman test with a significance level of 0.05. To model dose fall-off, expanding 2-mm-thick concentric rings were created around the PTV, and doses were recorded. Statistically significant differences ($p < 0.05$) were noted in the dose fall-off when using 10 MV and $VMAT_{3\text{-}arc}$, as compared with IMRT. $VMAT_{3\text{-}arc}$ improved the bladder V_{40}, V_{50}, and V_{60}, and the bowel V_{20} and V_{50}. All fitted regressions had an $R^2 \geq 0.98$. For cervical SBRT plans, a $VMAT_{3\text{-}arc}$ approach offers a steeper dose fall-off outside of the target volume. Faster dose fall-off was observed in smaller targets as opposed to medium and large targets, denoting that OAR sparing is dependent on target size. These improvements are further pronounced with the use of 10-MV photons.

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Introduction

Cervical cancer is the third most common gynecological cancer in the United States and the third leading cause of cancer death among females in less developed countries.[1] Radiation therapy is widely used in the treatment of

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cervical cancer consisting of external beam followed by brachytherapy (BT), which delivers a high dose to the center of the tumor while sparing organs at risk (OARs).[2] BT delivery, however, can be hindered for various reasons including the inability to cannulate the cervical ostium uteri, stenotic vaginas, and large tumors extending to the pelvic sidewall.[3,4] In these cases where BT is infeasible, available treatment options are conventionally fractionated external beam radiotherapy using either 3-dimensional conformal radiation therapy or intensity-modulated radiation therapy (IMRT), or stereotactic body radiation therapy (SBRT) techniques. Because of the close proximity of OARs, prescription dose conformity and fast dose fall-off are of utmost importance for cervical cancer, especially during SBRT, to minimize the irradiation of large volumes of the adjacent bowel, rectum, sigmoid, and bladder.[5] Although various studies have shown high conformity and fast dose fall-off in SBRT treatments of liver, lung, and kidney cancers, there is limited literature on the treatment plan quality as a function of radiation delivery technique for cervical SBRT planning.[6-8]

Several studies comparing the efficacy of IMRT and SBRT replacing BT for the treatment of cervical cancer have been performed.[9-16] However, most studies are retrospective analyses using various delivery techniques, dose fractionation schemes, and follow-up times in small patient populations. Moreover, studies were inconsistent in their reporting of dosimetric information for normal tissue as well as target volume, so challenges in deciphering the optimal deliveries technique is a challenge.[17,18] Currently, there is an ongoing phase II clinical trial at the University of Texas Southwestern Medical Center studying the efficacy of using a hypofractionated SBRT cervical boost treatment scheme in lieu of BT.[19] In seeking to establish conclusive clinical outcome data from this trial, an understanding of the optimal radiation delivery technique would be of substantial benefit.

A study has yet to demonstrate if an ideal radiation delivery technique may work to best deliver SBRT. It has been shown that using a 4π treatment planning approach with multiple non-coplanar beams offers superior planning target volume (PTV) coverage and improved dosimetric fall-off while increasing OAR sparing when compared with volumetric-modulated arc therapy (VMAT) in liver SBRT treatments.[20] Similarly, a recent study evaluating delivery techniques in prostate cancer found a decrease in dose fall-off, monitor units (MUs), and dose to OARs with the use of 10 MV compared with 6 MV photon energies.[21,22] In light of this, the purpose of this study was to evaluate the dose distributions of cervical SBRT treatment plans. Particularly, the dose fall-off for IMRT and VMAT techniques was evaluated by expanding the metrics from the traditional R_{50}, to metrics from R_{10} to R_{95}, using 2 photon energies (6 and 10 MV). Key objectives of the study were to quantify dosimetric differences among delivery techniques, between photon energies, and among target volume sizes.

Methods and Materials

Patient selection

This retrospective treatment planning study included 15 previously treated patients with non-bulky cervical tumors over a 2-year period. All patients were clinically treated with BT following external beam radiotherapy. Simulation computed tomography scans were acquired from L1 to the femur's diaphysis with 2.5-mm slice thickness, with patients positioned supine using a Vac-Lok (CIVCO Orange City, IA) immobilization device. Clinical target volume (CTV) definition was performed by a board-certified radiation oncologist conforming to the ongoing cervical cancer clinical trial volume guidelines.[19] In 4 of the 15 patients with no clearly defined tumor, 2 CTVs were created and planned separately. The first volume assumed no residual tumor, whereas the second volume assumed a 1-cm lesion at the cervical ostium uteri. Fifteen total PTVs for all 15 patients were analyzed using an isotropic 5-mm setup margin to create the PTV.

Planning techniques

Treatment plans were generated in Pinnacle[3] Version 9.10 (Philips Medical, Fitchburg, WI) using both 6 and 10 MV energies with the following delivery techniques: (1) step-and-shoot IMRT (SS-IMRT) with 10 non-coplanar, non-opposing beams, (2) VMAT using 2 coplanar arcs ($VMAT_{2\text{-arc}}$), and (3) VMAT using 3 non-coplanar arcs ($VMAT_{3\text{-arc}}$). Figure 1 illustrates a 3-dimensional view for a selected patient showing the beam arrangements for each delivery technique. For SS-IMRT, 10 non-coplanar, non-opposing fixed field beams were used for all patients. The coplanar VMAT plans ($VMAT_{2\text{-arc}}$) and non-coplanar VMAT plans ($VMAT_{3\text{-arc}}$) were defined as 2 coplanar 358° arcs with the collimator at 225°, and 3 arcs had 1 full 358° arc and two 180° arcs with couch kicks, respectively. For plan optimization and dose calculation, SS-IMRT beams were optimized using a direct machine parameter optimization technique, and VMAT beams were optimized using a SmartArc technique with 4° spacing. The optimization objectives were identical across all energies, beam arrangements, and patients. Final dose calculations were performed using the collapsed cone, adaptive convolve algorithm with dose grid voxel size of $2 \times 2 \times 2$ mm^3.

All plans were optimized with similar planning objectives and normalized such that 98% of the PTV received at least 28.0 Gy in 4 fractions. Target planning optimization objectives included a minimum and maximum dose for PTV and a minimum dose to CTV. Ring structures were created