Int. J. Radiation Oncology Biol. Phys., Vol. 77, No. 2, pp. 591–599, 2010

0360-3016/$–see front matter

ELSEVIER

doi:10.1016/j.ijrobp.2009.08.056

PHYSICS CONTRIBUTION

OPTIMIZATION OF COLLIMATOR TRAJECTORY IN VOLUMETRIC MODULATED ARC THERAPY: DEVELOPMENT AND EVALUATION FOR PARASPINAL SBRT

Pengpeng Zhang, Ph.D.,* Laura Happersett, M.S.,* Yingli Yang, Ph.D.,* Yoshiya Yamada, M.D.,† Gig Mageras, Ph.D.,* and Margie Hunt, M.S.*

Departments of *Medical Physics and †Radiation Oncology, Memorial Sloan-Kettering Cancer Center, New York, NY

Purpose: To develop a collimator trajectory optimization paradigm for volumetric modulated arc therapy (VMAT) and evaluate this technique in paraspinal stereotactic body radiation therapy (SBRT).
Method and Materials: We propose a novel VMAT paradigm, Coll-VMAT, which integrates collimator rotation with synchronized gantry rotation, multileaf collimator (MLC) motion, and dose-rate modulation. At each gantry angle a principal component analysis (PCA) is applied to calculate the primary cord orientation. The collimator angle is then aligned so that MLC travel is parallel to the PCA-derived direction. An in-house VMAT optimization follows the geometry-based collimator trajectory optimization to obtain the optimal MLC position and monitor units (MU) at each gantry angle. A treatment planning study of five paraspinal SBRT patients compared Coll-VMAT to standard VMAT (fixed collimator angle) and static field IMRT plans. Plan evaluation statistics included planning target volume (PTV) V95%, PTV-D95%, cord-D05%, and total beam-on time.
Results: Variation of collimator angle in Coll-VMAT plans ranges from 26° to 54°, with a median of 40°. Patient-averaged PTV V95% (94.6% Coll-VMAT vs. 92.1% VMAT and 93.3% IMRT) and D95% (22.5 Gy vs. 21.4 Gy and 22.0 Gy, respectively) are highest with Coll-VMAT, and cord D05% (9.8 Gy vs. 10.0 Gy and 11.7 Gy) is lowest. Total beam-on time with Coll-VMAT (5,164 MU) is comparable to standard VMAT (4,868 MU) and substantially lower than IMRT (13,283 MU).
Conclusion: Collimator trajectory optimization-based VMAT provides an additional degree of freedom that can improve target coverage and cord sparing of paraspinal SBRT plans compared with standard VMAT and IMRT approaches. © 2010 Elsevier Inc.

Volumetric modulated arc therapy, Treatment planning, Trajectory optimization, Paraspinal, SBRT.

INTRODUCTION

Sweeping window arc therapy (1, 2) or volumetric modulated arc therapy (VMAT) (3–6) is receiving broad interest and gaining research and development momentum. Planning studies from various institutions demonstrate that VMAT plans have similar dosimetric quality but much-reduced treatment delivery time compared with the standard intensity-modulated radiation therapy (IMRT) approach (7–11). Although shortening daily treatment time is a much desired feature in the context of patient motion management, improving the capability of VMAT for dose modulation is crucial for its viability in the clinic. In VMAT delivery, gantry, dose rate, and multileaf collimator (MLC) are optimized and synchronized to deliver modulated radiation. The linac mechanical axes that are possible but not addressed in the current VMAT optimization approaches are the collimator angle and couch angle. Otto and Clark (12) and Milette and Otto (13) investigated integration of collimator rotation into direct aperture-based IMRT optimization and found that rotating aperture optimization (RAO) can improve plan quality. In RAO approaches, there is either no restriction on collimator angle, or there is an equal angle increment between beams. RAO implicitly includes collimator rotation during optimization rather than explicitly optimizing the collimator in a separate step; therefore, RAO is not easily applicable to VMAT unless an optimal combined collimator-gantry trajectory is found. The purpose of this study was to develop a collimator trajectory optimization that can be used with VMAT (Coll-VMAT) to improve the ability of VMAT to modulate dose while maintaining the rapid feature of a single arc therapy.

Although most VMAT comparison studies in the literature thus far examined conventional fraction sizes (1.8 or 2 Gy), the shortened treatment time of VMAT could be

Reprint requests to: Pengpeng Zhang, Ph.D., Memorial Sloan-Kettering Cancer Center, Medical Physics Department, 1275 York Ave., New York, NY 10065. Tel: (646)888-5616; Fax: (646)888-5626; E-mail: zhangp@mskcc.org

Conflict of interest: Memorial Sloan-Kettering Cancer Center has a research agreement with Varian Medical Systems.

Acknowledgment—We thank Yves Archimbault from Varian Medical Systems, Palo Alto, CA for his help and discussion regarding Varian's implementation of RapidArc.

Received May 11, 2009, and in revised form Aug 18, 2009. Accepted for publication Aug 20, 2009.

beneficial for radiosurgery, stereotactic body radiation therapy (SBRT), and hypofractionated treatments in which fraction sizes can be as high as 24 Gy and treatment delivery times often exceed half an hour. For such cases, VMAT could become the treatment technique of choice as long as dosimetric quality comparable to fixed-gantry IMRT can be achieved.

Paraspinal lesions are typical of sites treated with high-dose single-fraction SBRT at our and other institutions (14, 15), in that the treatment volume is relatively small but planning is complicated by the close proximity of critical structures. In the case of paraspinal lesions, the planning target volume (PTV) often wraps partway around the spinal cord and a steep dose gradient along the PTV–cord boundary is required. The primary challenge is to deliver a high-prescription dose to the PTV while limiting the spinal cord maximum dose. At our institution, a dose of 24 Gy is typically delivered to the PTV, and the cord is limited to 14 Gy. Achieving the steep dose gradient between cord and PTV often is complicated by the concave shape of the PTV and the proximity to the spinal cord. A similar geometry is found in Bortfeld and Webb's (16) theoretical study comparing single arc VMAT to IMRT, using an analytical phantom originally proposed by Brahme (17). Bortfeld and Webb pointed out that the ideal fluence map blocks the cord from all beam orientations, has a high fluence in a narrow band at the PTV–cord boundary, and has a lower, rather broad and flat fluence elsewhere to cover the PTV.

A beam's-eye view (BEV) of the anatomy and MLC setup encompassing the PTV and excluding the cord is shown in Fig. 1. Many combinations of collimator angle (defined according to the International Electrotechnical Commission convention) and MLC aperture can be used to achieve the ideal fluence map. For any of these configurations, excess MLC blocking of the PTV at any given gantry angle occurs for two reasons: cord curvature relative to the direction of MLC leaf travel (pink area) and blocking of the PTV as a consequence of cord blocking (yellow area). The pink area is more or less randomly distributed and comparable for many collimator angles; however, the yellow area is dependent on the collimator angle. In the extreme case shown in Fig. 1, a poorly chosen collimator angle (0°, Fig. 1a) has much more excess PTV blocking than the optimal angle (110°, Fig. 1b), where MLC leaf travel is parallel to the cord primary orientation. Moreover, at 0° collimator angle, the left bank of leaves is used to block the cord, leaving only the right bank (seven leaves) to modulate the dose to PTV and spare the other critical organs. With the collimator rotated to 110°, only two leaf pairs are needed to block the cord and the remaining 14 leaves are available to shape the dose distribution. In other words, optimal choice of collimator angle increases the optimization "freedom" to shape a desired dose distribution. The potential for dosimetric improvement achieved through optimized collimator rotation during VMAT treatment is the motivation for this study. We explore methodology for such an optimization technique and present dosimetric results in the context of the Memorial Sloan Kettering Cancer Center paraspinal SBRT paradigm (14, 15).

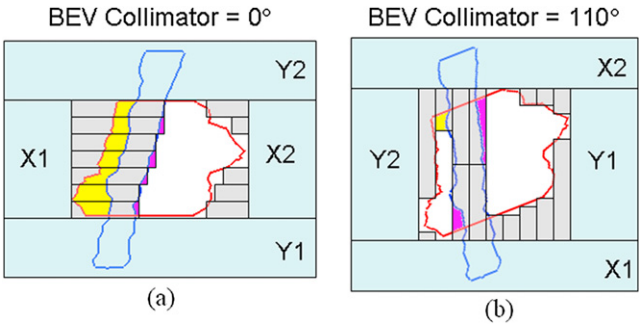

Fig. 1. Beam's-eye view (BEV) of a multileaf-collimated field that blocks the cord (blue curve) while treating a paraspinal lesion planning target volume (PTV; red), at (a) 0° and (b) 110° collimator angle. Optimal collimator rotation helps reduce excess blocking of PTV in volumetric modulated arc therapy.

METHODS AND MATERIALS

Collimator trajectory optimization

As the gantry rotates, the projection of the spinal cord in the beam's eye view changes, as does its primary orientation. Consequently, a single fixed collimator angle is not necessarily optimal. We apply a principal component analysis (PCA) (18, 19) to determine the orientation of the spinal cord at each BEV. We first extract the two-dimensional (2D) contour of the cord in the BEV at each gantry angle and then create a matrix A_{2xm}, where columns of A correspond to contour points, rows to x and y coordinates, and m is the number of points belonging to this specific contour projection. A 2-by-2 matrix P_{2x2} is subsequently formed where each row of P_{2x2} is an eigenvector of matrix AA^T. Finally, the eigenvector corresponding to the larger diagonal value of the 2-by-2 diagonal matrix $D \equiv PAA^TP^T$ was used as the first principal component, along which A has larger variance. For a 2D contour of the spinal cord, this principle component represents the long axis of the cord and is defined as the primary orientation, which is subsequently aligned with the direction of MLC travel. However, there exists a hardware constraint: the maximum collimator rotation speed is about 0.25 sec/degree (7). Our VMAT optimization assumes a maximum gantry speed of 72 sec/360° gantry rotation (16), and 360 equally spaced beams are used to model the 360° single arc. As a result, the maximum change in collimator angle between two adjacent beams without a decrease in gantry speed is 0.8°. Our process of designing the collimator trajectory uses PCA to sequentially calculate the optimal collimator angle at each gantry angle, beginning at gantry 180° and proceeding counterclockwise for 360° at a 1° increment. If the incremental change in the PCA derived collimator angle is larger than 0.8°, the collimator is set to move only 0.8° or –0.8°.

MLC and monitor unit optimization

MLC aperture and monitor units (MU) for each beam are optimized using an in-house optimization algorithm developed at Memorial Sloan-Kettering Cancer Center (MSKCC) (11). The algorithm uses a dose–volume histogram (DVH)-based objective function, identical to the one used for IMRT optimization (20). The dose calculation in VMAT plan optimization is modeled using up to 360 static beams with irregular MLC-shaped apertures. For the n^{th} point inside a region of interest, dose is calculated as: