Optimizing fiducial visibility on periodically acquired megavoltage and kilovoltage image pairs during prostate volumetric modulated arc therapy

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Purpose: Robust detection of implanted fiducials is essential for monitoring intrafractional motion during hypofractionated treatment. The authors developed a plan optimization strategy to ensure clear visibility of implanted fiducials and facilitate 3D localization during volumetric modulated arc therapy (VMAT).

Methods: Periodic kilovoltage (kV) images were acquired at 20° gantry intervals and paired with simultaneously acquired 4.4° short arc megavoltage digital tomosynthesis (MV-DTS) to localize three fiducials during VMAT delivery for hypofractionated prostate cancer treatment. Beginning with the original optimized plan, control point segments where fiducials were consistently blocked by multileaf collimator (MLC) within each 4.4° MV-DTS interval were first identified. For each segment, MLC apertures were edited to expose the fiducial that led to the least increase in the cost function. Subsequently, MLC apertures of all control points not involved with fiducial visualization were reoptimized to compensate for plan quality losses and match the original dose–volume histogram. MV dose for each MV-DTS was also kept above 0.4 MU to ensure acceptable image quality. Different imaging (gantry) intervals and visibility margins around fiducials were also evaluated.

Results: Fiducials were consistently blocked by the MLC for, on average, 36% of the imaging control points for five hypofractionated prostate VMAT plans but properly exposed after reoptimization. Reoptimization resulted in negligible dosimetric differences compared with original plans and outperformed simple aperture editing: on average, PTV D98 recovered from 87% to 94% of prescription, and PTV dose homogeneity improved from 9% to 7%. Without violating plan objectives and compromising delivery efficiency, the highest imaging frequency and largest margin that can be achieved are a 10° gantry interval, and 15 mm, respectively.

Conclusions: VMAT plans can be made to accommodate MV-kV imaging of fiducials. Fiducial visualization rate and workflow efficiency are significantly improved with an automatic modification and reoptimization approach. © 2016 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4944737>]

Key words: VMAT, intrafraction motion management, MV/KV tracking

1. INTRODUCTION

Monitoring patient position through the megavoltage (MV) treatment portal is highly desirable since these projections can be utilized to directly localize patient position in the most relevant beam's eye view (BEV) direction.^{1–10} Furthermore, intrafractional MV images are acquired “for free” via the MV imaging panel integrated on the modern Linacs: adding no extra radiation dose to the patient, and little burden to the existing clinical workflow. Although MV imaging using open apertures in combination with kilovoltage (kV) imaging via the orthogonal on-board imager is a cornerstone of intertreatment patient positioning and quality assurance, use of MV imaging for intratreatment motion monitoring during either intensity modulated radiation therapy (IMRT) or volumetric modulated arc therapy (VMAT) is limited by the poor visibility of implanted fiducials or anatomical structures due to frequent blockages by the multileaf collimator (MLC). As a consequence, fiducial detection and 3D localization are

often affected by large uncertainties or even complete failures and become unreliable for guidance of intrafractional motion management.

A straight forward solution to ensure fiducial visibility at scheduled MV imaging is to inspect each contributing control point (CP) in the treatment delivery sequence, and manually edit MLC apertures and expose fiducials if necessary.¹¹ This labor-intensive process often takes hours and is not practical for clinical implementation due to its free-form and error-prone nature. Efforts have also been made in the treatment planning process to automatically improve fiducial visibility. Zhao *et al.* designed a leaf sequencing algorithm to optimize MU efficiency and fiducial visibility for IMRT.^{12,13} For 15 clinical prostate fields, the fiducial visibility increased 20% on average, although two fields scored no improvements and remained problematic for localization. Ma *et al.* redesigned the optimization algorithm for step-and-shoot IMRT and introduced a tunable probability in the simulated annealing optimization scheme to reject MLC apertures that blocked

fiducials.¹⁴ Reasonable fiducial visibility was achieved but with a cost of moderate plan quality deterioration. While these results are encouraging, an optimization strategy that guarantees fiducial visibility at every scheduled imaging incidence without compromising plan quality and hindering clinical workflow still needs to be developed to facilitate MV imaging in routine clinical use.

The key to robust localization of fiducials during MV imaging is to integrate the desired MV imaging scheme into the optimization process. To achieve acceptable dose delivery accuracy in the presence of intrafractional prostate motion, MV/kV imaging surveillance should be deployed at a frequency ranging from once every 5 to 60 s.^{1,15,16} Full exposure of fiducials on the MV images is required only for those segments of the delivery that correspond to the prearranged MV/KV imaging points; visualizing the fiducials for the rest of the delivery is immaterial. Therefore, the nonimaging segments can be reoptimized using the original dosimetric objective function to recover plan quality loss resulting from exposure of the fiducials during the imaging segments. In this paper, we report on the implementation of a new VMAT optimization framework that flexibly accounts for intrafractional imaging strategies, guarantees fiducial visibility during the MV segments used for intratreatment localization, yet maintains the plan dosimetric quality and delivery efficiency compared to the optimal plan. We also investigate the scope of this application, and the impact of various imaging parameters.

2. METHOD AND MATERIALS

2.A. MV/kV imaging strategy

According to our institutional hypofractionated prostate protocol, patients with three implanted gold seed fiducials are treated with two full 360° VMAT arcs and a prescription of 8 Gy for 5 fractions. Periodic kV imaging triggered at 20° gantry intervals (every eighteenth of an arc) is scheduled on a TrueBeam Linac (Varian, Palo Alto, CA) and paired with a 4.4° MV short arc digital tomosynthesis (DTS) simultaneously acquired via iTools-Capture (Varian) to localize the 3D position of implanted gold fiducials in real time.¹⁷ MV-DTS was chosen over a single MV projection to improve the signal to noise ratio of the passively acquired MV images, which is crucial for robust detection and registration of fiducials. Exposure of at least one of the three implanted fiducials consistently throughout the 4.4° short arc is mandatory for clear fiducial visualization and accurate localization of translations, while full exposure of all three fiducials in the short arc is essential for deriving the rotation information. A purpose-built program registers the fiducials seen on the MV-DTS/KV projections to fiducial templates generated via the planning CT and calculates the 3D fiducial center-of-mass position via triangulation.¹⁸ If this fiducial center-of-mass deviates persistently from a predefined action threshold, the therapists may interrupt the treatment, reposition the patient to the planned position, and resume the treatment.

2.B. Approach 1: MLC aperture edit

In the current clinical workflow, an imaging template is attached to the VMAT beams within a treatment plan after that plan has been optimized and found to be clinically acceptable. Given that the plan has already been optimized, one straightforward method to ensure that it is compatible with MV-DTS is to simply edit the MLC positions and expose the fiducials when necessary. To evaluate this approach, we partitioned the delivery CPs according to the MV/kV imaging scenario. For MV/kV imaging indexed to every 20° gantry rotation, a full VMAT arc (360° rotation) was divided into 18 segments. With a gantry sampling resolution of 2° in VMAT plan optimization and dose calculation, four consecutive control points bracket a single 4.4° MV-DTS acquisition. Therefore each segment included four consecutive imaging CP and six consecutive nonimaging CP. We then identified segments where no fiducials (with appropriate margin to account for potential motion) were consistently visible within the included imaging CPs by examining the spatial overlap between each fiducial contour (from the planning CT) and MLC aperture in BEV. For each imaging CP, the potential cost, i.e., the increase in the value of the objective function used in the original optimization, that would be incurred by adjusting the MLC apertures and exposing each individual fiducial was calculated. MLC apertures within the 4.4° arc were subsequently edited only around the single fiducial that led to the least increase in cost. All eighteen segments were sequentially inspected and automatically modified as necessary.

2.C. Approach 2: Repeat of multiresolution VMAT optimization

Plan dosimetric quality loss was observed after simply enlarging MLC apertures to make fiducials visible on MV-DTS because additional exposure of adjacent organs at risk (OAR) such as urethra, rectal wall, and bladder wall was

Fig. 1. Flowchart of process to optimize fiducial visibility.

FIG. 2. Comparison of MLC apertures for a single imaging CP for the original plan, MLC aperture edit, and reoptimization methods. (a) Original plan: visualization of all three fiducials was blocked by the MLC. (b) MLC aperture editing exposed the yellow fiducial by moving the orange colored MLC. Due to the resulting increase in OAR dose and PTV dose inhomogeneity, the plan was renormalized, resulting in a decrease in PTV D98. (c) In reopt, MLC involved with exposing the yellow fiducial were kept intact, but other MLC positions were optimized to recover the compromised plan quality. PTV D98 was restored to 38.4 Gy, identical to the original plan and 3.6 Gy higher than the plan with simple MLC aperture editing (see color online version).

inevitable. To address this quality loss, the edited plan was used as a well-educated initial guess and the plan was then re-optimized in an attempt to recover the desired dosimetric quantities of the original plan. To ensure that the reoptimized plan resembled the original clinical plan as closely as possible, extra terms to minimize the differences between the dose-volume histograms (DVHs) of the original and reoptimized plans were included in the objective function in addition to the original dose and DVH constraints. The original VMAT planning was done using a multiresolution optimization process, operating on a successive gantry resolution of 16°, 8°, 4°, and 2°, respectively.¹⁹ However, for the reoptimization, resuming at the finest resolution (2°) was a natural choice because all the control points within imaging segments are explicitly accounted for, and extra planning time is minimized.

Our VMAT planning algorithm iteratively and randomly went through all the control points for the MLC aperture

optimization. For an imaging control point scheduled for MV acquisition, the MLC pairs associated with exposing the fiducial were kept intact, while the positions of the rest MLC pairs were optimized by randomly sampling the mechanically allowable travel range, comparing the objective function value, and descending toward the minimum. All MLC positions of the nonimaging control points were optimized and MLC mechanical constraints between the imaging and nonimaging control points were respected to eliminate potential delivery delay. The MLC position optimization was followed by a control point weight optimization via conjugate gradient search, where the minimal dose for each control point was kept above 0.4 MU to ensure acceptable MV image quality. The resulting plans were calculated and evaluated in the same way as the original plan in our in-house treatment planning system which has been commissioned and used in clinic for decades. The overall workflow is shown in Fig. 1.

FIG. 3. Eighteen segments are partitioned for a full VMAT arc integrating MV/kV imaging triggered at every 20° gantry rotation. In eight or eighteen segments, at least one fiducial is not consistently exposed. After reoptimization, one (yellow) fiducial is properly exposed (see color online version).

FIG. 4. Simple MLC aperture editing results in plan quality loss because of the additional OAR exposure. Reoptimization recovers the loss and maintains the original plan dosimetric properties.

2.D. Investigating appropriate imaging parameters

We investigated the impact of various imaging parameters on plan quality. These parameters and the range evaluated (felt to be appropriate for clinical implementation) were as follows: (1) gantry interval for imaging, ranging from 5° to 60° ; (2) margin around the fiducials, ranging from 0.5 to 2 cm; (3) number of visible fiducials for MV-DTS, 1 or 3.

Plans generated by solely editing the MLCs or by editing and then reoptimizing were all renormalized to respect the clinical objectives of the hypofractionated protocol, including the maximal dose to PTV and urethra below 44 and 42.5 Gy, respectively, and D1cc to bladder wall and rectal wall below 42 and 38.5 Gy, respectively. Therefore, we evaluated the change in dose to 98% of the planning target volume (PTV D98) and dose homogeneity inside PTV (difference between D05 and D95 divided by the mean dose) as the dosimetric end points for plan comparison. We also evaluated the addition to delivery time and the extra time spent on optimizing fiducial visibility as efficiency measure.

3. RESULTS

To acquire 4.4° MV-DTS triggered every 20° of gantry rotation, fiducials must be visible on 40% (72/178) of control points, given a 2° gantry interval between control points.

TABLE I. Change to PTV D98 for different MV/kV imaging frequencies. An imaging interval of 10° or more results in a change of less than 1 Gy.

Difference in PTV D98 (Gy)	Gantry interval of MV/kV imaging			
	5°	10°	20°	30°
MLC aperture edit—Original plan	-14.4	-9.2	-3.6	-0.4
Reoptimized—Original plan	-5.2	-0.2	0	0

Fiducials were consistently blocked by the MLC for, on average, 36.2% of the imaging control points for five retrospectively evaluated, clinically delivered hypofractionated prostate VMAT plans. Thus, the number of MLC apertures (CPs) requiring modification averaged 26, ranging from 24 to 32. A comparison of original and modified MLC apertures for a single imaging control point using either the MLC editing or reoptimization methods is shown in Fig. 2. After reoptimization, at least one fiducial was properly exposed for detection on MV-DTS. The imaging scheme for a VMAT arc, as well as an example of the modified apertures with MLC editing or with reoptimization for a single imaging control point segment is shown in Fig. 3. Reoptimization resulted in negligible dosimetric differences compared with the original plan, and out-performed MLC aperture editing as shown in the DVH comparison (Fig. 4). For the five patients included in this study, on average, the PTV D98 for the original plan was 37.8 Gy, degraded to 34.8 Gy with MLC aperture editing but recovered to 37.8 Gy with reoptimization. PTV dose homogeneity was originally 6.7%, increased to 8.6% with MLC editing, and then improved to 6.7% with reoptimization, as illustrated in Fig. 5. It took 2–3 min to complete the automatic MLC aperture editing procedure. Reoptimization took an additional 10–15 min. The MLC-edited and reoptimized plans were delivered on a Varian TrueBeam Linac, and no errors were found.

As shown in Table I, given a 1 cm margin around each fiducial identified for visualization, increasing the frequency of MV-DTS quickly resulted in a deterioration of plan quality when MLC aperture editing was applied. In fact, aperture editing was only capable of accommodating imaging every 30° without incurring a PTV D98 loss of ≥ 1 Gy. In contrast, reoptimized plans were capable of integrating MV-DTS with

FIG. 5. PTV D98 and PTV inhomogeneity comparison demonstrating that the characteristics of the original and reoptimized plans are indistinguishable, and superior to the plan with simple MLC aperture editing.

TABLE II. Change to PTV D98 for different imaging margins around the fiducial. An imaging margin of 15 mm or less results in a change of less than 1 Gy.

Difference in PTV D98 (Gy)	Fiducial margin (mm)			
	10	15	20	25
Reoptimized—Original plan	0	−0.8	−3.2	−5.6

a frequency of up to 10° , significantly extending the feasible range of imaging frequency. Note that exposing at least one fiducial at every control point, i.e., acquiring 4.4° MV-DTS every 5° gantry rotation, caused a 5.2% decrease in PTV D98, indicating that extra scrutiny would be needed to determine whether this monitoring cost was justified. If all three fiducials needed to be visualized on MV-DTS to robustly determine both translation and rotation, the achievable frequency (PTV D98 change <1 Gy) was imaging every 45° gantry rotation ($1/8$ of a full arc).

Given an imaging frequency of 20° , the largest margin achievable around fiducials, without violating plan objectives and compromising delivery efficiency, was 15 mm (Table II), well suited for detecting prostate motion.

4. DISCUSSION

The probability of MLC blocking fiducials increases when fiducials are implanted in locations that more frequently overlap with OAR in the BEV. Implanting fiducials in locations that have clear gaps with OAR in the BEV would reduce the blockage ratio and facilitate the following optimization of fiducial visibility. Even with the help from a thoughtful implantation, it is very challenging to ensure fiducial visibility while satisfying the strict OAR sparing objectives in optimization. Imposing a hard constraint of exposing all three fiducials at the start of optimization might be detrimental and prevent the generation of a clinically acceptable plan. Consistently exposing only one fiducial can still enable fiducial detection on MV-DTS. However such consistent exposure may increase the dose inhomogeneity inside PTV and violate PTV dose objectives. Furthermore, the choice of exposing which one of the three fiducials in all imaging CPs is not easy to be determined at the very beginning of optimization. Therefore no clear rule exists on how to best expose fiducials or to guide optimization for highly modulated dose distributions. This combinational problem becomes even more complicated when MV projections need to be acquired at a large number (36 in two arcs) of independent segments. As a practical alternative, our approach first produces an optimal plan without consideration of fiducial visibility and then retrospectively modifies MLC apertures to expose fiducials during imaging segments with the smallest increase in cost to the objective function. To further improve results, these new apertures can hold fixed during a reoptimization process that adjusts the apertures for nonimaging segments to recoup plan quality losses. The result is a reoptimized plan that best matches the original high quality plan and a method

for evaluating the final loss in plan quality, if there is any. We therefore can make an informed decision on whether to adopt the reoptimized plan for motion management and what imaging parameters are most suitable for the particular patient.

The proposed optimization framework is designed to accommodate MV/KV imaging strategies currently available on a conventional linear accelerator. It provides flexibility in selecting parameters such as imaging interval, margin around the fiducials, and number of fiducials exposed, to guarantee an acceptable plan quality. Given the increasing value of motion monitoring, we may want to change our perspective and try to include the imaging/localization strategy during plan optimization to see whether more useful information can be retrieved from the particular treatment plan and serve motion management. For example, translations can be consistently obtained by alternatively exposing one fiducial, but rotation can only be robustly obtained by exposing multiple fiducials, a situation that will likely increase plan quality loss. Therefore instead of trying to determine both translations and rotations at fixed, short intervals, we may wish to design localization approaches that evaluate true 3D translation/rotation only on occasion and estimate it based on Bayesian analysis otherwise. Furthermore, we may wish to explore scenarios that do not necessarily acquire images at a fixed interval, but rather at control points where the motion sensitivities are peak and monitoring is the most relevant. Since imaging strategy and plan optimization mutually affects each other, a more powerful optimization framework that truly combines imaging and delivery such as station parameter optimized radiation therapy (SPORT)^{20,21} is the ultimate answer, and the goal of our future development.

5. CONCLUSION

VMAT plans can be made to accommodate MV-kV imaging of fiducials. Fiducial visualization rate and workflow efficiency are significantly improved with an automatic modification and reoptimization approach.

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