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Intrafractional 3D localization using kilovoltage digital tomosynthesis for sliding-window intensity modulated radiation therapy

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Abstract

Purpose—To implement novel imaging sequences integrated into intensity modulated radiation therapy (IMRT) and determine 3D positions for intrafractional patient motion monitoring and management.

Method—In one method, we converted a static gantry IMRT beam into a series of arcs in which dose index and multileaf collimator positions for all control points were unchanged, but gantry angles were modified to oscillate $\pm 3^\circ$ around the original angle. Kilovoltage (kV) projections were acquired continuously throughout delivery and reconstructed to provide a series of 6° arc digital tomosynthesis (DTS) images which served to evaluate the in-plane positions of embedded-fiducials/vertebral-body. To obtain out-of-plane positions via triangulation, a 20° gantry rotation with beam hold-off was inserted during delivery to produce a pair of 6° DTS images separated by 14° . In a second method, the gantry remained stationary, but both kV source and detector moved over a 15° longitudinal arc using pitch and translational adjustment of the robotic arms. Evaluation of localization accuracy in an anthropomorphic Rando phantom during simulated intrafractional motion used programmed couch translations from customized scripts. Purpose-built software was used to reconstruct DTS images, register them to reference template images and calculate 3D fiducial positions.

Result—No significant dose difference ($<0.5\%$) was found between the original and converted IMRT beams. For a typical hypofractionated spine treatment, 200 single DTS (6° arc) and 10 paired DTS (20° arc) images were acquired for each IMRT beam, providing in-plane and out-of-plane monitoring every 1.6 and 34.5 seconds, respectively. Mean $\pm$ standard deviation error in predicted position was -0.3 ± 0.2 mm, -0.1 ± 0.1 mm in-plane, and 0.2 ± 0.4 mm out-of-plane with rotational gantry, 0.8 ± 0.1 mm, -0.7 ± 0.3 mm in-plane and 1.1 ± 0.1 mm out-of-plane with translational source/detector.

Conclusion—Acquiring 3D fiducial positions from kV-DTS during fixed gantry IMRT is technically feasible, and is capable of providing reliable guidance for intrafractional patient motion management.

Keywords

IMRT; digital tomosynthesis; intrafraction motion management

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

I. INTRODUCTION

Local control of cancerous tumors continues to be a challenge in numerous disease sites such as lung, paraspinal, gastro-intestinal sites, and prostate. Internal motion is one of the adverse contributors to targeting accuracy, especially for prolonged treatment such as hypofractionated radiotherapy or stereotactic ablative body radiotherapy (SABR). Monitoring intrafractional motion in a seamless clinical workflow is an active area of research. Most recently a number of groups reported fiducial localization strategies during volumetric modulated arc therapy (VMAT) based on continuously acquired megavoltage (MV) and kilovoltage (kV) projection pairs via the gantry-mounted imaging systems (Liu 2008, 2011, Cho, 2009), stereotactic kV images (Paulsen 2010, 2014, Ng 2014), or cine MV images (Azcona 2013). These images are registered to the planning CT, and the calculated real-time 3D fiducial positions are utilized for decision making in the motion management. For intensity modulated radiation therapy (IMRT) with a static gantry, the MV/kV pair approach remains a viable option for the step-and-shoot technique where fiducials are naturally visible in the MV projections (Wiersma, 2008, Mao 2008, 2009, Lin 2013). However, determination of 3D fiducial positions poses a bigger challenge for static gantry IMRT using the sliding window technique because the narrower moving apertures limit detection of implanted fiducials. For example, during a highly modulated IMRT delivery designed for hypofractionated prostate treatment, if a 3mm clearance around a fiducial is required to detect its position in MV images, on average only 23% of MV images can be used for localization. Redesigning the MLC sequencing algorithm to optimize fiducial visibility (Zhao 2009, 2014) may improve detectability to some extent, but it is far from a guarantee of continuous and robust localization. In this scenario, special designed software that incorporates prior knowledge of the motion trajectory has been employed to estimate 3D fiducial positions using kV projections alone (Hossain 2008, Mao 2009, Paulsen 2010, Li, 2012, Yan 2012). Imaging solutions designed for sliding window IMRT that can work independently to the motion prior and directly resolve 3D positions are highly desirable.

The Developer mode on the TrueBeam linac (Varian Medical System, Palo Alto, CA) enables programming of machine setup, imaging and dose delivery by means of scripts. As such it provides ample opportunities to explore the best usage of the linac's numerous mechanical degrees of freedom for radiotherapy delivery. In this paper we report on the development of novel imaging sequences integrated into the delivery of IMRT for hypofractionated radiotherapy under developer mode, and its utilization for 3D fiducial localization. This technique is part of the effort to guide intrafractional motion management and reduce delivery uncertainty.

II. METHOD AND MATERIALS

2.1 Clinical environment

In our institution, the clinical goal is to monitor patient position during hypofractionated paraspinal and prostate treatment by using a research workstation (iTools, VMS) to capture MV projections, and the gantry-mounted imaging system to simultaneously acquire kV projections. A typical paraspinal SABR plan is composed of five to seven fixed-gantry

IMRT beams executed using the sliding window technique, and delivers 24 Gy in a single fraction. The range of beam-on-time is 2000–3000 MU per beam, taking 3–5 minutes for delivery. A typical hypofractionated prostate plan has a prescription of 40 Gy (8Gy×5 fractions) using seven to nine IMRT beams. Delivery time for each beam is about 1 minute. Previous computer simulation studies have found that imaging the patient every ten to sixty seconds and adjusting the patient position accordingly is appropriate to ensure an accurate dose delivery (Zhang 2012). In the design of our intrafractional imaging protocol, our objectives are to obtain 3D localization at a clinically acceptable frequency, introduce minimal impact on the delivered dose to the patient, and minimize the associated time overhead.

The prototype imaging/radiating sequences are designed and executed using the TrueBeam developer mode. An IMRT treatment sequence can be described by control points (CP) in an XML file that is eventually loaded and executed on the linac control computer. The first portion of the XML file describes the megavoltage x-ray delivery through a series of CP that specify the gantry speed, multi-leaf collimator (MLC) travel, collimator rotation, couch motion, as well as dose index in a continuous delivery. The second portion of the XML files specifies the imaging acquisitions, listing the imaging mode (MV, KV, CBCT, etc), imager position, and the corresponding imaging parameters such as x-ray tube voltage and output. The dose delivery and imaging segments are synchronized through the control point number, which enables the intelligent integration of the two.

2.2 Imaging options during IMRT

We investigated four different methods of imaging during IMRT: MV imaging with open MLC apertures, short arc digital tomosynthesis (DTS) between beams, short arc DTS during a beam, and longitudinal kV-DTS. We describe each of these in turn.

2.2.1 MV/kV imaging: open MLC aperture—Orthogonal MV/kV image pairs have been shown to be a reliable method for 3D fiducial localization during treatment, but as mentioned above, the narrow apertures in sliding window IMRT pose an obstacle to fiducial localization in the MV images. In order to address this, appropriate MLC apertures for MV imaging need to be formed and synchronized with kV acquisition. In our study the design of these apertures employed the outline of the fiducials as seen in the beam's eye view, and added a uniform 1 cm margin to accommodate target motion and image processing needs. The coordinated MV/kV acquisition was implemented via an XML script. For every control point, in which a kV projection was scheduled but fiducials are blocked from detection, three additional control points were inserted: the first moved the MLC to the desired aperture with zero MV-dose, the second delivered 0.5 MU to acquire MV images and ensure proper fiducial exposure, and the third moved the MLC back to the planned position with zero dose.

In general, the field width in the direction of MLC travel ranges from approximately 7 to 12 cm for typical paraspinal or prostate plans. The additional time introduced by the MLC roundtrip travel from the narrow opening to the MV imaging aperture was, on average, 8 seconds (range 5 to 11 seconds) given a maximum leaf speed of 2.5 cm/s. Multiple (N_i)

MV/kV projections are needed to continuously monitor the patient. Therefore the additional time required for this imaging method was about $8 \times N_i$ seconds.

2.2.2 Stereoscopic kV-imaging between IMRT beams—For treatments that involve monitoring larger internal objects of interest, such as the spinal column adjacent to paraspinal tumors, retracting the MLC sufficiently to localize the object in MV images becomes impractical. We investigate instead the use of a pair of short-arc DTS images, to enhance object visibility and to yield 3D position by means of triangulation. Short arc kV-DTS has been used clinically to position a patient just before treatment with a systematic error of less than $1\text{mm}/1^\circ$ (Yoo, 2009). We extended this concept by developing an imaging method that acquires short arc kV-DTS while the gantry rotates between adjacent IMRT beams. In our clinical paraspinal and prostate IMRT plans, the separation between two adjacent IMRT beams is always larger than 30° , which is sufficient to use stereoscopic DTS imaging for 3D fiducial localization. To perform such an imaging procedure, an additional zero MV-dose control point that rotates the gantry between consecutive IMRT beams was inserted into the XML file, and the acquisition of a series of kV projections (11 frames per second) during this new control point was specified. kV-DTS images were then produced using the published reconstruction algorithm (Kolitsi, 1992, 1993).

Although this imaging option could be easily integrated into the auto-sequencing process, thereby introducing minimal impact to the clinical flow, the imaging frequency is limited by the delivery time of each IMRT beam, and the number of beams. The achieved imaging frequency of 60–180 seconds may not be adequate for high precision treatments or situations where significant motion is anticipated. Nevertheless, after treatment, the acquired kV projections could be assembled to reconstruct a cone beam computer tomography (CBCT) image serving as a quality assurance record and basis for adaptive radiotherapy (Nakagawa 2009, Ling 2011, van Herk 2011, Li 2013).

2.2.3 Short arc kV-DTS during an IMRT beam—Acquisition of short-arc DTS during beam delivery is implemented to allow monitoring at more frequent intervals than DTS between beams. As illustrated in Figure 1, spinal structures were better visualized with a 6° -DTS image (right) compared to a single kV projection (left), thus arguing for the use of short arc DTS to robustly determine fiducial/vertebral-body in-plane positions, or potentially applying a fiducial free protocol in which localization is achieved solely using anatomical structures. To integrate short arc kV-DTS into IMRT delivery, we converted each IMRT beam into a short oscillating arc. In the XML file describing the delivery sequence, the dose index and MLC positions are kept intact for each CP, but gantry angle is alternated by $\pm 3^\circ$ around the original beam angle. The imaging mode is set to “DynamicGainFluoro”, which continuously acquires kV projections. As a result, a 6° kV-DTS is completed between two adjacent CPs, and subsequently used to calculate in-plane fiducial positions.

Since the 6° kV-DTS alone does not yield 3D position information, an additional 14° gantry rotation with MV beam hold-off was inserted at ten equispaced time intervals during the dose delivery of the IMRT field to obtain the out-of-plane position. The triangulation of multiple 6° short arc DTS images acquired during the total 20° rotation was used to provide accurate 3D localization. A schematic of the sequence for a single IMRT field is illustrated

in Figure 2. This sequence (MLC position, dose index) was interpolated with a gantry resolution of 1° , converted into an RTPlan file, and imported to our in-house planning system. Dose was recalculated and plan was renormalized to meet all the clinical objectives. The dosimetric impact of selecting different oscillating angles was also evaluated.

For the sequence designed for paraspinal SABR as shown in Figure 2, completion of a single 6° rotation between two dose delivery CPs averaged 1.6 seconds. The incremental increase in time over standard fixed gantry delivery was 0.5 seconds, and was a result of the gantry acceleration and deceleration associated with changes in the gantry direction at each CP. The longer 20° gantry rotation round trip required 5.7 seconds; thus the additional time for the a single imaging process to determine 3D position using this method was 6.2 seconds, and the total overhead for the sequence described in Figure 2 is 62 seconds.

2.2.4 Longitudinal arc kV-DTS—As an alternative to gantry rotation, kV-DTS can also be acquired via concurrent longitudinal motions of the kV source and detector. This longitudinal kV-DTS is independent to MV gantry, thus introducing no alterations to fixed-gantry IMRT plan quality. By laterally shifting the source and detector in opposite directions, varying the vertical position to maintain a constant source-to-detector distance, and adjusting the source and detector pitch to keep the detector plane normal to the kV beam, images can be acquired along a longitudinal arc up to 15° off the origin (Figure 3). The triangulation of multiple 6° DTS images acquired during this 15° rotation was used to calculate 3D fiducial position. This longitudinal arc imaging trajectory was programmed using an experimental XML script with 11 imaging control points to synchronize the motion of the kV source and detector, and delivered on a TrueBeam linac in Developer mode. Acquiring a 15° longitudinal kV-DTS required 36 seconds. A simplified alternative version, in which the source and detector moved along a line trajectory (instead of an arc) spanning 15° , required only 13 seconds. In this scenario, only the two planar kV images acquired at 0° and 15° were used for stereoscopic calculation of fiducial position. Treatment dose delivery was unaffected by either longitudinal kV-DTS scheme. The movement of the source and detector of the imager did not cause any collisions with the anthropomorphic phantom and treatment couch. In addition, we envision that using arc of -7.5° to 7.5° for patient delivery will further reduce the risk of collision. However, for patient safety, a test run before imaging and delivery is recommended to avoid collisions.

2.3 Evaluating localization accuracy

An anthropomorphic Rando phantom was used to evaluate the localization accuracy. Two groups of three gold cylindrical fiducials ($3\text{ mm} \times 1.2\text{ mm}$) were inserted into the pelvis and lower thoracic spine region, targeting prostate and paraspinal respectively, for fiducial imaging and localization. We also imaged the upper thoracic spine region and performed vertebral body tracking using paraspinal IMRT plans.

We programmed intrafractional couch motion with known motion traces to translate the phantom during radiation in the Developer mode via an XML script. An in-house program (Regmi 2014) registered fiducial/vertebral-body seen in the acquired DTS to the corresponding templates and calculated localizations in real-time. A planning CT of the

anthropomorphic Rando phantom with slice spacing of 2 mm was obtained and used to generate 2D reference images at one degree gantry angle increments. Generation of the reference template images involved initial segmentation of the fiducial/vertebral-body on the planning CT, followed by the addition of a margin of several mm to create a region-of-interest (ROI), and then a final projection of the ROI into the image plane to create the reference template image. The fiducial/vertebral-body in the kV images were automatically matched with their counterpart in the template inside the predefined ROIs using a normalized cross-correlation cost function and simplex minimization. The registration results were compared to the known motions and the root mean square error (RMSE) was calculated for evaluation.

III. RESULTS

3D localization by acquiring MV/kV pairs with open MLC apertures (section 2.2.1) was tested using a paraspinal SABR plan. Opening of the MLC apertures to expose the fiducials every twentieth CP resulted in an increase to the maximum dose to the cord, and worsening in target dose homogeneity significant enough to require a plan renormalization. The dose to 95% of the planning target volume (PTV D95) was reduced by 4% compared to the original plan. The difference between planned and measured 3D fiducial positions with programmed motion (mean $\pm$ standard deviation) was less than 0.3 ± 0.3 mm in the lateral, anterior-posterior and superior-inferior directions. The time required for an automatic 3D localization calculation was 300–400 ms.

For the localization approach using $6^\circ/20^\circ$ kV-DTS (section 2.2.3) to monitor fiducials during a paraspinal SABR, no significant dose difference ($<0.5\%$) was introduced between the original and short-arc IMRT beams since the gantry deviation was only $\pm 3^\circ$ around the original beam angle. Increasing the oscillating angle of the short arc to $\pm 5^\circ$ caused a plan modification in which the cord maximal dose was renormalized to meet the clinical objective, but PTV D95 dropped 2%. Deterioration in plan quality with oscillating angle beyond $\pm 5^\circ$ (10° total) was substantial and deemed not acceptable as options in sequence design. In addition, the time cost of enlarging the oscillation angle is $0.3\text{s}/^\circ$. To evaluate the localization accuracy of short-arc kV-DTS during IMRT, two hundred 6° arc kV-DTS and ten 20° arc kV-DTS were acquired for each IMRT beam, providing in-plane and out-of-plane monitoring every 1.6 and 34.5 seconds, respectively. The fiducial detection accuracy in the lateral, anterior-posterior and superior-inferior directions was -0.3 ± 0.2 mm, 0.2 ± 0.4 mm, and -0.1 ± 0.1 mm, respectively. Meanwhile, we investigated the in-plane localization accuracy of tracking vertebral body instead of the implanted fiducials. The RMSE of using 6° kV-DTS was 0.4mm, compared to 0.8mm of using a single kV projection. The advantage of smaller fluctuations in RMSE demonstrates that 6° kV-DTS is more reliable in localization than a single kV projection.

The fiducial detection accuracy in the lateral, anterior-posterior and superior-inferior directions was 0.8 ± 0.1 mm, 1.1 ± 0.1 mm, and -0.7 ± 0.3 mm, for the 15° longitudinal-DTS (section 2.2.4), compared to 0.6 ± 0.1 mm, 1.2 ± 0.2 mm, and -0.8 ± 0.4 mm, for the stereoscopic imaging method using only two longitudinal images at 0° and 15° . Paired DTS

obtained with a 20° gantry rotation has better localization accuracy compared to a 15° longitudinal arc due to the larger relative shift in triangulation.

V. DISCUSSION

As an integrated component of the modern linac, the gantry-mounted imaging system plays a unique role in the intrafractional quality assurance of dose delivery, especially given the difficulties such as view blocking and potential collisions faced by other external monitoring systems. We have investigated four imaging methods that exploit different computer-controlled mechanical motions of a commercially available linac as a means of 3D localization during fixed gantry IMRT treatment using the sliding window technique. Each method has its intrinsic advantages and limitations as listed in Table 1. Acquiring MV/kV pairs is a versatile method to track instantaneous motion as well as slow but persistent drift in patient position. However the need to modify field apertures to visualize the fiducials leads to excessive dose that may violate the dose limits on the critical organs and targets, thereby requiring treatment plan renormalization and imposing additional workload to the clinic. An optimization algorithm that incorporates this dosimetric impact into treatment planning is essential to address this problem, (Ma 2009) but is currently not clinically available. This practical issue as well as the inherent MV image quality limitations restrain this option in clinical usage and argue for investigation of superior alternatives. In contrast, kV-DTS or stereoscopic imaging can be used to detect intrafractional patient drift with insignificant dosimetric impact, superior image quality, and relatively low time overhead. The three proposed DTS methods span the frequency of image acquisition from 13 to 180 seconds, and form basic building blocks for even more sophisticated imaging schemes. For example, rather than acquiring kV-DTS to localize 3D positions periodically, kV-DTS can be infrequently inserted into delivery to re-calibrate the kilovoltage intrafraction monitoring (Crocker 2012) at the most dosimetrically demanding period of delivery. The appropriate choice of temporal imaging pattern depends on the particular clinical use case. However the longitudinal-DTS imaging option is particularly promising since it introduces the least impact on the IMRT delivery and clinical workflow. Currently simultaneous beam on and movement of the gantry-mounted imaging system is not allowed. Enabling such a capability in the next version of linac controller is essential to improve the efficacy.

VI. CONCLUSION

Acquiring 3D fiducial positions from kV-DTS during fixed gantry IMRT delivery is technically feasible, and is a promising method to provide reliable image guidance for intrafractional patient motion management.

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Reference

1. Azcona JD, Li R, Mok E, et al. Development and clinical evaluation of automatic fiducial detection for tumor tracking in cine megavoltage images during volumetric modulated arc therapy. *Med Phys.* 2013; 40:031708. [PubMed: 23464303]
2. Cho B, Poulsen PR, Sloutsky A, Sawant A, Keall PJ. First demonstration of combined kV/MV image-guided real-time dynamic multileaf-collimator target tracking. *Int J Radiat Oncol Biol Phys.* 2009; 74(3):859–867. [PubMed: 19480969]
3. Crocker JK, Ng JA, Keall PJ, Booth JT. Measurement of patient imaging dose for real-time kilovoltage x-ray intrafraction tumour position monitoring in prostate patients. *Phys Med Biol.* 2012; 57(10):2969–2980. [PubMed: 22517054]
4. Hossain S, Xia P, Chuang C, Verhey L, Gottschalk AR, Mu G, Ma L. Simulated real time image guided intrafraction tracking-delivery for hypofractionated prostate IMRT. *Med Phys.* 2008; 35(9): 4041–4048. [PubMed: 18841856]
5. Kolitsi Z, et al. A multiple projection method for digital tomosynthesis. *Med Phys.* 1992; 19(4): 1045–1050. [PubMed: 1518466]
6. Kolitsi Z, Panayiotakis G, Pallikarakis N. A method for selective removal of out-of-plane structures in digital tomosynthesis. *Med Phys.* 1993; 20(1):47–50. [PubMed: 8455511]
7. Li R, Han B, Meng B, Maxim PG, Xing L, Koong AC, Diehn M, Loo BW Jr. Clinical implementation of intrafraction cone beam computed tomography imaging during lung tumor stereotactic ablative radiation therapy. *Int J Radiat Oncol Biol Phys.* 2013; 87(5):917–923. [PubMed: 24113060]
8. Li R, Mok E, Chang DT, et al. Intrafraction verification of gated RapidArc by using beam-level kilovoltage X-ray images. *Int J Radiat Oncol Biol Phys.* 2012; 83:e709–e715. [PubMed: 22554582]
9. Lin WY, Lin SF, Yang SC, et al. Real-time automatic fiducial marker tracking in low contrast cine-MV images. *Med Phys.* 2013; 40:011715. [PubMed: 23298085]
10. Ling C, Zhang P, Etmektzoglou T, Star-Lack J, Sun M, Shapiro E, Hunt M. Acquisition of MV-scatter-free kilovoltage CBCT images during RapidArc™ or VMAT. *Radiother Oncol.* 2011; 100(1):145–149. [PubMed: 21821301]
11. Liu W, Wiersma RD, Mao W, Luxton G, Xing L. Real-time 3D internal marker tracking during arc radiotherapy by the use of combined MV-kV imaging. *Phys Med Biol.* 2008; 53(24):7197–7213. [PubMed: 19043177]
12. Liu W, Wiersma RD, Xing L. Optimized hybrid megavoltage-kilovoltage imaging protocol for volumetric prostate arc therapy. *Int J Radiat Oncol Biol Phys.* 2010 Oct 1; 78(2):595–604. [PubMed: 20472354]
13. Ma Y, Lee L, Keshet O, Keall P, Xing L. Four-dimensional inverse treatment planning with inclusion of implanted fiducials in IMRT segmented fields. *Med Phys.* 2009; 36(6):2215–2221. [PubMed: 19610310]
14. Mao W, Riaz N, Lee L, Wiersma R, Xing L. A fiducial detection algorithm for real-time image guided IMRT based on simultaneous MV and kV imaging. *Med Phys.* 2008; 35(8):3554–3564. [PubMed: 18777916]
15. Mao W, Hsu A, Riaz N, et al. Image-guided radiotherapy in near real time with intensity-modulated radiotherapy megavoltage treatment beam imaging. *Int J Radiat Oncol Biol Phys.* 2009; 75:603–610. [PubMed: 19735886]
16. Nakagawa K, Haga A, Shiraishi K, Yamashita H, Igaki H, Terahara A, Ohtomo K, Saegusa S, Shiraki T, Oritate T, Yoda K. First clinical cone-beam CT imaging during volumetric modulated arc therapy. *Radiother Oncol.* 2009; 90(3):422–423. [PubMed: 19062117]
17. Ng JA, Booth JT, O'Brien RT, Colvill E, Huang CY, Poulsen PR, Keall PJ. Quality assurance for the clinical implementation of kilovoltage intrafraction monitoring for prostate cancer VMAT. *Med Phys.* 2014; 41(11):111712. [PubMed: 25370626]
18. Poulsen PR, Cho B, Ruan D, Sawant A, Keall PJ. Dynamic MLC tracking of moving targets with a single kV imager for 3D conformal and IMRT treatments. *Acta Oncol.* 2010; 49(7):1092–1100. [PubMed: 20831501]

19. Poulsen PR, Cho B, Sawant A, Ruan D, Keall PJ. Dynamic MLC tracking of respiratory target motion based on a single kilovoltage imager during arc radiotherapy. *Int J Radiat Oncol Biol Phys.* 2010; 77(2):600–607. [PubMed: 20133066]
20. Poulsen PR, Worm ES, Petersen JB, Grau C, Fledelius W, Høyer M. Kilovoltage intrafraction motion monitoring and target dose reconstruction for stereotactic volumetric modulated arc therapy of tumors in the liver. *Radiother Oncol.* 2014; 111(3):424–430. [PubMed: 24997991]
21. Regmi R, Lovelock M, Hunt M, Zhang P, Pham H, Xiong J, Yorke E, Goodman K, Mageras G. Tracking implanted fiducials using Kilovoltage (kV) projection images: A feasibility study. *Medical Physics.* 2014; 41(7)
22. van Herk M, Ploeger L, Sonke JJ. A novel method for megavoltage scatter correction in cone-beam CT acquired concurrent with rotational irradiation. *Radiother Oncol.* 2011; 100(3):365–369. [PubMed: 21924785]
23. Wiersma RD, Mao W, Xing L. Combined kV and MV imaging for real-time tracking of implanted fiducial markers. *Med Phys.* 2008; 35:1191–1198. [PubMed: 18491510]
24. Yan H, Li H, Liu Z, et al. Hybrid MV-kV 3D respiratory motion tracking during radiation therapy with low imaging dose. *Phys Med Biol.* 2012; 57:8455–8469. [PubMed: 23202376]
25. Yoo S, Wu QJ, Godfrey D, Yan H, Ren L, Das S, Lee WR, Yin FF. Clinical evaluation of positioning verification using digital tomosynthesis and bony anatomy and soft tissues for prostate image-guided radiotherapy. *Int J Radiat Oncol Biol Phys.* 2009; 73(1):296–305. [PubMed: 19100923]
26. Zhang P, Hunt M, Happersett L, Cox B, Mageras G. Incorporation of treatment plan spatial and temporal dose patterns into a prostate intrafractional motion management strategy. *Med. Phys.* 2012; 39(9):5429–5436. [PubMed: 22957610]
27. Zhao B, Dai J, Ling CC. Considering marker visibility during leaf sequencing for segmental intensity-modulated radiation therapy. *Med Phys.* 2009; 36(9):3906–3916. [PubMed: 19810463]
28. Zhao B, Dai J. Determining leaf trajectories for dynamic multileaf collimators with consideration of marker visibility: an algorithm study. *J Radiat Res.* 2014; 55(5):976–987. [PubMed: 24914104]

Figure 1.

Spinal structures were better visualized with a 6°-gantry-DTS image (right), compared to a single kV projection (left), thus arguing for the use of short arc DTS to determine fiducial/vertebral-body in-plane positions, or potentially applying a fiducial free protocol for patient localization.

Figure 2.

Delivery/imaging trajectory designed for a paraspinal IMRT beam. For every tenth of the treatment, twenty 6° arc kV-DTS, rotating around the superior-inferior axis, were acquired for in-plane localization, and one 20° arc kV-DTS was acquired for out-of-plane localization.

Figure 3.

A longitudinal arc trajectory, rotating around the anterior-posterior axis, is designed to acquire longitudinal kV-DTS for 3D localization via source/detector pitch and shifts.

Table 1

Comparisons among imaging options during hypofractionated IMRT delivery

	MV-kV image pairs with open MV apertures	kV-DTS between IMRT beams	kV-DTS during IMRT beams	Longitudinal kV-DTS during IMRT beams
3D localization	Yes	Yes	Yes	Yes
Achieved imaging frequency	~20 s	~60–180 s	~30 s	~13–35 s
Localization accuracy	<1 mm	<1 mm	<1 mm	~1 mm
Image quality	Fair	Excellent	Excellent	Excellent
Interfere delivery	Yes	No	Yes	No
Time overhead	~8 s/pair	None	~6 s/3D-imaging	None
Dosimetric impact	Yes, causing down-normalization	No	Not significant	No
Tracking suitability	Instant/drift	Drift	Drift	Drift
Future development	Incorporate aperture modification into plan optimization	Auto-sequencing with delivery in clinical mode	Reduce imaging time overhead	Enable concurrent beam-on and imager motion