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Optimized Hybrid MV-kV Imaging Protocol for Volumetric Prostate Arc Therapy

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Abstract

Purpose—To develop a real-time prostate position monitoring technique for modern arc radiotherapy through novel usage of cine-MV imaging together with as-needed kV imaging.

Methods—We divided the task of monitoring intrafraction prostate motion into two steps for rotational deliveries: (i) to detect potential target motion beyond a pre-defined threshold using MV images from different viewing angles by taking advantage of gantry rotation during arc therapy and (ii) to verify the displacement and determine whether an intervention is needed using fiducial/tumor position information acquired from combined MV-kV imaging (by turning on the kV imager). A Varian Trilogy™ linac with onboard kV imager was used to examine selected typical trajectories using a 4D motion phantom. The performance of the algorithm was evaluated using phantom measurements and computer simulation for 536 Calypso-measured tracks from 17 patients.

Results—Fiducial displacement relative to the MV beam was limited to within a range of 3mm for 99.9% of the time with better than 1mm accuracy. On average, only ~0.5 intervention per arc delivery was needed to achieve this level of accuracy. Compared to other fluoroscopy-based tracking techniques, kV usage is significantly reduced to an average of less than 15 times per arc delivery.

Conclusions—By focusing the attention to detecting a pre-defined abnormal motion (i.e., “failure” detection) and utilizing the inherent mechanism of gantry rotation during arc radiotherapy, the current approach provides us with a high confidence about the prostate position in real-time without paying the unwanted overhead of continuous or periodic kV imaging strategy.

Keywords

intrafraction prostate motion; onboard imaging; volumetric arc therapy

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I. Introduction

Numerous studies (1-6) have shown that prostate target moves during radiation therapy dose delivery process and the motion is generally unpredictable and can be over 1cm in some cases. Real-time monitoring of implanted fiducials using cine-MV and onboard kV beams has been proposed for real-time monitoring of the tumor target motion (7, 8). While continuous fluoroscopic kV and cine-MV imaging is capable to provide real-time information of the prostate position with spatial accuracy better than 1mm, a practical issue raised here is whether it is necessary to keep kV on continuously to monitor the prostate motion, which occurs only from time to time. A reliable reduction of kV beam usage is highly desirable to reduce the patient imaging dose (9).

If the therapeutic dose is delivered in an arc, by taking the advantage of the inherent mechanism of continuous gantry rotation, fiducial/tumor positions can be stereoscopically estimated through the analysis of the “free” MV images acquired from different angles, which forms a rational basis to minimize the kV usage. Indeed, during arc therapy the MV projections corresponding to different time points (gantry angles) do not give us the full 3D coordinates of the fiducials, with an adequately established baseline position of the prostate at the beginning of the treatment, they can potentially tell us whether the prostate has moved from the baseline position and whether the displacement is more than a pre-set threshold (say, ~3mm). Practically, the estimated displacement of the prostate target based on the MV projections at different time points can be used to direct the on and off of the orthogonal kV imaging. If a potential over-threshold motion is detected by the MV, the kV imaging is followed (for a single shot or a period of time) to accurately locate the 3D prostate position through simultaneous MV-kV imaging for possible intervention. The goal of this study is to develop such an MV data processing method and optimal kV imaging protocol for arc therapy. This scheme of using the kV imager on an “as needed” basis has potential to significantly improve the current “one-protocol-for-all-treatment” approach in prostate IGRT.

II. Methods and Materials

II.A. MV-kV imaging

Generally, there are three ways to combine the kV with cine-MV imaging for monitoring of implanted gold seeds during prostate IGRT: (i) continuous kV imaging (7); (ii) periodical kV according to previously established prostate motion statistics; and (iii) switching on the kV only if the estimated prostate displacement or speed from the up-to-date MV projections exceeds a threshold. The first two fall into the category of “one-protocol-for-all-treatments”. This study was focused on the development of the third approach. Because of the random and relatively infrequent nature of the prostate motion, as will be seen later, the third approach outperforms the first two in reducing kV usage while maintaining a high level of marker tracking accuracy compared with the continuous kV imaging strategy.

II.B. Prostate motion detection using cine-MV and as-needed kV projections

The central idea of the proposed strategy is to estimate the fiducial displacement using MV-only data by taking the advantage of continuous gantry rotation during arc therapy and not to

turn on the kV imager before the detection of a possible abnormal motion. Therefore, we divided the task of monitoring intrafraction prostate motion into two separate but related steps: (i) to detect any abnormal target motion through continuously updated MV images, and (ii) to confirm and accurately locate the fiducials by turning on the kV imager if a potential abnormal motion is detected. The accurate position information is then used to guide further intervention. The MV imaging geometry is sketched in Fig. 1. At a gantry angle, the projection point of the marker on the MV EPID plane (point P) is along the ray joining the X-ray source (S) and the marker (L_2). To determine/estimate the 3D marker position, (x,y,z), a triangulation of two projections is required. One MV image provides two knowns and, therefore, at least one more constraint is needed to solve the three unknowns. This additional constraint can come from either a kV image or another MV image acquired at a different gantry angle.

Fig. 2 shows a flowchart of the proposed motion management procedure. Because of the absence of prior knowledge at the beginning of treatment, the kV imager is turned on once to acquire the first accurate 3D marker position. This data can also come from the patient setup images provided that the time elapse between the setup and treatment is sufficiently short.

II.B.1 Displacement estimation using MV projections at different times—

Referring to Fig. 1, let the fiducial position be L_0 , determined by simultaneous MV-kV imaging at time t_0 . At later times, only cine-MV images are acquired to estimate fiducial displacement from checkpoint L_0 . Let S_0 , S_1 , and S_2 represent the X-ray source positions at t_0 , t_1 , and t_2 , and their projections of the fiducial on the imager P_0 , P_1 , and P_2 , respectively. The task is to estimate whether the fiducial has moved away from L_0 more than a pre-defined threshold at a time t_2 based on its projection position P_2 and other system information. To locate the position of the marker at t_2 , a projection different from S_2P_2 is necessary. During gantry rotation, cine-MV images are acquired from a wide variety of angular views. Here the projection acquired at an earlier time t_1 is used as the second projection for estimation of the extent of prostate motion. Because t_1 and t_2 correspond to two different instants, the triangulation of S_1P_1 and S_2P_2 is not meaningful unless marker motion is insignificant during the sampling time interval of t_1 and t_2 . As long as this time interval is sufficiently small (i.e., < the average time for the prostate to move significantly, say 2mm), the triangulation should provide a reasonable estimate of the marker position. On the other hand, the angular separation between two MV images should not be too small. Otherwise, the reconstruction would be too susceptible to image noises and other small errors in the projection data. Theoretical and experimental studies (Appendices 1-3) showed that $\sim 10^\circ$ separation is a balanced choice for prostate motion monitoring. It usually takes 2 – 3 sec for the gantry to rotate 10° during arc delivery. The distance L_0L_2 obtained using S_1P_1 and S_2P_2 with 10° separation provides a reasonable estimate of the marker displacement with respect to the checkpoint L_0 . If $L_0L_2 > 3\text{mm}$, kV imaging is triggered to more accurately locate the fiducial. The checkpoint is updated (e.g., the target is repositioned or the MLC is shifted) if the MV-kV confirms the over-threshold movement. With an objective accuracy of image guidance better than 3mm, we set the MV-kV action level for checkpoint update at 2.5mm to count for various uncertainties. Using an action

level less than 3mm enhances our confidence level in catching an over-threshold motion, but at the cost of slightly increased number of checkpoint repositioning events.

II.B.2 High speed motion—The above estimation method is well suited for slow prostate motion where the displacement corresponding to the two projections is less than ~ 2 mm within any ~ 2 sec duration, which represents the majority of the clinical situations (as presented in the Results section, this is true in 99.5% of the time). In some rare but possible situations, the prostate may move more than a few mm/s, caused by, e.g., passing gas in rectum. Although the above estimation does not yield accurate results because the marker positions are dramatically different at the two instants when the projections are taken, it can be used to reliably detect potential large displacement for most of the time. The kV was also triggered when the projected fiducial motion speed on the MV imager was large because this is the time when the MV-only localization is not accurate. In the proposed method, the kV-on action was prompted if the MV-pair derived displacement > 3 mm (regardless the speed value) or if the MV-estimated displacement > 2 mm and the MV-estimated fiducial 2D projection speed > 1 mm/s. Appendix 4 presents more detailed descriptions on handling high speed motion.

II.C. Experimental and simulation studies

The performance of the prostate motion detection technique was evaluated experimentally using an 8cm cubic plastic phantom placed on a motion platform (Washington University, St Louis, MO). An arc plan ($5^\circ - 355^\circ$) was delivered to the phantom with an embedded ball bearing of 3mm diameter. Both MV and kV source-to-imager-distances were 150cm. MV and kV experimental setup have been described in details in (7). Three typical tracks (continuous target drift, persistent excursion, and high frequency excursion) (3) were used to program the motion trajectories of the test phantom. They were selected from 536 prostate motion tracks recorded with implanted electromagnetic transponders (Calypso Medical Technologies Inc., Seattle, WA) from 17 patients (5). Experiments were repeated twice for each track to confirm the reproducibility. The estimated positions using the proposed method were compared to the known trajectories.

To validate the current methodology without extensive measurements, a simulation strategy was developed to further evaluate the performance of the proposed technique. The simulation geometrically projected a fiducial onto the MV and kV imagers and provided the projected positions as a function of time, which were then used as input for the proposed marker monitoring algorithms to estimate the status of prostate motion. The inaccuracy of the data acquisition system was assumed to be either negligible or correctable through a careful system calibration (7). A Gaussian detection noise with zero mean and 0.5 pixel standard deviation was, however, added to the projected fiducial positions, which was reasonable based on previous phantom measurements of static fiducials (7).

Computer simulations were performed for all the 536 continuous Calypso-measured prostate position tracks. We assumed a $5^\circ/\text{sec}$ gantry rotation speed in our simulation studies. As shown in the Results section, the simulation strategy is valid because the phantom measurements were very similar to the simulations.

III. Results

Fig. 3 summarizes the data of real-time tracking of a marker obtained using different approaches for a motion type of “continuous target drift” (3). The experimental and simulation results are displayed in panels (a) and (b), respectively. The measured data using the MV-pair method show a high frequency fluctuation of 0.5 – 1mm in amplitude, which is attributed to the position reconstruction noise and other uncertainties in the fiducial detection. Such fluctuation is not seen in the simulation study (Fig. 3(b)) because the random detection noise was not added here in order to show the small difference between ideal simulation and real measurements. The simulated and measured positions have similar behavior and both tracks are very close to the reference inputted motion. Since our goal of prostate motion monitoring is to keep the marker position to within 3mm from a previously determined checkpoint, 3D displacement of the fiducial (with respect to the fiducial's initial position) is more relevant and this is displayed in Figs. 3(c) – (e) for different data acquisition/processing schemes. The proposed method caught the over-threshold displacement right away and prompted a kV-on signal thereafter (Fig. 3(d)). In contrast, when the periodic (22.5° interval) MV-kV method was employed for motion monitoring, this large displacement was not detected until the gantry rotated to 180° (Fig. 3(c)). It is a coincident that the periodic MV-kV method detected the large displacement at gantry angle of 180°, which is not too far from 177°. The situation could be worse if the large motion occurs, say, right after 180° (the displacement would not be detected until the gantry rotates to 202.5°) or when the kV is on less frequently. In this case, the threshold was reached only once during the whole delivery process. Due to the lack of guidance in the periodic kV-on method, the kV imager was switched on 15 times during the arc delivery. Because of the more intelligent use of the kV system, the proposed approach significantly reduced the usage of kV beam as compared with a continuous (7) or periodic kV-on scheme.

An analysis of the 536 Calypso tracks indicated that, in 98.5% (99.5%) of the time, the prostate does not move more than 1mm (2mm) in any duration of 2sec. This suggests that majority of prostate patient motions are slow and can be efficiently monitored with cine-MV method, as exemplified in Fig. 3. A “persistent excursion” case is presented in Fig. 4. Here the displacement was rather large (~9mm), occurring in between gantry angles of 150° and 250° (~20sec). Once again, the experimental and simulation results closely reproduced the Calypso track. Periodic kV-on of every 22.5° was not sufficient to pick up all the over-threshold displacements in time, whereas the proposed method caught all three over-threshold displacements reliably without delay. It is worth to point out that there are 3 unnecessary kV-on alerts at angles between 225° and 230°, caused by the fluctuation in the cine-MV displacement estimation. As shown in Fig. 4(e), the MV-pair estimated displacement reached 3mm three times (red curve) before the MV-kV measurement confirmed the displacement (blue curve) had reached the 2.5mm action level and triggered an checkpoint update (repositioning). The total number of kV snapshot requests triggered by cine-MV estimation was 8 for this particular case, half of the number used in the periodic (every 22.5°) kV-on scheme. Not only the kV usage was reduced, but also the tumor targeting performance was improved.

The prostate motions presented above were slow and the speed criterion described in section II.B.2 was not triggered. Experimental results for a motion type of “high frequency excursion” are shown in Fig. 5. Simulation study yielded similar results and is thus omitted here. The marker speed parallel to the MV imaging plane (2D projection speed) is plotted in Fig. 5(c), along with the 3D vector speed derived from the programmed motion and continuous MV-kV measurements. In general, the 2D projection speed reasonably reflects the motion behavior of the marker. In this case, the fiducial moved rapidly from time to time and this led to large MV-estimation errors (track reconstruction artifacts). With the use of speed criterion (i.e., requesting the kV-on when the projection speed $>1\text{mm/sec}$), the cine-MV method rapidly detected fast and large motions happening at $\sim 5\text{ sec}$ ($\sim 30^\circ$) and $\sim 50\text{ sec}$ ($\sim 250^\circ$).

Fig. 6 shows the simulation study of an extreme track where the 3mm threshold was exceeded 25.9% of the time when the periodic (22.5° interval) MV-kV method was used. This was reduced to 1.7% by using the current approach, resulting in significantly better beam targeting. It indicates sudden large displacements can be detected more effectively by the proposed approach than by the periodic MV-kV imaging (22.5° interval) method. This is understandable because the cine-MV imaging continuously estimates the marker displacement and triggers kV as needed, while the periodic MV-kV method acquires marker position information only at fixed time points.

Finally, the simulation results using all 536 Calypso-measured tracks are summarized in Table 1. It is worthwhile to emphasize again that the simulation strategy had been verified by the experimental results and thus simulation is valid in evaluating the proposed method. Three useful evaluation quantities listed in the table are (1) the percentage of time that the marker displacement exceeds the preset threshold of 3mm, which quantifies the undetected/uncorrected over-threshold displacement; (2) the number of kV-on events; and (3) the number of checkpoints (repositionings) confirmed by simultaneous MV-kV imaging. Out of the 536 tracks, only 74 of them had a displacement $>3\text{mm}$, partly because only the first 70 sec out of $\sim 10\text{ min}$ of the tracks in the original studies (4, 5) was used. This observation highlights the importance of the proposed cine-MV approach – it implies that continuously or periodically switching on the kV system is over-done for the majority of treatment fractions in prostate arc therapy. As compared to no motion monitoring, Table 1 shows that the periodic MV-kV scheme reduced the percentage of over-threshold time, leading to improved beam targeting. The targeting performance was improved if the kV was used more frequently (refer to the results of kV-on every 22.5° vs. those of kV-on every 45°). Compare to the periodic (every 22.5°) MV-kV method, the proposed method significantly reduced the over-threshold time at similar amount of average kV usage. It is worth noting that no track had percentage of over-threshold time more than $\sim 2\%$ using the proposed method, whereas the corresponding value is as large as $\sim 26\%$ for the periodic (every 22.5°) kV imaging scheme. The total number of checkpoint update was doubled for the proposed method. Together with better timing in checkpoint update, this explains why the percentage of over-threshold time was significantly reduced. The histograms of the percentage of over-threshold time, which is a good indicator of the motion monitoring efficiency, are shown in Fig. 7 for the periodic kV imaging and the proposed protocols for the 74 tracks that contained over-threshold motions. The non-zero percentage of over-threshold time of the

current method is attributed to the missed or delayed detection of over-threshold motion due to its small but finite probability of underestimating the marker displacement. These histograms further demonstrate the advantage of the current method in minimizing the time percentage of over-threshold displacement.

IV. Discussion

A necessary step in combating the adverse effects of intrafraction prostate motion is the real-time monitoring of the target position. Several methods of obtaining the data in real-time have been proposed (10-12). Notably, prostate tracking using EM transponders has recently been developed. Unfortunately, in addition to its large physical size, the transponder produces severe MRI artifacts and hinders MR-based post-treatment assessment. Currently, x-ray imaging with implanted metallic fiducials remains the most reliable method to monitor organ motion.

Prostate motion tends to be random without a fixed pattern (3, 13). A survey of previous studies indicates that, in a time interval of 2min, prostate motion larger than 3mm exists in ~5% of the observations. This increases to ~12% and ~25% at 5 and 10min, respectively (5). These results suggest that the intrafraction prostate motion during arc therapy is an important issue, even though VMAT delivery takes less time as compared with fixed-gantry IMRT. Conservatively, after the initial patient setup, a RapidArc or VMAT treatment takes 2 – 5 min for 2 Gy/fraction deliveries. With increased interest in hypofractionated treatment and the use of multiple arcs (14), which protract the delivery, the need for intrafraction motion monitoring during arc therapy is further increased. Moreover, to document and verify the target position during arc therapy deliveries, real-time monitoring of prostate position is also important.

Different from the conventional prostate motion monitoring strategy, which seeks to accurately and continuously localize the marker(s) using fluoroscopic kV imaging, a scheme similar to the “failure detection” strategy widely used in industrial engineering, where a continuous accurate monitoring of system is not pursued until a warning signal from a failure detection device is triggered, is proposed for prostate IGRT. Practically, it is neither necessary nor dose efficient to use a continuous or periodic fluoroscopic kV imaging together with MV beam because the prostate motion does not occur all the time. Here a kV-on signal is triggered only when the motion is over an abnormality limit. Compared to other continuous kV-tracking modalities, which generally require frequent use of kV beam(s), this technique offers sufficiently accurate target monitoring with reduced imaging dose to the patient by utilizing the mechanism that the treatment is delivered in an arc. The scheme uses the treatment beam for “failure detection” and individualizes the use of kV imaging to each treatment session. Upon the confirmation of an over-threshold displacement, a number of interventional strategies can be implemented to compensate for a motion, e.g., moving the couch or shifting the subsequent MLC apertures, subjects of future research. The proposed approach is also suitable for monitoring other organs with slow and unpredictable motion.

We note the position estimation in this work was done by using MV projection pairs of ~10° apart. More sophisticated estimation of fiducial displacement by optimal usage of

multiple MV projections at different times and even other prior knowledge of prostate motion can be developed. While this is useful and may yield more accurate result, we do not anticipate any significant change when multiple projection data are used for reconstruction.

When an intensity modulated beam is used for in-line imaging, a potential difficulty is that the fiducials may be partially or completely blocked by the MLC leaves at certain angle(s). The fiducial blockage avoidance strategy has recently been studied in the context of IMRT (15). It was shown that it is possible to ensure “seeing” at least one of the implanted fiducials in any of the IMRT segments for monitoring the fiducial(s) during a step-and-shoot dose delivery by adding to the objective function a hard or soft constraint that characterizes the level of preference for the fiducial to be included in the segmented fields. It was found that the final dose distributions of three plans (constraint-free, soft and hard constraints) were very similar, which is understandable because the fiducials are generally placed inside the target volume, or prostate in the context of the current study. The strategy may be implemented to VMAT in a similar fashion. Combined gantry, marker, and MLC motion during VMAT, however, increases the problem complexity and the possibility of detection confusion among markers. More efficient use of the information from neighboring frames and incorporating speed constraints may alleviate the problem. Nevertheless, because three or four markers are usually used during treatment, the probability of detecting at least one marker is high even with current RapidArc planning. Moreover, several sources of information that can help to estimate the coordinates of an MLC-blocked fiducial were discussed in a previous paper (7).

Although a relatively large marker was used in our experiments, it was found that segmentation of clinically used gold marker can be achieved in real time with relatively high accuracy from simultaneously acquired MV and kV images of a pelvic phantom (16). Therefore, we do not foresee any major performance degradation in our ongoing clinical studies, which will be reported later.

V. Conclusions

A novel prostate motion tracking algorithm based on cine-MV and as-needed kV imaging has been described. A distinct feature of the method is that the continuous accurate position information is not actively pursued during the delivery process. Instead, the technique focuses its attention to detecting any motion potentially greater than a preset threshold (i.e., “failure” detection) by taking the advantage of continuous gantry rotation during arc deliveries. If this happens, the kV imaging is triggered to accurately locate the current position of the prostate through a triangulation with the MV data. Experimental and simulation data have shown that the proposed technique is capable of reliably tracking the prostate position during arc therapy delivery process. It provides us with a high confidence about the prostate displacement, yet without paying the unwanted overhead of continuous or periodic kV imaging. The technique can be readily implemented on LINACs equipped with EPID and onboard kV imaging devices.

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Appendices

In Appendices 1-3 we present a theoretical analysis of position estimation errors when the proposed MV arc-tracking method is used. We define the first image of an MV image pair as the reference and the second one as the sample. In Appendix 4 we extend section II.B.2 and provide more detailed description on handling high speed sudden prostate motion.

1. Position estimation errors for static object

Following the definition of the coordinate systems and symbols in (10), let the fiducial position be

$$\vec{M}=(X, Y, Z)^T \text{ and } \vec{M}'=(X', Y', Z')^T$$

in the two radiation source-fixed coordinate systems (reference and sample) and let their projections on the reference and sample image plane be

$$\vec{P}=(x, y, f)^T \text{ and } \vec{P}'=(x', y', f')^T,$$

where f and f' are the SID of the reference and sample (see the left panel of Fig. 1). They are approximately the same. The two source-centered coordinate systems are related by a known rotation $\mathbf{R}$ and Translation $\mathbf{T}$ (defined in the sample coordinate system):

$$\vec{M}' = \mathbf{R}\vec{M} + \mathbf{T},$$

$$\mathbf{R} = \begin{bmatrix} \cos\varphi & 0 & -\sin\varphi \\ 0 & 1 & 0 \\ \sin\varphi & 0 & \cos\varphi \end{bmatrix}, \quad \mathbf{T} = \begin{bmatrix} r\sin\varphi \\ 0 \\ r(1 - \cos\varphi) \end{bmatrix},$$

where φ is the gantry rotation angle between the reference and sample images and r is the source-to-axis distance (SAD). Because $\vec{P}$ and $\vec{M}$ are parallel, we have

$$\vec{M}' \times \vec{P}' = 0 \Rightarrow Z\mathbf{R}\vec{P} \times \vec{P}' = -\mathbf{f}\mathbf{T} \times \vec{P}'.$$

Considering the case of a small φ and using the y-component of the above equation, the unknown distance Z of the fiducial in the reference source-centered coordinate system can be approximately recovered from the disparity $(x - x')$,

$$Z \approx \frac{f \cdot r \sin \varphi}{(x' - x) \cos \varphi + f \sin \varphi} \Rightarrow Z - r \approx \frac{x - x'}{f \cdot \varphi},$$

where $Z - r$ is the distance from the fiducial to the isocenter.

The error of the position (Z is depth; the other two coordinates can be derived once Z is solved) estimation can then be expressed as:

$$\Delta(Z - r) = \frac{\Delta(x - x')}{f \cdot \varphi} + \frac{(x - x')}{f^2 \cdot \varphi} \Delta f + \frac{(x - x')}{f \cdot \varphi^2} \Delta \varphi \quad (1)$$

Assuming the SID is 1500mm and the fiducial is 20mm away from the isocenter in the direction perpendicular to the imager, we consider the following two situations: (i) A short baseline (small angular separation) case of 1.5° separation between two MV images, where Eq. (1) can be rewritten as

$$\Delta(Z - r) \approx 26\Delta(x - x') + 0.013\Delta f + 0.8\Delta \varphi \quad (2)$$

In this case, provided no other error presents, 0.3 pixel (~ 0.12 mm) fiducial detection error in the position disparity would result in a 3mm error in the position (depth) estimation, and 0.2° gantry angle error would result in a 3mm position (depth) estimation error.

(ii) A longer baseline (larger angular separation) case of 10° separation between two MV images, where Eq. (1) can be recast to

$$\Delta(Z - r) \approx 3.8\Delta(x - x') + 0.013\Delta f + 0.11\Delta \varphi \quad (3)$$

In this case, it is estimated that the resultant errors to be less than 1mm for any measurement inaccuracy seen in a typical linac and EPID used in our clinic. It typically takes ~ 2 sec for a 10° rotation under current IEC safety regulations (gantry rotation cannot be faster than 1min per rotation). Therefore, accurate 3D reconstruction is difficult for fast moving fiducials because of the static fiducial assumption used in the triangulation. It is important, however, to emphasize that, for prostate, the probability for a fast motion (> 1 mm/sec) is rare, and thus motion monitoring using MV image pairs with a relatively large angular separation is a reasonable approach.

2. Optimal angular separation between MV image pairs for 3D fiducial position reconstruction

The angular separation dependence of the proposed MV arc-tracking method (section II.B.1) was evaluated using a static marker. An arc plan was delivered to a phantom with an embedded marker. The fiducial position was reconstructed by using MV image pairs with different angular separations. The position estimates were compared to the known static

fiducial position. Three measurements with the fiducial placed at different positions were carried out.

Fig. A-1. RMS and max absolute tracking error as a function of angular separation for a single static fiducial

The RMS and maximum absolute errors of the detected fiducial position for a static fiducial are plotted as a function of the angular separation of MV image pairs (Fig. A-1). As expected, the localization error is small in the SI direction for any angular separation. The RMS errors in the AP and LR directions are found to be 0.3mm when the separation is approximately 10°. Further increase of the separation does not result in noticeable increase in accuracy. Note that the results are based on the tracking of a static fiducial marker. Therefore, this represents the best achievable monitoring accuracy.

3. Position estimation errors for a slow-moving object

Assuming that the fiducial moves a short distance ΔAP in the AP direction between the two MV images (reference and sample), the difference between the projected positions of the fiducial on a sample image plane with and without the fiducial motion can be expressed as

$$\Delta x' \approx -\sin \alpha \cdot \Delta AP \cdot f/Z$$

where α is the gantry angle of the Linac. Therefore, the change of the reconstructed depth is

$$\Delta(Z - r) \approx -\frac{-\Delta x'}{f \cdot \varphi} \approx \frac{\sin \alpha \cdot \Delta AP}{Z \cdot \varphi}.$$

The errors of fiducial position estimation in AP and LR directions are approximately given by:

$$\Delta X_{AP} \approx \frac{\Delta AP}{Z \cdot \varphi} \cdot \sin \alpha \cos \alpha, \Delta X_{LR} \approx \frac{\Delta AP}{Z \cdot \varphi} \cdot \sin^2 \alpha \quad (4)$$

The position estimation error depends upon the fiducial movement with respect to the gantry position. Assuming a 10° separation (~2sec) and a 2mm fiducial motion in AP direction between the MV image pair, Eq. (4) can be reduced to

$$\Delta X_{AP} \approx 6 \cdot \sin(2\alpha), \Delta X_{LR} \approx 6 \cdot (1 - \cos(2\alpha)) \quad (5)$$

The error can be over 5mm in some cases. However, it is reasonably small (< 2mm) for most of the time and the majority of the prostate motion cases (motion speed smaller than 1mm/sec). Note that the method tends to over-estimate the displacement. In reality, because of fiducial detection error, the chance for over-estimation is even larger. The chance of under-estimation is relatively small.

4. Handling high speed sudden prostate motion

The estimation method described in section II.B.1 is well suited for slow prostate motion. In some rare but possible situations, the prostate may move more than a few millimeters within a second. It is not surprising that the above estimation does not yield accurate results because the marker positions are dramatically different at the two instants when the projections are taken. The information so obtained is, however, still useful because our interventional decision relies only on whether the estimated displacement exceeds a pre-defined threshold or not. Our analysis of the Calypso data from all the 536 tracks suggested that the alert from the MV estimation was correct in ~83% of the time when a sudden displacement of 3mm or more occurred within 2 sec. Considering the rareness of sudden large prostate movement, it was estimated that the false negative events happened only in 0.1% of the time when the MV-pair method was used for kV-on decision-making. Nevertheless, to enhance the robustness of the MV-based decision-making, the apparent marker motion velocity on the EPID plane was also monitored in our study because the marker's true 3D vector motion speed cannot be reliably estimated through MV-only information. We define the marker's 2D projection speed as the velocity of marker motion parallel to the EPID plane. It was estimated by calculating the time differentiation of the marker position on the imager with respect to the projection of the checkpoint on the imager and scaling it back to the plane that is parallel to the imager plane and contains the isocenter. This 2D projection speed of the marker was computed continuously and a kV-on was prompted when the speed was greater than an empirical value of 1mm/sec. While the speed criterion is instructive, false alert may happen at this choice of action level because of the

fluctuation of the estimated speed. A combinational use of the speed check and the above displacement criterion provided a practically useful decision-making tool to deal with a sudden prostate motion: the kV was turned on if the speed $>1\text{mm/s}$ and, simultaneously, the MV-pair estimated displacement was greater than a value that is less than the displacement threshold used to trigger on the kV for slow prostate motion (II.B.1). Thus the kV-on action was prompted if the MV-pair derived displacement $>3\text{mm}$ (regardless the speed value) or if the MV-estimated displacement $>2\text{mm}$ and the MV-estimated fiducial 2D projection speed $>1\text{mm/s}$.

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Fig.1. Projection geometry (left) and estimation of the fiducial position based on sequential MV projections (right).

Fig.2.
Flowchart of prostate motion monitoring and intervention based on cine-MV and as-needed kV imaging.

Fig.3.

Real-time marker tracking using different methods for a motion type of "continuous target drift". Panels (a) and (b) show the experimental and simulation results, respectively. The solid black curves represent the Calypso-measured tracks. The cross, star, and circle symbols are the results in the LR, SI, and AP directions obtained using a previously established method of continuous (7.5Hz) simultaneous MV-kV imaging (7). The triangles show the marker positions estimated using the cine-MV method. Panels (c) and (d) compare the periodic MV-kV triangulation (every 22.5°) and the proposed technique, in which the

red circles show the gantry angle/time when kV imager was switched, and the green squares denote the checkpoint update (repositioning) event determined by MV-kV data. The black solid curve in panel (e) displays the vector distance with checkpoint update in the proposed method. The red and blue curves show the tracks derived from the proposed method and the continuous MV-kV method, respectively. An update of checkpoint occurs at $\sim 177^\circ$ in response to the detected over-threshold marker displacement and this is reflected by a sudden drop of the vector distance curves.

Fig.4. Real-time marker tracking using different methods for a motion type of "persistent excursion". See Fig. 3 for captions.

Fig.5.

Real-time marker tracking using different methods for a motion type of "high frequency excursion". Panel (a) shows the experimental results (see Fig. 3(a) for notations). Panel (b) displays the motion monitoring strategy using the proposed method (see Fig. 3(c) for notations). In panel (c), red curve shows the absolute value of 2D projection motion speed of the marker (Appendix 4). For comparison, the programmed and the continuous MV-kV measured 3D speed are also displayed in black and blue curves, respectively. Panel (d) shows the 3D vector distances to the checkpoints (see Fig 3(e) for notations).

Fig.6.

(a) Calypso-measured prostate coordinates in the LR, SI, and AP directions. (b) Motion monitoring strategy using the proposed method (see Fig. 3(c) for notations). (c) Motion speed estimations (see Fig. 5(c) for notations). (d) 3D vector distances (see Fig. 3(e) for notations).

Fig.7. Histograms of the percentage of time of over-threshold displacement for periodic (every 22.5°) kV-on scheme (left) and the proposed method (right).

Table 1

Comparison of different motion monitoring strategies. The proposed method yielded better targeting efficiency.

	Original motion tracks (no monitoring)	kV on at 5°, 45°, 90°, 135°, ..., 315°	kV on at 5°, 22.5°, 45°, 67.5°, ..., 337.5°	Proposed method
Mean of percentage of over-threshold time *	21.4%	6.0%	4.0%	0.4%
Maximum (95th percentile of) percentage of over-threshold time *	95.6% (86.2%)	36.9% (18.1%)	25.9% (11.7%)	2.1% (1.5%)
Mean number of kV-on per track †	-	7	15	13.4
Mean number of checkpoint update (repositioning) per track †	-	0.16	0.23	0.49

* These numbers are obtained based on the 74 3D tracks that contained over-threshold motion.

† These numbers are obtained by averaging over all 536 3D tracks.