Beam’s-eye-view Prostate Motion Detection during Arc Radiotherapy

**Introduction:** Fiducial-based targeting is an efficient technique to control inter-fraction prostate position during external beam radiotherapy. Cine EPID imaging during volumetric modulated arc therapy (VMAT) provides angular-indexed projections in the beam’s-eye view (BEV). If implanted radiopaque fiducials are within the beam aperture, their projections can be used to monitor the prostate position during the treatment delivery. The challenge comes from the complexity of the VMAT delivery in which the multi-leaf collimator (MLC) frequently blocks the radiation. As a consequence, projection images that include fiducials may only exist for certain gantry angles. To address this problem, we developed a statistical motion tracking algorithm for arc-radiotherapy, which can monitor 3-D fiducial motion using limited BEV projections. In this work, our aim is to apply our method to prostate motion tracking during clinical VMAT treatment.

**Materials and Methods:** We first examined the algorithm accuracy using the CIRS dynamic thorax phantom with a custom tumor model. Two fiducials were placed on the surface of the tumor at 3 cm apart from each other. Clinical VMAT plans were delivered to the phantom based on a single 360 degree arc. In the clinical study, the data from two patients receiving prostate VMAT treatment were analyzed. For each patient, two gold fiducials (X-Mark, 1cm and 2cm in length) were implanted into the prostate at clinically relevant distances apart from each other. The patients were setup with two orthogonal kV image and cone-beam CT. A total of 35-fraction VMAT with 2-field full arcs were delivered for each patient. BEV images were acquired in cine mode every five fractions at a frame rate of 2 fps with a pixel size of 0.784mm. The same VMAT plans were delivered to the solid water phantom with two fiducials.

The fiducial spatial positions were measured by two sequential steps: fiducial detection and motion estimation. In the first step, we use a block matching method to remove the noise and enhance the fiducials in the BEV images. The image is block-wise processed into multiple blocks, and the blocks with the same features are matched and grouped. Then, each group is filtered by wavelet filters with shrinkage methods. This procedure is able to recover details shared by grouped blocks and at the same time it preserves the essential unique features of each individual block. Fig. 1c) shows the detected fiducials in BEV images. As results of detection, the trajectory of fiducials along the projection angle was generated for further analysis.

![Fig.1. Fiducials detected in EPID images for fractions 1(a) and 21(b). The images are acquired at gantry angle t1 (Arc 1) and t2 (Arc 2). The fiducial superimposition (c) shows a large displacement at t2 of fraction 21.](image1)

![Fig.2. The fiducial tracking for 3 fractions with 2 full Arcs delivery: fraction 1 (green), 11(blue), and 21(red). The blue bar indicates the closed aperture. The displacement (0.5cm) is observed for fraction 21 (red line).](image2)
The 3D fiducial positions were estimated using the limited-aperture maximum a posteriori (MAP) algorithm, which was developed in our earlier study. The 3-D fiducial displacement is estimated by maximizing the probability of displacement using a set of 2-D projection positions in BEV images. A moving window strategy is implemented to extract the spatial position in a continuous sequence of projections. The fiducial positions at each given angle were tracked as long as the projections are available. If the projections at certain angles were blocked by the modulation of the MLC, the estimation for these gantry angles were skipped without interfering with the estimation at other angles. By adjusting the size of the moving window, the minimum number of required projections was reduced to five, while still satisfying the tolerance accuracy of 1 mm root mean square (RMS) measure.

**Results:** A total of 8,400 BEV images with the size of [512X384] were processed for fiducial detection. Among them, the images with a fiducial in open apertures were further processed for fiducial motion estimation. The phantom experiments show that the accuracy of 3D fiducial position estimation is 0.69 +/- 0.56 mm in RMS by comparing with the ground truth. In the clinical study, the kV images and CBCT images show that inter-fractional prostate positioning was within 1mm for both patients. For patient 1, intra-fraction prostate motion was measured at 0.98 +/- 0.51 mm for all fractions, and individual fraction motion less than 1 mm. For patient 2, intra-fraction motion was 1.12 +/- 0.65 mm for all fractions. However, a large displacement (4.9 +/- 0.74 mm) was measured for fraction 21. Fig. 2 shows the fiducial displacement during two full arc deliveries for fractions 1, 11 and 21. The prostate remained static for fractions 1 and 11, however a large displacement was measured during the second arc delivery of fraction 21. The results were confirmed by comparing the fiducial positions between two images, which were acquired at the same gantry angle but different fractions (Fig. 1(c)).

**Conclusions:** Prostate motion during arc-therapy can be estimated from a limited number of projections using our statistical motion estimation method. We have shown that the proposed method can rigorously track the 3D spatial fiducial locations to an accuracy of one millimeter. Clinical studies show that the prostate displacement as large as 5mm was observed during one fraction for one of the patients. The results indicate that our algorithm is well suited for in-treatment room prostate tracking and post-treatment evaluation.