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Technical note

Variable angle stereo imaging for rapid patient position correction in an in-house real-time position monitoring system

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ABSTRACT

Purpose: To develop and validate a variable angle stereo image based position correction methodology in an X-ray based in-house online position monitoring system.
Materials and methods: A stereo imaging module that enables 3D position determination and couch correction of the patient based on images acquired at any arbitrary angle and arbitrary angular separation was developed and incorporated to the in-house SeedTracker real-time position monitoring system. The accuracy of the developed system was studied by imaging an anthropomorphic phantom implanted with radiopaque markers set to known offset positions from its reference position in an Elekta linear accelerator (LA) and associated XVI imaging system. The accuracy of the system was further validated using CBCT data set from 10 prostate SBRT patients. The time gains achieved with the stereo image based position correction was compared with the manual matching of seed positions in Digitally Reconstructed Radiographs (DRRs) and kV images in the Mosaiq record and verify system.
Results: Based on phantom and patient CBCT dataset study stereo imaging module implemented in the SeedTracker shown to have an accuracy of 0.1(σ = 0.5) mm in detecting the 3D position offset. The time comparison study showed that stereo image based methodology implemented in SeedTracker was a minimum of 80(4) s faster than the manual method implemented in Mosaiq R&V system with a maximum time saving of 146(6) s.
Conclusion: The variable angle stereo image based position correction method was shown to be accurate and faster than the standard manual DRR–kV image based correction approach, leading to more efficient treatment.

1. Introduction

Real-time target position monitoring and position correction during radiation treatment ensures the accurate delivery of dose to the intended target volume (TV). In Stereotactic Body Radiation Therapy (SBRT) real-time position monitoring of the TV is critical as any random variation in the TV position during treatment will have a significant impact on the dose delivered to the TV and a greater impact on the treatment outcome [1–5]. Many systems, using a range of modalities and with different physical configurations, have been developed to enable real-time position monitoring during treatment. These include electromagnetic transponders implanted in or in the vicinity of, the tumour [6], kV X-ray based systems with fixed angle stereoscopic configuration [7], ultrasound image based position monitoring systems [8], infrared marker based systems to monitor the infrared markers positioned on the skin in the treatment area [9] and stereo vision based skin surface tracking [9]. In general these systems are integrated with general purpose or SBRT dedicated linear accelerators (LAs) to enable position monitoring during treatment delivery. The integration of a magnetic resonance imaging device (MRI) with a LA is currently underway to enable higher contrast soft tissue image visualisation during treatment delivery [10].

Modern LAs come equipped with a kV imaging system to enable cone beam computed tomography (CBCT) image based pre-treatment image verification. Recent studies have demonstrated utilisation of the single imager in the kV CBCT imaging system to allow real-time position monitoring of the prostate during

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radiotherapy [11,12]. These systems use gold radio-opaque markers implanted in the prostate to determine the position of the prostate during treatment. Our group has developed and validated one such system, SeedTracker [12], which enables the real-time position monitoring of the prostate by comparing the seed positions in the single planar image acquired during treatment to the expected seed positions calculated from the 3D position of the seed centroids. While this enables real-time position monitoring during treatment delivery it does not provide 3D patient position offset and the resultant required table corrections, due to the limitation in the 2D information that can be derived from single planar imaging. With the current workflow the intrafraction position correction is performed utilising either CBCT image based registration or manual registration of standard Anterior-Posterior (AP) and Lateral (lat) orthogonal DRR and kV planar images. This results in significant time between treatment interruption, position correction and treatment resumption.

In this work we present the implementation and validation of a variable angle stereoscopic imaging method that quantifies the 3D position deviation of the patient based on implanted radiopaque markers and provides the resultant couch shifts to reposition the patient to the planned position efficiently using images acquired at any arbitrary gantry angle.

2. Material and methods

2.1. SeedTracker position monitoring system

SeedTracker is an in-house developed position monitoring system that enables real-time position monitoring of patients implanted with radiopaque markers, treated with a conventional C-arm gantry linear accelerator and its associated kV imaging system [12]. In the real-time position verification process the images are acquired using the continuous fluoroscopy mode during treatment delivery with 120 kVp x-rays and exposure settings of 25 mA tube current and 40 ms exposure time per frame. The SeedTracker system establishes the planned seed positions for a given projection images based on the centroid of seeds and isocentre position derived from the treatment planning system (TPS). The system also automatically segments the seeds in the planar kV projection images acquired during the treatment delivery and compares the detected position with the planned position. The deviation of patient position in comparison to the planned position is currently presented as two dimensional co-ordinates in anterior- posterior and lateral (AP-lat) and Superior-Inferior (SI) directions, as a function of gantry angle and image acquisition time. The system will alert the user if any one of the position co-ordinates exceeds the predefined tolerance value and the treatment can be stopped by the user. The SeedTracker system installed on a computer with 32 GB memory and 2.6 GHz processor speed takes 280(20) ms to process each of the images and provide results to the user. During real-time monitoring, the latest image acquired after completing the processing of the current image is used for the analysis. More details on the algorithms, implementation and performance validation of SeedTracker can be found elsewhere [12]. The SeedTracker system is being used for real-time position monitoring of prostate cancer patients treated with SBRT in South West Sydney Local Health District (SWSLHD) within the PROstate Multicentre External beam radio THErapy Using Stereotactic boost (PROMETHEUS) trial [13].

2.2. Patient position correction with online imaging system

The SeedTracker system enables patient position monitoring using sequential monoscopic X-ray images acquired during treatment delivery. In the initial implementation of SeedTracker, if the position deviation of the patient exceeds the tolerance limits during treatment delivery, the treatment was interrupted then orthogonal planar image based position verification was used to obtain the 3D positional deviation. The resultant couch correction was then used to correct the patient position. Fig. 1 shows the overall treatment workflow and imaging protocols implemented for the pre-treatment and real-time position verification. The orthogonal planar image based 3D position offset determined during treatment through the Mosaiq record and verify (R&V) system is shown in the dotted region (right side) of the workflow (Fig. 1). The major limitation in this workflow is increased overall treatment time mainly due to:

i). The requirement of full CBCT image based verification if the patient position exceeds more than 5 mm in any of the three (AP, lat and SI) directions and

ii). The orthogonal images used to correct patient position during treatment. In this approach the seed positions are determined manually in the AP and Lateral planar images and compared against the seed positions in the TPS generated Digitally Reconstructed Radiographs (DRRs). The position offset and resultant couch corrections are then determined by the R&V system.

2.3. Variable angle stereo imaging

In order to increase the efficiency of the treatment workflow and rapid position correction of the patient when the prostate position exceeds the tolerance limits, a stereoscopic image based 3D position and resultant couch correction calculation was implemented into the SeedTracker system. In this approach the 3D position deviation of the isocentre with respect to planned position can be determined by acquiring a pair of images at projection angles θ_1 and θ_2. Typically with real-time monitoring, if a prostate position deviation is observed during the treatment delivery at gantry angle θ the treatment beam will be stopped. The kV planar images will then be acquired at gantry angles θ and $\theta + \Delta\theta$. The stereo imaging module in SeedTracker auto segments the seeds in the stereo images, determines the 3D position of the seeds and compares it with the planned position to calculate the 3D position deviation of the patient. After the couch correction the treatment beam can be resumed from its stopped position of θ. The patient position correction workflow for deviations observed during treatment delivery using the stereo imaging module in SeedTracker is shown in the dashed region (Left side) of the workflow (Fig. 1).

2.4. 3D position calculation using variable angle stereo images

The variable angle stereoscopic imaging geometry using a hypothetical phantom implanted with three fiducial gold seeds (Number of seeds n = 3) is shown in Fig. 2. If (X_i^{Pl}, Y_i^{Pl}, Z_i^{Pl}) is the Cartesian co-ordinates of the centroid of the ith seed in a co-ordinate system whose origin coincides with the planned isocentre, the 3D position deviation of the prostate with respect to the planned position can be determined as follows:

1. The x and y co-ordinates of the current position of the nth seed in a projection image acquired at angles θ_1 and θ_2 is

$$x_{i,\theta_1}^{pr} = \left((X_i^C \cos\theta_1 - Z_i^C \sin\theta_1) * \frac{SAD}{SID} \right) - IF_{x,\theta_1} \tag{1}$$

$$y_{i,\theta_1}^{pr} = \left(Y_i^C * \frac{SAD}{SID} \right) - IF_{y,\theta_1} \tag{2}$$