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ORIGINAL PAPER

Registration of on-board X-ray images with 4DCT: A proposed method of phase and setup verification for gated radiotherapy

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Abstract Current gated radiation therapy starts with simulation 4DCT images of a patient with lung cancer. We propose a method to confirm the phase of 4DCT for planning and setup position at the time of treatment. An intensity-based rigid algorithm was developed in this work to register an orthogonal set of on-board projection X-ray images with each phase of the 4DCT. Multiple DRRs for one of ten 4DCT phases are first generated and the correlation coefficient (CC) between the projection X-ray image and each DRR is computed. The maximum value of CC for the phase is found via a simulated annealing optimization process. The whole process repeats for all ten phases. The 4DCT phase that has the highest CC is identified as the breathing phase of the X-ray. The phase verification process is validated by a moving phantom study. Thus, the method may be used to independently confirm the correspondence between the gating phase at the times of 4DCT simulation and radiotherapy delivery. When the intended X-ray phase and actual gating phase are consistent, the registration of the DRRs and the projection images may also yield the values of patient shifts for treatment setup. This method could serve as the 4D analog of the conventional setup film as it provides both verification of the specific phase at the time of treatment and isocenter positioning shifts for treatment delivery.

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Introduction

A major difficulty for 3D conformal radiotherapy of cancers in the thorax and upper abdomen is the intrafraction motion caused by respiration. A population based margin has been used widely to take the motion into account. Respiratory gating provides an improved way to deal with the problem [1,2] because of its potential to individualize the treatment margin. A gated radiation therapy treatment is usually planned based on a simulation breath-hold CT or a pre-determined phase of 4DCT images of the patient. Prior to treatment, both spatial and temporal verification of the patient setup are crucial for the success of a gated radiation delivery [3—9]. In reality, there is currently no universally accepted method for this verification, and methods used in 3D radiation therapy, such as the comparison of orthogonal portal images with DRRs, are employed. Samson et al. and Boer et al. [10,11] developed a technique to evaluate lung cancer patient positioning by comparing portal images and digitally reconstructed radiographs. For intrafractional motion, 6—12 sequential images were generated with an electronic portal imaging device (EPID) and one of them was chosen to be the reference image. Visible structures such as the trachea, carina, the upper chest wall, aortic arch, clavicle, and paraspinal line were manually contoured in all the EPID images including the reference and the floating images. Using these contoured anatomic landmarks, the intrafractional setup shifts were determined by maximizing the correlations between the reference and the floating images. This technique relies on the localizations of certain thoracic structures visible on MV EPID and cannot account for soft tissue motion within the lung. Drawing contours and edges takes time and this may be impractical for daily use. Alternatively, a real-time tumor-tracking radiotherapy (RTRT) system was designed to estimate setup shifts by tracking 2 mm gold fiducial markers placed into lung tumors [12,13,15]. The system consists of four fluoroscopic imagers, which offer views of the patient to determine the 3D positions of the fiducial markers before treatment. Through overlapping and comparing the positions of the fiducial markers in the RTRT system and 3D treatment planning system, the patient position can be corrected to obtain the best match. The RTRT system is able to accurately track the markers. The method is, however, invasive, and not possible for all patients. According to a phantom study, patients with a daily 2 Gy irradiation receive an extra $0.208–21.48 \times 10^{-3}$ Gy dose for 2 min diagnostic exposure, accounting for 0.01—1% of the total dose [14]. Furthermore, radiotherapy usually starts a week after the marker insertion, and dislocation of the markers may present a practical problem.

For accurate gated radiation delivery, a simple and robust solution to the tumor localization problem is needed to ensure that the planned dose distribution will be delivered to the patient in a clinical setting. In this paper, we propose a noninvasive method to verify the phase and shifts for gated radiotherapy based on the registration of on-board X-ray and 4DCT images. Immediately prior to each treatment fraction, the method registers the on-board X-ray images with the planning 4DCT spatially and temporally. Thus, the method may be used to examine the consistency between the gating radiotherapy planning and delivery phases. Because the method is based on internal anatomy information, no reliance on implanted markers or manual identification of structures is required.

Materials and methods

Overview of phase and setup verification method

Our method applies to the 4DCT treatment planning and delivery technique where during planning one of the phases is used so that the tumor is assumed to be static and therefore the treatment delivery is gated at this selected phase [14,16—19, 27]. Accurate treatment delivery requires that both the phase and isocenter position for treatment match those used in planning. For standard radiotherapy, portal images are used as an independent verification of the patient position even though external markers are placed on the patient during simulation and used as reference points for alignment in the treatment room. We believe that relying on one system for both simulation acquisition and treatment delivery is inadequate and that an independent protocol must be used to verify the phase and position for 4D treatment.

We propose performing this verification by registering DRRs from the 4DCT simulation with digital X-ray images from an on-board imager. For each 4DCT phase, about 100 DRRs are generated by translating the isocenter in the corresponding 3DCT data set during the optimization process. For a rigid transformation, there are six transformation parameters: three translations (x,y,z) and three rotation angles around the x, y and z axes. In this analysis, we assume rigid body motion and ignore rotations as they are typically small and difficult to implement clinically. Furthermore, the purpose of this work is to demonstrate our technique and this assumption was used to reduce the parameter space to speed up the analysis. The CCs of these DRRs and the X-ray images are calculated and the maximum CC value is found by an optimization process. The 4DCT is separated into 10 breathing phases, so that 10 maximum CC values are found. The breathing phase of the patient at the time of X-ray acquisition is the one with the overall maximum CC. The isocenter position is given by the translations used to generate the DRR with the overall maximum CC value.

Data acquisition

The 4DCT was acquired using a commercially available respiratory gating system, Real-Time Position Management (RPM) (Varian Medical Systems, Palo Alto, CA) interfaced with a clinically available CT scanner (Discovery-ST, GE Medical System) operating in cine mode. This is an eight-row multislice scanner. The scan was performed using 2 cm couch increments with 2.5 mm slice thickness. For each couch position, CT slices were collected over the entire patient respiratory cycle. After the data were recorded by the tracking system, they were subsequently resorted into different phases according to the temporal information provided by the respiratory signal.