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Kilovoltage intrafraction motion monitoring and target dose reconstruction for stereotactic volumetric modulated arc therapy of tumors in the liver ☆

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ABSTRACT

Purpose: To use intrafraction kilovoltage (kV) imaging during liver stereotactic body radiotherapy (SBRT) delivered by volumetric modulated arc therapy (VMAT) to estimate the intra-treatment target motion and to reconstruct the delivered target dose.
Methods: Six liver SBRT patients with 2–3 implanted gold markers received SBRT in three fractions of 18.75 Gy or 25 Gy. CTV-to-PTV margins of 5 mm in the axial plane and 10 mm in the cranio-caudal directions were applied. A VMAT plan was designed to give minimum target doses of 95% (CTV) and 67% (PTV). At each fraction, the 3D marker trajectory was estimated by fluoroscopic kV imaging throughout treatment delivery and used to reconstruct the actually delivered CTV dose. The reduction in D_{95} (minimum dose to 95% of the CTV) relative to the planned D_{95} was calculated.
Results: The kV position estimation had mean root-mean-square errors of 0.36 mm and 0.47 mm parallel and perpendicular to the kV imager, respectively. Intrafraction motion caused a mean 3D target position error of 2.9 mm and a mean D_{95} reduction of 6.0%. The D_{95} reduction correlated with the mean 3D target position error during a fraction.
Conclusions: Kilovoltage imaging for detailed motion monitoring with dose reconstruction of VMAT-based liver SBRT was demonstrated for the first time showing large dosimetric impact of intrafraction tumor motion.
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Volumetric modulated arc therapy (VMAT) allows efficient delivery of highly conformal dose distributions in radiotherapy [1–3]. However, for thoracic and abdominal tumors respiratory motion may compromise the accuracy of the dose delivery. This is of particular concern for stereotactic body radiotherapy (SBRT) due to tightly conformed target dose distributions [4] that may be peaked in a central high dose region intended to coincide with the hypoxia-prone tumor center [5–10].

In liver SBRT, image-guidance often relies on implanted fiducial markers because liver tumors are difficult to visualize by in-room imaging. The implanted markers are typically used for patient setup [11], but the marker motion may also be monitored during treatment with stereoscopic kV imaging [12], MV portal imaging [13], or combined kV–MV imaging [14]. For a conventional linear accelerator, stereoscopic kV imaging requires non-standard imagers while continuous localization with MV imaging may be unfeasible for VMAT where MLC motion sometimes hinders marker visibility [15]. These limitations have stimulated intra-treatment motion monitoring with a single kV imager, which is standard equipment for image-guided radiotherapy (IGRT) on many linear accelerators. Adamson and Wu used a single kV imager to estimate the three-dimensional (3D) prostate motion during intensity modulated radiotherapy by triangulation from different field directions, assuming static target positions between subsequent field deliveries [16]. This assumption reduces the temporal resolution of the estimated target motion and is invalid for thoracic and abdominal tumors. In a recent study, Ng et al. [17] acquired fluoroscopic kV images perpendicular to the treatment beam during prostate VMAT treatments and estimated the 3D target position for each individual kV image by a probability-based method [18]. Accurate intra-treatment 3D localization with the same frequency as used for the kV imaging (5–10 Hz) was obtained by this method, which was termed kilovoltage intrafraction monitoring (KIM) by the authors [17].

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Several methods have been proposed to calculate the impact of intra-treatment motion on the delivered VMAT dose. For quasi-periodic respiratory motion, one approach is to split the VMAT plan into phase-specific sub-plans, calculate the dose of each sub-plan in the corresponding phase of a four-dimensional computed tomography (4DCT) scan, and accumulate the total dose using deformable image registration (DIR) [19,20]. Dose reconstruction with a phase specific patient anatomy can also be performed by Monte Carlo calculations using a transport grid with time dependent grid densities formed by interpolation of the 4DCT phases and mapping the dose back to a static reference grid by DIR [21]. While these approaches account for breathing induced anatomy deformations, they restrict the dose calculation to the motion range of the 4DCT scan, which may not cover the motion range of the treatment delivery. VMAT dose reconstruction beyond the 4DCT motion range can be obtained by constructing a time resolved dose matrix for the VMAT delivery to a static volume and trace the motion of each target voxel in this dose matrix while accumulating the voxel dose [22,23]. However, this approach neglects the 3D dose distribution modifications that occur even with rigid tumor shifts and may be quite substantial for lung tumors. This limitation can be overcome by modeling the tumor motion during VMAT as multiple isocenter shifts [24]. Phantom studies have demonstrated that this method results in accurate dose reconstruction for dynamic treatments delivered to a rigidly moving water density target embedded in lung density material [24], but the method has not yet been applied clinically for VMAT treatments of respiratory moving tumors. The purpose of this study was to combine the novel methods of KIM [17] and dynamic dose reconstruction [24] for VMAT-based liver SBRT treatments, in order to perform a detailed investigation of the dosimetric impact of intrafraction motion during actual clinical liver SBRT treatments.

Methods and materials

Method overview

Fig. 1 summarizes the methods of this study. Fluoroscopic kV images acquired during VMAT-based liver SBRT (Fig. 1a) were used to estimate the 3D trajectory of an implanted gold marker [17,18] (Fig. 1b, c), which was in turn used to reconstruct the actually delivered target dose distribution [24] (Fig. 1d).

Patients, planning, and treatments

This study includes six patients with liver metastases who received SBRT delivered by VMAT in three fractions between March 2011 and February 2013, following our standard SBRT treatment protocol. Guided by ultrasound, each patient had 2–3 cylindrical gold markers (1 mm × 3 mm) implanted close to the metastases. The clinical target volume (CTV) was delineated in the mid-ventilation phase of a 4DCT scan with 3 mm slice thickness. The planning target volume (PTV) was formed by adding 5 mm margins in the left–right (LR) and anterior–posterior (AP) directions and 10 mm in the cranio-caudal (CC) direction. Using the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA, USA) a 6MV VMAT plan with 5–6 arcs was designed to give a CTV mean dose of 100% and minimum target doses of 95% (CTV) and 67% (PTV), i.e. a non-uniform PTV dose distribution with 50% higher dose in the central part [5–8]. Following a risk-adapted strategy, fraction doses of 12.56 Gy or 16.75 Gy were prescribed to the 67% isodose surface (tightly enclosing the PTV surface) resulting in 100% dose levels of 18.75 Gy or 25 Gy. The arc fields spanned between 134° and 234° and were delivered with a maximum dose rate of 600 MU/min. The degree of VMAT intensity modulation can be characterized by the number of monitor units (MU) per Gy (Table 1) or the mean MLC aperture area relative to the total area covered by the arcs, which ranged from 15% to 47% for the six VMAT plans (average 27%). The table rotation was 15° for four out of six arcs for one patient (Patient 2) and 0° for all other arcs. A Stereotactic Body Frame (Elekta, Crawley, UK) or an in-house modified breast board was used for immobilization. Abdominal compression was used for all patients. Table 1 summarizes relevant patient and image data.

The treatments were delivered using five different Trilogy accelerators equipped with an MV PortalVision AS500 or AS1000 portal imager and an On-Board Imager (OBI) (Varian Medical Systems). Prior to treatment, a cone-beam CT scan was used for marker-based patient setup. Continuous portal images (12.8 Hz for AS500, 7.5 Hz for AS1000, 160 cm source-imager-distance (SID)) and orthogonal kV images (5.0 Hz, 125 kV, 80 mA, 11–19 ms, full-fan bow-tie filter, 180 cm SID) were acquired throughout the treatment delivery. The kV field size (Table 1) was chosen as the patient specific minimum size that covered all markers plus a 1.5–2 cm margin as seen from all kV imaging angles of the arc field. The effective dose from intra-treatment kV imaging was coarsely estimated to be 3–6 mSv per fraction from a CBCT scan mode with similar settings (11.0 Hz, 125 kV, 80 mA, 25 ms, full-fan bow-tie filter) by scaling the CBCT dose (9.1 mSv) with the number of images, CC field size, and exposure duration (Table 1). The image and motion data of one patient were previously reported as part of a pilot study on image-based intrafraction motion monitoring (Patient 1, who is identical to Patient 6 in Ref. [14]) while image data for the remaining five patients and all dose reconstruction data and KIM accuracy data are new in this study.

Cross-scattering of the MV treatment beam onto the kV imager degraded the quality of the intra-treatment kV images. As a coarse indicator of the VMAT field size and thus the amount of MV irradiation hitting the patient, Table 1 shows the average jaw size for each treatment plan. Since the kV image quality also depended on the kV beam path length through the patient, Table 1 presents the longest kV water equivalent path length (WEPL) that passed through the monitored gold marker.

Intra-treatment kV imaging was not attempted for three other liver SBRT patients treated with VMAT in the same period as the

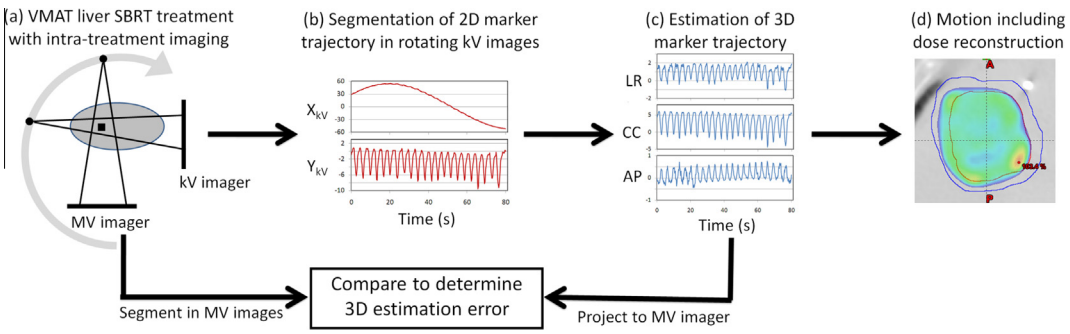

Fig. 1. Method overview.

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