Rapid MRI – 4D Image Guidance for Motion Management in Lung Cancer Radiotherapy

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Objective: We investigate rapid MRI as a non-invasive, dose-free, modality for image-guided motion management in lung stereotactic body radiotherapy (SBRT). To our knowledge, such a tool will represent the first truly 4D, non-ionizing radiation-based image guidance for lung SBRT.

Introduction: Lung tumors can move up to 50 mm, causing significant image artifacts and uncertainties in tumor delineation, dose calculations, and dose delivery.[1, 2] The effects of such uncertainties are amplified for lung stereotactic body radiotherapy (SBRT), which aims to deliver very high doses with a high degree of accuracy and precision. Unfortunately, the workhorse of current image-guidance, 4D computed tomography (4DCT), yields only a single, artificially-averaged respiratory cycle, ignoring complex effects such as baseline shifts and cycle-to-cycle variations. In this work, we investigate the feasibility of rapid 2D+t and 3D+t (4D) MRI (t = time) as a non-invasive image-guidance tool. Beyond the current scope, it is expected that such images can be used to augment 4DCT so as to combine the superior contrast and long-term temporal information from MRI with the geometric fidelity and electron density information from CT.

Methods and Materials: – Under an IRB-approved protocol, two lung cancer patients were imaged under free breathing conditions, without extrinsic contrast on a 1.5T MRI scanner using a 4-channel cardiac coil. A balanced steady-state free precession (b-SSFP) sequence (TE/TR: 1.68/3.16 ms; FOV: 240 x 240 mm^2; half-Fourier acquisition; voxel: 2.4 x 3 x 5 mm^3) was used to image a time series (~20 s) of 2D sagittal slices. For each time series, the tumor centroid, the diaphragm and ~15 points on the tumor boundary were manually contoured on one image frame. A fluid-flow-based deformable image registration algorithm[3] was applied to the time series to map the trajectory of each pixel on each contour.

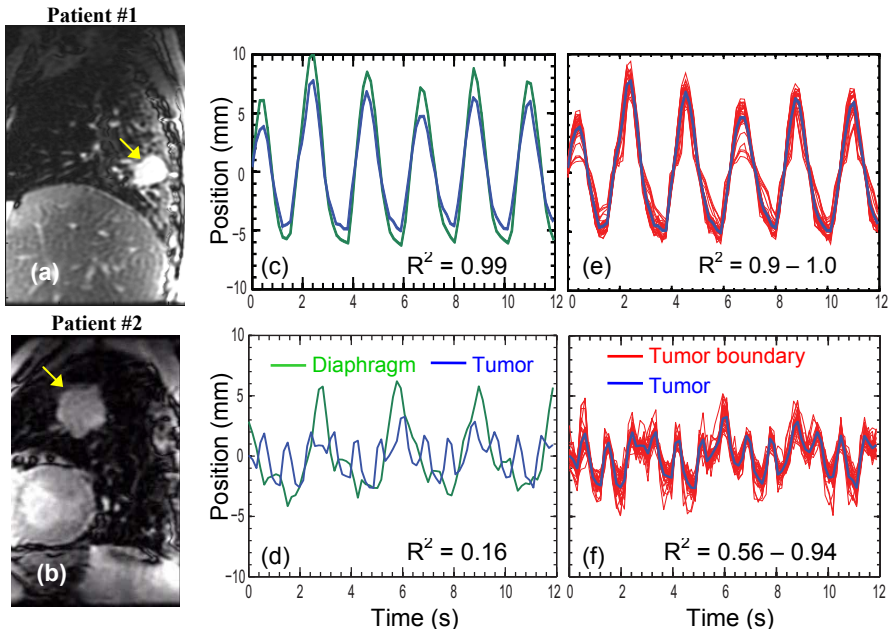

Figure 1. Real-time sagittal MR images of two lung cancer patients acquired on a 1.5T scanner using a b-SSFP sequence (T_{acq} = 152 ms). **(a)** Patient#1 with an ~40 mm diameter tumor (yellow arrow) in the right lower lobe and **(b)** Patient#2 with an ~60 mm diameter tumor (yellow arrow) in the left upper lobe. **(c)** and **(d)** Mean-subtracted motion trajectories of the tumor centroid and the dome of the diaphragm for Patient#1 and Patient#2, respectively. **(e)** and **(f)** Trajectories of the tumor centroid and ~15 points on the tumor boundary for Patient #1 and Patient#2, respectively.

Results – Figures 1 a and b show images acquired from Patients 1 and 2 respectively. The image quality is adequate to clearly delineate the tumor, the diaphragm and the cardiac wall. The achieved acquisition speed of over 6.5 frames/s can be considered adequate for imaging most respiratory motion.[4] Such longer-term monitoring yields some interesting observations that are not captured by 4DCT. In the case of Patient#1, the motion of the tumor centroid was well-correlated with the motion of the edge of the diaphragm (Fig. 1c) as well as with the motion of individual points on the tumor boundary (Fig. 1e). These data indicate the absence of any significant rotation or deformation in the tumor mass. However, in the case of Patient#2, the motion of the tumor centroid was very poorly correlated with diaphragmatic motion (Fig. 1d) and relatively poorly correlated with that of the points on the tumor boundary (Fig. 1f). This complex motion is likely caused by the cardiac wall leading to cycle-to-cycle variations as well as tumor rotation and deformation. The b-SSFP sequence was used with parallel imaging (acceleration = 4) to acquire a time series of 3D volumetric images (8 slices/volume, thickness = 5 mm) from Patient#2 (Fig. 2a). Acquisition time was significantly longer: ~1.5s/vol. Fig. 2b shows a surface-rendered tumor-inclusive volume in four different respiratory phases. The tumor as well as surrounding anatomy exhibit significant phase-to-phase deformation.

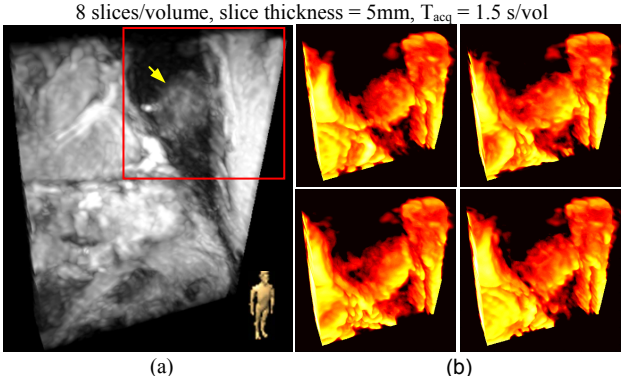

Figure 2 (a) bSSFP, 3D acquisition with parallel imaging (accn = 4) from Patient#2. **(b)** Surface-rendered volume of interest [red box in (a)] for four different respiratory phases.

Conclusion: The results demonstrate that conventional MR sequences can be used with minimal modifications for acquiring rapid 2D+t images to track the motion of lung tumors and structures of interest. Rapid 4D MRI is more challenging and may require sparse k-t space sampling and reconstruction strategies in order to achieve the desired spatiotemporal resolution. Nevertheless, these early results indicate that "guidance-quality" rapid MRI can yield useful motion-related information that is not available with 4DCT – the current standard of clinical care.

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