Empirical investigation of tools and imaging techniques for MRI-guided radiotherapy of lung cancer

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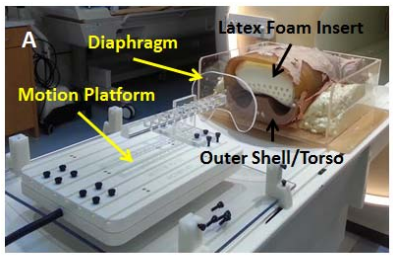
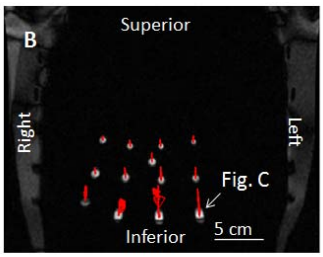
Target Audience. Researchers in MRI Guided Radiation Therapy.

Purpose. MRI represents an attractive tool for one of the most challenging problems in modern image-guided radiation therapy (RT) – namely, the management of respiratory motion in the treatment of thoracic and abdominal tumors. Irregularities in respiratory motion such as baseline shifts, amplitude and frequency changes, result in major dosimetric uncertainties and, often, radiation damage to critical organs. Since long-term soft-tissue-based monitoring is not feasible using x-ray-based imaging modalities (e.g., 4D computed tomography) due to concerns of imaging dose, MRI represents an attractive, ionizing radiation-free tool. Given the unique requirements of RT guidance-quality images (high temporal resolution, and modest spatial resolution and SNR) compared to diagnostic MRI, our group has been investigating the adaptation of sparse sampling and reconstruction techniques such as k-t BLAST [1] for soft-tissue-based respiratory motion monitoring in lung RT. In order to facilitate the optimization of imaging parameters, we created a realistic, MRI-compatible, programmable, deformable lung motion phantom. The phantom is used to replicate respiratory motion trajectories acquired from lung cancer patients and is used to characterize the k-t BLAST sequence for the purpose of image-guided motion management in lung RT. To our knowledge, this is the first programmable, and externally and internally deformable, MRI-compatible lung phantom reported and the first use of k-t BLAST for lung cancer radiotherapy motion management.

Methods. The lung motion module shown in Fig. A consists of three parts; an outer shell resembling a human torso with an embedded ribcage and spinal column (Radiology Support Devices Inc., Long Beach, CA), a deformable latex foam inserted into the inner cavity, and a diaphragm attached to an MR compatible piezo-motor-driven motion platform. Thirteen 1.5 ml conical test tubes filled with water were embedded into the latex foam insert and served as internal fiducial markers in the imaging plane. The motion platform moves in the superior-inferior direction and its stroke motion is programmable with 50 Hz refresh rate and 100 microns precision. The diaphragm motion was a respiratory motion trajectory obtained from a lung cancer patient using the Synchrony system (Accuray Inc., Sunnyvale, CA). As the diaphragm advances into the inner cavity of torso, it presses the foam insert, resulting in the deformation of the foam. The internal deformation of the insert was monitored as variational displacement of fiducials. Data were collected on a 3.0 T body scanner (Ingenia, Philips, Best, the Netherlands). A single 2D coronal slice (0.7 x 0.7 mm^2, with a slice thickness of 10 mm) [Fig. B]. A balanced FFE sequence (TE/TR = 1.3 ms/2.5 ms, flip angle = 40 deg) was used in conjunction with k-t BLAST. The patient's respiratory motion data included nine inspiratory peaks over 27 seconds. Data after the second peak were used for this analysis in order to cope with the system latency and the initial offset error of the motion platform. k-t BLAST acceleration factors 1, 2, and 16 were chosen, which yielded image acquisition speeds of 2.4, 4.6, and 18.8 Hz, respectively.





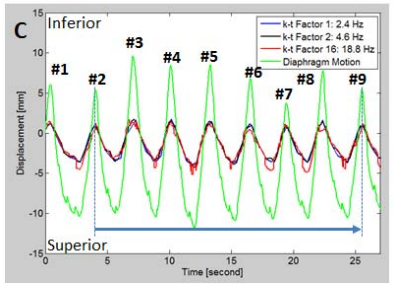


Table. Comparison in trajectories in Fig. C with respect to k-t factor of 1

k-t factor	RMS Error (mm)	R^2
2	.22	.98
16	.56	.89

Figures. **A:** Lung motion module in the MR scanner room. **B:** A representative k-t BLAST image (k-t factor of 1) in coronal and magnified centroid motion trajectories (x5) of thirteen fiducials (red solid lines) from the second inspiratory peak to the ninth. A white solid line represents 5 cm. **C:** Measured marker (indicated in Fig. B) displacements using three different k-t factors (blue: 1, black: 2, red: 16) over nine inspiratory peaks. The arrow represents a timespan where RMS and R^2 in Table 1 are computed. The solid green line represents the programmed diaphragm stroke motion. **Table 1**. Comparison in trajectories in Fig. C from the second inspiratory peak to the ninth with respect to k-t factor of 1. RMS: root mean square. R^2: coefficient of determination.

Results. Figure A shows the lung motion module setup in the MR scanner room. Thirteen fiducial markers were observed in the imaging plane (Figure B). The red solid line superimposed on each marker in Figure B represents the magnified motion trajectory of each centroid by factor of five from the second to the ninth inspiratory peak. The displacement vector field was heterogeneously distributed throughout the insert; the amplitude of marker displacement in superior-inferior (SI) direction was greater in the basal region than in the apex. Figure C shows the measured displacements of a marker (indicated in Fig. B) in SI direction using three k-t acceleration factors, 1, 2, and 16. The difference in the measured trajectories in Fig. C using different k-t factors was shown in the table. Root mean square error (RMS error) and the coefficient of determination (R^2) with respect to the trajectory of k-t factor = 1, from the second inspiratory peak to the ninth were used as metrics for the comparison, assuming k-t factor 1 exhibits the most accurate spatial fidelity at sampling time points. RMS error for k-t factor 2 and 16 were .22 and .56 mm, respectively while R^2 of k-t factor 2 and 16 were .98 and .89, respectively.

Discussion. The latex foam inside the model thoracic cavity deforms significantly and its deformation traces a stroke driven by the motion platform. The deformation is programmable using the motion platform. Thus, the lung module can simulate realistic patient tumor motion repeatedly in the MR scanner. Table 1 indicates, as expected, that increased acceleration in acquisition results in reduced accuracy of motion tracking. However, the RMS error of the measured trajectories between k-t factor 1 and 16 was .56 mm (more than adequate for radiation therapy guidance), for an acquisition speed of close to 19 Hz for a single slice. It is of significant importance in lung radiation therapy since such high speeds allow us to capture regular respiration as well as sudden respiratory movement such as coughing.

Conclusion. The MR-compatible lung motion module replicates the deformable nature of patient's tumor motion. Sparse sampling and reconstruction-based sequences such as k-t BLAST, which were originally developed for cardiac imaging, can be easily adapted for lung radiotherapy guidance, yielding an image acquisition frequency of approximately 19 Hz, with sub-1 mm error in motion monitoring. Future work will involve optimizing sparse-sampling-based sequences to give real-time volumetric images (3D+time) at high spatial and temporal frequencies. These images will be incorporated into multimodality, patient-specific motion models which can be used in the radiation treatment room to provide real-time, soft-tissue-based volumetric image-guidance for lung radiotherapy.

Reference. [1] Jeffrey Tsao et al. MRM 40:1031-42 (2003)