3-D Lung Motion Estimation Via Non-Rigid Registration Using Volumetric MR and CT

T. Sundaram[1], J. Gee[2], M. Nishino[3], S. Kiryu[3], Y. Mori[3], M. Kuroki[3], M. Takahashi[3], H. Hatabu[3]

[1]Bioengineering, University of Pennsylvania, Philadelphia, PA, United States, [2]Radiology, University of Pennsylvania, Philadelphia, PA, United States, [3]Beth Israel Deaconess Medical Center, Boston, MA, United States

Introduction

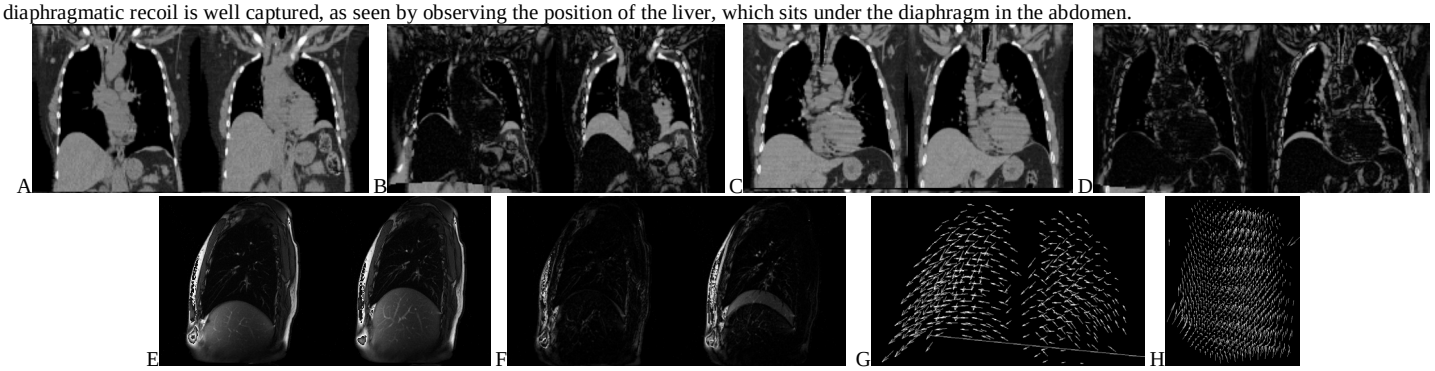
Quantification of pulmonary deformation is useful in characterizing normal lung motion as well as the changes that occur as a result of pathological processes. Diseases such as emphysema typically disrupt the intricate architecture of the alveolar air spaces and disrupt the lung's ability to effectively expand and contract [5]. Medical imaging can be applied to observe such morphological changes and their effects on normal lung motion. We have previously demonstrated and validated a non-rigid image registration algorithm for computing the deformation between successive magnetic resonance (MR) images of the lung [2,3,6]. The algorithm incrementally computes a deformation field that seeks to minimize the total potential energy Π, which is composed of the image similarity (normalized cross-correlation) and the constitutive response (isotropic linear elasticity). The normalized correlation computes image similarity over a neighborhood of voxels centered on the image location. By taking local image structure into account, we expect it to provide better results than pointwise measures such as the squared intensity difference. The constitutive response treats each image as an elastic body in a first order approximation to true parenchymal behavior. The resulting deformation field represents an estimate of the pulmonary motion between two sequential images. Explicit correspondences between images are not required; the extensive pulmonary vasculature and other parenchymal features are treated as natural sources of spatial markers that are tracked between the configurations given by the image data. Other groups have explored the application of alternative non-rigid registration techniques to axial computed tomography (CT) volumes of the lung for construction of static atlases and nodule detection [1,4]. Here, we apply our technique to both high-resolution CT (HRCT) volumes and 3-D MR data. The results provide regional information about volumetric deformation of the lung through the respiratory cycle, and can be used to study the effects of pathological processes on the expected deformation of the lung, as well as to make regional comparisons within or between individuals.

Methods

Three data sets depicting the lungs of healthy volunteers (two male, one female), acquired with breath-holding, were chosen for analysis. Two were acquired using a new volumetric expiratory HRCT protocol with one scan at end-inspiration and another at maximal end-expiration using a 4-detector CT scanner (GE Lightspeed, 2.5 mm collimation, 120kVp, 240mA, 0.5s gantry rotation time, 15mm per rotation). Images were reconstructed using a high spatial frequency algorithm to obtain contiguous inspiratory and expiratory HRCT images with 1.25 mm thickness and 512x512 matrix. The third dataset was a FIESTA scan of the right lung only (GE Signa, TR=3.21ms, TE=1.45ms, 15mm slice thickness, 15mm slice spacing, 256x256 matrix, 35cm FOV) at five phases between end-inspiration and end-expiration. All three datasets were preprocessed to set the image backgrounds to zero. The HRCT datasets were resized to 128^3 volumes, while the MR dataset was resized to 256^2x128 volumes. Estimates of pulmonary motion between each sequential image pair were obtained using a multi-resolution scheme, which solved the registration at two coarser image resolutions before solving at the highest resolution. The multi-resolution strategy was adopted in an effort to first match the coarser features of the images at lower image resolutions and subsequently refine the correspondences at higher resolutions. In each HRCT dataset, the resulting motion was an estimate over the entire expiratory phase of the respiratory cycle, since only two images were available. In the MR dataset, the results represented incremental deformations during expiration.

Results

Figure A shows mid-coronal slices of the two respiratory time points registered in the HRCT scan of the female volunteer. Figure B shows the final (left) and original (right) registration errors at the corresponding slices. In this dataset, there is a large change in volume between end-inspiration and end-expiration, yet the registration is still able to capture the deformation and reduce the misalignment between the volumes. Figure C shows mid-coronal HRCT slices from the male volunteer, with the post- and pre-registration errors in figure D. In this dataset, the expiratory deformation of the lung is much less than in the previous one, and is easily captured by the registration. Figure E shows a pair of sequential MR image slices during expiration, while figure F shows the post- and pre-registration errors at that slice. Correspondence between the intricate vasculature of the lungs is improved by the registration, although some edge mismatches still remain. Furthermore, diaphragmatic recoil is well captured, as seen by observing the position of the liver, which sits under the diaphragm in the abdomen.



Discussion & Future Work

In figures G & H, we demonstrate the volumetric displacement fields that are acquired via 3-D non-rigid registration. Figure G shows the deformation of the lungs for one of the HRCT studies. It is interesting to note the influence of the two main driving forces for expiration: diaphragmatic recoil and intercostal muscle relaxation. The force exerted on the lungs by the relaxation of the diaphragm is evident upon examination of the vectors in the lung bases. Additionally, the effects of the intercostals, which contract during inspiration to lift up the ribs like bucket handles, can be seen in the anterior mid-axial to apical segments of the lungs in the form of downward-facing vectors, representing the return of the ribs to their original position (lowering of the bucket handles, so to speak). In figure H, the displacements over the whole body and lung computed with the MR data are shown, and consist primarily of the effects of diaphragmatic recoil. This is understandable given the lower intensity of the rib cage in the MR data as compared to the HRCT data. Furthermore, these effects are being studied in one lung alone. It would be interesting to observe the motion of both lungs together in order to make more direct comparisons to results observed with the HRCT data. In this preliminary work, we motivate the use of non-rigid elastic registration to estimate pulmonary deformation during expiration. The HRCT data is advantageous due to the ease of segmentation. However, the MR data produces equivalent results with better vascular image contrast, without the requirement for radiation exposure or intravenous contrast agents. This analysis can be extended to examine pulmonary kinematics over the entire respiratory cycle, and compare the lung motion of multiple individuals or of the same individual after some therapeutic intervention. Future extensions of this work include the use of patient-specific finite element models to refine the registration over interesting anatomical regions, as well as reconstruction of whole-lung motion over the entire respiratory cycle from a set of temporal samples, with an ultimate interest in the construction of a dynamic atlas of normal lung motion and further *in vivo* MR quantitation of regional pulmonary biomechanics.

References

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