Self-calibrated voxel-wise assessment of ventilation during respiration using dynamic hyperpolarized 3He MRI

D. Santoro[1], A. Voorhees[2], V. Pai[1], I. Kamenetskiy[1], J. Reid[1], and G. Johnson[1]

[1]Department of Radiology, New York University School of Medicine, New York, New York, United States, [2]Siemens Medical Solutions, Inc., Malvern, Pennsylvania, United States

Introduction: Hyperpolarized gas and proton MRI have both been shown effective for assessing regional pulmonary function (1,2). In this work, a novel method for tracking regional lung motion is applied to provide the local air volume and volumetric flow rate on a voxel scale – information that is inaccessible with traditional spirometry. The method is based on motion-tracking of the lungs over a series of real-time, hyperpolarized ^{3}He images. The automated algorithm (1) uses contrast between the blood vessels (which appear dark) and airspaces (which appear bright) as fiducial markers to regionally track lung motion during respiration. A coarse yet regional volumetric flow rate can be calculated using the Jacobian of the velocity field; regional volume is calculated by integrating the regional flow rate over time. These volumetric calculates of flow are relatively low resolution, on the order of 10 pixels, but can then be combined with signal intensity changes to measure flow on a pixel scale. This technique is based on the assumption that signal change, when corrected for relaxation effects, is directly proportional to the air volume in the lungs and to the density of the gas, which can be assumed constant (1). The result is a self-calibrating voxel-wise technique for calculating lung ventilation.

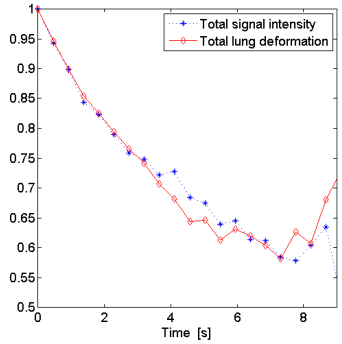

Figure 1: Normalized total lung volume (per unit depth) and total signal intensity vs. time. The signal intensities have been corrected for relaxation using a second data set acquired during breath-hold. The last data points indicate rebreathing.

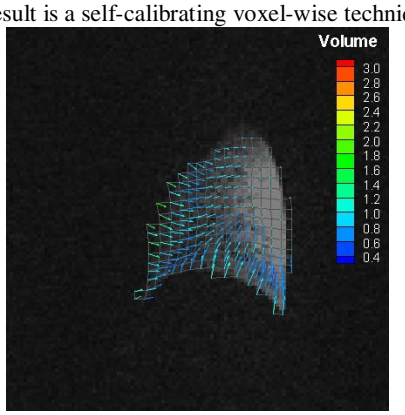

Figure 2: Regional deformation shown with displacement vectors, depicting lung deformation from the start of expiration; vector color represents regional volume fraction, as calculation from the Jacobian of the deformation matrix.

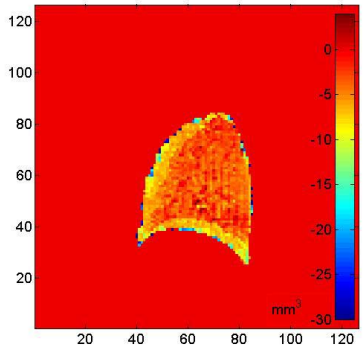

Figure 3: Flow map at a voxel scale between t=0 and t=5s.

Methods: ^{3}He was polarized by spin exchange with an optically pumped rubidium vapor to the level of 35-45% using GE Healthcare helium polarizers. Helium diluted with N_2 to a net polarization level of 12% was transferred to 1 liter Tedlar plastic bags and delivered to healthy human subjects. A FLASH sequence was used in conjunction with TSENSE to acquire the 2D data sets every 225ms. Studies were performed on a clinical whole-body 1.5T Siemens Avanto scanner using a 3×4×2 element phased-array coil built in-house (3). Data acquisition was performed over 9 seconds during a forced slow expiration of the inhaled ^{3}He. A second data set was acquired with same sequence but during breath-hold. Scan parameters were: TR 5.1ms; TE 2.4ms; parallel imaging acceleration rate 4; slice thickness 9 mm; 128 x 128 samples; field-of-view 350 x 350 mm^2. An interval of 225ms was applied between consecutive images in order to preserve polarization for the total maneuver, so that the temporal resolution of the images was 450 ms; a series of 20 images were acquired. The sagittal slice was positioned at the middle of the right lung to avoid motion artifacts induced by the heart. The images acquired during breath-hold were used to assess signal loss due to T1 and excitation effects which were subsequently used to correct for these effects in images acquired during expiration. Data was processed using automated motion tracking software (4). Motion of intrinsic features (largely the pulmonary vasculature) was tracked between pairs of images using a cross-correlation algorithm (5). Volume and flow were calculated both using the deformation map and signal intensity, using home-written Matlab code. Assuming the gas density is constant, the signal intensity, I, is proportional to the volume of air spaces, V, i.e. $I \sim V$. Thus the intensity changes of the dynamic series $(\partial I/\partial t)$ can be used to calculate flow $(\partial V/\partial t)$ with voxel resolution.

Results: Figure 1 shows the agreement between the total volume changes and the total signal changes, corrected for relaxation due to T1 and RF excitations using a second data set. Using one single data set signal intensity change corrections are possible when the maneuver is comprised of a breath-hold followed by an expiration. Figure 2 shows an image of the set in which the visible blood vessels have been used for the motion-tracking, the results of which are superimposed. Effectively, this provides a non-rigid registration of the lungs and allows for a regional measure of flow. In Fig. 3 the registration is also used to scale local signal intensity changes and obtain a flow map on a voxel scale.

Discussion and Conclusion: We have demonstrated a novel method of assessing air flow in the lungs on a pixel-by-pixel basis. Volumetric methods of measuring flow can be implemented using proton MRI. However ^{3}He MRI offers a number of advantages. First, no signal originates outside the lungs so that tracking at boundaries between static structures such as the chest wall and lungs is simplified. Second, volumetric changes can be combined with signal intensity changes to measure flow on a pixel scale. This final estimate can be improved with a faster expiration maneuvers and higher temporal resolution combined with improved SNR and fast acquisition methods such as higher parallel imaging acceleration rates. Furthermore, the combination of motion tracking and voxel-wise signal analysis yields a high-resolution technique for examining ventilation that is effectively self-calibrated for deformation and relaxation.

References:

1. Voorhees A, et al., Magn Reson Med 2005;54:1146.
2. Salerno M, et al., Magn Reson Med 2001;46:667.
3. Lee R, et al., Magn Reson Med 2006; 55:1132-1141.
4. Suga K, et al., J Magn Reson Imag 1999;10 : 510-520.
5. Hsu TY, et al, Journal of Fluid Mechanics 2000;410:343-366.