IN-VIVO IMAGING OF THE SPECTRAL LINE BROADENING OF THE HUMAN LUNG IN A SINGLE BREATH-HOLD

Flavio Carinci[1,2], Cord Meyer[2], Felix A. Breuer[1], and Peter M. Jakob[1,2]

[1]*Research Center Magnetic Resonance Bavaria (MRB), Würzburg, Bayern, Germany*, [2]*Department of Experimental Physics 5, University of Würzburg, Würzburg, Bayern, Germany*

Introduction: Susceptibility differences at air/tissue interfaces in the lung result in a broad NMR spectral line [1]. The line broadening provides a quantitative fingerprint for lung inflation, as previously demonstrated [2,3]. This makes it an interesting parameter to diagnose air trapping or ventilation defects. Quantification of the line broadening of the lung has been proposed and performed *ex vivo*, using an asymmetric spin-echo (ASE) sequence [3,4]. In this technique, the violation of the CPMG conditions prevents the use of turbo spin-echo sequences. Therefore, *in vivo* application would require relatively long acquisition times and is not suitable for investigations on patients with lung diseases. In this work, a fast technique based on a HASTE sequence with ASE preparation is presented, which allows for quantification of the spectral line broadening of the human lung *in vivo*, in a single breath-hold. It is shown that the violation of the CPMG conditions can be overcome by means of phase cycling [5], together with GRAPPA reconstruction [6].

Methods: The ASE-prepared HASTE sequence, as shown in Fig.1, was implemented on a 1.5T MR-scanner. The key parameters of the sequence are: the asymmetry time τ and the phase φ of the refocusing pulse train in the readout-block, which can be arbitrarily chosen. The phase shift between excitation and refocusing pulses in the preparation-block is $\pi/2$, like in the standard spin-echo experiment. Spoiling gradients were used to cancel eventual free induction decay signals of the refocusing pulses and to prevent formation of unwanted echoes generated by the residual longitudinal magnetization after ASE-preparation.

For $\tau \neq 0$, phase shifts due to frequency off-resonances corrupt the image quality: the in-phase signal component ($S_\parallel$ = parallel to φ) generates the main image; the out-of-phase component ($S_\perp$ = perpendicular to φ) generates a ghost artifact, shifted by half field of view (FOV), due to phase reversing between odd and even echoes. The basic idea of this technique is to acquire two images with $\varphi = 0$ and $\pi/2$, such that $S_\parallel$ and $S_\perp$ can be obtained as the main images from each of the two acquisitions, respectively. The ghost artifact is eliminated in both acquisitions as follows: 1) GRAPPA reconstruction, with acceleration factor 2, is used to generate two separate *k*-spaces from odd and even echoes; 2) the complex sum of the two *k*-spaces is calculated, to cancel the signal components with opposite phases, such as the ghost; 3) images of $S_\parallel$ and $S_\perp$ are reconstructed from the summed *k*-spaces of each acquisition. Finally, the signal amplitude image is obtained as a combination of the two: $S(\tau) = \mathrm{sqrt}(S_\parallel^2 + S_\perp^2)/2$. For $\tau = 0$, $S_\perp$ is negligible and only $S_\parallel$ is acquired. This acquisition is used also as auto-calibration scan for GRAPPA reconstruction.

Phantom experiments were first performed to demonstrate ghost elimination (Fig.2).

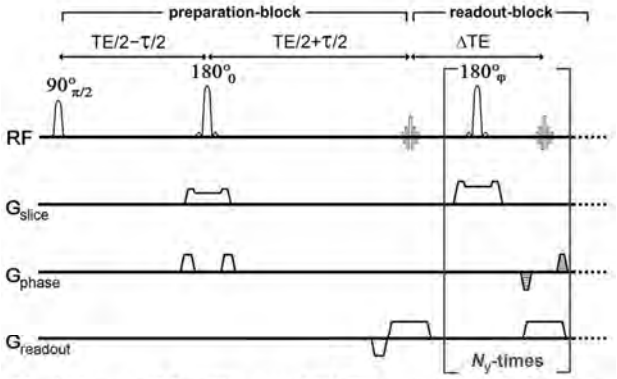

Fig. 1 Diagram of the ASE-prepared HASTE sequence used to image the spectral line broadening of the lung. The echo-time (TE), the asymmetry time (τ) and the inter-echo time (ΔTE) are defined as shown. Signal refocusing and readout are repeated N_y-times (N_y=number of phase-encoding steps). Linear reordering of the phase-encoding steps was used.

In vivo experiments were then performed on healthy volunteers to investigate the dependence of the line broadening on lung inflation. Three images were acquired in a single breath-hold of about 15s duration: one image ($S_\parallel$) with $\tau = 0$ ms and two ($S_\parallel$ and $S_\perp$) with $\tau = 2$ ms. TE = 6 ms was the same for all images. The model used to describe the signal amplitude dependence on τ is [3]:

$$\frac{S(\tau)}{S(0)} = \exp\left(-\frac{\Delta\upsilon^2\tau^2}{2}\right)$$

The line broadening (in ppm) is given by $\sqrt{\Delta\upsilon^2}/\gamma B_0$. The corresponding maps were calculated on a voxel-by-voxel basis.

Experiments were performed, with ECG triggering in the diastolic phase, at different breathing states: functional residual capacity (end expiration) and total lung capacity (end inspiration). Both sagittal and coronal slices were acquired.

Imaging parameters: FOV = 500×500 mm^2, matrix size = 128×128, slice thickness = 15 mm, partial Fourier factor = 5/8, ΔTE = 2.4 ms, TR = 6000 ms.

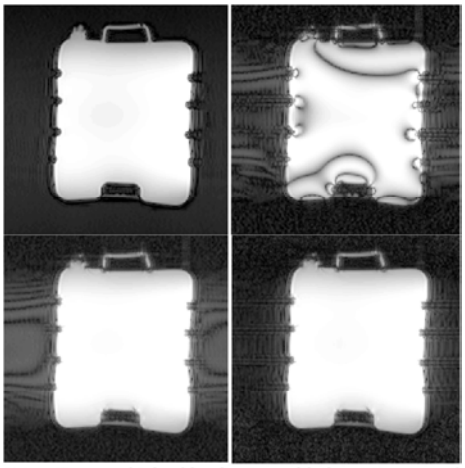

Fig. 2 Images obtained in phantom with the ASE-prepared HASTE. Top: in-phase images ($S_{||}$) acquired with τ=0ms (left) and τ=10ms (right). Bottom: combined images $S(\tau)$=sqrt($S_{||}^2 + S_\perp^2$)/2 acquired with τ=10ms, before ghost elimination (left) and after ghost elimination (right).

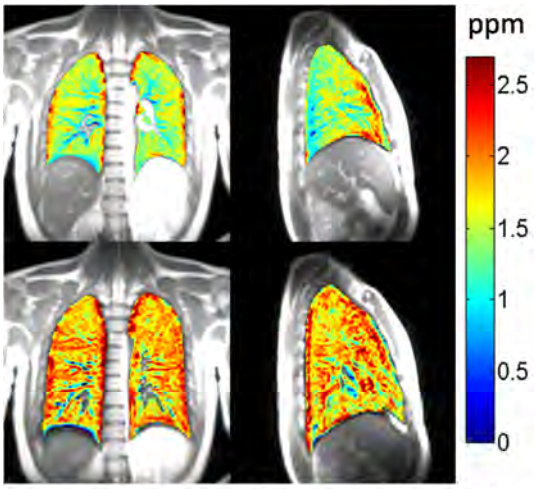

Fig. 3 Coronal (left) and sagittal (right) maps of the spectral line broadening of the human lung acquired with the ASE-prepared HASTE in-vivo. Each map was obtained in a single breath-hold, at end expiration (top) or end inspiration (bottom).

Results / Discussion: Fig.2 shows the images obtained in phantom. For $\tau \neq 0$, the in-phase image presents signal modulations due to frequency off-resonances. In the combined image $S(\tau)$ this modulation is canceled but a ghost artifact shifted by half FOV can be observed. The proposed reconstruction procedure effectively eliminates the ghost. Fig.3 shows the line broadening maps of the human lung *in vivo*. Increase of the line broadening can be observed in inspiration, compared to expiration, confirming normal lung inflation. The average value within the lung parenchyma increases by about 25%, from 1.5ppm to 1.85ppm for both the coronal and sagittal data sets. These values are in very good agreement with the ones predicted by numerical simulations [2,4]. Sagittal maps also show a gravitational dependence in expiration. A smaller line broadening is observed at the bottom of the lung, which means less inflation. This is in perfect agreement with the slinky effect theory [7].

Conclusion: The presented method offers a fast and reproducible way to obtain the spectral line broadening of the human lung *in vivo*. Data acquisition is feasible in a single breath-hold and may be suitable for clinical studies on patients with lung diseases. The technique may be used also for oxygen-enhancement imaging, due to the susceptibility dependence on oxygen concentration. Preliminary results (not shown) exhibit an increase of about 8% in the line broadening when breathing pure oxygen.

References: [1] Morris AH, 1985, *J Appl Physiol*, 58; [2] Case TA, 1987, *J Magn Reson*, 73; [3] Ganesan K, 1993, *J Magn Reson*, 102; [4] Christman RA, 1996, *Magn Reson Med*, 35; [5] Fransson A, 1993, *Magn Reson Imaging*, 11; [6] Griswold MA, 2002, *Magn Reson Med*, 47; [7] Hopkins SR, 2007, *J Appl Physiol*, 103.

Acknowledgements: SIEMENS; Pulmonary Imaging Network (PINET) - 7th Framework Program of the European Union (PITN-GA-2010-264864); Competence Network Asthma/COPD - Federal Ministry of Education and Research (FKZ 01GI0881-0888); German Research Foundation (DFG JA 827/8-1 DFG JA 827/8-2).