High temporal resolution radial bSSFP sequence with nonlinear inverse reconstruction for the measurement of the pulmonary blood inflow time using Fourier decomposition MRI

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Introduction

Development of pulmonary function assessment techniques with proton MRI causes well-known problems because of a sponge-like structure and low proton density of the lung. A novel approach acquires time-resolved sets of images using a very short echo time pulse sequence during free breathing [1]. Each image is registered to a reference image for correction of respiratory motion. Subsequently, pixel-wise Fourier analysis is used to separate periodic signal intensity variations induced by parenchyma deformation and by flow dependent signal dephasing. Amplitude of these regional signal intensity changes is used to create ventilation-weighted (Vw) and perfusion-weighted (Qw) images. The technique is known as Fourier decomposition (FD) MRI. The aim of this work was to show feasibility of a radial balanced steady-state free precession (bSSFP) sequence combined with nonlinear inverse reconstruction (NLINV) for accelerating the proton lung image acquisition. High temporal resolution offered by this technique can be used to track fast physiological changes in the lung such as blood inflow time in the thoracic vessels and lung parenchyma with FD MRI by using phase information.

Methods

Three healthy volunteers and a child (5 year old, male) with cystic fibrosis (CF) were examined on a 1.5T whole-body MR-scanner (Magnetom Avanto, Siemens Healthcare, Erlangen, Germany). A combination of 6-channel body and 24-channel spine matrix coil in triple mode was used. Coronal chest images were acquired by using an untriggered 2D+t bSSFP (TR/TE/TA=2.0/1.0/51 ms, FA=35-55º, radial spokes/frame=25 with 5 interleaves, 256 samples per spoke, ST=10 mm, matrix size=128, FOV=350 mm^2, bandwidth=1700 Hz/pixel). For every slice, 300 images were obtained with the total acquisition time T=15 s. Thus, a spectral resolution of $\Delta f=1/T=0.07$ Hz and a spectral width of $f_B=1/(2TA)=10$ Hz were achieved. Reconstruction of the 2D+t bSSFP data has been performed using the NLINV algorithm for improved parallel imaging [2], which has previously been extended with temporal regularization and filtering to reconstruct a time series of radially acquired data with ultra-high temporal resolution [3]. In this work, the number of Newton steps has been set to 8 and the scale factor for the temporal regularization was set to 0.9. For comparison of signal-to-noise ratio (SNR) in the lung parenchyma the data was reconstructed with standard gridding procedure by using non-uniform FFT (NUFFT) [4]. Subsequently, nonrigid image registration was used to correct for the respiratory motion [5]. Fourier decomposition of the registered bSSFP images was used to detect and separate periodic changes of lung proton density caused by breathing and blood flow at the cardiac frequency [1]. Vw and perfusion-weighted Qw images were created by pixel-wise amplitude calculation at the respiratory and cardiac frequencies, respectively. Furthermore, phase angle images containing information regarding the temporal distribution of the blood flow were calculated:

$$\phi(f) = \operatorname{atan}(\operatorname{Im}[s(f)]/\operatorname{Re}[s(f)])$$

where: s – the Fourier transformed time-resolved set of bSSFP images. At the cardiac frequency f_C, the angle values in calculated phase map lie within a time duration of one heart cycle $[0,1/f_C]$. Time values in the pulmonary artery were set to zero and selected as a time reference.

Additionally, dynamic contrast-enhanced MRI (DCE MRI) was performed in the CF patient using a 3D+t fast low angle shot sequence (TR/TE=1.82/0.77 ms, FA=25º, ST=5.5 mm, FOV=350 mm^2 , matrix size =138x256, FOV=350 mm^2 , 20 volumes, TA of one volume=1.79 s, GRAPPA factor=2). The measurement started simultaneously with an intravenous administration of Gd-DTPA in dose of 0.1 mmol/kg body weight at the flow rate of 2mL/s. Maximum contrast enhancement map was calculated by finding a maximum voxel value along the temporal direction of the DCE MRI data set and by subtracting the baseline data set acquired before injection of contrast agent.

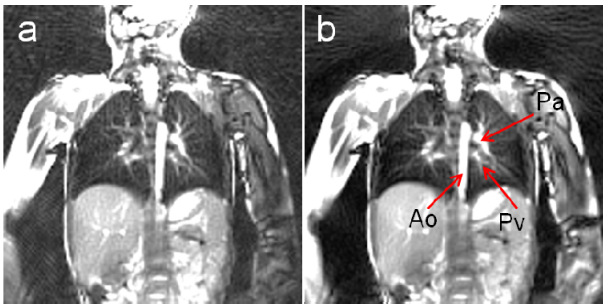

Fig. 1. Comparison between radial bSSFP images from a CF patient and reconstructed with gridding using NUFFT (**a**) and NLINV (**b**). Pa – pulmonary artery, Pv – pulmonary vein, Ao – aorta.

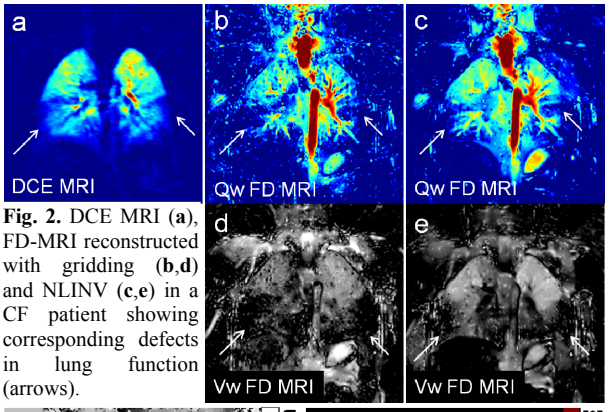

Fig. 2. DCE MRI (**a**), FD-MRI reconstructed with gridding (**b**,**d**) and NLINV (**c**,**e**) in a CF patient showing corresponding defects in lung function (arrows).

Results

Figure 1 presents improvement of the quality and noise reduction in bSSFP images reconstructed with NLINV algorithm in comparison to the standard gridding approach. SNR in the lung parenchyma was 7.57±2.81 for gridding and 12.97±3.65 for NLINV. Maximum contrast enhancement map obtained in CF patient by using the DCE MRI, Qw and Vw FD-MRI from the registered bSSFP data reconstructed with gridding and NLINV are presented in figure 2. Impaired perfusion is visible in corresponding lung areas on the DCE MRI and FD MRI. However, the Qw and Vw images calculated using the NLINV method show visual improvement. The phase angle image created from the bSSFP data corresponds to the blood inflow time map (Figure 3). The map shows physiological differences in the inflow time between the pulmonary arteries, veins and parenchyma. A lung region with delayed perfusion, corresponding to low amplitude on the Qw image was found on the blood inflow time map.

Discussion

In this work we present the application of the nonlinear inversion reconstruction of radial bSSFP lung data for FD MRI. With this acquisition and reconstruction technique a very high temporal resolution up to 20 images per second can be achieved. Thus, additional functional information regarding the blood inflow time within an averaged heart cycle can be gained when using the spectral analysis of the data. Pulmonary arteries and aorta pulsate almost in the same phase and are displayed with similar time values. On the contrary, pulmonary veins have larger time values. Furthermore, this technique allows characterization of lung regions with delayed pulmonary perfusion in presence of lung pathology. Thus, pulmonary blood inflow time mapping as a possible marker for hypoxic vasoconstriction could serve for local therapy guiding in patients.

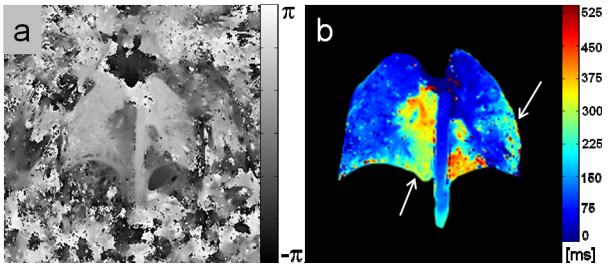

Fig. 3. Phase angle map at the cardiac frequency from the CF patient (**a**). After segmentation of the lung and aorta, the blood inflow time map was calculated by converting the phase angle to time values within one heart cycle (**b**). Lung regions with delayed pulmonary perfusion are indicated by arrows.

References:

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