3D pulmonary perfusion MRI with radial ultra-short echo time and spatial-temporal constrained reconstruction

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Purpose

Dynamic contrast-enhanced (DCE) imaging is becoming a clinically well-established and an increasingly popular MRI method to study lung perfusion. However, MR sequences used clinically are limited by low signal-to-noise ratio (SNR) in the lung parenchyma and temporal blurring due to k-space view sharing techniques that reduce the accuracy of hemodynamic parameters calculated from the contrast agent (CA) dynamics. One solution to improve parenchymal SNR and temporal resolution is to use ultra-short echo (UTE) radial pulse sequences [1]. In this work we propose a novel technique that combines a time-resolved 3D UTE acquisition with constrained reconstruction for assessment of regional lung perfusion. High isotropic spatial resolution is achieved by acquiring incomplete data for each time frame and reconstructing it using dimensionality reduction in temporal domain via principal component analysis (PCA) and soft-thresholding of wavelet coefficients in the spatial domain. We present feasibility of this technique in simulations using a fractal-based digital lung phantom and for an *in vivo* experiment in a human subject.

Methods

Simulated and *in vivo* MR data: To assess the proposed technique we implemented a fractal-based digital lung phantom [2] (**Figure 1**), as a ground truth for optimization of the reconstruction method. Arterial, venous and lung tissue components were generated on a 512^3 matrix. An inverse gridding procedure was performed on the phantom data using a time-resolved 3D radial trajectory with an interleaved bit-reversed projection reordering (7986 unique projections over 33 time frames). The CA-signal enhancement in the arterial network, capillary bed and venous network was simulated using the gamma variate function. In vivo data were acquired in a 23y old female human subject with Factor V Leiden on 1.5T scanner (MR450w, GE Healthcare, Waukesha, WI, USA) using 32-channel chest coil. The time-resolved 3D UTE acquisition started after IV administration of 0.05 gadobenate dimeglumine followed by 35ml saline flush at the flow rate of 4mL/s. The imaging parameters of the 3D UTE sequence were: TR/TE=3.3/0.08 ms, 1 ms readout time, flip angle=15º, field-of-view=400^3 mm^3, matrix=256^3, nominal resolution=1.56 mm^3, bandwidth=250 kHz, 7986 unique center-out projections. The acquisition time for one 3D volume was 1 s, and 29 consecutive undersampled volumes were acquired during the end expiratory breath-hold.

Image reconstruction and postprocessing: The data were reconstructed using an iterative algorithm (**Figure 2**) that combined reconstruction in temporal principal component basis (PCB) and spatial domain wavelet soft-thresholding (ST). Both constraints were integrated into a cost function that was solved to enforce consistency with the PC [3] and measured data, **s**, while minimizing the L1-norm of the wavelet coefficients:

$$\min_{f \in span(\mathbf{D})} \|\mathbf{Wf}\|_1 \ s.t. \ \|\mathbf{Ef} - \mathbf{s}\|_2 < \epsilon$$

where **f** is the vectorized image series, **W** is the wavelet transform, **E** is the encoding matrix (consisting of Fourier and coil sensitivity terms), and **D** is the basis of chosen temporal principal components. The PCB was obtained from low resolution training images reconstructed using the same data set. The reconstructions were performed on a 256^3 matrix with an undersampling factor of 747. Coil sensitivities were obtained using the ESPIRiT [4] Images were also reconstructed using several reference methods for comparison including PCB, FISTA [5], PILS [6] and PILS with k-space adaptive filter temporal view sharing technique. Reconstruction quality and temporal fidelity was assessed using structural similarity index (SSIM). Quantitative perfusion maps (PBF–pulmonary blood flow, PBV–pulmonary blood volume, MTT–mean transit time) were calculated using the singular value decomposition method, indicator dilution theory and the central volume principle.

Results

The quality of digital lung phantom images reconstructed using different techniques is compared to the ground truth at peak parenchymal enhancement in **Figure 3**. The results qualitatively support the benefits of combined principal component and wavelet thresholding in conjunction with training data as a means to reduce streak artifact, especially compared to direct reconstructions with PILS and view sharing. The constrained iterative reconstruction incorporating both the PC basis and wavelet soft-thresholding is seen to further improve spatial resolution compared to either the PC basis or wavelet soft-thresholding alone. The SSIM increased from 0.867 for FISTA, 0.889 for PCB to 0.949 for PCB+ST. For non-iterative methods SSIM was 0.752 PILS with view sharing and 0.459 for PILS alone. The estimated perfusion parameter results in human subjects using the datasets reconstructed with PCB+ST are displayed on **Figure 4** and were within expected physiologic values from the literature [7].

Discussion and Conclusion

In this work we have demonstrated the feasibility of constrained reconstruction of highly under sampled time-resolved 3D radial UTE data for regional lung perfusion imaging. It is feasible to use the reconstructed fractal-based lung phantom and *in vivo* datasets to generate estimated perfusion parameter maps in 3D with isotropic high spatial resolution and high temporal fidelity. However, further experimental and clinical studies are needed for validation of the quantitative hemodynamic parameters obtained using this technique.

References: [1] Johnson et al. MRM 2012 (doi:10.1002/mrm.24570) [2] Johnson et al. ISMRM Scientific Workshop 2013, Sedona, AZ, US [3] Samsonov A. Proc 20th Annual Meeting ISMRM, Melbourne; 2012. p 358. [4] Uecker et al. MRM 2013 (doi:10.1002/mrm.24751) [5] Beck et al. SIAM J Im Sci. 2009; 2(1):183-202., [6] Griswold et al. MRM 2000 Oct;44(4):602-9, [7] Hatabu et al. MRM 1999, Dec;42(6):1033-8.
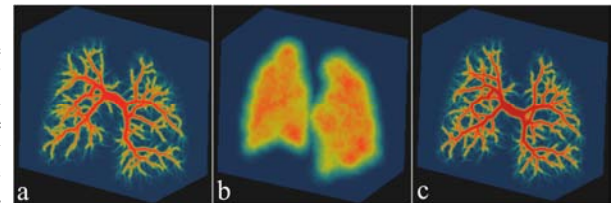
Figure 1. *Fractal-based digital lung phantom and its a) arterial, b) parenchymal and c) venous components.*
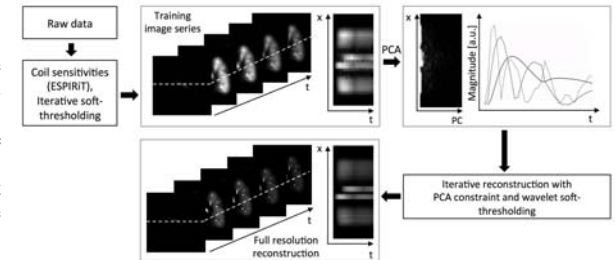

Figure 2. *Workflow of the PCB+ST reconstruction algorithm. Raw data is used to calculate the time-resolved training data at low spatial resolution. PCA was performed on the reconstructed training data set. Subsequently, the high-resolution time-resolved dataset was iteratively reconstructed using the PCA constraint and wavelet soft-thresholding.*
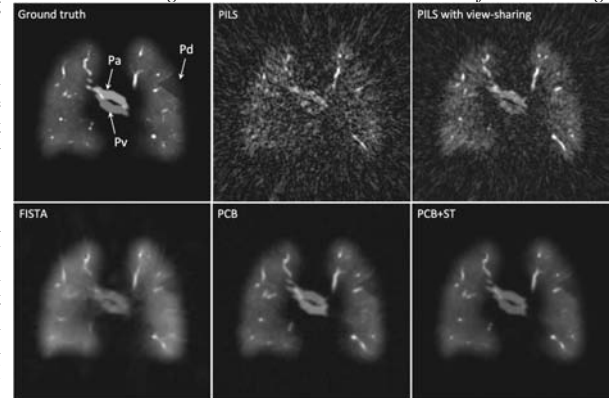

Figure 3. *Comparison between the fractal-based 3D digital lung phantom ground truth and the different reconstruction techniques. The arrows indicate pulmonary artery (Pa), pulmonary vein (Pv) and a wedge-shaped perfusion defect (Pd).*
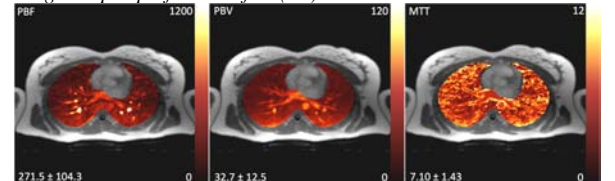

Figure 4. *Quantitative evaluation of PBF (ml blood/100ml lung/min), PBV (ml blood/100ml lung) and MTT s in a 23 years old female patient with Factor V Leiden using PCB+ST reconstruction.*