Ultra-fast steady-state free precession pulse sequence for pulmonary Fourier decomposition MRI

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Target audience. Physicists and physicians interested in lung imaging methods.

Purpose. Recently, a novel non-contrast-enhanced functional lung imaging method, known as Fourier decomposition (FD) MRI, has been introduced[1]. The technique uses dynamic free-breathing native 2D bSSFP imaging with subsequent image registration and FD to construct perfusion-weighted (Qw) and ventilation-weighted (Vw) images. Despite the approach has already shown promise for clinical use[2,3], its application may be hampered by the appearance of banding artifacts, or can be limited in some groups of patients, e.g., chronic obstructive pulmonary disease, from the presence of emphysematous lung destruction leading to very low regional signal intensity. Only recently, however, major methodological advances have been demonstrated for lung imaging based on an ultra-fast SSFP technique (ufSSFP): banding artifacts and image acquisition time are substantially reduced from the decreased TR, whereas the parenchymal signal is increased from the shortened TE[4] - representing an ideal framework for FD MRI. To this end, ufSSFP imaging was adapted for improved FD lung MRI in the clinical setting.

Methods. All measurements were performed on 1.5T MR scanner (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany) using a 12-channel thorax and a 24-channel spine coil. Three healthy volunteers were scanned with an adapted ufSSFP sequence for FD MRI. Adaptation was divided into three parts:

First, the dependence between the signal intensity (SI) in the lung tissue and the flip angle, RF pulse length, and interval time (TW) between each image acquisition, as well as spatial resolution, was investigated. To this end, scans were acquired in expiratory breath hold with variable flip angle α = 5º–75º, waiting time TW = 0–280 ms, and RF pulse length τ = 250–500 us (fixed time bandwidth product = 1.6), resulting in a variable TE = 0.61–0.75 ms and TR = 1.37–1.61 ms, for an acquisition time TA = 80-160 ms per image. Spatial resolutions ranged from 4.69×4.69 mm^2 (96×96 matrix) to 2.56 mm^2 (176×176 matrix) for a fixed acquisition rate of 3.33 images/s, by adapting the TW accordingly. Other parameters were: fixed field-of-view (FOV) = 450^2 mm^2, slice thickness = 12 mm, bandwidth = 2056 Hz/px, 64 images per slice, parallel imaging GRAPPA[5] factor 2, total TA = 20 s.

Second, regional ventilation and perfusion information was derived from sets of 200 coronal images acquired in free breathing. The scans were performed with identical fixed parameters and with variable resolution in 2D as in the breath hold acquisitions. The flip angle and pulse length were fixed to α = 65º, τ = 360 us, total TA per slice was 66 s. In addition, the sequence allowed for an optional fat saturation (FS) pulse prior to each image acquisition. For reference, FD MRI using contemporary bSSFP imaging[1] was also performed with a TE/TR/TA = 0.87/1.90/118 ms, TW = 180 ms, acquisition rate = 3.33 images per second, α = 75º, FOV = 450^2 mm^2, slice thickness = 12 mm, matrix = 128×128, GRAPPA factor 3.

Third, a non-rigid registration algorithm as well as Fourier decomposition routine was used (fMRLung 4.5, Siemens Corporate Research, Princeton, NJ) to derive Vw and Qw images.

Results. The parenchymal signal as a function of the flip angle α, the time interval *TW*, the RF pulse length τ, as well as the matrix size is shown in Fig. 1. Generally, SI decreases with increasing matrix size, and increases with increasing *TW* and α (but leveling off around 60°), reflecting the overall transient nature of the signal. Interestingly, the RF pulse length has only a marginal effect on the SI, indicating that magnetization transfer effects are of limited impact here. As a result, a ~ 60°, TW = 180 ms, TE/TR = 0.67/1.46 ms is suggested for FD adapted ufSSFP.

Exemplary native chest images of a volunteer from contemporary bSSFP MRI, as well using the adapted ufSSFP and ufSSFP- FS techniques are shown in Fig. 2. The observed native SI for a region of interest were: 34 ± 4 (bSSFP), 41 ± 3 (ufSSFP), 38 ± 5 (ufSSFP-FS). Residual banding artifacts are visible on the bSSFP image, especially in the lung apices, regions near ribs, and along the spine, whereas ufSSFP images show no banding over the complete FOV. This essentially results in artifact-free Vw and Qw images of notable homogeneous contrast, as expected for healthy lung tissue. Furthermore, from to reduced GRAPPA factor with ufSSFP ($3 \rightarrow 2$), no ghosting artifacts are visible.

Overall decreased image acquisition times and increased parenchymal SI with ufSSFP as compared to bSSFP might be spent for increased resolution FD MRI, as shown in Fig. 3, using a 160^2 imaging matrix yielding 2.8 mm^2 in-plane spatial resolution. In the corresponding Qw image, this provides visualization of vessels in the arterial tree in the lung up to the fifth generation, by keeping the signal from the capillary bed in the lung parenchyma still on a high level.

Discussion and Conclusion. In this work, ufSSFP was adapted for FD MRI. Major improvements of ufSSFP over contemporary bSSFP imaging, as applied in previous FD MRI studies, arise from its decreased, minimal, TE and TR settings. For the standard matrix size of 128^2 used for FD the TE/TR values were 0.67/1.46 ms and 0.87/1.90 ms for ufSSFP and bSSFP, respectively. Eddy currents and pulsation artifacts were mitigated by a linear reordering k-space acquisition scheme. Overall, the adapted ufSSFP scheme performs beneficially over bSSFP imaging in terms of SI and banding artifacts, providing either increase resolution or overall image quality for ventilation- and perfusion-weighted FD images.

References: [1] Bauman G et al. MRM 2009; 62:656-64; [2] Bauman G et al. EJR 2013;82:2371-7; [3] Sommer G et al. EJR 2013;82:e879-87. [4] Bieri O. MRM 2013;doi: 10.1002/mrm.24858; [5] Griswold MA et al. MRM 2002;47:1202–1210

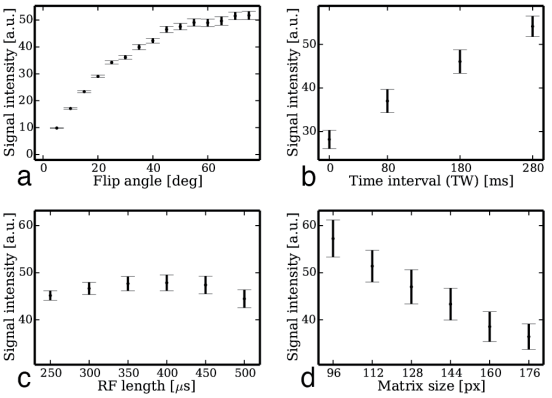

Figure 1. *Signal intensity in the lung parenchyma in expiration at 1.5T using ufSSFP imaging as functions of the flip angle (a), time interval (TW) between consecutive image acquisitions (b), the RF pulse length (c), and resolution (matrix size) (d).*

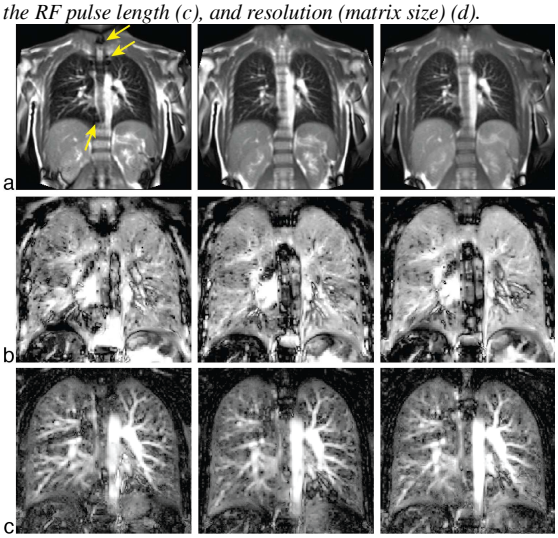

Figure 2. *Native coronal images of the chest from FD MRI at 1.5T (a), Vw (b) and Qw images (c) using contemporary bSSFP (left column), ufSSFP (middle column), and ufSSFP-FS (right column). The arrows indicate banding artifacts.*

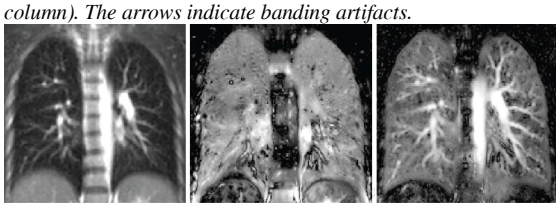

Figure 3. *FD ufSSFP MRI with increased spatial resolution (matrix size) of 2.8 mm^2 (160^2): native ufSSFP image (left), and corresponding Vw (middle) and Qw (right) images from a volunteer (TE/TR/TA/TW = 0.73/1.55/140/150 ms).*