Model-based Reconstruction for Real-Time Flow MRI – Improved Spatiotemporal Accuracy

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Purpose

To develop a model-based reconstruction technique for real-time phase-contrast flow MRI with improved spatiotemporal accuracy compared to methods using the phase difference between two separately reconstructed images with differential flow encodings.

Theory

Phase-contrast flow MRI requires at least two acquisitons with differential velocity encodings, e.g. one flow-compensated and one flow-encoded acquisition. Conventional methods that rely on parallel MRI, e.g. nonlinear inversion (NLINV) [1,2], reconstruct images (and sets of coil sensitivity maps) from each acquisition, and then perform a pairwise subtraction of the phase to yield a phase-contrast map, which is linearly proportional to the flow velocity.

In contrast, the proposed method jointly computes a magnitude image, a phase-contrast map, and a set of coil sensitivity maps from each pair of datasets using the signal model below.

Signal Model and Inverse Problem

$$y_{j,l}(t) = \int \rho(\vec{r}) \cdot e^{i \cdot \Delta\phi(\vec{r}) \cdot S_l} \cdot c_j(\vec{r}) \cdot e^{i \vec{k}_l(t) \vec{r}} d\vec{r} \qquad \text{with } j \in [1, N], l \in [1, 2]$$

ρ : magnitude image shared by each pair of acquisitions

$\Delta\phi$: phase-contrast map

c_j : coil sensitivity map of the j^{th} coil

$\vec{k}_l(t)$: k-space trajectory of the l^{th} acquisition

$S_1 = 0$: flow-compensated acquisition

$S_2 = 1$: flow-encoded acquisition

This signal model requires the solution of a nonlinear inverse problem with an operator F that maps the image, the phase-contrast map, and coil sensitivity maps to the measured data. Thus, the forward operation on the j^{th} coil of the l^{th} acquisition is

$$F_{j,l}(x) = P_l \mathcal{F}\{\rho \cdot e^{i \cdot \Delta\phi \cdot S_l} \cdot c_j\} \qquad \text{with } x = (\rho,\ \Delta\phi,\ c_1,\ \ldots,\ c_N)^T$$

P_l : orthogonal projection onto the l^{th} trajectory

$\mathcal{F}$: discrete Fourier transform

To jointly estimate the unknowns shown above, the proposed method applies the iteratively regularized Gauss-Newton method to minimize the following cost function

$$\Phi(x) = \|y - F(x)\|_2^2 \quad .$$

Because the cost function is ill-posed, Tikhonov regularization is applied to the magnitude image, the phase-contrast map and the high spatial frequencies of the coil sensitivity maps. In addition, the estimation of the current maps is subject to a temporal regularization by the previous maps.

Methods

This work presents real-time flow MRI data of the aorta obtained at 3 T (Magnetom Prisma, Siemens Healthcare, Erlangen, Germany) using extremely undersampled radial FLASH [3,4] (5 or 7 spokes per image). While studies of a flow phantom employed the 64-channel head coil, blood flow in the aorta was studied during free breathing by combining an 18-element thorax coil with 32 elements of the spine coil. Measurements had 1.5 mm in-plane resolution, field-of-view 256 mm (flow phantom) and 320 mm (human aorta), 6 mm slice thickness, and 35.7 ms (7 spokes) or 25.6 ms (5 spokes) temporal resolution corresponding to 28 or 39 frames per second, respectively. Velocity encoding gradients (VENC) of 200 cm/s and 400 cm/s were used in this work.

The model-based reconstruction was implemented on a single graphics processing unit and performed offline after data acquisition. Conventional image reconstruction and display in real time was achieved by a parallelized version of the NLINV algorithm [5] and a bypass computer equipped with two processors and 8 graphics processing units. The system was fully integrated into the reconstruction pipeline of the commercial MRI system. Quantitative analyses of blood flow were obtained with CAIPI prototype software (Fraunhofer MEVIS, Bremen, Germany).

Results

Flow Phantom

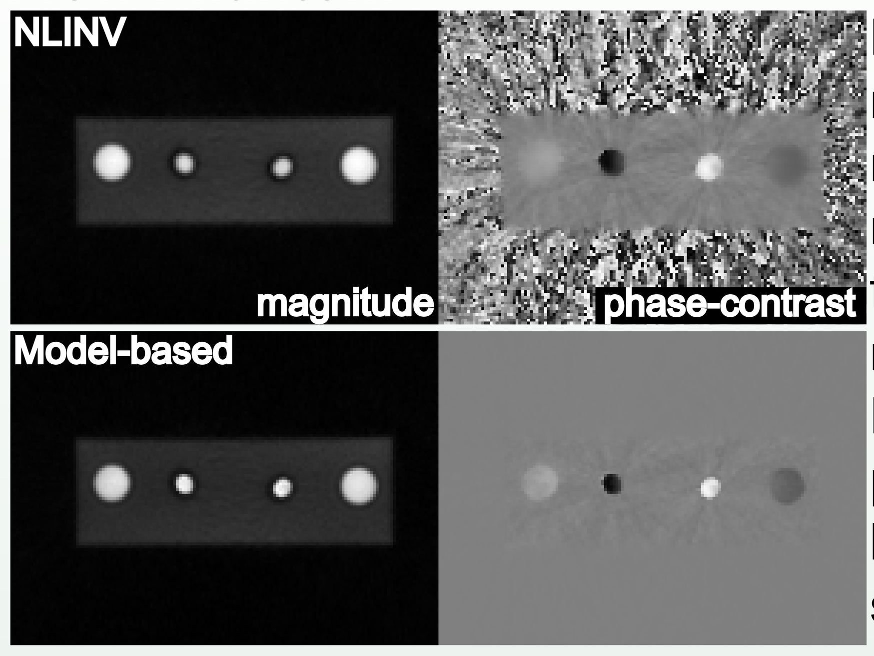

Figure 1. (Top) NLINV and (bottom) model-based reconstructions of magnitude images and phase-contrast maps for a phantom with constant flow (real-time flow MRI at 35.7 ms resolution and VENC = 200 cm/s). Phase-contrast maps obtained by the proposed method present with much less background phase noise and sharper "vessel" definition.

Human Aorta

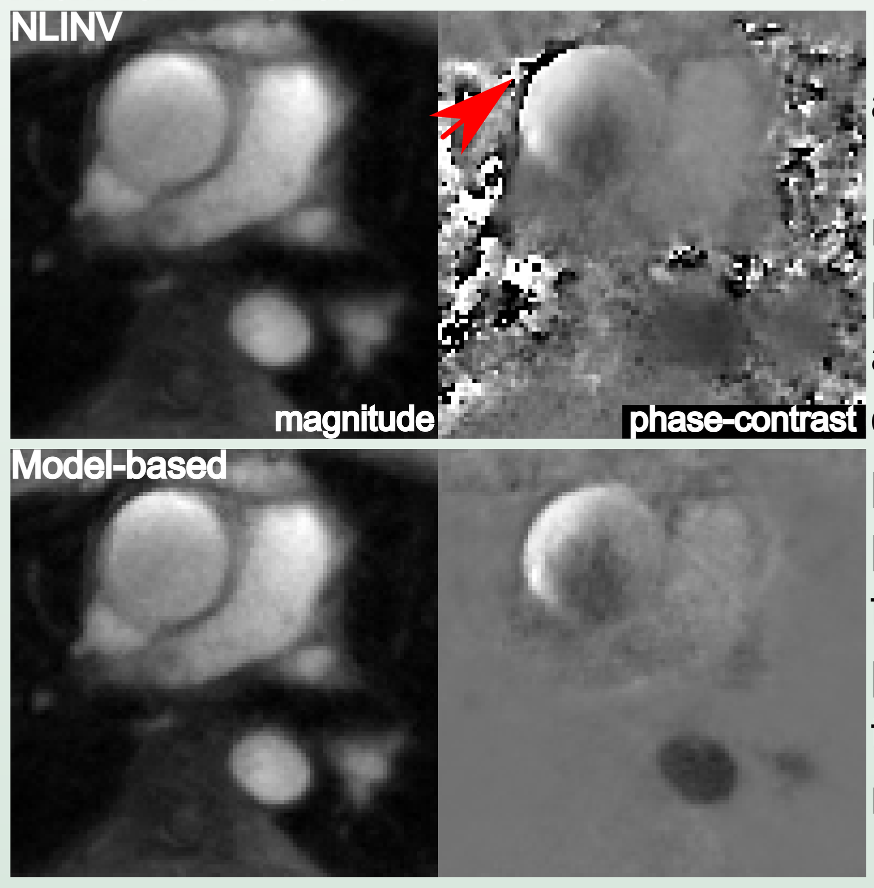

Figure 2. Systolic magnitude images and phase-contrast maps for real-time MRI of aortic blood flow (35.7 ms resolution, VENC = 400 cm/s) in a patient with aortic valve insufficiency and partial stenosis. While the border of the ascending aorta (arrow) in the phase-contrast map suffers from phase overlap of stationary and flowing spins for the conventional phase-difference reconstruction (top), this effect is largely suppressed in the model-based reconstruction (bottom).

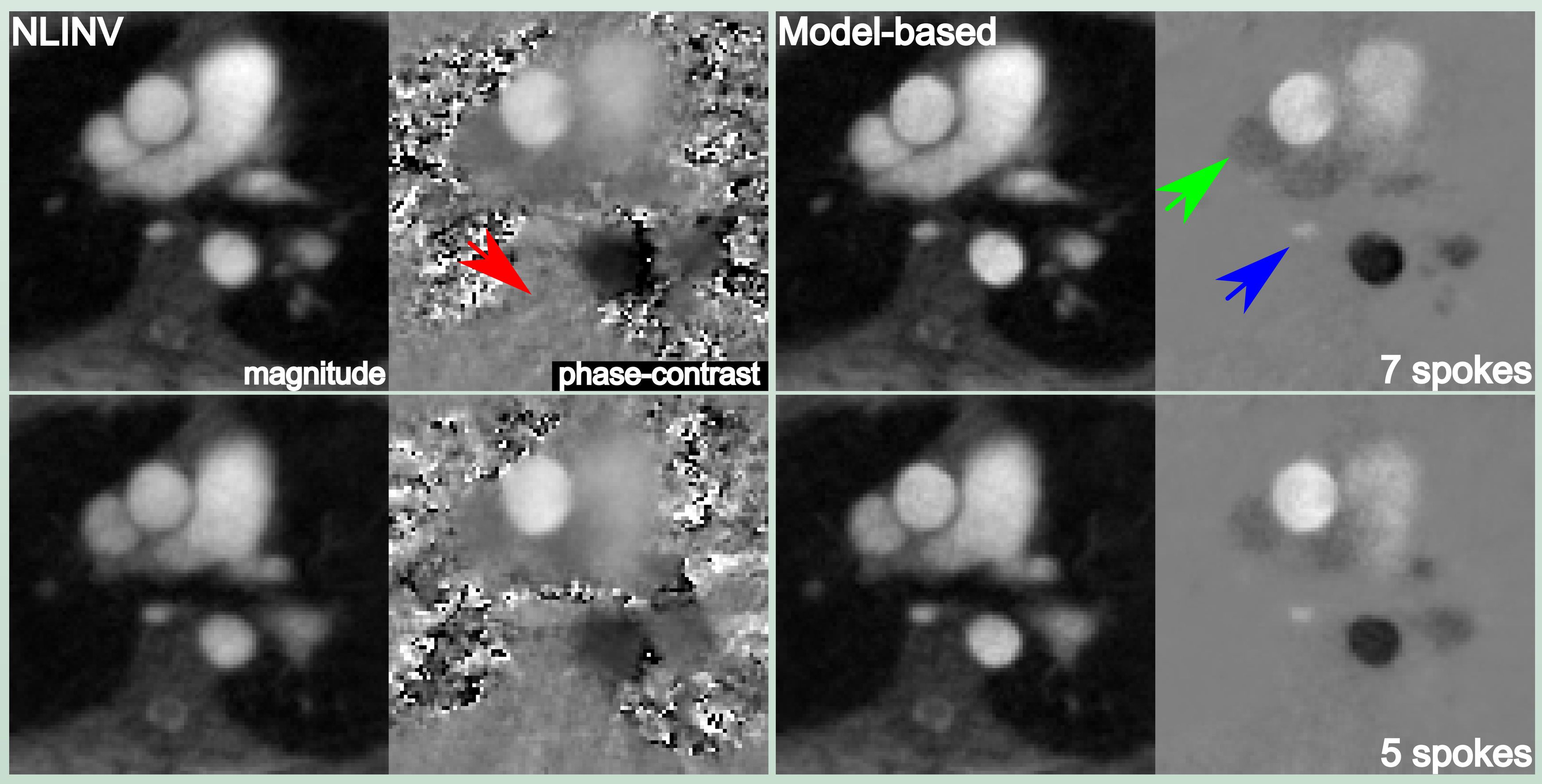

Figure 3. (Left) NLINV and (right) model-based reconstructions of systolic magnitude images and phase-contrast maps for real-time MRI of aortic blood flow (VENC = 200 cm/s) in a healthy volunteer using (top) 7 spokes per frame and (bottom) 5 spokes. Model-based reconstructions reduce residual streaking artifacts (red arrow) around the descending aorta (dark) and improve the spatial definitions of the superior vena cava (green arrow) and azygos vein (blue arrow).

Conclusion

In comparison to a previously developed real-time flow MRI method [4], the proposed method yields quantitatively accurate phase-contrast maps with improved spatial acuity, reduced phase noise, reduced streaking artifacts, and reduced partial volume effects. This novel model-based reconstruction technique may become a new tool for clinical flow MRI in real time.

References

[1] Uecker M, Hohage T, Block KT, Frahm J. Image reconstruction by regularized nonlinear inversion - Joint estimation of coil sensitivities and image content. Mag Reson Med 2008;60:674-682.

[2] Uecker M, Zhang S, Voit D, Karaus A, Merboldt KD, Frahm J. Real-time MRI at a resolution of 20 ms. NMR Biomed 2010;23:986-994.

[3] Joseph AA, Kowallick JT, Merbolt KD, Voit D, Schaetz S, Zhang S, Sohns JM, Lotz J, Frahm J. Real-time flow MRI of the aorta at a resolution of 40 ms. J Magn Reson Imaging 2014;40:206-213.

[4] Untenberger M, Tan Z, Voit D, Joseph AA, Roeloffs V, Merboldt KD, Schaetz S, Frahm J. Advances in real-time phase-contrast flow MRI using asymmetric radial gradient echoes. Magn Reson Med 2015; doi:10.1002/mrm.25696.

[5] Schaetz S, Uecker M. A multi-GPU programming library for real-time applications. In: Algorithms and Architectures for Parallel Processing (Springer). Lect Notes Comp Sci 2012;7439:114-128.