Real-time Simultaneous Multi-Slice MRI Using Nonlinear Inverse Reconstruction: Acquisition Strategies And In-Vivo Example

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Abstract: We combine Regularized Nonlinear Inverse image reconstruction with the Simultaneous multi-slice technique and demonstrate the advantages of our method compared to ESPIRiT for Cartesian data with few reference lines. We investigate different spoke distribution schemes for radial acquisitions and test the technique both on a phantom and in-vivo on a human heart where we yield a time resolution of 33 ms for three slices.

Zusammenfassung: Wir kombinieren die Regularized Nonlinear Inverse Bildrekonstruktion mit der Simutlaneous multi-slice Technik und demonstrieren die Vorteile unserer Methode gegenüber ESPIRiT für Kartesische Daten mit wenigen Referenzlinien. Wir untersuchen verschiedene Speichenakquisitionsschemata für radiales Sampling und testen die Technik am Phantom und in-vivo am Menschenherz, wobei wir eine Zeitauflösung von 33 ms für drei Schichten erreichen.

Motivation

MRI is an intrinsically slow imaging modality for which the study of fast moving objects such as the human heart is extremely challenging. New fast MRI methods to monitor the heart in real-time[1] are limited to single 2D slices which often does not suffice for a thorough cardiac examination. To overcome this limitation we combine real-time MRI with Simultaneous multi-slice (SMS) MRI[2].

In SMS MRI multiple slices of an object are acquired simultaneously which allows for a reduction of measurement time and improves the SNR as well as the overall image quality.

For high quality reconstructions in MRI, a precise estimation of the receiver coil sensitivities is mandatory. This is particularly challenging for real-time imaging of moving objects such as the beating heart since coil sensitivities are likely to vary from frame to frame. Conventional reconstruction approaches for SMS data pursue a two-step approach: 1) The coil sensitivities are estimated using a calibration region, 2) A linear reconstruction is performed using the acquired samples and the coil sensitivities computed in step 1. However, this procedure is time-consuming and inefficient since only a subset of samples is used for coil calibration which results in suboptimal image quality.

Here, we propose an extension of the Regularized Nonlinear Inversion (NLINV)[2] algorithm to radial SMS data (SMS-NLINV)[3]. With this reconstruction technique, coil sensitivities and image content are simultaneously estimated for each frame without prior knowledge. This makes the proposed technique especially well-suited for real-time SMS imaging. Moreover, SMS-NLINV does not rely on a fully sampled calibration region which provides more flexibility in the choice of the acquisition pattern, which further improves image quality.

Material and Methods

SMS sequence. We use a 2D radial FLASH sequence with multiband RF excitation pulses. For the acquisition of *M* slices we perform *M* (undersampled) partition measurements. In each measurement $\boldsymbol{p = 1, \dots, M}$ the simultaneously excited slices $\boldsymbol{q = 1, \dots, M}$ are modulated by the phase factor $\boldsymbol{\Xi_{pq} := \exp(-2\pi i \cdot \frac{(p-1)(q-1)}{M})}$ (Fourier encoding).

SMS-NLINV reconstruction. The signal equation in MRI can be written as $\boldsymbol{F(X) = Y}$, where $\boldsymbol{F}$ is the nonlinear forward operator, $\boldsymbol{X}$ is a vector containing the image content and coil sensitivities of each slice and $\boldsymbol{Y}$ consists of the acquired data of each partition measurement and receive channel. We solve this nonlinear inverse problem using the Iteratively Regularized Gauss-Newton Method (IRGNM).[1]

Experiments. Static measurements were conducted on a SIEMENS Skyra B_0 = 3T scanner using a 20-channel head coil. For the in-vivo measurement we utilized 26 channels of a body/spine coil.

We compare SMS-NLINV to ESPIRiT[4] for 4-fold accelerated Cartesian data with 4

reference lines and multiband factor 2 and provide difference images to reconstructions with fully sampled k-spaces.

For radial data acquisitions we investigate an aligned spoke distribution scheme, where the same spokes are acquired in each partition, a linear-turn scheme where the spoke distribution of the first partition is rotated by a linearly increased angle α_{trn}, and a golden-angle-turn scheme where α_{trn} is chosen according to the golden angle (Fig. 1).

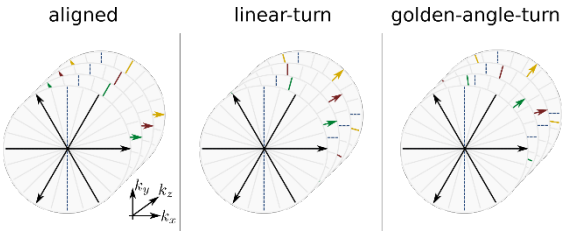

Fig. 1: Schematic for three radial sampling schemes.

We measure three slices (thickness 6mm) at a distance of 30 mm and acquire 29 spokes per measurement using the aligned, the linear-turn and the golden-angle-turn scheme.

To demonstrate the real-time capability of our reconstruction technique we simultaneously measure three slices of a human heart (short-axis view) using the turn-based scheme at a frame-rate of 33 ms.

Results and Discussion

The SMS-NLINV reconstruction can recover both slices without significant artifacts, whereas ESPIRiT fails due to the small calibration region (Fig. 2).

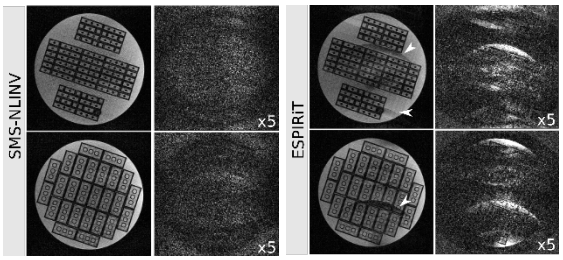

Fig. 2: SMS-NLINV and ESPIRiT reconstructions of 4-fold undersampled Cartesian k-spaces with 4 reference lines and corresponding difference images to reconstructions from fully sampled k-spaces.

For radial acquisition, the turn-based schemes provide a distinctly higher image quality than the aligned scheme (Fig. 3). By using turn-based spoke distributions, complementary k-space information is acquired in each partition measurement, which, together with Fourier and sensitivity encoding in axial direction, yields an improved image quality.

Fig. 4 shows three slices of an exemplary frame of a real-time in-vivo measurement. The images provide a clinically relevant time resolution and image quality.

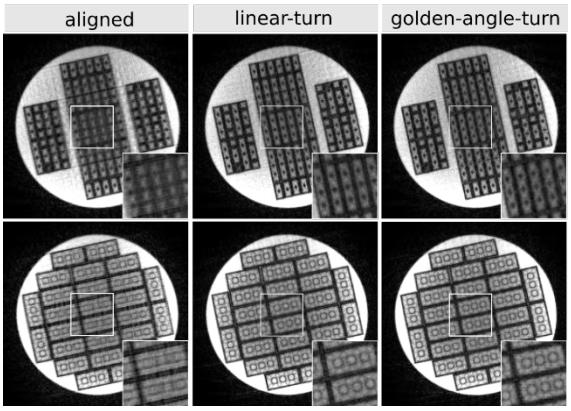

Fig. 3: SMS-NLINV reconstructions using different spoke distributions (29 spokes per partition, multiband factor 3, slice distance 30 mm, only the outermost two slices are shown).

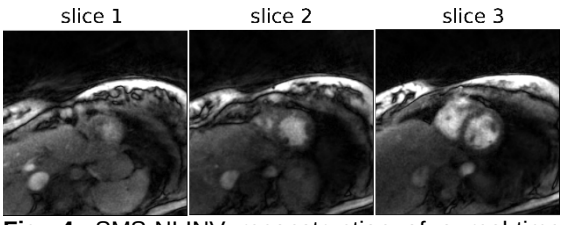

Fig. 4: SMS-NLINV reconstruction of a real-time SMS FLASH measurement with multiband factor 3. Frames extracted from a real-time movie of a human heart (time-resolution 33 ms per frame for three slices, slice distance 15 mm).

Conclusion and Outlook

In this work, we extended the technique of Regularized Nonlinear Inversion to radial SMS MRI. We demonstrated its benefits over ESPIRiT and investigated several spoke distribution schemes. We successfully reconstructed real-time movies of three slices of a human heart. One possible next step is the use of a bSSFP sequence, which - compared to FLASH - provides an enhanced blood myocardium contrast.

References

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