A time-efficient sub-sampling strategy to homogenise resolution in PatLoc imaging

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Introduction Varying spatial resolution is one of the characteristic properties of MR imaging when using nonlinear gradient fields for spatial encoding, as realised by PatLoc [1]. In the particular configuration of two orthogonal quadrupolar encoding fields as recently reported [2], voxel size is inversely proportional to the distance to the FOV centre. Compared to linear encoding, higher resolution is obtained at the periphery of the FOV at the cost of lower resolution at the centre. Currently, to improve object resolvability in the centre, the matrix size has to be increased. This requires a longer acquisition time, which is partly wasted for still higher, probably redundant, resolution at the FOV periphery and consequently lower local SNR.

In this work we present an iterative reconstruction method for sub-sampled PatLoc data. Based on the property of varying voxel size, this sub-sampling strategy improves the local resolution at the centre, leading to shorter scan times for equivalent central resolution recovery. The method is demonstrated in 1D simulations and in real imaging of a vegetable phantom.

Theory Conceptually, the proposed approach encodes the image in several iterations with varying FOVs and resolutions. For the sake of clarity the imaged object is assumed to have a limited spatial frequency spectrum. In the first step, the FOV is selected to cover the entire object and the resolution is chosen to correctly resolve the smallest structures at the periphery of the object. In the next step, the FOV is reduced to the edge of the area still correctly resolved in the first step and resolution is increased. Aliasing arising from the periphery of the object can be deterministically predicted based on the reconstruction of the first step. Iterations are repeated with an ever smaller FOV, step-by-step resolving the centre of the image.

Fig. 1 describes the method in more detail, assuming a 1D phantom and one iteration step only. The non-uniformly sampled k-space allows extraction of n = 2 lines (S_1, S_2, Fig 1 a), each composed of N equidistant spaced k-space points, but with increasing Δk_i according to $\Delta k_i = 2^{(i-1)} \times \Delta k_1$. The resulting FOV_1 of the reconstructed spin density FT_1 from line S_1 covers the whole object. However, within the smaller FOV_2 the spin density (FT_2) is now resolved with double resolution. The relative size of the respective uniform voxels in encoding-space is indicated by the colour-coded bins. In order to replace the centre part of FT_1 with the higher resolved FT_2, aliasing resulting from parts outside of FOV_2 has to be removed. To achieve this, the lower-resolved spin density FT_1 is interpolated to match FT_2 resolution via Fourier interpolation, as well as aliased to simulate FT_2. This allows description of the aliasing by subtraction of both interpolated spin densities (Fig. 1 b). With this knowledge it is possible to eliminate the aliasing in the higher-resolved FT_2 (Fig. 1 c). Now FT_2 forms the centre part of the new spin density FT_{1new} (Fig. 1 d). For n > 2, the iterative process starts with the spin reconstructions with smallest FOV, (FT_{n-1} & FT_n), as multiple folded aliasing has to be refolded backwards. In order to allow an iterative procedure, the version FT_{new} with equal voxel size throughout, but interpolated side parts, has to be used. Due to the lower information content of the lateral voxels in encoding space, this can be done without significantly decreasing information content. This would not be possible in case of standard linear gradients.

Methods 1D data simulation and reconstruction was performed using Matlab. The k-space line of a 1D phantom consisting of a series of Gaussian peaks was simulated for 8192 equidistant points, assuming an x^2 encoding field. Up to n = 4 lines, each with N = 1024 data points, were extracted with increasing Δk_i as described above. Added noise in k-space corresponded to 0.1 % of the maximum k-space signal. For easier evaluation, folding of spin density due to the x^2 field ambiguities was ignored within reconstruction. In addition, single-slice GE data (matrix: 512 × 512, slice thickness: 5 mm TR/TE: 500/16 ms, FA: 50°, BW: 100 Hz) was acquired on a Siemens 3T Tim Trio system, fitted with a quadrupolar gradient system [3]. To be able to ignore folding due to field ambiguities in this initial experiment, only half of the circular FOV with approx. 200 mm diameter was filled by the phantom. Sub-sampling followed in the time-consuming phase encoding direction only. For every of the 512 lines in raw data, n = 3 lines with N = 128 points were extracted for reconstruction.

Results Fig. 2 shows the reconstructed spin density FT_{new} in image space, using up to n = 4 lines. Without sub-sampling (n = 1), the phantom in the lateral part of the FOV is highly resolved, whereas in the centre information is missing. With increasing iterations n, this part of the FOV is better resolved with each step. In contrast to standard imaging, to achieve comparable resolution in the centre, only (1+0.5(n-1)) N instead of $2^{(n-1)} \times N$ k-space points were necessary. Added noise in k-space only slightly influenced the quality of the iterative reconstruction. Fig. 3 presents the result of the first imaging experiments. Compared to Fig. 3 a) without any sub-sampling, in Fig. 3 b) and c) the increasing resolution towards the centre after one and two iteration steps is clearly visible. As varying voxel size requires an intensity correction of the images, the intrinsic lower SNR in the higher resolved regions becomes more apparent and indicates the borders of the individual FOVs.

Discussion Analysis of simulated and experimentally acquired data showed that the presented sub-sampling strategy improves resolution in the centre of the FOV, thus achieving a more homogeneous image resolution in the case of quadrupolar encoding fields. Compared to the present alternative of acquiring a fully sampled k-space, this results in an acquisition time reduction of, for example, 31 % for n = 4. We expect further time saving by including receiver coil array encoding into the algorithm.

Acknowledgement This work is a part of the INUMAC project supported by the German Federal Ministry of Education and Research, grant #13N9208

References [1] Hennig et al., MAGMA 2008, 21:5-14; [2] Schulz et al. ISMRM 2008, #786; [3] Welz et al., ISMRM 2009, # 3073

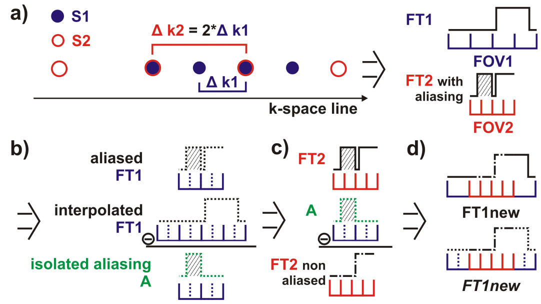

Fig. 1: Principle of sub-sampling strategy for n = 2 lines (S_1, S_2), each consisting of N = 4 points.

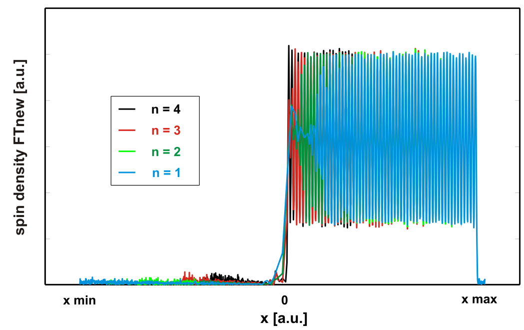

Fig. 2: Reconstructed spin density (FT_{new}) of simulated 1D phantom using up to n = 4 lines (N = 1024).

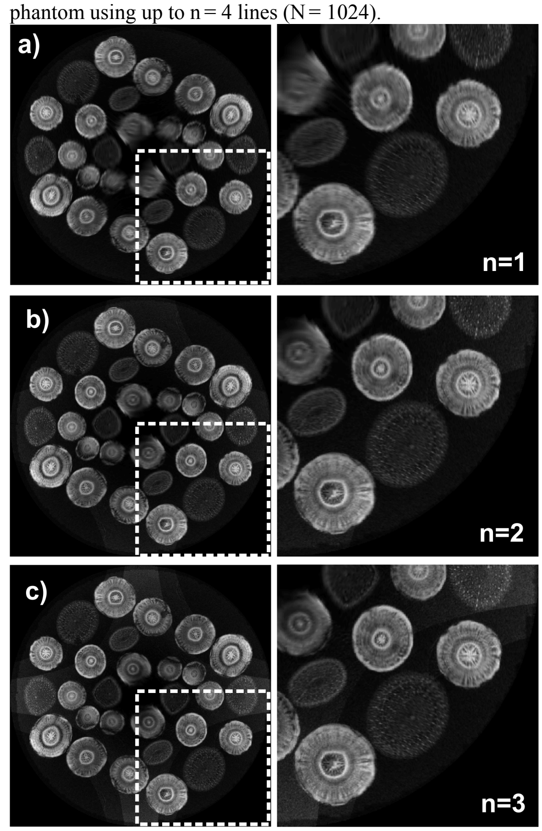

Fig. 3: Reconstructed image (FT_{new}), for n between 1 and 3 (N = 128). The right side shows the magnification of the dashed box.