Local Resolution Adaptation for Curved Slice Imaging

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Purpose The application of nonlinear spatial encoding magnetic fields for both excitation and geometrically matched encoding (ExLoc [1]) allows the acquisition of curved slices with adjustable shape and thus increases the flexibility of MRI. However, both spatially varying slice thickness and in-plane resolution resulting from the nonlinearity of the fields is an unwanted side effect for most applications. Whereas a constant slice thickness can be achieved with dedicated multidimensional RF-pulses [2], spatially varying resolution is still an open issue. The purpose of this study is therefore to reduce the spatial variation of the voxel sizes. This is obtained by applying a concept for alias-free undersampling previously developed for PatLoc imaging [3].

Theory: The concept of alias-free undersampling exploits a unique property of nonlinear encoding that causes k-space samples to have a spatially localized contribution to the reconstruction of the spin density. Figure 1 illustrates a 1D example, assuming a purely quadratic encoding field ($\Psi(x) = x^2$). Let the spin density $\rho(x)$ of the object to be encoded be described by a Fourier series with the component $\rho_n(x) = \sin(K_n x)$ (Fig. 1a) describing its finest structure to be resolved. Turning to encoding space (Fig. 1b, [4]), the transformed component $\rho_n'(a)=\sin(K_n \Psi^{-1}(a))$ is distorted. (Note that for the sake of clarity, the issue of field ambiguity is ignored by assuming that the object is placed solely on the positive side of the parabola x^2). The actual variation of spatial frequency $K'_n(a)$ (Fig. 1c, solid line) depends on the applied encoding field shape. For a purely linear field, the spatial frequency would be constant ($K'_n(a)= K_n$) and thus k-space sampling up to $k_l = K_n$ would allow resolving the spin density $\rho_n(x)$ within the total FOV. For the nonlinear field, the component can be fully resolved up to position a_l only, with $k_l = K'_n(a_l)$ (see Fig 1b, dotted line). In order to further fully resolve the spin density, k-space coverage has to be extended. However, effectively, these additional k-space samples contribute to the reconstruction of $\rho_n'(a)$ only within the remaining "local FOV", as in the remaining part the object is fully resolved already (see corresponding area in Fig. 1c).

As for conventional linear encoding, undersampling k-space corresponds to a reduction of the acquisition FOV, resulting in a periodical repetition of the spin density on a higher rate. Based on the findings above, undersampling solely those additional k-space signals for $k>k_l$ (as indicated by the lighter shading in Fig. 1d) only affects the spin density originating from the local FOV. Thus undersampling the additional k-space signals causes no aliasing within the sampling-density related FOV, as long as it covers the local FOV. (In the sense of Fig. 1d this means that the replica does not overlap with the original area.) The spin density within the local FOV can therefore be fully reconstructed from a combination of both the undersampled, high frequency k-space signal part for $k>k_l$ and the fully sampled, low frequency part for $k \le k_l$. By iteratively applying this concept, sampling density can be further decreased. Within each iteration step the local FOV is split up into a new local FOV and an outer part.

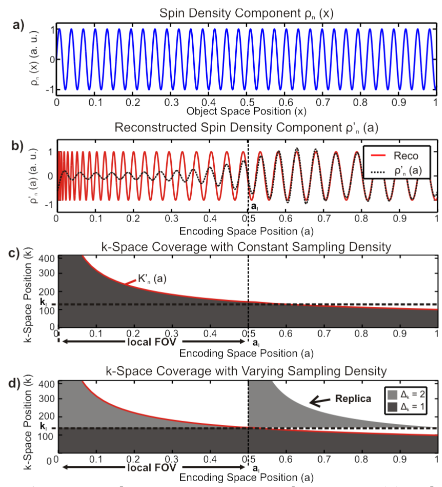

Fig. 1: Spin density component in object space (**a**) and after transformation into encoding space (**b**) for a quadratic encoding field. Full resolvability of the component requires k-space sampling up to its spatial frequency $K'_n(a)$ (**c**). Undersampling result in a replica of the corresponding spin density (**d**).

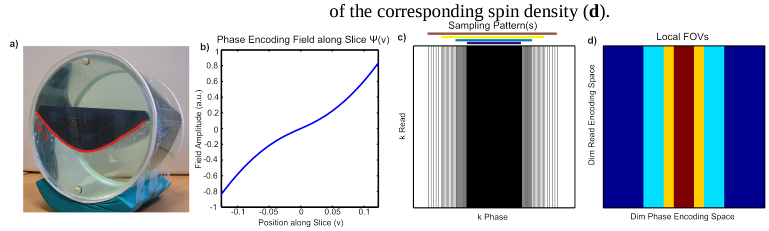

Fig. 2: Phantom with curved plate (**a**). The read line marks the curved dimension of the slice. Along the curved dimension v, the encoding field has nonlinear variation (**b**). Each sub-pattern (**c**, see color coding) allows reconstruction of a local FOV (**d**).

Methods Data acquisition was performed on a Siemens 3T system equipped with a PatLoc gradient insert [5]. The five available field components (x, y, z, 2xy, x^2-y^2) allowed adaptation of the slice shape to a structured plate with one curved dimension in a phantom filled with doped water (Fig. 2a). For the sampling pattern to be defined, a fully sampled central sampling region with extensions exhibiting stepwise-reduced sampling density by doubling the k-space sampling distance Δk was chosen (Fig. 2c). The doubling of Δk results in a bisectioning of the local FOV per iteration step. To determine the total number of required phase encoding lines, the k-space coverage k_l for each local FOV and therefore the spatial frequency $K'_n(a)$, is needed. Its relative variation was derived from the slope of the phase encoding field along the curved dimension ($\Psi(v)$, Fig. 2b) of the current slice shape (Fig. 2a). Its absolute value was determined empirically by choosing the k-space coverage of the central sampling region to ensure sufficient resolvability of the object outside the first local FOV. This resulted in a total of 176 phase encoding lines, with the outermost lines corresponding to the coverage of the fully sampled k-space with 248 lines. Each local FOV was reconstructed from its respective k-space data samples, the corresponding allocation is indicated in Fig. 2c. Within this experiment, all k-space samples were extracted from a fully sampled data set (Spin Echo sequence, matrix: 512 x 512, TR/TE: 1000/20 ms). The total FOV was assembled in encoding space prior to transformation to the final object space as described in [1]. For comparison, a reference image was reconstructed from a fully sampled k-space pattern with the number of lines equal to the total number of lines required to form the undersampled patterns.

Results and Discussion Both reconstructed images are shown in Fig. 3. For easier visualization, the curved slice was unwarped onto a plane and interpolated on an equidistant grid. Along the curved dimension *v* (left to right), image resolution is decreasing towards the center for the reference image (a). This is in accordance with the expected relative variation in voxel size (b), which yields a 3x greater voxel size in the FOV center than at the periphery. The curved slice image with locally adapted resolution (c), exhibits a much more homogenous resolution distribution. As expected, a general variation in image resolution is still present, but its magnitude value is adapted in each local FOV. The lower cut-off voxel size for the innermost local FOVs results from the restriction to an equidistant k-space grid. Within the image with adapted resolution, aliasing is observed for the finest structure only. This shows that the maximum object frequency K_n was estimated sufficiently.

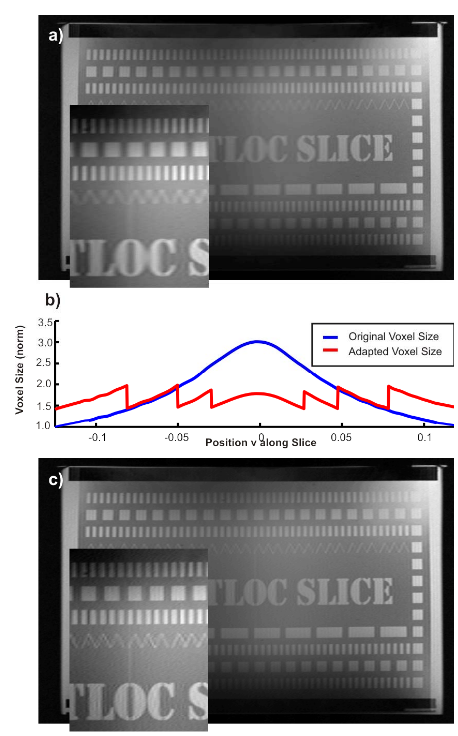

Fig. 3: Curved slice in undistorted object space without (a) and with (c) local resolution adaption. The variation in voxel size (b) was normalized on the minimum of the original voxel size.

Conclusion Alias free undersampling allows for reducing the variation in image resolution with curved slice images, which results from the nonlinearity of the encoding fields. In combination with local thickness adaptation during excitation, this allows curved slice imaging with image properties similar to those of conventional, planar imaging.

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References [1] H. Weber et al., MRM 2012, doi: 10.1002/mrm.24364; [2] H. Weber et al., Proc. ISMRM 2012, #2206; [3] H. Weber et al., Proc. ISMRM 2010, #548; [4] G. Schultz et al., MRM 2010, 64:1390-1404; [5] A. Welz et al., Proc. ESMRMB 2009, #316;