3D Imaging with Multidimensional Nonlinear Encoding

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Introduction: To overcome present limitations of gradient performance and to investigate unconventional encoding topologies a PatLoc (parallel imaging technique using localized gradients) concept was proposed [1]. PatLoc relaxes requirements of gradient homogeneity and global uniqueness of spatial encoding in favour of local gradient strength. PatLoc and similar concepts make new encoding strategies possible, also in combination with traditional linear gradients [2,3]. Generalised multidimensional encoding (MDE) with the number of k-space dimensions exceeding the number of spatial directions is the area of active research [4,5]. By using multiple spatial encoding magnetic fields (SEMs) it is expected to achieve a control over the local image properties and best exploit the acceleration capabilities of the receiver arrays. However it is yet unclear, how sampling trajectories in multiple dimensions may be designed. Null-space [2,4] and 4D-RIO (radial-in-out) are the two examples of possible readout trajectories. Concepts for MDE encoding with randomized sampling have also been proposed recently, e.g. [5]. It is however unclear, how such concepts can be translated into an actual continuous sampling trajectory.

In this work we propose using MDE for two phase encoding directions in 3D imaging, where a traditional linear gradient is used for the signal read out. We demonstrate a feasibility of this approach by implementing a RIO scheme as a pure phase encoding (PE). 3D imaging with its two slow, intrinsically sequential phase encoding directions will benefit most from the acceleration options offered by MDE.

Methods: a 3D gradient-recalled echo (GRE) sequence with a flexible PE reordering has been implemented on a modified 3T Trio a TIM MR System (Siemens, Erlangen, Germany) equipped with 6 gradient channels. All channels were served by the same gradient amplifiers (Avanto, Siemens, Erlangen, Germany), capable of providing 625A peak current and 2kV voltage. Three additional channels were used to drive a non-linear head gradient insert (Resonance Research Inc, Billerica, MA, USA) generating fields approximating c2, s2 and z2 spherical harmonics [6]. Measurements were done with a 1ch TX / 8Ch RX PET/MR RF assembly (Siemens) in a cylindrical phantom containing parallel plastic tubes and filled with doped water.

The same 3D sequence was used to calibrate the SEMs by repeating the scan with additional blips on the corresponding gradient channels. To compensate for hardware imperfections and frequency drifts the different calibration blips were applied sequentially for each PE step and a square spiral-out-in PE reordering was applied. From images thus acquired phase differences were calculated and fitted to the spherical harmonic basis (2nd order for linear 4th order for non-linear SEMS). B1 maps were calculated using the same 3D acquisition, where individual coil maps were fitted in the complex domain using spherical harmonics up to 11th order and extrapolated to fall of smoothly outside the object. Imaging parameters were: FOV 224mm, TR=9ms, TE=2.3ms, for 128^2 matrix: spatial resolution 1.75mm, TA 2min 30s. Image reconstruction was done in Matlab. First a FT was applied along the RO direction. Thereafter for Cartesian sequences a 2D FT was applied. For MDE sequences iterative reconstruction was done by minimizing the cost-function $f(\mathbf{x})=\|\mathbf{Ex}-\mathbf{s}\|_2^2$, where **E** is the encoding matrix and **s** is the signal [6]. Minimization was done using a conjugate gradient algorithm with GPU acceleration on a 512^2 matrix.

Results and Discussion: RIO strategy uses 4 SEMS (x, y, c2, s2) to encode a single transversal slice (Fig.1), where both linear and non-linear fields are following projection-like k-space trajectories. A speciality of the RIO is that when linear fields are strong quadratic ones are weak and vice versa (see colour code in Fig. 1). RIO trajectory is very sensitive to SEM calibration errors it was therefore necessary in this work to figure out a calibration strategy compensated for various imperfections, in particular eddy currents and B0 drifts. Local k-space plots based on the measured SEMS and the actual RIO trajectory are presented in Fig. 2. As seen, a spatial variation of resolution across the FOV is expected to exceed a factor of 2. The central segment corresponds to the pure linear encoding and the nominal spatial resolution of 1.75mm. Fig. 3a shows a reference image acquired with linear gradients on a doubled matrix. Fig. 3b is a pure radial PatLoc image, showing a typical variation of resolution: at the periphery it is almost as high as in Fig 3a and degrades towards the centre. Fig. 3c shows the effect of using MDE, which eliminates the complete loss of resolution in the centre and further improves the resolution at the periphery. Note that for encoding of this image only 16384 PE steps were used, a factor of 4 less than for Fig. 3a. Fig 3d shows an attempt of pushing the acceleration even further (≥8) by trying to achieve a higher spatial resolution with the same number of the encoding steps. As seen, the rescaling the trajectory has increases sampling intervals in the local k-spaces at some positions and results in streaking.

We have shown the feasibility of MDE approach for the 2D phase encoding of a 3D gradient echo sequence. A particular advantage of this approach is that the 2D phase encoding places little constrains on the continuity of the trajectory. Therefore further encoding schemes may be evaluated with this technique, in particular highly-optimized randomised strategies as in [5]. Very recently we have acquired an ethical approval for imaging human subjects with the gradient insert used in this work. In vivo imagin will be attempted upon the implementation of the approved protocol.

References: [1] Hennig, MAGMA 2008 21(1-2):5-14; [2] Stockmann, MRM 2010 64(2):447-56; [3] Gallichan, MRM 2011 65(3):702-14; [4] Tam, MRM 2012 68(4):1166-75; [5] F-H Lin MRM early view; [6] Zaitsev, ISMRM 2012 #2591 [7] Schultz, IEEE TMI 2011 30(12):2134-45.

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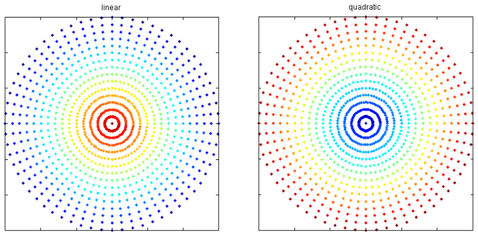


Fig. 1. *RIO k-space trajectory: linear (left) and quadratic gradients (right). 'Jet' palette encodes the acquisition order.*

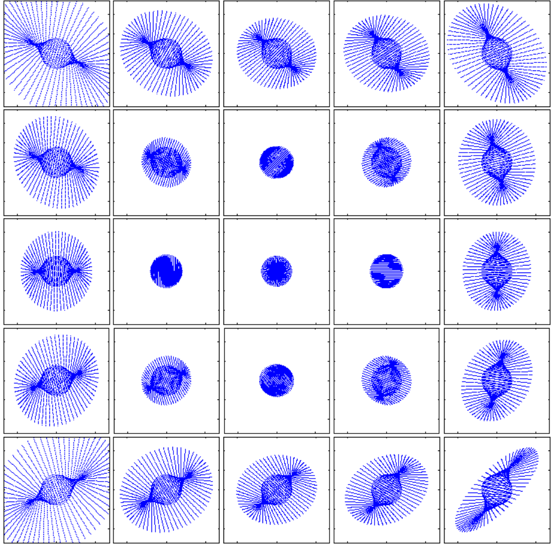
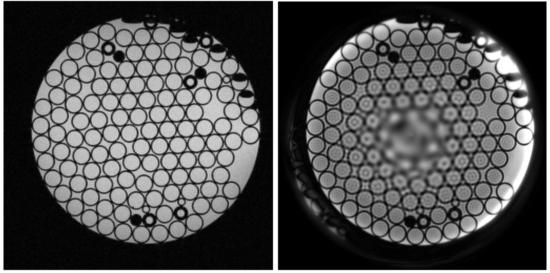
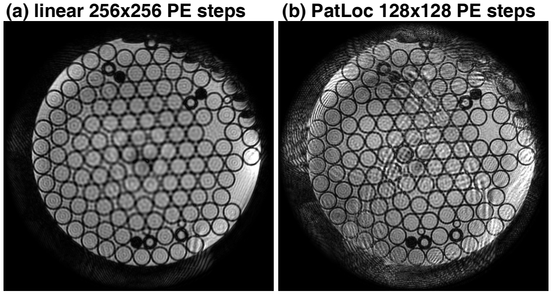


Fig. 2. *Local k-space of the actual RIO trajectory produced using the measured SEMs. Local k-space extent at the FOV periphery exceeds the double of that in the centre.*



(a) linear 256x256 PE steps **(b) PatLoc 128x128 PE steps**



(c) RIO, 128x128 PE steps **(d) RIO scaled up**

Fig. 3. *Slices through 3D volumes showing two phase-encoding dimensions: (a) linear gradients with 65536 PE steps; (b) pure quadratic with 16384 radially-ordered PE steps; (c) RIO with 16384 PE steps and nominal gradient strength; (d) same as (c) with gradient strength ×1.5. RIO-encoded image in (c) at its periphery achieves and even exceed the resolution of the fully-encoded image (a) using only 1/4th of the PE steps. Image in (d) has an effective undersampling of 8, where the unregularized CG reconstruction starts to produce streaking artefacts.*