Region-specific trajectory design for single-shot imaging using linear and nonlinear magnetic encoding fields

Kelvin J. Layton[1,2], Daniel Gallichan[3], Chris A. Cocosco[4], Anna M. Welz[3], Frederik Testud[3], Christoph Barmet[5], Klaas Prüssmann[5], and Maxim Zaitsev[3]
[1]*Electrical & Electronic Engineering, University of Melbourne, Melbourne, Victoria, Australia,* [2]*National ICT Australia, Melbourne, Victoria, Australia,* [3]*Dept. of Radiology, Medical Physics, University Medical Center Freiburg, Freiburg, Germany,* [4]*Radiology, Medical Physics, University Medical Center Freiburg, Freiburg, Germany,* [5]*Biomedical Engineering, University & ETH Zürich, Zürich, Switzerland*

INTRODUCTION The recent introduction of nonlinear magnetic fields for spatial encoding holds great promise to improve on traditional linear gradient approaches. The general concept of a Parallel Acquisition Technique with Localised gradients (PatLoc) has been successfully demonstrated in-vivo to produce images with spatially varying resolution [1,2]. O-Space imaging [3] and Null-space imaging [4] propose nonlinear encoding schemes to compliment the spatial encoding provided by the sensitivities of multiple receive coils. The use of additional spatial encoding fields necessitates the use of multidimensional trajectories to describe the imaging scheme.

In this work, we develop a general algorithm to design multidimensional trajectories that provide improved resolution in a region-of-interest. We demonstrate this algorithm to design single-shot trajectories that use a combination of linear and nonlinear encoding fields. Single-shot imaging is particularly well suited to multidimensional trajectories, where the additional encoding channels can overcome the limitations associated with rapid switching. The resulting trajectories are verified in simulation and in-vivo experiments.

THEORY A general framework to analyse nonlinear encoding schemes has previously been proposed using the concept of "local k-space" [5]. We use local k-space as the criteria for automated trajectory design. With knowledge of the spatial derivatives for each of the encoding fields, the local k-space trajectory, $\boldsymbol{k}(\boldsymbol{x})$, at position, $\boldsymbol{x}$, is obtained by a linear operation on the gradient moments, $\boldsymbol{\nu}$, as described in Equation (1).

$$\boldsymbol{k}(\boldsymbol{x}) = A(x)\boldsymbol{\nu} \qquad (1)$$

$$\begin{array}{ll} \text{minimise} & \|\tilde{\boldsymbol{k}} - A\boldsymbol{\nu}\| \\ \text{subject to} & \mathrm{B}\boldsymbol{\nu} = \boldsymbol{0},\ \mathrm{C}\boldsymbol{\nu} \leq \mathbf{b} \end{array} \qquad (2)$$

The vectors $\boldsymbol{k}$ and $\boldsymbol{\nu}$ contain a concatenation for all times of the local k-space trajectory and gradient moments, respectively. We design trajectories that improve the resolution in a region-of-interest by specifying a target trajectory, $\tilde{\boldsymbol{k}}$, at a set of control locations within the region. In this way, the algorithm for trajectory design reduces to a linear constrained optimisation problem in Equation (2). The operators A, B and C capture, respectively, the spatial derivative of the encoding fields, the initial conditions of the gradient system and the hardware constraints associated with peak gradient and slew rates (specified in $\boldsymbol{b}$).

METHODS Our experiments used a combination of two linear and two quadrupolar fields to encode a two dimensional slice (selected using a third linear gradient). Our goal was to double the resolution in the top-left region of the image. Thus the target single-shot trajectory was an EPI sequence covering twice the k-space extent achievable in fixed time using linear gradients alone. The assumption here is that any undersampling due to increased k-space extent can be resolved using the sensitivities of multiple RF coils. The trajectory contains 64 lines with 64 readout points each line for a total time of 41.6ms. The peak slew rates were 170T/m/s for the linear channels and 772T/m^2/s for the nonlinear channels (derived from the same dB/dt constraint at the periphery).

All computations were performed using MATLAB (The Mathworks, Natick, MA). The optimisation algorithm in Equation (2) was solved using the MATLAB algorithm, `quadprog`, which exploits the inherent sparsity of the A matrix. Given the gradient moments, the corresponding local k-space trajectory was calculated using Equation (1) for points in a 5x5 grid over the field-of-view.

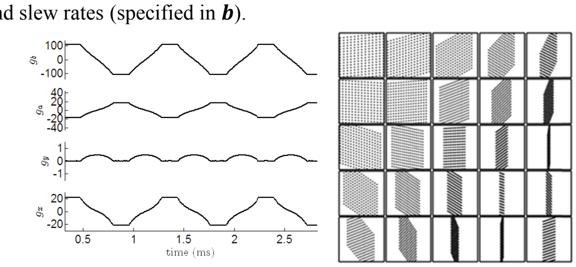

Figure 1: (**a**) The gradient waveforms, calculated from the time derivative of moments, for the 4D trajectory (first 3ms after prephase is displayed) and (**b**) the corresponding local k-space.

Simulations: Synthetic data was generated using eight RF coils arranged concentrically around the field-of-view with sensitivities obtained from the Biot-Savart equation. A high-resolution (512x512) numerical checkerboard phantom was used to simulate the calculated 4D trajectory and a linear 2D trajectory for comparison. **Hardware Setup:** After IRB approval, in-vivo experiments were performed on a 3T clinical imaging system (MAGNETOM, Trio Tim, Siemens Healthcare) fitted with a custom-built gradient insert-coil. This setup has been previously described in [6] and allows simultaneous and independent control of three linear and two quadrupolar fields. A Siemens head coil containing an eight channel coil array was used for receiving. The RF sensitivities and nonlinear encoding shapes were determined using data from a custom 8 echo GRE sequence. The single-shot acquisitions had a 3mm slice thickness and field-of-view of 220mm. The actual trajectories were measured using a 16-probe field monitoring device. In both simulated and in-vivo experiments, the data was reconstructed to a 128x128 grid using a conjugate gradient algorithm.

RESULTS Figures 1a and 1b present the calculated gradient waveforms for the four-dimensional trajectory and the corresponding local k-space, respectively. As required, the local k-space has increased extent in the region-of-interest, suggesting improved resolution in that region. Figure 2 displays reconstructed images from the simulated data for the standard 2D linear EPI trajectory and the optimised 4D trajectory. The fine details of the checkerboard phantom are completely blurred out for the 2D trajectory, which is limited by the slew rate. Conversely, the 4D trajectory reconstruction clearly demonstrates improved resolution in desired region. Finally, Figure 3 displays the corresponding reconstructions for in-vivo data and further illustrates the resolution improvement of the 4D trajectory in the target region.

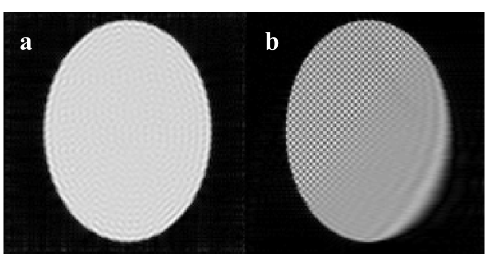

Figure 2: Reconstructed images of a checkerboard pattern from simulated data for the (**a**) linear-only 2D trajectory and (**b**) the calculated 4D trajectory.

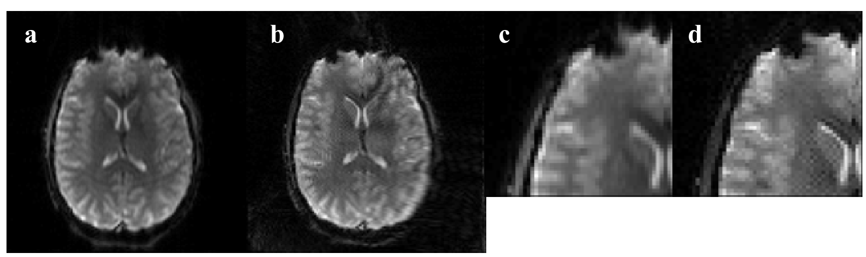

Figure 3: Reconstructed images from data acquired in-vivo for (**a**) The linear-only 2D trajectory and (**b**) the calculated 4D trajectory using two linear and two nonlinear channels. (**c**) and (**d**) display the magnified region-of-interest from (**a**) and (**b**), respectively.

DISCUSSION We have provided a general framework to design multidimensional trajectories that provide improved resolution in a target region. We have successfully demonstrated our technique for single-shot imaging both in simulations and in-vivo. The achieved local increase in resolution leads to an elevated noise level within the target region, which reflects the usual trade-off between the resolution and SNR. Consequently, this framework is most useful for schemes limited primarily by resolution such as single-shot imaging. This technique is readily applicable to functional studies concerning a particular anatomical region.

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