Simultaneous Linear and Nonlinear Encoding in a Single Shot

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Introduction: The general concept of PatLoc (Parallel Imaging Technique using Localized Gradients) [1] is to use nonlinear fields for spatial encoding. Relaxing the requirement that the encoding fields must be linear may lead to improved gradient performance or reduced peripheral nerve stimulation (PNS). Encoding performed using two quadratic spatial encoding magnetic fields (SEMs) of the form $\psi_a = x^2 - y^2$ and $\psi_b = 2xy$ is non-bijective, but these ambiguities can be resolved by applying parallel reconstruction techniques [2]. The resulting images exhibit variation in encoded resolution across the FoV, with a higher resolution towards the edge and lower resolution towards the center – with no effective spatial encoding at the very center due to the spatial derivative of both encoding fields falling to zero. It has recently been demonstrated that combined encoding, simultaneously yet independently driving the quadratic SEMs and the conventional linear gradients, can preserve the PatLoc property of variable spatial resolution yet avoiding the complete loss of spatial resolution in the center of the FoV [3]. In this work we seek to push the limits of the custom-built gradient insert which generates the two quadratic SEMs by performing a single-shot version of this 4-Dimensional Radial In/Out (4D-RIO) trajectory, and testing this trajectory in-vivo. A field camera was used to track the actual encoding trajectory up to 3rd order to assist image reconstruction.

Method: The 4D-RIO trajectory simultaneously covers both the linear (k_x,k_y) and quadratic (k_a,k_b) k-spaces with radial spokes, but with staggered timing such that the edge of (k_x,k_y)-space is reached concurrent to passing the center of (k_a,k_b)-space, and vice-versa. This was previously implemented by a dual-echo sequence, where the read-out was split into two to allow a sweep-back to the opposite edge of (k_x,k_y)-space when the center of the (k_a,k_b)-space is reached [3]. In order to implement a single-shot version of 4D-RIO, we treated each traversal between the center and the edge of these 2D k-spaces as a separate element of the trajectory – and then arranged these elements to connect them together while minimizing the distance, in 4D Euclidean space, between their ends, as shown in Fig. 1. These connections need to respect the maximum amplitudes and slew rates of both the linear and the quadratic SEMs, but can be designed using methods directly analogous to existing 2D or 3D approaches [4]. Assuming a nominal resolution of 64x64 and FoV of 256 mm, we were able to generate a 43 ms readout train which fulfils these criteria. A comparison of the local k-space (local spatial derivatives of the net encoding phase) plots for the two trajectories is shown in Fig. 2.

Following IRB approval a single healthy subject was scanned using a clinical 3T MRI scanner (Siemens TIM Trio) with a custom gradient insert driven by high-performance amplifiers which generates the two quadratic fields ψ_a and ψ_b, as previously described in [5] and [6]. Although the quadratic fields are expected to result in lower levels of PNS, existing models for PNS are empirical and accurate predictions are difficult. A conservative approach was taken here, slowly ramping up the amplitude of all current in the readout module in a series of measurements with regular communication between the operator and subject. No PNS or other unusual effects were observed.

The 4D-RIO trajectory is known to be highly sensitive to the accuracy of the assumed encoding fields [3], and with a custom-built gradient coil we expect calibration to be necessary to account for the effects of eddy currents, timing delays and potentially also concomitant fields. To account for all of these effects simultaneously, we measured the actual trajectory in a separate acquisition with an array of 16 ^{1}H field probes [7]. The probes were approximately distributed across the surface of a 18cm sphere and operated independently in Tx/Rx mode when placed inside the standard 8-channel head RF coil, with the probe data being collected by the scanner spectrometer. Via an external trigger a separate transmit chain (signal generator: N5181A, Agilent, Santa Clara, CA, USA; RF Amplifier: 75A400, Amplifier Research, Souderton, PA, USA; power splitter: MITEQ-ESTONIA, Estonia) was used to excite the field probes independently from the scanner and with shorter RF-pulses. The plugs of the standard head coil were connected to a coil test-bench for detuning and grounding during the experiments. Image reconstruction was then performed using a conjugate gradient method including trajectory effects up to 3rd order.

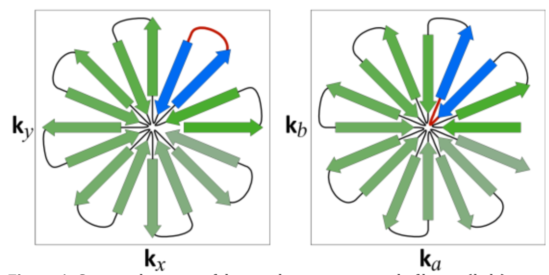

Figure 1: Cartoon depiction of the simultaneous traversal of linear (k_x,k_y)-space and quadratic (k_a,k_b)-space for single-shot 4D-RIO. The red connection between the two blue elements is concurrently at the edge of the (k_x,k_y)-space and at the center of (k_a,k_b)-space.

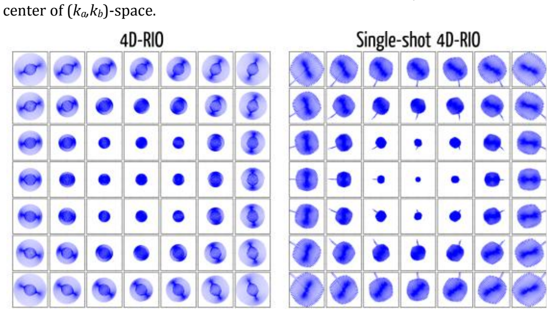

Figure 2: Comparison of local k-spaces for multi-shot 4D-RIO (left) and the novel single-shot version (right). The single-shot version maintains the variable spatial resolution and isotropic local coverage.

Results and Discussion: As shown in Fig. 3 we were able to reconstruct reasonable quality images, both in a phantom and in the human brain in vivo, using this novel single-shot higher-order encoding trajectory. Even with such a demanding non-Cartesian trajectory running simultaneously on the linear gradients and on a custom-built quadratic gradient coil, through the use of field monitoring we were able to reconstruct images of reasonable quality. We expect that, due to the reproducibility of the measured trajectories, by further calibration of our hardware setup even more demanding acquisitions for higher resolution undersampled imaging will also be possible, and similar techniques may also be applied to other custom gradient hardware arrangements such as O-space [8] or FlatLoc [9].

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[1] Hennig et al. MAGMA (2008) 21:5; [2] Schultz et al. MRM (2010) 64:1396; [3] Gallichan et al. MRM (2011) 65:702; [4] Hargreaves et al. MRM (2004) 51:81; [5] Welz et al. Proc ESMRMB (2009) p316; [6] Cocosco et al. Proc ISMRM (2011) p717; [7] Wilm et al. MRM (2011) 65:1690; [8] Stockmann et al. MRM (2010) 64:447; [9] Littin et al. Proc ISMRM (2011) p1837.

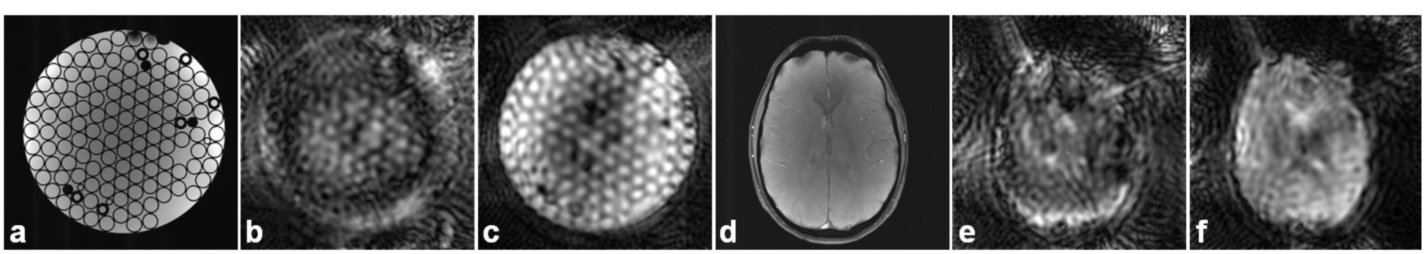

Figure 3: Reconstructed images of a phantom and a human brain in vivo using single-shot 4D-RIO using (b)/(e) the nominal trajectory and (c)/(f) the trajectory measured with the field camera.