Designing k-space trajectories for simultaneous encoding with linear and PatLoc gradients

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Introduction: It has recently been successfully demonstrated that imaging can be achieved with non-linear encoding fields using a Parallel Acquisition Technique with Localised gradients (PatLoc) [1]. Imaging with localised gradients has potential benefits due to reduced peripheral nerve stimulation, as well as offering the flexibility to tailor the encoding fields to better match the geometry of the anatomy of interest. This flexibility can be increased further if a system is used which is capable of driving more than 3 gradient channels – the non-linear fields can then be manipulated simultaneously with the standard three linear gradient axes: our Siemens TIM Trio system is currently in the testing phase for independent control of 6 gradient channels. Here we present an initial exploration of the space of possible 'combined' trajectories, using two quadrupolar PatLoc gradients in addition to the standard linear gradients. We also introduce the concept of a 'local k-space' to allow comparison of trajectory properties, as the non-linear encoding gradients mean that the interpretation of resolution and FoV directly based on the conventional concept of k-space is no longer possible.

Method and Results: For simplicity, we restrict our considerations to imaging a 2D slice, and that the *z*-gradient is used for slice selection. We then have 4 gradient channels available during the imaging readout: the linear *x* and *y*-gradients in addition to the two PatLoc fields. In the case of our self-built PatLoc coil [2], the two PatLoc fields available approximate the (x^2 - y^2) and ($2xy$) solid harmonics.

Imaging trajectories which combine non-orthogonal linear and non-linear fields can, in general, no longer be reconstructed using the Fourier transform, necessitating the use of iterative reconstruction strategies such as the conjugate gradient method [3]. Here we use Matlab to simulate the data acquisition process for a particular trajectory, where the phantom is defined on a 128x128 grid. The acquisition is defined to be a total of 32x32=1024 points for 8 receive coils, reconstructed onto a 64x64 grid. This represents an effective net acceleration factor of 4 (although it should be noted that due to the non-uniform spatial resolution of the reconstructed image, the definition of acceleration factor may in future need to be considered in more detail for the case of PatLoc imaging).

To calculate the 'local k-space' we find the local gradient in the *x* and *y* directions of the total encoding field (i.e. including the contributions of all linear and PatLoc fields) at the time that each sample of data is acquired. To visualise how this local k-space varies across the object, we propose plotting the full local k-space for a reduced number of points spread across the object, as in Fig.1a where a 5x5 matrix of the local k-space has been plotted for trajectory A: a Cartesian trajectory using only the two quadrupolar fields. The equivalent of the conventional interpretation of extent of k-space coverage corresponding to image resolution can now be interpreted from the local k-space: the local image resolution corresponds to the extent of coverage of the *local* k-space. This is confirmed by the simulated reconstruction of a digital chequerboard phantom using this trajectory (Fig. 1d) where the high resolution at the periphery of the FoV and the lower resolution towards the centre are clearly observable.

When trajectories are designed which include linear gradients as well as quadrupolar gradients, the net effect is that the centre of the 'saddle' shape of the quadrupolar field gets shifted around the FoV. If we wish to maintain approximately even resolution across our FoV, it is intuitive that the trajectory which the saddle centre follows during the readout should also be evenly distributed. We found that this is difficult to achieve with a Cartesian trajectory, but greater flexibility is offered by radial trajectories. If both the 2D 'linear k-space' and the 2D 'PatLoc k-space' simultaneously follow similar trajectories, however, the resulting 4D trajectory tends to produce a strongly asymmetric trajectories for the saddle centre, and consequently asymmetric local k-space distributions. To overcome this restriction we split the radial readout in two, such that whilst the 2D linear k-space is progressing towards the centre, the 2D PatLoc k-space is moving outwards, and vice-versa. There remains the option of choosing the angle of advance of both radial components to the 4D split-radial sequence. If the advance angles are chosen to be identical, the resulting trajectory of the saddle centre is directionally un-biased, and the local k-space is highly symmetric about the centre (Fig 1b). From the local k-space we can also see that whilst the advantage of the higher peripheral resolution of the trajectory in Fig 1a is maintained, the resolution in the centre of the FoV is also improved. The reconstruction using this trajectory (Fig 1e) confirms this recovery of resolution in the object centre. By varying the relative strength of the linear vs. PatLoc gradients it is possible to independently choose the effective resolution at the centre and the periphery.

A further interesting observation is that if the angle of advance of the 2D linear k-space is set to twice the angle of advance for the 2D PatLoc k-space, the resulting 4D trajectory causes the saddle centre to only 'visit' half of the FoV. This results in the local k-space shown in Fig 1c, where the top half of the FoV has no samples at the local k-space centre. Correspondingly, when a reconstruction is simulated from this trajectory (Fig 1f) we find that the top half of the FoV is almost entirely missing, with only the higher resolution information (corresponding to the edges of the local k-space) present in this area. This further demonstrates that the local k-space representation not only provides information regarding the local resolution, but also regarding the local completeness of sampling.

Conclusion: We have presented a 4D acquisition trajectory combining linear and non-linear encoding which has the benefit of higher resolution at the periphery of the FoV whilst introducing control over the resolution at the centre. We look forward to the exciting possibilities of using this trajectory on the new 6-gradient channel hardware in the near future. We expect the concept of local k-space to be useful in designing and optimising 4D trajectories.

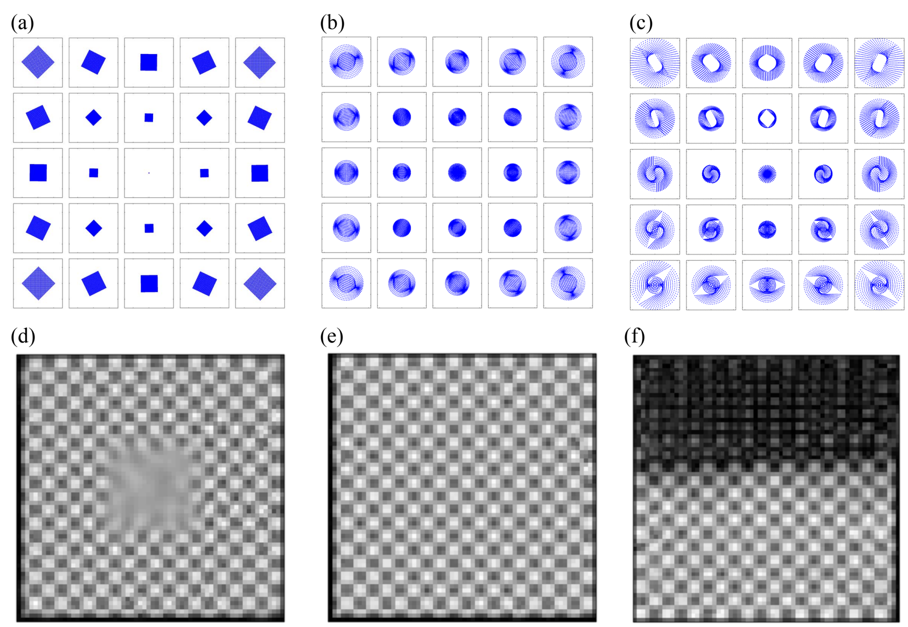

Fig. 1: 'Local k-space' plots for (a) a Cartesian trajectory in 2D quadrupolar PatLoc fields (trajectory A); (b) a 4D trajectory comprised of split-radial linear and radial quadrupolar components; (c) as (b), but with unmatched angles of advance in the two 2D radial spaces. (d-f) The corresponding simulated reconstructions of a 4x accelerated acquisition of a chequerboard phantom using the trajectories (a-c).

References: [1] J.Hennig *et al.* (2008) MAGMA 21:5-14; [2] A.M.Welz *et al.* (2009) Proc. ESMRMB p316; [3] K.P.Pruessmann (2001) MRM 46:638-651