Multidimensional Gradient Encoding: Artifacts Resulting from Destructive Signal Interference

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Target Audience: Researchers and engineers working with nonlinear gradient fields and generalized encoding strategies.

Purpose: The purpose of this work is to derive an approach that helps to understand and avoid imaging artifacts in multidimensional trajectories.

Background: Within the previous years, spatial encoding with nonlinear gradient fields has become a topic of increasing interest [1-4]. It offers unique encoding options that may eventually result in highly efficient organ-specific or other novel imaging applications, see e.g. [1,5]. Of special interest are multi-dimensional trajectories, i.e., encoding schemes that make use of more than three gradient channels. Maybe the most challenging problem with such trajectories is that they tend to be extremely sensitive to calibration errors [2,4]. Compared to conventional imaging, a large amount of new artifacts is created that are hardly understood and cannot be controlled up to now. One particularly interesting artifact has been described in [6]. It has been observed that for a special multidimensional trajectory, 4D-RIO (two linear and two quadrupolar fields), extensive bands of signal voids (see Fig. 1b,c) occur whose number increases with an augmented level of miscalibration. This problem is addressed in this work.

Theory: As shown in [3], the signal generated with a nonlinear gradient hardware is given by $s(\mathbf{k}) = \int \rho(\vec{x}) \exp(-\mathbf{i}\mathbf{k}^{\mathrm{T}}\mathbf{\Psi}(\vec{x}))$, where ρ is the spin density, $\mathbf{k}$ the multidimensional PatLoc k-space trajectory and $\mathbf{\Psi}$ the true encoding function whose components are proportional to the field geometry of the encoding fields. Consider a miscalibration $\mathbf{\Delta\Psi}$. Then, the assumed encoding function $\widehat{\mathbf{\Psi}}$ differs from the true function via $\widehat{\mathbf{\Psi}} \coloneqq \mathbf{\Psi} + \mathbf{\Delta\Psi}$ and the signal can also be written as:

$$[1] \qquad s(\mathbf{k}) = \int \rho(\vec{x}) \exp(\mathbf{i}\mathbf{k}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x})) \exp(-\mathbf{i}\mathbf{k}^{\mathrm{T}}\widehat{\mathbf{\Psi}}(\vec{x})).$$

This expression proves useful (see Discussion) in explaining the banding artifact.

Methods: Simulations were performed with MATLAB (The Mathworks, Natick, USA) and measurements on a Tim Trio 3T with a modified gradient hardware. The 4D-RIO trajectory as well as the O-space imaging trajectory were investigated in this work. Calibration errors were artificially introduced by translating and/or rotating one or more of the encoding fields prior to CG reconstruction.

Results: First, compare Fig. 1b,c with Fig. 2a,b. The comparison illustrates that the shape of the banding artifact and the phase error maps of Fig. 2 are very similar. A qualitative explanation is given in the caption to Fig. 2c. The measurement results shown in Fig. 3 show almost perfectly symmetric phase cancellations (Fig. 3b,c), however, they do not match the corresponding phase error image (Fig. 3d). Hence, for 4D-RIO, the similarity only exists as long as only a single encoding field is not well calibrated. Fig. 4 illustrates that miscalibrated O-space imaging data is also heavily affected, but no banding artifact occurs. A qualitative explanation is found in the figure caption.

Discussion: Equation [1] is very helpful in understanding the occurrence of the banding artifact. The equation shows that the phase error $\exp(\mathbf{i}\mathbf{k}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x}))$ is introduced by the miscalibration. This phase changes along the trajectory $\mathbf{k}$. However, considering that most signal energy results from the center of local k-space (see [2]), the most important contribution comes from only a few (spatially dependent) time points with $\mathbf{k}(\vec{k}_{\mathrm{loc}} \approx 0)$**.** Fig. 2c shows that for 4D-RIO the local k-space center is traversed always twice at $\mathbf{k}_1$ and $\mathbf{k}_2$**,** but the introduced local k-space shifts are opposed to each other. It may occur that the introduced phases $\mathbf{k_1}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x})$ and $\mathbf{k_2}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x})$ point in the same direction (constructive interference) or in the opposite direction (destructive interference), in which case signal loss will result. At least when $\mathbf{k}_1 = -\mathbf{k}_2$, it therefore seems reasonable that phase error map $\mathbf{k_1}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x})$ and banding artifact are closely related to each other. This behavior is indeed observed for 4D-RIO as long as only a single field is not well calibrated. However, the question may be raised why this behavior is not observed in all cases, such as the cases shown in Fig. 3 or Fig. 4. For O-space imaging, no destructive interference is possible because $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{0}$. But for 4D-RIO, this argument cannot count. However, consider that as the miscalibration $\mathbf{\Delta\Psi}$ is typically not known, the term $\exp(\mathbf{i}\mathbf{k}^{\mathrm{T}}\mathbf{\Delta\Psi}(\vec{x}))$ is neglected in the forward evaluations of the CG reconstruction. It is obvious that this omission affects the reconstruction of $\rho(\vec{x})$. This might lead to phase cancellations and the banding artifact; but also other errors may occur: Aliasing, the intensity may be not well represented and distortions or misplacements of the object may result. Consider for example a situation, where all four fields are rotated. Then, a perfect reconstruction will result; however, the reconstructed object itself will appear rotated. From this perspective, the congruence of Fig. 1 and Fig. 2 rather seems unusual.

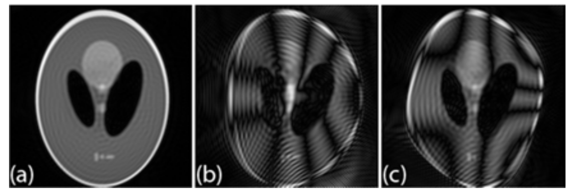

Figure 1: Image reconstruction results for (mis-)calibrated 4D-RIO data in simulations. (a) With perfect calibration, the image is well depicted. (b, c) Miscalibration introduces heavy artifacts. Particularly obvious are the signal voids along black bands. In (b), the miscalibration corresponds to a translation of one of the four encoding fields by 7% of the field-of-view (64²-acquisition). In (c), the miscalibration is due to a 7° rotation of one of the four fields.

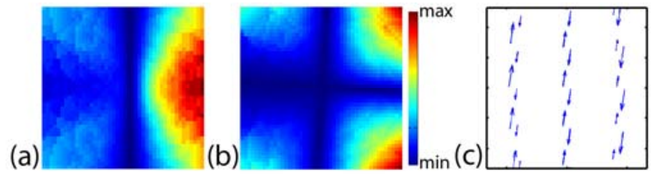

Figure 2: The images shown in (a,b) represent the phase error at the local k-space center, introduced by the miscalibration. The left image corresponds to Fig. 1b and the central image to Fig. 1c. Observe the similarity between these images: Banding artifact and phase error are closely related to each other. (c) This image provides the key for understanding the cause of the banding artifact. Shown is the local k-space center at an example location. More exactly, the arrows indicate the shift of local k-space that is introduced by the miscalibration. The important observation is that for each arrow in one direction a second arrow exists that shows exactly in the opposite direction. As a result, two overlapping signals accrue the same phase, but with opposite signs. Therefore, constructive interference occurs if the phase difference of the two superimposing signals is a multiple of 2π and destructive interference occurs for odd multiples of π. This is where the black bands come from.

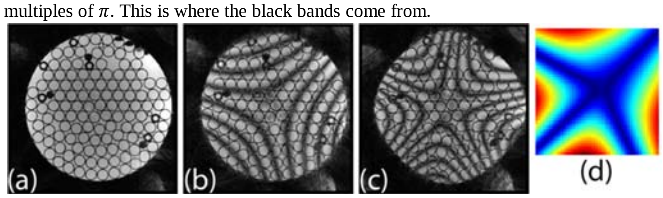

Figure 3: The same artifact behavior is also observed for measurement data. Notice the surprising three-fold and five-fold symmetry of the artifact, despite the two-fold symmetry of the quadratic encoding fields. In the case shown two out of the four fields were rotated. In (b) the two quadrupolar fields were rotated by 3.5° (128²-acquisition) in the same direction, and in (c) in the opposite direction. The phase error image in (d) corresponds to (b) and shows no congruence. This behavior is different if only a single encoding field is miscalibrated (cf. Fig. 1 and Fig. 2). A similar non-congruent behavior is also observed for Fig. 3c (not shown).

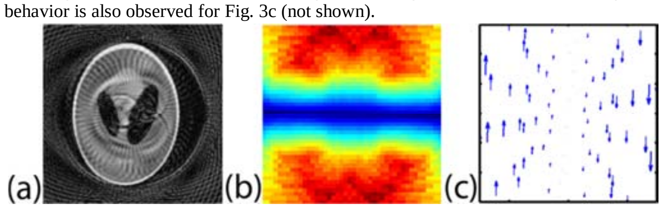

Figure 4: (a) Miscalibrated image, (b) phase error and (c) local k-space shift as in the above figures, but here for an O-Space imaging trajectory. Again, a single field was rotated by 7° for a 128²-simulation. Heavy artifacts are observed, but no banding artifact as for 4D-RIO. Also for this O-Space imaging trajectory, k-space shifts are in opposite directions; however, at the relevant local k-space center, no k-space shift and hence no phase error is introduced (the phase image in (b) actually incorporates also the vicinity of the local k-space center). This explains that no banding artifact is observed as for the 4D-RIO trajectory.

Conclusions: It could be shown that a banding artifact can result from miscalibration if the local k-space center is visited twice during imaging and the introduced shift of local k-space is directed in opposite directions. When designing a multidimensional encoding scheme, such a situation should therefore be avoided if accurate methods for calibration are not available.

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References: [1] Hennig et al., MAGMA 21(1-2):5–14, 2008; [2] Gallichan et al., MRM 65:702-14, 2011; [3] Schultz, PhD thesis, Freiburg, Germany, 2012; [4] Stockmann et al., MRM 64:447-56, 2010; [5] Witschey et al., MRM 67:1620-32, 2012. [6] Kroboth et al., #199, ESMRMB 2012.