# Iterative parallel imaging reconstruction of time-resolved data using 3D variational regularization

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**Introduction:** Constrained iterative image reconstruction of undersampled data from multiple coils has shown its high potential to deliver images with excellent image quality from highly accelerated measurements [1]. With this strategy, image reconstruction is modelled as an inverse problem, which is usually ill-posed. Additionally, due to the size of the problem, dedicated routines for optimization are needed to obtain a solution. To eliminate aliasing artifacts, regularization methods are facilitated, which introduce a-priori knowledge about the structure of the desired solution. Usually, regularization is applied only in 2D, and data is reconstructed slice by slice. While this approach reduces the size of the problem and therefore the amount of memory that is needed in the computation, it neglects the potential of introducing a-priori information in the third dimension. This work introduces an approach which treats a whole 3D volume of images as a single data set, and also includes 3D regularization.

**Materials and Methods:** Second Order Total Generalized Variation ($TGV^2$) was recently introduced as a regularization model. This method shares the benefits of the total variation (TV), which is edge preserving and has shown to be a very efficient regularizer to eliminate aliasing artifacts from undersampled radial or pseudo-random trajectories. The additional benefit of $TGV^2$ is that it eliminates the problem of staircasing artifacts, which is one of the main drawbacks of the TV method. The results of this work were obtained by extending this approach to the third dimension, which leads to the following constrained optimization problem:

$$\min_u \frac{1}{2}\left\|F(u)-k\right\|_2^2 + \lambda \cdot TGV^2(u).$$

In this equation, $F$ is the subsampled Fourier Operator, $u$ is the reconstructed 3D volume of images, $k$ is the measured $k$-space data, $TGV^2()$ is the penalty functional and $\lambda$ is a regularization parameter. The proposed approach was tested during the 2010 ISMRM image reconstruction challenge ("Need for speed" challenge, undersampled spiral data set). The data consisted of 200 timeframes of an undersampled angiography measurement of a contrast agent bolus injection, each consisting of a single spiral interleave, with coil sensitivities from an 8 channel head coil. More details about the data can be found on the MRI-Unbound website of the ISMRM (http://www.ismrm.org/mri_unbound/simulated.htm). The resolution of a single timeframe was 512×512, and each frame was reconstructed from 5 spiral interleaves, each with 2000 sample points. This corresponds to subsampling of approximately 26 in comparison to a fully sampled Cartesian scan. In the proposed approach, the images of all timeframes were considered to be one single 3D volume stack for the purpose of image reconstruction. Therefore the dimension of the data was 200×2000×8 (number of spiral interleaves × number of samples on a spiral trajectory × number of coils), which was used to reconstruct a single volume of dimension 512×512×40. 3D $TGV^2$ was used as a penalty during image reconstruction. Due to the increased computational demand of solving a single optimization problem for all timeframes, a variant of the primal-dual algorithm of Chambolle and Pock [3] already used in [2] was implemented. It does not dualize the discrepancy leading to a linear subproblem which is solved by the CGNE-method. The implementation benefits from the massively parallel compute capabilities of modern graphics hardware.

**Results:** Reconstruction results of a conventional minimum norm method (zero filling and NUFFT reconstruction with density compensation), slice by slice reconstructions using an equivalent 2D version of the algorithm that was used in the 3D case, and the proposed 3D regularized reconstruction are displayed in **Figure 1**. Four different timeframes, which show the wash-in-phase of the contrast agent, are shown. As expected, conventional minimum norm solutions exhibit pronounced spiral aliasing artifacts, which are reduced significantly $TGV^2$-constrained reconstructions. When comparing the 2D- with the 3D-reconstruction, pronounced further improvements of image quality can be observed, especially concerning the perceptibility of smaller vessels.

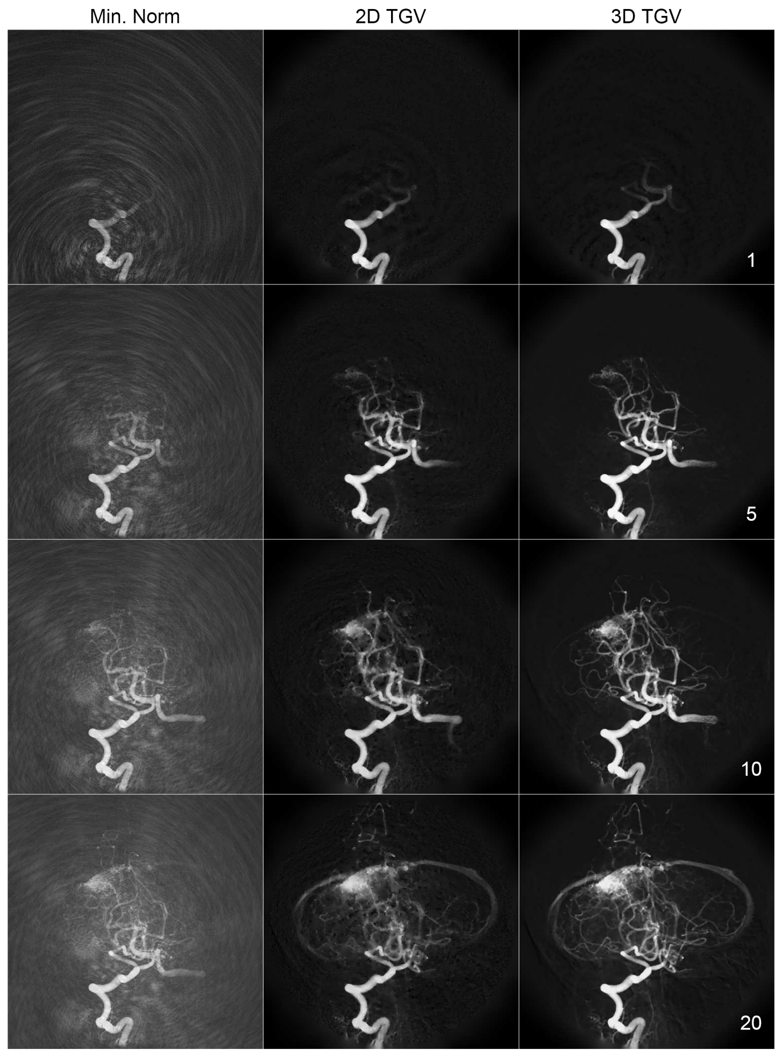


**Figure 1:** Reconstruction of subsampled spiral data. Conventional minimum norm solution (left column), 2D $TGV^2$ regularized reconstructions (middle column) and 3D $TGV^2$ regularized reconstructions (right column). Timeframes 1, 5, 10 and 20 are displayed.

**Discussion:** This work introduces 3D iterative image reconstruction with 3D regularization to reconstruct volume data or time-resolved data sets. The interesting feature of this approach is that it is also possible to exploit the structure of aliasing artifacts in the third dimension, information that is neglected with conventional slice by slice reconstruction. This requires aliasing artifacts with a slightly different pattern in different slices. For radials and spirals, this can be achieved by rotating the angles of the spokes/interleaves of adjacent slices. An interesting comparison can be made with recent work in the field of real-time-MRI [4]. In this work, the authors use a median filter in the temporal domain to reduce radial streaking artifacts, while preserving sharp transitions. As a median filter can also be interpreted as a practical implementation of an $L_1$ minimization problem, it is expected that a comparison of these two approaches, which the subject of future work, will yield compareable results.

**References:** [1] Block et al., MRM 57: 1086-1098 (2007), [2] Knoll et al., Proc. Intl. Soc. Mag. Reson. Med. 18: 4855 (2010), [3] Chambolle and Pock, Technical Report 685, Ecole Polytechnique, Centre de Math´ematiques Appliqu´ees (2010), [4] Uecker et al., NMR Biomed 23: 986-994 (2010).