Design of Temporally Constrained Compressed Sensing Methods for Accelerated Dynamic MRI

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Introduction: Many clinical applications necessitate a limited scan time for dynamic MRI acquisition, e.g. due to breath hold or contrast passage. This often restricts attainable spatial and temporal resolution, limiting potential diagnostic or research applications. To reconstruct significantly undersampled time frames at clinically desired spatial/temporal resolution a number of approaches have been proposed, including compressed sensing (CS) CS reconstruction from incomplete data relies on the assumption that the underlying signal has a sparse representation in some basis. Typically, CS utilizes spatial sparsity of the image itself or its discrete gradient. However, in time-resolved imaging, the level of spatial sparsity may not be sufficient to support the required high accelerations, leading to residual artifacts and loss of spatial resolution. Temporal filtering methods based on quadratic minimization such as k-t SENSE were shown to mitigate these problems [1]. However, recent reports indicated limitations on acceleration achievable with such techniques [2]. CS approaches exploiting sparsity in temporal dimension in addition to or instead of spatial dimensions promise to overcome these limitations. Previously proposed methods include utilization of the temporal derivative [3-5] and sparsity in *x-f* space [6]. Critical to success of such approaches is the choice of the sparsifying basis, as an improper choice may lead to significant image artifacts and loss of spatial/temporal resolution [2]. In this work, we propose a novel approach that uses 2nd temporal derivative for improved temporal waveform fidelity and hybrid l_1 / l_2 norm penalty on the roughness in the time dimension for better noise properties. We compare the performance and characteristics of the proposed method to other temporally constrained CS methods, including *k-t* FOCUSS (sparsity of the image series in *x-f* space) [6] and temporal constraint (total variation minimization in time direction [4]).

Theory and Methods: We propose to apply temporal regularization directly in *x-t* space: $\bar{\mathbf{f}} = \arg\min_{\bar{\mathbf{f}}} \left(\left\| \bar{\mathbf{E}}\bar{\mathbf{f}} - \bar{\mathbf{m}} \right\|_2^2 + \lambda \Phi\left(\mathbf{L}\bar{\mathbf{f}}\right) \right)$, where $\bar{\mathbf{E}}$ is the encoding matrix for *n* time frames composed of Fourier terms and coil sensitivity values, $\bar{\mathbf{f}}$ and $\bar{\mathbf{m}}$ are solution and data vectors, respectively, and λ is the regularization parameter. $\mathbf{L}$ is a temporal sparsifying transform based on the 2nd temporal difference, and $\Phi(.)$ is a measure of sparsity. Several norms $\Phi(.)$ have been utilized so far for temporally constrained reconstruction, including l_2 [3], l_1 [4], and focusing inversion [5] (l_0-type of norm). In this work, we chose a hybrid l_1 / l_2 norm to provide both SNR optimization (via l_2 norm) and CS acceleration (via l_1 norm). The norm is given by $\Phi(\mathbf{x}) = \sum_k \left(\sqrt{1 + \left(x_k / \sigma \right)^2} - 1 \right)$, where $\sigma = 0.6\mathrm{std}(x)$ [7]. CS minimization was implemented using iteratively reweighted least squares approach [8]. All methods used conjugate gradient iterations with stopping relative error value of 1e-8. Regularization parameters were chosen empirically to minimize RMS error. A digital flow phantom (Fig. 1a) was created as an object consisting of elliptical structures imitating different types of motion (heart motion, vessel motion, and contrast enhancement). Realistic velocity curves simulating laminar flow were assigned to the vascular structures in the phantom. 2D, though-plane phase contrast (PC) velocity measurements were performed in healthy volunteers on a 3.0T clinical scanner with an 8ch Cardiac coil (MR 750, GE Healthcare; Waukesha, WI). During a single breath hold, aortic outflow measurements were performed using both fully sampled radial acquisition that was undersampled retrospectively and severely undersampled radial data.. Contrast-enhanced angiographic data was collected in the brain of a normal volunteer during the first pass of contrast using radial (in plane)/Cartesian (slice encoding) sampling.

Results: Plots in Fig. 1b represent velocity curves measured in the small moving vessel of the phantom for acceleration factor 8. The use of 2nd temporal difference as a sparsifying transform both reduced image ghosts (not shown) and preserved temporal fidelity, while the other two methods underestimated the waveform due to lack of sparsity produced by motion. When measured in the stationary vessel, flow curves for all methods coincide (not shown). Figure 2 compares reconstruction results of PC data acquired within a single 15 s breath hold (10 ms temporal resolution, acceleration factor 13) using different approaches and flow measurements (only 50% of the cardiac cycle shown) in the descending aorta. Note that the use of 2nd temporal difference preserves the shape of the waveform while two other CS methods underestimate the peak flow. Similar effect was observed in the reconstructions of contrast-enhanced angiographic data for acceleration factor of 40 (temporal resolution 0.5 s, 24 slices, 8 channel coil).

Discussion and Conclusions: Constrained reconstruction methods based on minimization of sparsifying norms are promising methods to accelerate dynamic MRI. Our results, however, indicate that it is important to design such methods carefully. For example, *x-f* basis may not be sparse enough to support the required high acceleration in cases of complex motion and respiratory motion., As a result, the performance of related methods, may be compromised. In such cases, the developed temporal regularization approach (sparsification in *x-t* space) may be advantageous. Our initial results both in digital phantoms and *in vivo* normal volunteers indicate that all three temporal CS methods (*k-t* FOCUSS, 1st and 2nd temporal differences) perform similarly for moderate acceleration factors (up to 6). However, in the presence of complex motion (both anatomical motion and flow) and at high acceleration factors (8-40), the proposed method reduced ghosting artifacts and improved waveform fidelity, thereby rendering itself a valuable method for highly accelerated PC velocimetry and CE MRA. Finally, compared to l_1 minimization (total variation), hybrid l_1 / l_2 norm provided optimized noise performance, which is especially important as applying higher order difference operators increases noise level.

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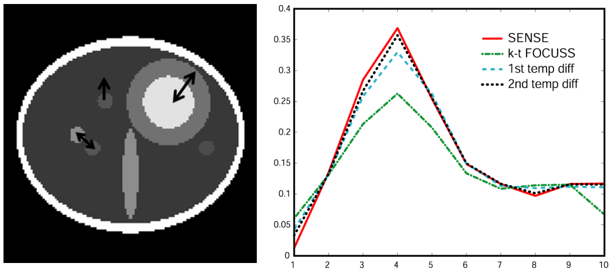

Figure 1. Simulation results. **a:** Digital flow phantom (10 frames) imitating cardiac motion (arrows indicate direction). **b:** Comparison of flow waveforms in the top vascular structure.

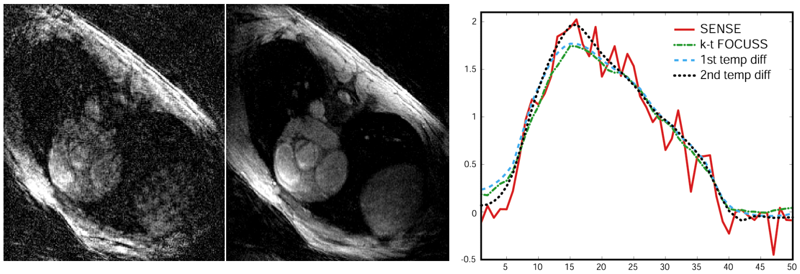

Figure 2. Magnitude images for peak flow frame reconstructed using (a) SENSE; (b) 2nd temporal difference regularization. (c) Flow measurements in the descending aorta.