Improving Temporal Fidelity in *k-t* BLAST MRI Reconstruction

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Abstract. Studies of myocardial motion using magnetic resonance imaging usually require multiple breath holds and several methods have been proposed in order to reduce the scan time. Rapid imaging using *k-t* BLAST has gained much attention with its high reduction factors and image quality. Temporal smoothing, however, may reduce the accuracy when assessing cardiac function. In the present work, a modified reconstruction filter is proposed, that preserves more of the high temporal frequencies. Artificial decimation of a fully sampled data set was used to evaluate the reconstruction filter. Compared to the conventional *k-t* BLAST reconstruction, the modified filter produced images with sharper temporal delineation of the myocardial walls. Quantitative analysis by means of regional velocity estimation showed that the modified reconstruction filter produced more accurate velocity estimations.

1 Introduction

In the setting of myocardial ischemia, the assessment of regional wall motion is of great importance. Since the introduction of delayed enhancement magnetic resonance imaging (MRI) of late uptake of gadolinium in scarred tissue [1], this has become the method of choice to quantify viable myocardium. In combination with this, MRI has become an important method to assess myocardial function. Its ability of arbitrary three-dimensional coverage is appealing, compared to echocardiography which is restricted to certain acoustic windows. A limitation of MRI compared to echocardiography is the longer imaging time. Imaging is usually carried out during several cardiac cycles in a gated fashion. In order to reduce artifacts caused by respiratory motion, this is usually done during a breath hold. Multiple slice coverage of the entire heart will not fit into a single breath hold without sacrificing spatial and/or temporal resolution. For patients, using multiple breath holds can be a burden, and the risk that the separate breath holds are not consistent is impending. Several methods for scan

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time reductions have been applied to limit this problem or to increase resolution or coverage. These methods include parallel signal reception from multiple coils with different signal encoding sensitivities [2,3], efficient k-space trajectories [4], variable sampling density with subsequent interpolation [5,6,7] and alias suppressing reconstruction from lattice subsampled data [8,9].

Of the aforementioned methods, the k-t BLAST (Broad-use Linear Acquisition Speed-up Technique) approach [9] has shown impressive reductions of scan time by a factor 5 or 8 with little perceived loss of image quality. k-t BLAST works by subsampling the k-t space (spatial frequency and time) sparsely on a lattice grid. By using a sheared lattice, the resulting signal aliasing will be shifted in the reciprocal x-f space, i.e. low temporal frequencies of one spatial position will be aliased to higher temporal frequencies at a different spatial position. By also acquiring so-called training data, an estimate of the distribution of the signal and aliased signal in x-f space is obtained. This estimate can be used to separate the true signal from the aliased copies. The rationale is that large parts of the imaging field of view will only contain low temporal frequencies, and the signals will not interfere. The separation is accomplished by a Wiener filter approach in x-f space, using a filter R:

$$R = \frac{M^2}{M^2 + \sum M^2_{\mathrm{alias}} + \Psi^2} \tag{1}$$

where M^2 is the signal distribution estimate, $\sum M^2_{alias}$ is the estimated aliased energy and Ψ^2 is the measurement noise variance. For wide-sense stationary sources, the Wiener filter is the optimal linear reconstructor in the least squares sense [10]. However, the least squares error norm is not necessarily the best norm for motion analysis.

The result after k-t BLAST reconstruction is visually appealing, even with high subsampling, in single time frames. When considering temporal variations, however, it becomes apparent that temporal fidelity is suffering from the regularization. When the aliased signal or noise dominates over the true signal, the reconstruction filter R will attenuate the output in order to suppress the aliasing signal and noise. The attenuation is more pronounced for signal with high temporal frequency, because it is more easily dominated by noise or aliased signal with low temporal frequency. The attenuation of high temporal frequencies translates into temporal smoothing and loss of rapid motion.

The aim of this work was to investigate if the conventional k-t BLAST reconstruction filter could be improved to preserve more of the high temporal frequency content by reducing the amount of regularization of noise and aliased signal.

2 Method

To evaluate the conventional k-t BLAST reconstruction and an alternative reconstruction, a fully sampled reference data set was artificially decimated and reconstructed using different reconstruction filters.

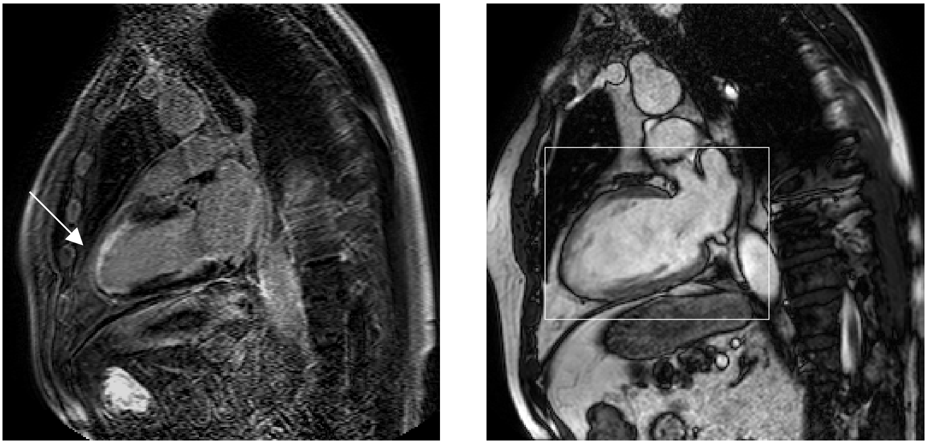

Fig. 1. A Two-chamber delayed enhancement image (left) and an end diastolic time frame from the dynamic image sequence (right). Note the scarred tissue in the antero-apical region of the left ventricle, indicated by the arrow. The box indicates the region shown in subsequent images.

Data were used from a clinical follow-up of a patient who recently had suffered an ST-elevation myocardial infarction treated with percutaneous coronary intervention. Image acquisition was done on a Philips Achieva 1.5T MRI scanner (Philips Medical Systems, Best, The Netherlands). Using delayed enhancement imaging the extension of the infarction in the anterior-apical region was demonstrated, as shown in a two-chamber view in Fig. 1. A time resolved slice in the same two-chamber orientation was acquired using a retrospectively gated balanced steady-state free precession pulse sequence with the following parameters; slice thickness 8 mm, field of view 320 mm, repetition time 3.2 ms, echo time 1.6 ms, flip angle 60°, *k*-space segmentation factor 11, acquisition matrix 192×187 and reconstruction matrix 256×256. The SENSE-Cardiac coil was used for signal reception, but SENSE was not utilized for image acceleration. An end diastolic time frame from this image sequence is also shown in Fig. 1.

The time resolved slice was reconstructed by the scanner into 30 time frames. Since the actual temporal resolution was 35 ms and the heart rate was 71 beats per minute, the data were subsequently temporally interpolated into 24 time frames using linear interpolation. This also allowed a *k-t* BLAST reduction factor of 8, since the number of time frames must be divisible by the reduction factor. These 24 time frames were considered to be the reference image data.

The reference data were Fourier transformed along the spatial dimensions to obtain data in *k-t* space. The central 16 *k*-space lines were kept in all time frames as training data to be used for the signal estimate M^2. The reference data were then artificially decimated using the lattice shown in Fig. 2. The lattice was obtained by maximizing the shortest distance between signal aliases in *x-f* space [11]. After decimation, the data were Fourier transformed in both

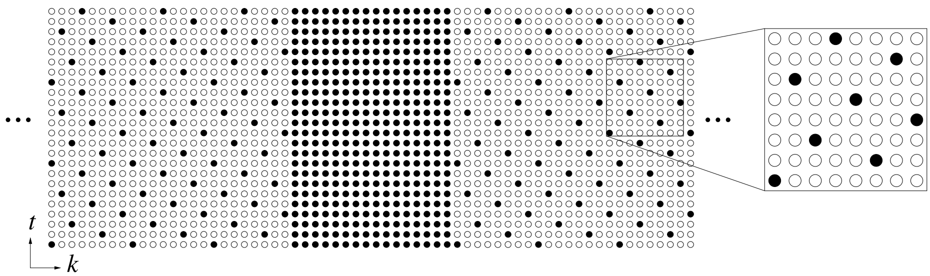

Fig. 2. The lattice in k-t space that was used for artificial decimation. Open circles represent the data points that were discarded and filled circles represent the data points that were retained. The 8×8 tile was repeated to cover the full k-t space of 256×24. The central 16 lines in k-space were fully sampled and used for estimation of M^2.

spatial and temporal dimensions, yielding data in x-f space. The reconstruction filter (described below) was applied, and after Fourier transformation in the temporal dimension, resulting images were obtained.

The terms in the conventional k-t BLAST reconstruction filter as described in Eq. 1 were obtained as follows. The central 16 k-space lines acquired for the training data were windowed using a Hamming window and zero-filled in the phase-encoding direction to a size of $256 \times 256 \times 24$ and then Fourier transformed into x-f space. The squared magnitude of the result is used as M^2 in the reconstruction filter. In order to preserve high temporal frequencies, temporal frequency windowing as described in the original k-t BLAST paper [9] was not performed in this work. The variance of a non-moving area close to the heart was used as the noise variance estimate Ψ^2.

For the alternative reconstruction approach, a modified version of the conventional k-t BLAST filter was considered:

$$R_{\text{alt}} = \frac{M^2}{M^2 + \alpha(\sum M^2_{\text{alias}})^{\gamma} + \beta\Psi^2} \tag{2}$$

In this work, β was empirically set to 0.1 to reduce the noise regularization. The exponent γ was set to 2, with α used as a normalization factor to keep the maximum value of $\sum M^2_{\text{alias}}$ constant. This was used to reduce suppression of weak aliased signal while reverting to full suppression where the aliased signal is very strong.

To study the temporal fidelity of the data, the temporal evolution of a line through the ventricle was displayed. Analogous to M-mode ultrasound, the temporal dimension was combined with one spatial dimension to create a two-dimensional image.

In order to evaluate the different reconstruction filters quantitatively, the velocity of the wall was estimated in five regions in the left ventricle. The regions are shown in Fig. 3. The velocity estimation was based on quadrature phase optical flow [12,13] and performed as follows. All images were filtered using three

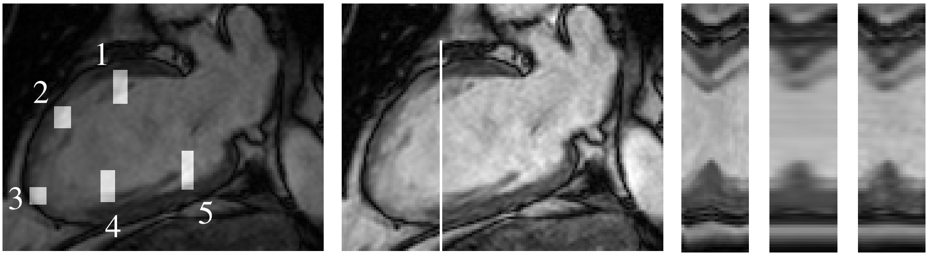

Fig. 3. Region placement (a), M-mode line position (b) and M-mode projections over time for the reference data set (c), conventional *k*-*t* BLAST data set (d) and alternative *k*-*t* BLAST data set (e). Note the induced temporal smoothing in both *k*-*t* BLAST reconstructions, and the better preservation of high temporal frequency content in the alternative reconstruction.

quadrature lognorm filters in the directions 0°, 60° and 120°, with $\cos^2$ shaped angle envelop and a lognorm radial response with center frequency of $\pi/6$ and 3 octaves relative bandwidth.

Phase differences (φ) and corresponding certainties (Q) in the x, y and t directions were formed from conjugate products according to

$$\begin{aligned} Q_x e^{i\varphi_x} &= f_{yt} * \big(q(\mathbf{x})\, q'(\mathbf{x} + \mathbf{\Delta}_x)\big) \\ Q_y e^{i\varphi_y} &= f_{xt} * \big(q(\mathbf{x})\, q'(\mathbf{x} + \mathbf{\Delta}_y)\big) \\ Q_t e^{i\varphi_t} &= f_{xy} * \big(q(\mathbf{x})\, q'(\mathbf{x} + \mathbf{\Delta}_t)\big) \end{aligned} \tag{3}$$

with $'$ denoting complex conjugate, $\mathbf{\Delta}_x$, $\mathbf{\Delta}_y$ and $\mathbf{\Delta}_t$ are one pixel in the x, y, and t directions, respectively, and f_{yt}, f_{xt} and f_{xy} are convolution kernels to center the phase differences around a common pixel.

The speed of the local region was estimated as a weighted sum of the phase difference ratio weighted by the local certainty of the speed estimate

$$s = \sum_{\Omega} \sqrt{Q_t \sqrt{Q_x^2 + Q_y^2}} \frac{|\varphi_t|}{\sqrt{\varphi_x^2 + \varphi_y^2}} \tag{4}$$

The sum was performed over all pixels in the region and all filter directions (Ω).

Using similar energy weighted sums, a vector $\mathbf{v}$ in the direction of motion was obtained as

$$\mathbf{v} = -\begin{pmatrix} \sum_{\Omega} \sqrt{Q_x Q_t} \frac{\varphi_x}{\varphi_t} \\ \sum_{\Omega} \sqrt{Q_y Q_t} \frac{\varphi_y}{\varphi_t} \end{pmatrix} \tag{5}$$

The certainty weighting coefficients were normalized in all sums in Eqs. 4 and 5.

The speed and direction were combined to a velocity vector as $s\frac{\mathbf{v}}{|\mathbf{v}|}$, that was projected onto the direction of the edge. The edge orientation was obtained from

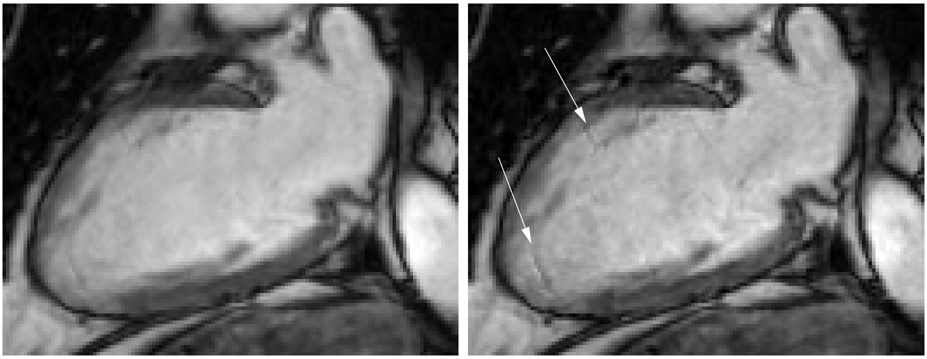

Fig. 4. An end diastolic time frame reconstructed using conventional k-t BLAST (left) and with the alternative reconstruction filter (right). The alternative reconstruction suffers from slightly increased artifacts, as indicated by arrows, and increased noise.

a local structure tensor description of the neighborhood based on the quadrature filter responses [13]. The sign of the velocity estimate (inwards or outwards motion) was determined from the phase of the local structure. An inward motion from the dark myocardium to the bright ventricle is considered as positive.

3 Results

Images in end diastole reconstructed using the two reconstruction filters are shown in Fig. 4. The alternative reconstruction results in slight artifacts from signal aliasing and increased noise. The normalized root-mean-square error decreased from 9.8% to 7.9% by using the alternative k-t BLAST reconstruction.

The temporal evolution of a single line through the ventricle is shown in Fig. 3. Both k-t BLAST methods introduce temporal smoothing, but qualitatively sharper temporal evolution is observed in the alternative k-t BLAST data set, along with slightly increased noise.

The estimated velocities across the edge from the different regions in the three image series are shown in Fig. 5. Positive values indicate inward motion. The velocity traces in the reference data set from the normal regions (1, 4 and 5) show a clear systolic peak, and two diastolic peaks related to early filling and atrial contraction. The regions placed in the scar tissue show paradoxical bulging in early diastole. The k-t BLAST reconstructions result in lower velocity estimates which makes these events less apparent. The conventional reconstruction filter produces lower velocity estimates than the alternative reconstruction filter. A paired Wilcoxon signed rank test showed that the magnitude error in edge velocity, with the fully sampled data set used as reference, was larger in the conventional k-t BLAST data set compared to the alternative k-t BLAST data set ($p < 0.01$). The root-mean-square error of the velocity estimates was reduced from 1.4 cm/s to 1.0 cm/s using the alternative approach.

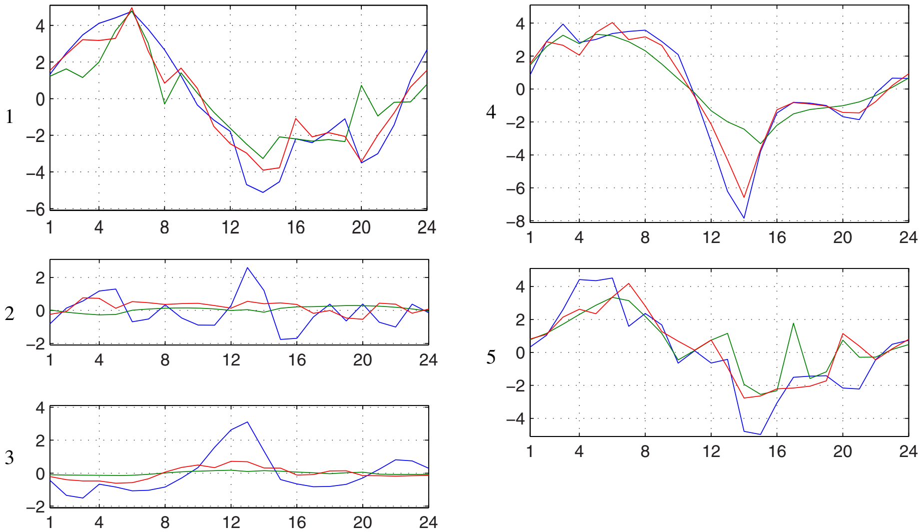

Fig. 5. Edge velocities [cm/s] in the different regions over time in the reference images (blue), conventional *k-t* BLAST reconstructed images (green) and the alternative *k-t* BLAST reconstructed images (red). Regions 2 and 3 are located in the infarcted area. The direction of positive velocities is inwards.

4 Discussion

An alternative reconstruction filter for *k-t* BLAST subsampled data has been proposed and compared to a conventional filter. Velocities estimated in five regions in an infracted left ventricle were less underestimated using the alternative filter. The alternative reconstruction filter preserves more of the high frequency content, at the expense of more artifacts from aliased signal and increased noise. Since the velocity analysis used in this work is based on regional image information, it is not highly sensitive to a slightly increased aliasing artifact or noise level, which do not manifest coherently in adjacent time frames.

Although regional analysis methods are in principle robust to the types of artifacts introduced, optimal filter parameters have to be determined for specific analysis strategies. The improved reconstruction filter suggested was designed with few simple parameters, and optimization of these for other analysis tools and acquisition parameters such as reduction factor and temporal resolution might yield even better results. In the present setting, the reduced noise regularization seemed to have largest impact on the temporal fidelity. Other types of reconstruction filters may also be considered. The choice of reconstruction filter does not affect the MRI data acquisition, allowing multiple reconstructions targeted for different analysis tools to be performed from the same raw data.

Optimizing the filter kernel with respect to temporal support [14] was attempted, but did not produce significantly improved results in this setting. In cases with lower reduction factors, however, applying such a filter optimization might have a larger effect since the relaxed settings allow shorter filters in the temporal domain.

In conclusion, the conventional *k-t* BLAST filter suppresses the high frequency content more than necessary for certain applications and better temporal fidelity can be achieved by merely changing the reconstruction filter. Velocity estimation has been shown to be significantly improved using a modified reconstruction filter.

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