k-t² BLAST: Exploiting spatiotemporal structure in simultaneous cardiac and respiratory resolved volume imaging

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Introduction: The recently introduced k-t BLAST technique [1] for accelerating acquisition of dynamic imaging has shown promising results. By exploiting lower temporal frequency content in parts of the imaging region, and the ability to estimate this frequency content, aliasing resulting from undersampling the signal can to a significant extent be resolved. Imaging resolving both cardiac and respiratory phase simultaneously [2, 3] might also benefit from the k-t BLAST technique. Having two temporal dimensions increases the opportunities for exploiting the spatiotemporal structure. The acceleration of the acquisition can be useful to increase spatial or temporal resolution. The shortened scan time is especially beneficial for volumetric imaging, where traditional acquisitions are long (19 minutes [3]). It might also enable other sequences than the rapid SSFP sequence, such as phase contrast imaging. This is important for physiological studies, such as the study of respiratory effects on right ventricular filling. Simultaneous cardiac and respiratory phase resolution may also be beneficial for study and evaluation of respiratory artifact suppression schemes and with the use of accelerated imaging, essentially respiratory artifact free images may be obtained in a relatively short acquisition time.

Methods: Two acquisitions were performed consecutively on the same geometry on a healthy volunteer; one fully sampled and one sparsely sampled 5D acquisition (cardiac and respiratory resolved volume imaging). An artificially decimated version of the fully sampled data set was also included for evaluation. The axial 3D volumes were acquired using an SSFP pulse sequence on a 1.5 T GE scanner using a k-space matrix of 128x64x32 (spatial resolution 2x4x4 mm) with 16 cardiac time frames and 8 respiratory time frames using the modified TRIADS acquisition scheme described in previous work [3]. Pulse oximeter and respiratory bellows were used for cardiac and respiratory synchronization, respectively. Respiratory phase estimation was performed by detecting end inspiration and dividing the time since last detected inspiration by the average of the last three respiratory intervals. Cardiac phase was estimated in the same manner by detecting peaks in the pulse oximeter signal. The acquisition scheme collects a complete - or, in the sparsely sampled case, a subsampled - 3D k-space for each combination of cardiac and respiratory time frames. The fully sampled data set was interpolated in time with Gaussian interpolation using a retrospective estimate of cardiac and respiratory phase, but since it is unclear how such interpolation would affect the k-t² BLAST reconstruction, the prospectively estimated cardiac and respiratory phases were used in the artificially decimated and sparsely sampled data sets.

The requirement of lattice sampling in k-t BLAST limits the choice of acceleration factors, since the factor must divide the number of phase encodings in each direction and the number of time frames evenly. For the sparsely sampled acquisition, an acceleration factor of 8 with sampling pattern optimized with respect to maximum distance separation of the main lobes of the point spread function[4] ($k_y + 2k_z + 3t_{cardiac} + 4t_{respiratory}$ constant modulo 8) was used. The central 16 by 8 k-space lines were acquired in full temporal resolution in an interleaved fashion, to be used for estimation of temporal frequency content. The same sampling positions were used for the artificially decimated data set. This resulted in a scan factor of 18% of the fully sampled data set.

The artificially decimated data set and the sparsely sampled data set were reconstructed using the same k-t² BLAST reconstruction algorithm. The temporal frequency content estimate (called M^2_{xf} in the original literature) was computed as the squared magnitude of the safety margin times the temporally attenuated Hamming windowed central 16 by 8 k-space lines that were fully sampled in both temporal dimensions. The safety margin was set to 2.0 and the temporal attenuation was performed by Hanning windowing the highest 5 temporal frequency components separably in both temporal dimensions.

The reconstruction filter was computed as $M^2_{xf} /(\psi+M^2_{xf} \otimes PSF)$, where M^2_{xf} is the temporal frequency content estimate, ψ is a noise estimate for regularization and PSF is the point spread function associated with the lattice subsampling. Before filtering, the baseline, as computed by temporal averaging of the subsampled data, was subtracted from the signal. The baseline was then added again after filtering.

Results: An M-mode type of image is shown in Figure 1. The horizontal axis shows eight cardiac cycles, each in its own respiratory time frame with schematic respiratory and ECG curves below. All three data sets are shown (fully sampled (a), artificially decimated (b) and sparsely sampled (c)). The M-mode line is placed across the midlateral wall of the left ventricle, as shown by the long yellow line in Figure 2, and computed using linear interpolation in the spatial domain. At the intersection of the two yellow lines, the magnitudes of the images were compared over time, and the temporal plots are shown in Figure 3.
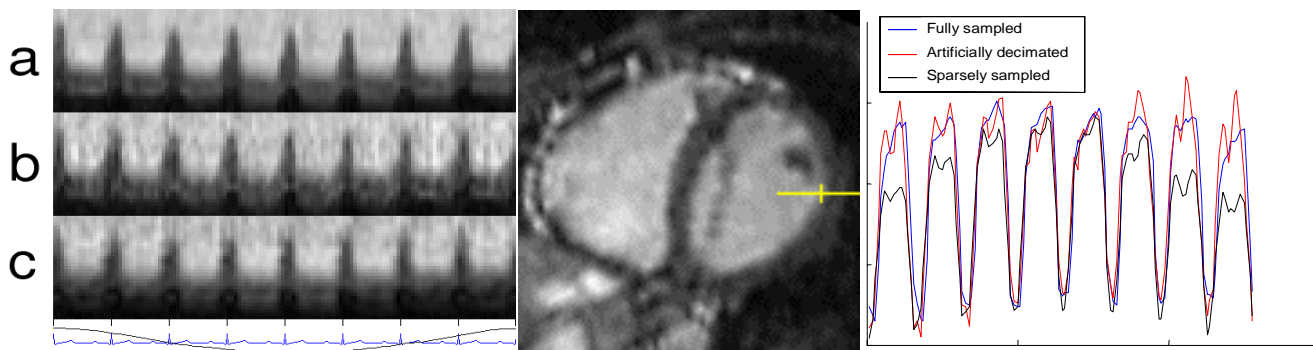

Figure 1   *Figure 2*   *Figure 3*

Discussion: The results shown above clearly demonstrate feasibility of the method. What remains to be studied is what is actually lost in the subsampling, how high acceleration factors that still produce acceptable image quality, and if the reduction in image quality can be offset by the shorter acquisition time or the increased resolution that can be acquired in the same imaging time. Ideally, we should also compare the fully sampled data set to such a scan with increased resolution. Comparing the fully sampled data set to the artificially decimated version, some reduction in image quality can be seen in the Figure 1, but good temporal agreement is seen in Figure 3. The sparsely sampled data set show more temporal blurring in Figure 1 and seems to deviate from the other two data sets in Figure 3 on the respiratory time scale but still captures the cardiac events. A possible explanation could be that the two acquisitions were performed approximately 15 minutes apart, which allows for change in subject position and breathing pattern.

In conclusion, it has been shown that k-t BLAST can be extended to simultaneous cardiac and respiratory phase resolved volume imaging (k-t² BLAST), but further evaluation must be performed to assess image quality and possible acceleration factors as well as how to utilize the extra time.

References:
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