Reconstruction Exploiting Phase-Correlation Motion Estimation and Motion Compensation Methods for Cine Cardiac Imaging

M-L. Chu[1], J-S. Hsu[1], and H-W. Chung[1]
[1]Graduate Institute of Biomedical Electronics and Bioinformatics, National Taiwan University, Taipei, Taiwan

Introduction

Motion estimation (ME) and motion compensation (MC) are both essential to video compression [1], which have also been successfully applied to dynamic MRI with reduced k-space acquisition as baseline estimation adjunct for enhancing image reconstruction. [2] However, ME and MC have not been exploited as a standalone approach for direct dynamic MRI reconstruction. The current main challenges come from the absence of full-resolution frames. To address this issue, this work proposes a reconstruction technique based solely on the phase-correlation ME method [3] to estimate the motion vectors (MVs) needed for reconstruction, without incorporating extra computational routines as in previous works. [2,4] The experimental results show that the proposed method successfully reconstructs full-resolution dynamic frames at substantially reduced acquisition time without incurring aliasing artifacts and loss of object motion information. The performance is competitive even with acquisition of only the central k-space for most of the frames.

Fig.1: Sampling pattern: N_y/R central phase encoding lines are obtained for R-fold acceleration

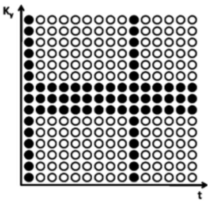
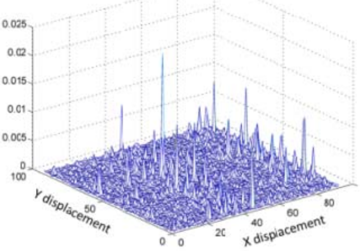


Fig.2: Multiple peaks in correlation map



Theory

k-t FOCUSS successfully utilizes block-matching method (BM), which is the most popular ME technique in video compression [5], for baseline estimation to sparsify the residue [2]. However, reconstructing dynamic images solely by BM suffers from inaccurate ME due to absence of the full-resolution frame, as BM estimates MVs according to mean square errors of pixel intensity. Therefore, BM is not directly applicable for reconstruction with reduced k-t space sampling.

On the other hand, the phase-correlation method [3] directly measures the movement between two blocks (i.e., sub-regions in the image) from their phases. Assuming a translation between two blocks,

$$s_i = s_j(x+d_x, y+d_y) \qquad (1),$$

where d_x and d_y are the translation between block i and block j. According to the Fourier shift property, the shift in spatial domain is reflected as a phase change in the spectral domain. We obtain the phase of cross-power spectrum between two blocks:

$$\Phi[\, C_{i,j}\,(f_x, f_y)\,] = \exp[\, -j2\pi(fx\ dx + fy\ dy)\,] \qquad (2),$$

where $C_{i,j}$ is the cross-power spectrum of blocks i and j. The 2-D inverse Fourier transform is given by a correlation map:

$$c_{i,j}(x,y) = \delta(x - d_x\,, y - d_y\,) \qquad (3).$$

Therefore, we can obtain the displacement, which is the MV, by finding the peaks in Eq. (3) corresponding to the maximal correlation. The MVs can then be used to recover full-resolution frames in a block-by-block manner. The phase-correlation method estimates the MVs accurately since translation of blocks remains identical even at low spatial-resolution. Furthermore, the phase-correlation method is relatively insensitive to changes in contrast, since Fourier phases are not affected by shift or multiplication of the image contrast.

Methods

With a given accelerating factor, the sampling pattern in k-t domain is depicted in Fig.1. Down-sampled image frames at low spatial resolution are used as training data (called the P frames). Several full-sampled frames are used as reference frames (called the I frames). In our testing series containing 30 time frames, 5 reference frames are picked up. Typical implementation, divides each P frame into small blocks 4x4 pixels in size, with the blocks extended to 8x8 pixels centered around them for estimating MVs because increased overlapping area leads to better estimation. A 2-D Hanning window is applied to each 8x8 block to increase the weight of the formerly defined 4x4 region, to which an MV will be assigned. Phase-correlation ME is then performed between corresponding 8x8 blocks on two P frames. In general, the motion is not purely translational, which results in multiple peaks in cross-power spectrum as shown in Fig.2. While the highest peak in correlation map usually provides the best displacement match between the 8x8 blocks, it may not necessarily be the best for the smaller 4x4 block. Therefore, several candidates are selected instead of just one highest peak. The candidate with highest image correlation [4,5] would best represent the MV for the 4x4 block. The reconstruction employs MC by applying MVs on the blocks of each I frame to obtain the compensated frames, with the residue compensated as well. Results from different acceleration factors are compared with their counter-part using k-t BLAST [4] , k-t FOCUSS[2], and BM for benchmarking.

Results and Discussion

Four sets of cine cardiac images have been tested with the proposed method. Short-axis 2D TrueFISP with ECG gating was performed on a Philips Achieva 3T scanner with matrix size 256x256, 32 cardiac phases, 35° flip angle, and 10mm slice thickness. The reconstructed images are illustrated in Fig.3. Images reconstructed by BM suffered from lost details and blurring, and variations in x-t space were not preserved. Other reconstruction methods revealed slight blurring in the myocardium in the systolic phase. As for the temporal change for myocardium, the dynamics of myocardium reconstructed by k-t BLAST were somewhat weakened (x-t space at bottom of Fig.3), while our method and k-t FOCUSS preserved the dynamics as indicated by the arrows. In addition, k-t BLAST and k-t FOCUSS led to temporal smoothing in x-t space, while temporal variation is largely preserved with the proposed method.

Root mean square (RMS) error is shown in Fig.4. BM reveals high RMS error. The proposed method is comparable to k-t FOCUSS in terms of RMS error and provides improved reconstruction when compared with k-t BLAST. Moreover, the reconstruction time of phase correlation remains comparable to that of k-t FOCUSS, while the sampling trajectory and underlying sequence programming is relatively straight-forward.

Fig.3: 8-fold accelerated selected images and x-t spaces of the indicated region of interest reconstructed by phase-correlation (a), k-t FOCUSS (b), k-t BLAST (c), BM (d), and non-accelerated reference (e).

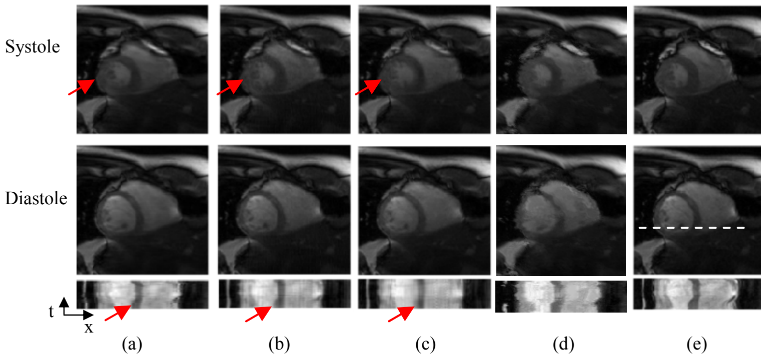
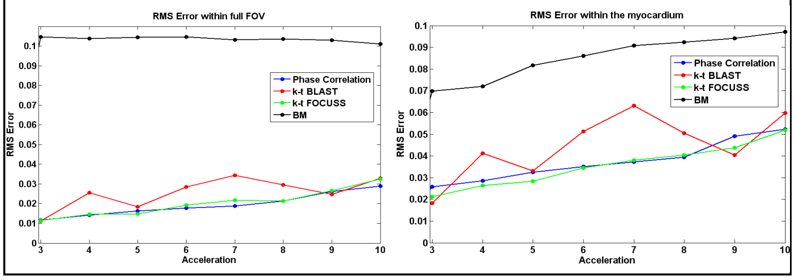


Fig.4: RMS error from acceleration of 3 to 10 within full FOV (left) and within myocardium (right) of the proposed method (blue), k-t BLAST (red), and k-t FOCUSS(green).



Conclusion

A robust method for directly reconstructing dynamic images by ME and MC without incorporating extra reconstruction routine was presented in this study. The experimental results indicate that the proposed method can achieve improved temporal resolution and leads to reduced artifacts even from substantially down-sampled k-space data. The principle can theoretically be extended to other dynamic imaging, such as functional MRI or contrast-enhanced MRI and is not restricted to cardiac applications.

References

[1] D. Le Gall, Communications ACM 1991;34:46-58.
[2] H. Jung et al., Magn Reson Med 2009;61:103-116.
[3] H. Foroosh et al., IEEE T Image Proc, 2002;11:188-200.
[4] J. Tsao et al., Magn Reson Med, 2003;50:1031-1042.
[5] J. Watkinson, *The Engineers' Guide to Motion Compensation*, Snell and Wilcox, 1994.