Accurate Myocardial Velocity Imaging with Consistent Blood Saturation and Respiratory Navigation

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Introduction

Changes in intrinsic contractile behaviour of the myocardium can be detected by a number of MR techniques. Advances in HARP imaging and post-processing for MR tagging have extended the role of MR in clinical assessment of myocardial contractility. Phase contrast myocardial velocity mapping overcomes some of the major limitations of the existing techniques to measure myocardial motion, but the method is limited by blood flow artefacts, low temporal resolution, long scan times, and phase errors due to concomitant terms and eddy currents. We describe here a framework for acquiring, reconstructing and processing myocardial velocity data to obtain robust and accurate deformation information.

Methods

Data was acquired on a 1.5T Siemens Sonata MR scanner with a peak slew rate of 200mT/m/s and maximum gradient strength of 40mT/m. The blood flow artefact from the left ventricle is known to create considerable errors in myocardial velocity mapping. This problem was overcome by using a spectrally shaped RF pulse to saturate blood adjacent to the imaged slice. A black-blood, view-shared, segmented FLASH phase contrast sequence was used with respiratory gating using navigator echoes to allow higher velocity sensitivity[1]. Prospective navigator echoes were used with the column, area 10x10mm^2, positioned through the dome of the right hemi-diaphragm. The gating window of ±4mm was set at end-expiration. The following image parameters were used: venc 13cm/s, image matrix 256x96, field of view 400x300mm^2, flip angle 15°, slice thickness 8mm and TR 60ms. For comparison of accuracy of in-plane strain rate distributions, a breath-hold version of the sequence with venc 20cm/s was also used. Mid-ventricular short axis slices were acquired in five normal subjects, 2 male, mean age 27±5 years. Phase correction was carried out for the concomitant terms online during image reconstruction[2] and offline using CMRtools (London, UK) to eliminate linear phase errors. Noise removal and restoration of the in-plane velocity fields was carried out using a vector restoration method. This restores the vector direction without affecting the velocity magnitude by providing a systematic way for constructing the total variational energy function for the whole image[3]. This reduces the problem to a constrained optimisation problem, which is further simplified to a relatively simple iterative scheme as follows:

$$u_\alpha^{n+1} = u_\alpha^n + \Delta t \cdot \prod_{u_\alpha}\left[\sum_{\beta\in N_\alpha} wt_\alpha^\beta u_\beta + \lambda^n u_\alpha^0\right] \quad \text{and} \quad \lambda^{n+1} = \lambda^n + \Delta t \cdot \frac{1}{2}\left[\sum_{\alpha\in\Omega} d_l^2(u_\alpha, u_\alpha^0) - |\Omega|\sigma^2\right] \quad \text{where} \quad wt_\alpha^\beta = \left(\frac{1}{e(u;\alpha)} + \frac{1}{e(u;\beta)}\right)$$

u is the velocity vector to be calculated, λ is the regularisation parameter and wt is the weighting term for each adjacent pixel. e is the strength function at pixel α while β is a neighbouring pixel. Using this iterative scheme, the restored velocity fields can be calculated within seconds, even for a large number of iterations.

Results

Figure 1 illustrates the overall framework used for myocardial strain rate imaging. Results for the vector restoration algorithm can be seen in Figures 1(d, e, g, h). A marked improvement was seen in the in-plane velocity vector map throughout the cardiac cycle. The proposed respiratory gated sequence, which has a higher velocity-to-noise ratio, allowed detailed strain rate measurement as illustrated in Figure 2. This study provides a robust framework for measurement of myocardial velocities subsequently allowing detailed strain rate imaging. Possible phase errors and errors from blood flow artefacts have been minimised using a combination of sequence design, phase correction algorithms and vector restoration. Cardiac strain rate imaging allows decoupling of global and local motion, inter-subject comparison and intuitive representation of myocardial motion in a cylindrical co-ordinate system. This framework would be invaluable for detecting subtle regional changes in myocardial contractility in diseases such as myocardial ischaemia, cardiomyopathies and hypertension. The framework could be extended to 7D (3 spatial dimensions, 3 motion directions and time) visualization of strain rate distribution by acquiring myocardial velocity maps covering the entire left ventricle.

Figure 1

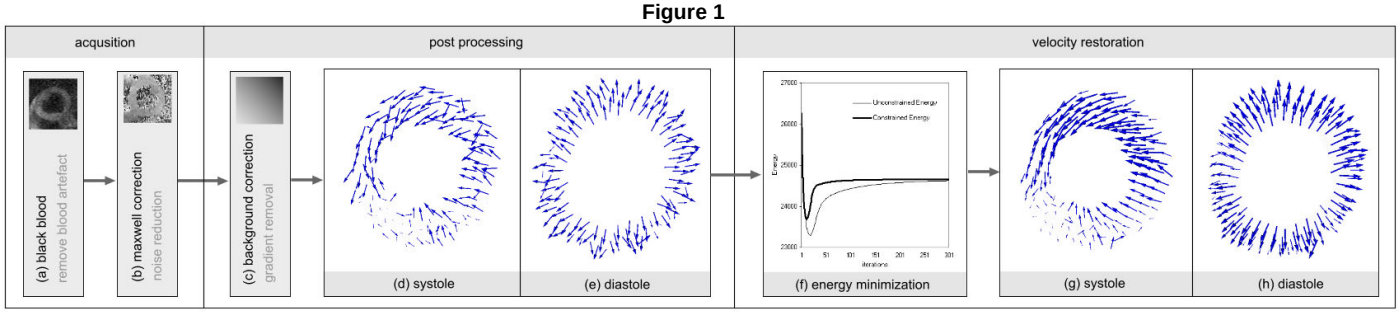

Figure 2

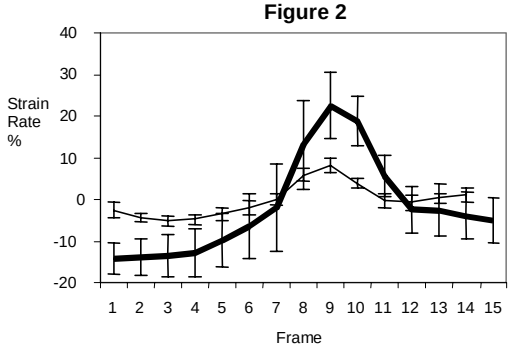

Figure 1. Framework for myocardial strain rate imaging. From left to right: (a) 3D velocity acquisition using the black-blood, view-shared segmented FLASH sequence. (b) Online phase correction for the Maxwell terms carried out during image reconstruction. (c) Offline correction of background velocity errors caused by eddy currents. Vector map of in-plane velocities in (d) systole and (e) diastole before further processing. (f) Plot of energy against number of iterations illustrates the efficiency of the vector restoration algorithm as the minimum energy is reached in around 10 iterations. Velocity vector map in (g) systole and (h) diastole after restoration.

Figure 2. Plot of normalised mean circumferential strain rate for five normal subjects in the anterolateral region. The dark solid line shows the strain rate measured using venc 13cm/s and the lighter line shows venc 20cm/s. The vertical axis represents the strain rate while the horizontal axis represents time frame through the cardiac cycle. There is a marked improvement in strain rate delineation, however the standard deviation is also increased as the velocity sensitivity has improved.

References

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