Consistent Strain Rate Mapping with MR Velocity Imaging

J. Gao[1], S. Masood[1], D. N. Firmin[2], G-Z. Yang[1,2]

[1]Royal Society/Wolfson Foundation MIC Lab, Imperial College, London, United Kingdom, [2]CMR Unit, Royal Brompton Hospital, National Heart and Lung Institute, Imperial College, London, United Kingdom

Introduction

Regional myocardial contractility is of clinical importance in assessing patients with ischaemia and myocardial infarction. Traditional MR methods for assessing myocardial contraction include MR tagging and MR velocity mapping. MR tagging allows easy visual assessment of regional contractile abnormalities but is limited by the long post-processing time needed to obtain functional indices. Clinical use of myocardial velocity mapping is hindered by the long scan time necessary to acquire all three directions of motion with sufficient velocity sensitivity and spatial resolution. It is further hampered by phase artefact introduced by inconsistencies in ventricular flow. The use of ventricular flow suppression with black-blood velocity mapping [1, 2] can overcome some of the difficulties, but in practice major differences in velocity-to-noise ratio (VNR) in in-plane and through-plane velocities can introduce significant difficulties in deriving clinically useful contractile indices. Further improvement of VNR for in-plane velocity components is currently limited by simultaneous requirement for high spatial and velocity sensitivity. The purpose of this study is to introduce the use of a divergence-free constraint and the different VNRs of the velocity components to improve the intrinsic consistency of the velocity data. We demonstrate how consistent strain rate distribution can be derived across subjects, which facilitates the production of a probabilistic atlas of normals that can be used to detect changes in patients.

Methods

Assuming that the myocardium is incompressible and that the through-plane motion is measured with a high VNR the overall consistency of the in-plane velocity distribution can be improved by using the incompressibility constraint. The incompressibility of a velocity field (v_x, v_y, v_z) is expressed as

$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0$ therefore the restoration of a noisy velocity distribution can be achieved by optimizing the following cost function:

$$Cost = \sum (\vec{v}_0 - \vec{v})^2 + \lambda \sum \left| \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right|$$

where $\vec{v}_0 = (v_{0x}, v_{0y}, v_{0z})$ and $\vec{v} = (v_x, v_y, v_z)$ are the measured and optimised velocity fields, respectively. Since the through-plane component is measured with high accuracy as compared to the in-plane counterparts, it is kept unchanged during the optimisation process. Only the in-plane components are evolved iteratively. The above equation aims to achieve a balanced improvement in both the divergence and fidelity of the velocity data as dictated by λ. To determine the optimal weighting factor, a first-order Lagrange technique was utilised. After velocity restoration, strain rate was derived for each pixel located within the myocardial region where

$$\varepsilon_e = \sqrt{\left((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right)/6}$$

and $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the three principal strain rate components.

In order to provide a detailed comparison of regional strain rate distribution across subjects, strain rate derived from a group of 11 normal subjects (7 male, mean age 25±5) was used to create a probabilistic atlas at different phases of the cardiac cycle. This entails the normalisation of the anatomical details both in time and space. This was achieved by first choosing the mid-ventricular slice from each 3D dataset and manually selecting the RV insertion as the anatomical alignment landmark. A polar co-ordinate system is chosen with the origin at the centre of the rectangle that compactly covers the LV region. The myocardial ring was then spatially warped to achieve spatial registration. Temporal alignment was achieved by choosing the peak systolic and diastolic frames for each dataset followed by temporal interpolation as necessary. The mean shape and strain rate distribution was used to compare to those derived from patients. All images were acquired using a Siemens Sonata 1.5T system with a peak slew rate of 200mT/m/ms and peak amplitude of 40mT/m. A segmented FLASH phase contrast velocity mapping sequence with venc 20cm/s was used. Reduction of flow artifacts was achieved by using a spectrally shaped RF pulse that saturated the regions adjacent to the imaged slice. Image matrix was 256x96, field of view 400x300mm, flip angle 15°, slice thickness 8mm, approximately 8 slices, and a temporal resolution of 62ms was used. The normal strain rate ε_e was calculated for the mid-ventricular slice in all 11 subjects, and the mean and standard deviation across subjects was plotted. To evaluate the accuracy of the proposed method, a 3D simulation dataset was produced which corresponded to a cylindrical structure under cyclic deformation involving expansion, contraction and torsion. The three velocity components were simulated with the incompressibility constraint. The dataset aimed to simulate cardiac motion and the actual CMR imaging set-up where the imaging planes were fixed in space while the mass points moved cyclically.
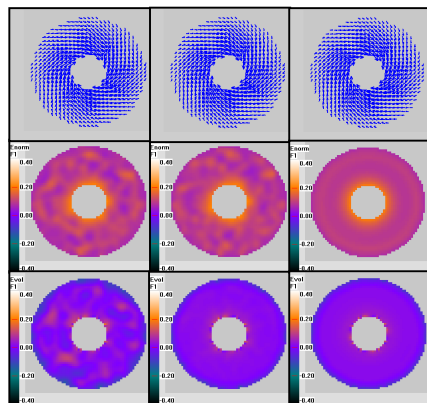

Figure 1. First column shows the result from simple smoothing, second column from the divergence free algorithm and last column shows the original noise free dataset for comparison.
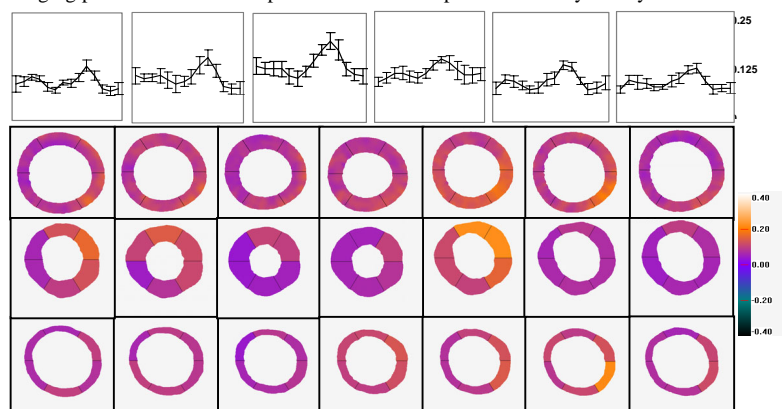

Figure 2. Top row shows the mean and standard deviation of the strain distribution over time for the 11 normal subjects in different regions of the heart. Left to right: anterior, anterolateral, inferolateral, inferior, inferoseptal, anteroseptal. The second row shows the normalised results in 11 normal subjects over time for 8 frames of the cardiac cycle. This can be compared to the strain rate distribution in an ischaemic (third row) and dilated cardiomyopathy (bottom row) patient.

Results and Conclusions

The synthetic dataset, with added noise, was used to evaluate the robustness and accuracy of the method. The zero divergence of the velocity field was used as a measure of its physical accuracy. In comparison to weighted averaging, the new incompressibility algorithm performed much better for subsequent strain rate calculation as illustrated in Figure 1. *In vivo* validation in normal subjects and patients is illustrated in Figure 2. It is evident that for patients, significant changes in strain pattern distribution can be detected. It is well known that strain rate obtained from velocity mapping is too noisy for deriving consistent clinical results. The use of vector restoration based on different VNRs of the velocity data provides an effective way of improving the internal consistency of the data, allowing strain rate distribution to be reliably extracted. The probabilistic atlas of normal strain rate distribution showed a trend of high strain rates in diastole that correspond to the "snapping back" of the myocardium to start rapid filling of the LV, and allowed easy comparison with patient data.

References

1. Hennig, J. et al., J Mag Res Imag, 1998. **8**(4): p. 868-877.   2. Jung, B. et al. *ISMRM*. 2003. Toronto, Canada.