Assessment of the Sensitivity of Ventricular Flow Boundary Conditions on the Accuracy of Reconstructed Flows with Computational Fluid Dynamics

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Introduction

The relationship between the morphology and blood flow of the left ventricle during myocardial remodeling is complex and not yet fully understood. Cardiovascular MR (CMR) velocity imaging is a versatile tool for the observation of general flow patterns *in-vivo*. More detailed understanding of the coupled relationship between blood flow patterns and myocardial wall motion can be further enhanced by the combined use of Computational Fluid Dynamics (CFD) and CMR. This permits the generation of comprehensive high-resolution velocity fields and the assessment of dynamic indices, such as mass transport and wall shear stress, that are important but cannot be measured directly by using imaging alone. One of the key drawbacks of ventricular flow simulation using CFD is that it is sensitive to the prescribed inflow boundary conditions. Current research in this area is limited and the extent to which this affects *in vivo* flow simulation is unknown. In this work, we measure this sensitivity as a function of the inflow direction and determine the limit that is required for accurate ventricular flow simulation.

Methods

Flow simulations were performed with ventricular models created from the CMR images of 5 healthy subjects. The images were acquired using a multislice TrueFISP sequence on a Siemens Sonata 1.5Tesla scanner. The software package LVtools (Imperial College, London) was used to construct detailed dynamic models of the left ventricle which include both inflow and outflow tracts. These models were then used to create a volume mesh for the ventricular flow domain. CFD simulations were performed with CFX4 (CFX international, AEA technology, Harwell) by solving the Navier-Stokes equations that govern the motion of fluid within the prescribed morphology. The inflow boundary conditions were set up by using a hybrid pressure/velocity boundary with a plug flow profile [1]. The first experiment measured the sensitivity of the CFD simulation to the direction of the inflow for a single healthy subject. Simulation was performed by using the mean inflow direction measured from two orthogonal CMR velocity images. Further simulations were then performed with the inflow direction modified by 5°, 10°, 15° and 20° in each of the 4 orthogonal directions towards A'(anterior), P' (posterior), I' (inferior) and S'(superior), respectively. The sensitivity was measured by comparing each flow field to the first simulation and calculating the mean angle between velocity vectors at corresponding points within the ventricle. The second experiment evaluated the reproducibility of these results across a further 4 normal subjects. A total of 5 simulations were performed for each subject. The first of these utilised the average inflow direction measured from the CMR velocity images. This was then followed by simulations with 5° of variation in each of the 4 orthogonal directions.

Results

Figure 1 (a) shows a single frame of a ventricular model used for CFD simulation. In this diagram, the four directions in which the inflow jet was modified are labeled A', P', I' and S', respectively. The velocity maps (b) and (c) demonstrate the correspondence between flow fields measured by CMR imaging and CFD simulation. Our study has shown that whilst the topology of the flow is relatively consistent between these flow fields, the detailed flow features can vary dramatically, depending on the errors involved in the inflow measurement. Figure (d) shows the sensitivity when changing the inflow direction by 5° in the four orthogonal directions. It is evident that the flow fields gradually become more sensitive to the inflow direction throughout each simulation. This is to be expected due to the accumulation of errors that is inherent in CFD techniques. Of greater importance however, it is demonstrated from (e) that the sensitivity of the simulations increase dramatically as a function of the inflow angle. From an observational perspective, there were no significant variations in flow topology when the inflow direction was modified by only 5°. However, the flow patterns varied significantly for angles larger than this limit.

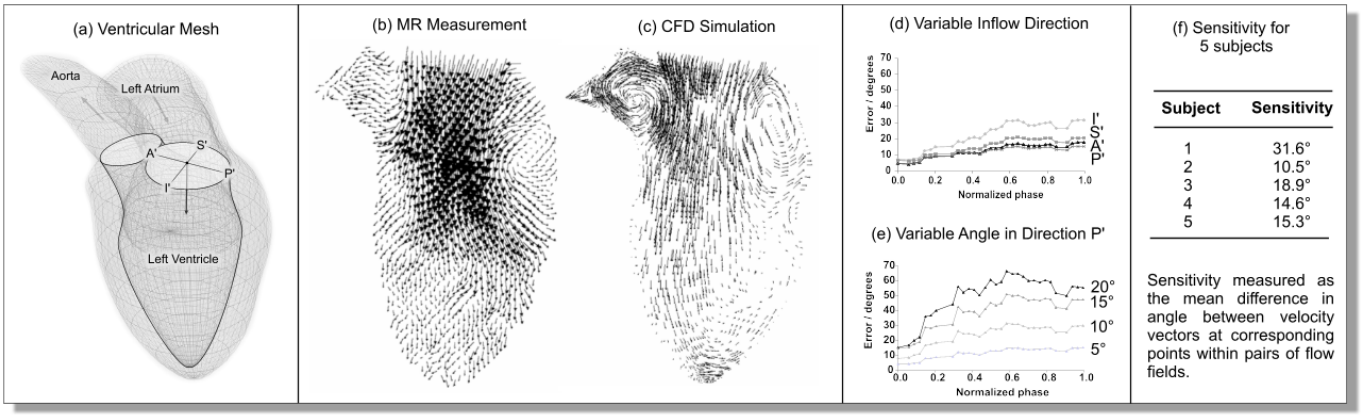

Figure 1. (a) An example model of the left ventricle used for CFD simulation. (b) A single plane depicting the left ventricular flow as measured by CMR velocity imaging. (c) The corresponding flow field as calculated using CFD simulation. (d) The mean difference in angle between flow fields generated with an inflow direction determined by MR velocity measurements and those generated with the direction modified by 5° in the directions A', P', I' and S'. (e) The differences between flow fields when the inflow direction was changed by 5°, 10°, 15° and 20° in the direction P'. (f) A table characterizing the sensitivity of the flow simulations over 5 normal subjects using inflow directions modified by 5° from the measured inflow direction.

Conclusions

This study has evaluated the sensitivity of the ventricular flow simulations to changes in the inflow direction. The aim of this work was to establish how accurately the inflow boundary conditions must be specified in order to give reproducible simulations. It has been shown that changes to the inflow direction of 5° did not significantly affect the flow topology. These changes did bring about slight differences between the directions of the corresponding velocity vectors however. Changes of 10° or more did produce flow patterns with an altered topology. The differences between the velocity vectors were also substantial. For detailed quantitative assessment, however, the inflow direction needs to be specified with as high an accuracy as possible. This is a significant finding in that it justifies the importance of using CMR velocity mapping for providing detailed inflow boundary conditions for accurate quantitative analysis. This would be particularly important for prognostic assessment of myocardial remodeling and establishing the efficacy of therapeutic procedures.

[1] Long Q, Merrifield R, Xu XY, Kilner PJ, Firmin DN, Yang GZ. The Influence of Inflow Boundary Conditions on Intra Left Ventricle Flow Predictions. Journal of Biomechanical Engineering, 2003. 125(1).