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A novel methodology for personalized simulations of ventricular hemodynamics from noninvasive imaging data

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ABSTRACT

Current state-of-the-art imaging techniques can provide quantitative information to characterize ventricular function within the limits of the spatiotemporal resolution achievable in a realistic acquisition time. These imaging data can be used to personalize computer models, which in turn can help treatment planning by quantifying biomarkers that cannot be directly imaged, such as flow energy, shear stress and pressure gradients. To date, computer models have typically relied on invasive pressure measurements to be made patient-specific. When these data are not available, the scope and validity of the models are limited. To address this problem, we propose a new methodology for modeling patient-specific hemodynamics based exclusively on noninvasive velocity and anatomical data from 3D+t echocardiography or Magnetic Resonance Imaging (MRI). Numerical simulations of the cardiac cycle are driven by the image-derived velocities prescribed at the model boundaries using a penalty method that recovers a physical solution by minimizing the energy imparted to the system. This numerical approach circumvents the mathematical challenges due to the poor conditioning that arises from the imposition of boundary conditions on velocity only. We demonstrate that through this technique we are able to reconstruct given flow fields using Dirichlet only conditions. We also perform a sensitivity analysis to investigate the accuracy of this approach for different images with varying spatiotemporal resolution. Finally, we examine the influence of noise on the computed result, showing robustness to unbiased noise with an average error in the simulated velocity approximately 7% for a typical voxel size of 2 mm^3 and temporal resolution of 30 ms. The methodology is eventually applied to a patient case to highlight the potential for a direct clinical translation.

1. Introduction

Cardiac pathologies often show a high interindividual variability in both the anatomy and the response to treatment, making population-based metrics less effective in defining therapy. A patient-specific approach is therefore crucial for successfully evaluating the pump function in the diseased heart and customizing treatment to the patient's pathophysiology. Recent developments in clinical imaging have underpinned the value of personalized medicine as a powerful alternative to traditional healthcare. For example, blood flow velocity and direction can now be quantified noninvasively from both 3D+t echocardiography and Phase-Contrast MRI (PC-MRI) (Gatehouse et al., 2005; Gomez et al., 2015, 2013b). Metrics derived from these hemodynamics parameters, such as the diastolic vortex formation, have been recognized as indicators of cardiac performance, placing emphasis on the importance of the intraventricular blood flow patterns (Pedrizzetti et al., 2014; Sengupta et al., 2012). Intraventricular flow propagation speed can also be used to estimate left ventricular filling pressures and to evaluate diastolic function (Bruch et al., 2005; Firstenberg et al., 2000; Greenberg et al., 2001; Nagueh et al., 2009). Similarly, ejection parameters and blood kinetic energy obtained from both PC-MRI and 3D+t echocardiography by flow mapping can yield information on the cardiac energetic efficiency (Markl et al., 2011; Yang et al., 2007), and techniques of wall motion tracking are routinely used to infer the distribution of strains and their rate. These are generally based on tagged MRI data (Axel et al., 2005; Chandrashekara et al., 2004; Pan et al., 2005); however, algorithms

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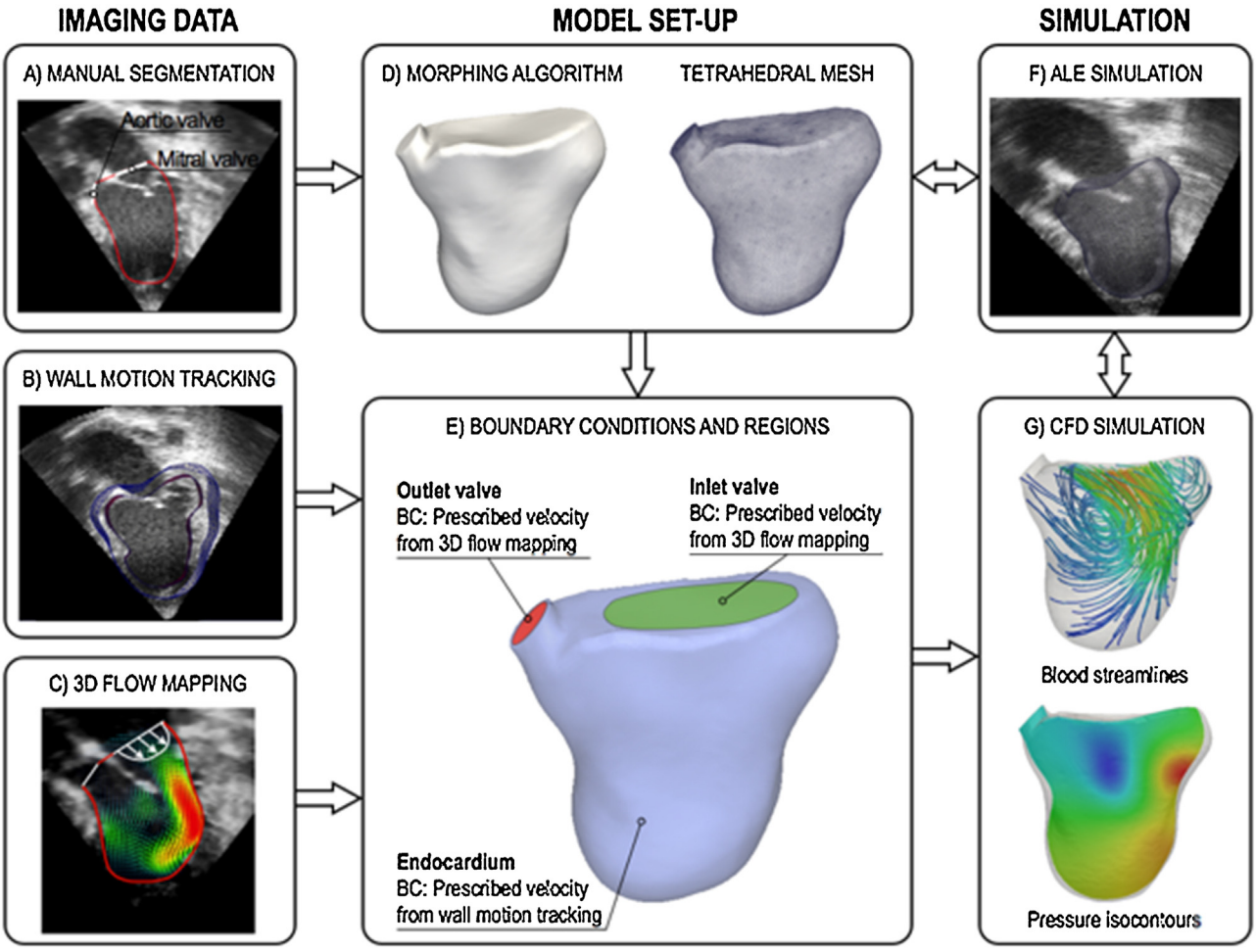

Fig. 1. Diagram of the methodological framework, consisting of image processing (A–C), model generation (D–E) and numerical simulations (F–G).

have also been developed for 3D+t echocardiography and standard MRI Cine sequences (Papademetris et al., 2001; Shi et al., 2013). Despite this progress, however, the accuracy of measurement depends on the temporal and spatial resolution of the images, which is dictated by technical limitations and by the necessity to keep the acquisition times at a minimum. The errors associated with low spatiotemporal resolution are particularly significant when derivatives of velocity are used to quantify metrics such as the power loss in the blood flow, or in the derivation of relative pressures from the reconstructed velocity field (Lamata et al., 2013; Yotti et al., 2004). Metrics derived from echocardiographic data have also been proved unable to track reliably ventricular pressure variations as a result of treatment within individual subjects (Bhella et al., 2011).

In this context, a synergy between clinical imaging and computer modeling has the potential to provide accurate patient-specific information to assist the clinical decision-making process. Recently, computational modeling has reached a stage of development with capability to simulate cardiac function realistically and to augment the traditional clinical approaches (McCormick et al., 2013; Tang et al., 2010). However, this potential is currently not fully exploited, as model personalization often relies on invasive pressure data acquired through catheterization, which in complex pathologies is limited by technical difficulties and risks for the patient, and on detailed information on the orientation of the myocardial fiber architecture. These factors currently limit the extent to which this technique can be effectively used for individual treatment planning. The main challenge lies therefore in the capability to personalize the models accurately with the least number of assumptions, given the available clinical data. Thanks to their very high spatial and temporal resolution, patient-specific models can provide an accurate quantification of velocity-based metrics and pressure gradients, and thus complement the information from imaging data. Specifically, the value of the approach resides in the ability to make use of the most reliable image-derived information available to build patient-specific models that, in turn, can quantify metrics that cannot be directly derived from the imaging data, such as pressure gradients and flow energy. Where a full description of myocardial properties and pressures is not available, computational fluid dynamics (CFD) simulations of ventricular hemodynamics can be driven by velocities extracted from time-resolved image sequences. In this context, the ability to personalize the models solely based on velocity data would result in a more robust and time-efficient modeling strategy, with the additional advantage of not relying on invasive or non-standard measurements.

This modeling strategy is promising but has a number of mathematical and numerical challenges. Even where low-noise imaging data are available, the exclusive imposition of velocity values (via Dirichlet boundary conditions) leads to a non-unique pressure solution and to a potential violation of mass conservation in the Navier–Stokes problem. For these reasons, commonly used models for ventricular flow tend to prescribe Dirichlet conditions on only a portion of the domain boundary. Traction or pressure conditions are then imposed on the valve planes in the attempt to recover an inlet or outlet velocity profile similar to that reconstructed from