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AUTOMATING MODEL GENERATION FOR IMAGE-BASED SIMULATIONS OF CARDIAC FLOW

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INTRODUCTION

Altered left ventricle (LV) hemodynamics has been associated with many cardiovascular diseases. Understanding and evaluating the flow pattern inside the LV is thought to be essential to identify cardiovascular dysfunction at early stages and in turn reduce mortality and morbidity rates [1]. Computational fluid dynamics (CFD) models derived from medical imaging have been used to provide more thorough understanding of patient-specific LV flow patterns and pressure fields. Such image-based modeling may advance the diagnostic and treatments of CVDs and help guide clinicians to the most effective therapy [1].

Prior imaged-based CFD studies of LV hemodynamics have mostly utilized manual or semi-manual approaches to model construction, which require significant human efforts and processing time [1]. Prior model construction pipelines usually start with segmentation of the LV by manual delineation or region growing techniques, followed by mesh generation and registration techniques using separate software tools [1-3]. These labor-intensive steps need to be performed on multiple time frames of the cardiac image data covering one or more cardiac cycles, limiting the feasibility of LV flow modeling techniques on large-scale analysis or to clinical application. Here we present an efficient and fully automated framework that generates CFD-ready LV models from patient CT or MR scans: the framework utilizes convolutional neural network (CNN) to perform automatic segmentation of cardiac tissues from 3D patient CT or MR scans and then applies a series of surface processing and image registration strategies to generate meshed models. The proposed framework can be executed from the command-line as an automated process and has only open-source software dependencies. We demonstrate the viability of this framework by performing CFD simulations using the generated LV models for a number of patient-specific image data.

METHODS

The proposed automated framework consists of three major steps to generate CFD models for LV flow simulations: segmentation, mesh generation and registration (**fig. 1**). The whole framework was implemented in Python with several open-source Python packages (TensorFlow, VTK, SimVascular, SimpleElastix).

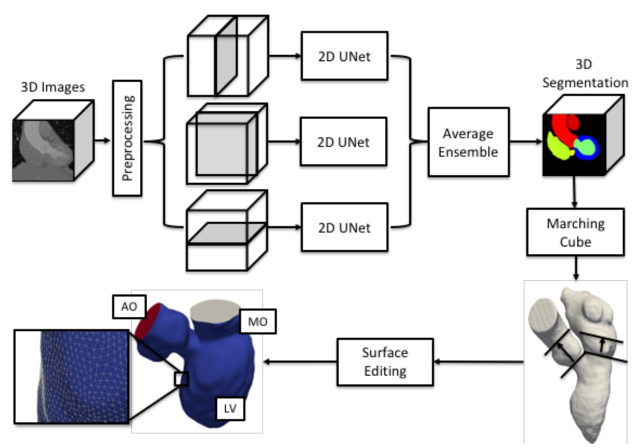

Figure 1: Diagram of the automated model generation framework for LV CFD simulations

Automatic segmentation was performed using a CNN model based on the U-Net architecture specialized for medical image segmentation [4]. The CNN model was trained with the Multi-Modality Whole Heart Segmentation (MMWHS) dataset which consists of 20 patient CT and 20 patient MR scans with manual ground truth segmentations of atriums, ventricles, aorta and pulmonary artery [5]. Namely, we sliced the 3D image volumes along axial, sagittal or coronal axis to obtain corresponding 2D image datasets. One U-Net model was trained for each 2D dataset to predict the probabilities of each pixel belonging to different tissue classes. The 2D predictions from each U-Net model were stacked together to form 3D predictions, which were then averaged across all models to improve the segmentation accuracy.

A marching cube algorithm was applied to generate a watertight surface mesh from the segmentation of the LV, left atrium (LA) and aorta. The mitral plane or aortic plane was fitted through points at the boundary between the LV and LA or aorta. The LA was trimmed by a plane parallel to the mitral plane and located at 70% distance from the mitral plane origin to the LA centroid. We detected the aortic root and trimmed the structure above by a plane normal to the centerline of the aortic root. The obtained mitral inlet opening and aortic outlet opening were filled with triangular meshes. SimVascular Python functions were used to re-mesh the processed surface mesh and create a volume mesh.

We validated our framework with an additional 40 patient CT scans and 40 patient MR scans in the MMWHS dataset and performed CFD simulations on two sets of time-series CT data to further verify the framework. The patients scanned had diastolic dysfunction. LV surface and volume meshes were created at the start of diastole and the wall motion was calculated from the deformation fields obtained by non-rigid image registration among different time frames using SimpleElastix. Cubic spline interpolation was applied to obtain 2000 interpolated meshes to impose the movement on the volume mesh. We applied the Arbitrary Lagrangian-Eulerian (ALE) formulation of the incompressible Navier-Stokes equations with a stabilized finite-element Galerkin method [6] in the open-source FEniCS project to simulate the intraventricular flow and account for the moving boundary. Diastole and systole phases were determined based on increase and decrease of LV volume. Pressure boundary conditions were applied at the inlet during diastole, and at the outlet during systole.

RESULTS

Table 1: Dice, jaccard scores and surface distance errors of the LV, LA, aorta and whole heart segmentation results.

		Dice	Jaccard	SD (mm)
CT	LV	0.935± 0.036	0.879±0.060	0.872±0.354
	LA	0.932±0.029	0.874±0.050	0.128±0.401
	Aorta	0.948±0.020	0.903±0.036	0.612±0.282
	Whole Heart (Ours)	0.915±0.020	0.844±0.034	1.042±0.291
	Whole Heart [5]	0.908±0.086	0.823±0.037	1.117±0.250
MR	LV	0.902±0.081	0.830±0.110	1.313±0.985
	LA	0.851±0.105	0.750±0.118	1.667±0.792
	Aorta	0.864±0.078	0.767±0.107	2.397±1.725
	Whole Heart (Ours)	0.859±0.069	0.758±0.092	1.712±0.769
	Whole Heart [5]	0.874±0.039	0.778±0.06	1.631±0.580

The segmentation accuracy was evaluated with both surface distance errors and similarity indices between our segmentation and the ground truth (dice and jaccard scores). Our whole heart segmentation accuracy exceeded that of the best previously published [5] automatic segmentation model for CT data and approached the best for MR data (**table 1**). Among the 40 CT and 40 MR image volumes in the MMWHS dataset, LV meshes were successfully generated from segmentations for all but two patients, which corresponded to low segmentation accuracy with whole heart dice scores of 0.54 and 0.70, respectively.

CFD-ready LV models were automatically generated from the time-series CT data of two patients with diastolic dysfunction (**fig. 2**). The average total model construction time from image data for a single phase was 2.6 minutes, while image registration for obtaining the wall motion took 21.4 minutes on a 3.5 GHz Intel Core i7 processor. From the CFD simulations, the maximum outflow velocity during systole for patient A and patient B was 1.35 and 0.67 m/s respectively and the maximum inflow velocity during diastole was 0.53 and 0.26 m/s, respectively. Velocity streamlines of LV demonstrated the converging flow pattern during systole and the circulatory flow pattern during diastole (**fig. 3**).

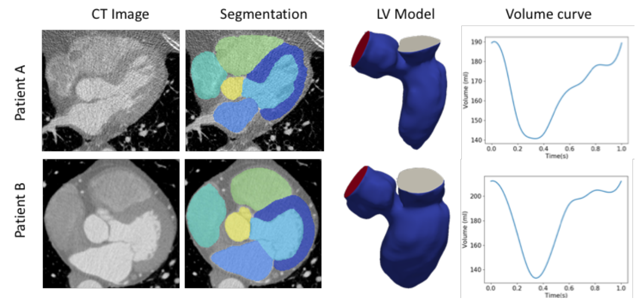

Figure 2: Visualization of the patient image data, segmentation results, constructed LV models and LV volume curves.

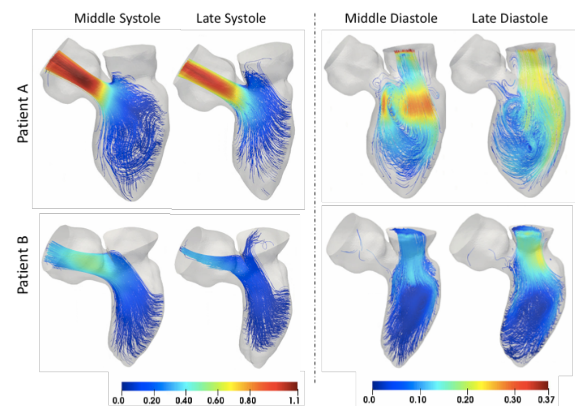

Figure 3: Velocity streamlines computed from patient-specific LV CFD simulations at middle systole, late systole, middle diastole and late diastole. Color map represents velocity magnitude (m/s)

DISCUSSION

CFD simulations of LV flow, although powerful in understanding patient cardiac hemodynamics, usually requires significant efforts in the model generation process, which makes this approach costly for potential clinical applications. Indeed, prior cardiac flow simulations have been limited to single or very few models [3]. We have developed methods to fully automate the modeling pipeline for CFD simulation of LV flow to significantly reduced both time and human efforts involved. Our framework can be conveniently executed from the command-line as a program. The proposed framework achieved highest segmentation accuracy for CT data compared to previous segmentation models [5] and the simulated LV flow patterns were consistent with prior findings [2-3]. Ongoing and future work include adding mitral valve and aortic valve structures for a more realistic inflow and outflow boundary condition and replacing image registration with surface registration to further reduce computational cost.

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