FSI modeling approach to develop right ventricle pulmonary valve replacement surgical procedures with a contracting actuator and improve ventricle ejection fraction

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Abstract

Image-based computational modeling has been used more and more for cardiovascular disease management and surgical planning in recent years. Computational modeling could perform virtual surgery with different surgical options avoiding risks associated with actual surgical experimentation on patients. For patients with repaired tetralogy of Fallot (TOF) needing right ventricle (RV) pulmonary valve replacement (PVR), the current surgical approach, which includes pulmonary valve replacement/insertion, has yielded mixed results. In this paper, we propose a new surgical option placing a contracting actuator in the right ventricle to improve RV function measured by ejection fraction (EF). An interdisciplinary approach is proposed to combine cardiac magnetic resonance (CMR) imaging, modeling, and mechanical engineering techniques to construct the mechanical actuator, build the ventricle models, perform virtual surgery, demonstrate feasibility of the new surgical procedure with actuator insertion, and identify optimal mechanical conditions under which optimal surgical outcome could be achieved.

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1. Introduction

Image-based computational modeling has been used more and more for cardiovascular disease management and surgical planning in recent years. The modeling approach could perform virtual surgery with different surgical options avoiding risks associated with actual surgical experimentation on patients. We have introduced fluid-structure interaction (FSI) models for patients with repaired tetralogy of Fallot (TOF) for right ventricle (RV) pulmonary valve replacement (PVR) surgical procedures optimization. Those patients account for the majority of cases with late onset right ventricle (RV) failure. The current surgical approach, which includes pulmonary valve replacement/insertion, has yielded mixed results [1,2]. In this paper, we propose a new surgical option placing a contracting actuator in the right ventricle to improve RV function measured by ejection fraction (EF) which is defined as:

$$RV\ EF = \frac{EDRV-Vol - ESRV-Vol}{EDRV-Vol},$$

where EDRV-Vol is end diastolic RV volume and EDRV-Vol is end systolic RV volume. Details are given below.

2. Method

An interdisciplinary approach is proposed to combine cardiac magnetic resonance (CMR) imaging, modeling, and mechanical engineering techniques to construct the mechanical actuator, build the ventricle models, perform virtual surgery, demonstrate feasibility of the new surgical procedure with actuator insertion, and identify optimal mechanical conditions under which optimal surgical outcome could be achieved.

2.1. Cardiac magnetic resonance data

Cardiac magnetic resonance (CMR) imaging was acquired from a patient with ToF for model construction at Harvard Medical School with informed consent obtained (Fig. 1). The RV and LV were imaged using ECG-gated, breath-hold steady state free precession cine MR in the ventricular short axis. The valve and patch positions were determined with cine MR imaging, flow data, and delayed enhancement CMR to delineate location and extent of scar/patch. Band location was determined by Dr. del Nido based on his surgical experience and ventricle anatomic limitations. Three-dimensional RV/LV geometry and computational mesh were constructed following the procedures published earlier [3-5]. Figure 1 shows pre-operative CMR images from a patient with repaired TOF and severe RV dilatation, segmented contour plots, the 3D re-construction RV/LV geometry with the actuator band and the patient-specific model with fiber orientations.Echo image data were acquired from ten people, five patients with myocardial infarction (Group 1) and five healthy volunteers as control (Group 2). Standard echocardiograms were obtained using an ultrasound machine (E9, GE Mechanical Systems, Milwaukee, Wisconsin) with a 3V probe and data were segmented for model construction. Fig.1 and Fig. 2 show the echo images and re-constructed 3D LV geometries from the two group patients. The location of infarction was defined as a decrease in or cessation of myocardial contractility, which was determined by two experienced observers through visualization of all LV wall segments, combining with the electrocardiogram and results of coronary angiography.

2.2. Biaxial testing of myocardium tissue properties

Tissue mechanical properties are essential to computational ventricle models. However, human heart tissue material properties are not readily available from the literature. Based on the methods of Sacks and Choung [6] for canine hearts and informed by our previous biaxial testing [7] and the methods of Humphrey and colleagues [8,9], we generated the first complete multiaxial mechanical data set for ventricular tissues using a cadaveric human heart sample (Fig 2). A detailed description of the custom planar biaxial testing device and method has been previously described [6,7]. The stress-strain data were recorded for computational modeling use.
2.3. FSI model

For the FSI model, blood flow in the right ventricle was assumed to be laminar, Newtonian, viscous and incompressible. The Navier-Stokes equations with arbitrary Lagrangian-Eulerian (ALE) formulation were used as the governing equations. The RV and left ventricle (LV) materials were assumed to be hyperelastic, anisotropic, nearly-incompressible and homogeneous. Patch and band materials were assumed to be hyperelastic, isotropic, nearly-incompressible and homogeneous. The nonlinear Mooney-Rivlin model was used to describe the nonlinear anisotropic and isotropic material properties. Parameter values in the material model were chosen to fit CMR-measured RV volume data (See Fig. 3). The details of the FSI RV/LV/Patch/Band model can be found from Ref.[4,5].
3. Results

The full RV/LV/Patch/Band models were solved by ADINA (ADINA R&D, Watertown, MA, USA) using unstructured finite elements and the Newton-Raphson iteration method [4,5]. RV ejection fraction was calculated to seek the optimal surgical design for potential RV EF improvement. Stress/strain distributions and flow shear stress conditions on the band were calculated which will provide important information for band design and tissue regeneration (Fig. 4). Our modeling results indicated that the band insertion, combined with active band contraction and tissue regeneration techniques that restore RV myocardium, has the potential to improve right ventricle ejection fraction. Contractions from the actuator could help the RV to improve EF by 2-5%. This compares favorably with recently published drug trials to treat heart failure where an improvement in LVEF of 3-4% resulted in a significant improvement in functional capacity. Detailed results will be presented at the conference.

4. Discussion and conclusion

It should be noted that the proposed surgical procedure requires long-term efforts from multi-disciplines to get close to and be implemented in clinical practice. The computational simulations (virtual surgery) provided a “proof of concept” for further investigations using in vitro experiments, animal models and final patient studies. Computational models are non-invasive and may be used to supplement/replace empirical and often risky clinical
experimentation, or even guide the design of new clinical trials to examine the efficiency and suitability of various reconstructive procedures in diseased hearts. Tissue engineering and regeneration techniques also need to be developed to generate the contracting bands and viable myocardium.

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