Virtual Surgical Modification and Fluid Structure Interaction CFD simulation for planning Tetralogy of Fallot repair

Masters Applied Project
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1. Introduction

Treatments for congenital heart disease originally focused on sustaining life into adulthood as a primary goal. Current treatments now achieve routine success, and survival into adulthood is not only common, but expected. In fact, adults who have survived the most common form of cyanotic congenital heart disease, tetralogy of Fallot (TOF), outnumber children in many countries [1]. Accordingly, late complications associated with congenital heart defect (CHD) repair have become a major concern. Late complications associated with free pulmonary insufficiency (FPI) following TOF repair represent a prime example [15]. Not long ago, FPI was regarded as a relatively unimportant consequence of TOF repair that resulted from inevitable sacrifice of the pulmonary valve (PV). Surgical convention placed an emphasis on complete relief of right ventricular outflow tract (RVOT) obstruction, even at the expense of FPI and progressive outflow tract dilation [1]. More recently, FPI has been linked with severe late complications, and one study demonstrated that pulmonary regurgitation is the predominant lesion associated with ventricular tachycardia and sudden death in post-repair TOF patients [14, 15]. As a result, patients who are symptomatic or who suffer from arrhythmias or ventricular dysfunction commonly undergo PV replacement late after TOF repair[35]. Clearly repairs that leave the PV intact are not appropriate in all cases, since an extreme pressure gradient across that valve would put the patient at risk for acute right ventricular (RV) failure due to excessive afterload [11]. However, an acceptable pressure drop may be achievable in many cases without modification of the RVOT or PV, or through modification of the RVOT alone. The goal of this project is to identify those cases through a surgical planning tool that combines medical imaging, virtual surgery, and Fluid Structure Interaction (FSI) based computational fluid dynamic (CFD) simulation. CFD has been applied similarly to simulate many flows in the cardiovascular system, and has been used extensively for planning CHD repairs [4, 9, 10, 23{25, 34]. The primary goal of our surgical planning application is to enable more successful TOF repair by avoiding unnecessary PV sacrifice and the late complications that accompany FPI.

a. Tetralogy of Fallot

TOF is present in 4 of every 10,000 live births, making it the predominant cyanotic heart defect in newborns [8]. The pathology, represented in Figure 1, is characterized by four specific lesions: a large Ventricular Septal Defect (VSD), an obstructed RVOT, right ventricular hypertrophy, and an overriding aorta (Ao)[27]. A VSD is a hole in the septal wall that permits communication between the two ventricles. As a result of the VSD, there are two outlets from the right ventricle (RV): the normally present RVOT (which leads to the pulmonary arteries) and the abnormal VSD that leads to the left ventricle (LV) and eventually the left ventricular outflow track (LVOT) (which leads to the aorta). In a normal heart there is only one outlet for the RV,
the RVOT. The magnitude of clinical symptoms for TOF, including poor blood oxygenation, is largely based on the severity of RVOT obstruction [26].

![Figure 1: Comparison between a normal heart and a tetralogy of Fallot affected heart.](Image source: National Heart Lung and Blood Institute (NHLBI)]

Ventricular pressure rises more quickly on the left side of the heart as compared to the right side during the cardiac cycle [26]. This phenomenon causes blood to flow from the LV to the RV, and ultimately through the pulmonary artery, when a VSD is present. Only when RVOT obstruction is significant will blood flow tend towards the Ao [26]. When blood flow favors the pathway through the Ao in TOF cases, it bypasses the lungs and leaves the patient in a state of hypoxia. Poorly oxygenized blood is then pumped to the body and the patient becomes cyanotic. To alleviate this condition, surgical intervention is required to force blood to the lungs [26].

b. Surgical repair methods

Depending on the size and/or cyanotic nature of the infant, an initial palliation procedure may be performed to aid in directing additional blood to the lungs [7]. Regardless, TOF patients require a complete surgical repair within their first few years [33]. This complete surgical repair involves closure of the VSD and opening of the obstructed RVOT, which may include surgical manipulation of the PV [18].

Ideally, no surgical manipulation of the PV would be required. If the maximum pressure
gradient across the PV is expected to be low enough after VSD closure, then the valve could be spared, and would adapt to new conditions over time [32]. Leaving the PV intact is preferable since alterations to the valve may result in FPI, which is associated with right ventricular dysfunction, arrhythmias, and sudden death [32]. However, if the maximum pressure gradient across the valve is too great, then the patient is at risk for acute RV failure due to excessive afterload [11, 16, 19, 30]. Accordingly, if an extreme pressure gradient is expected across the valve after VSD closure, then surgical manipulation of the PV is called for. This situation presents a problem for surgical planning. Specifically, the decision as to whether or not the PV should be manipulated is a difficult one since the actual maximum post-operative pressure drop across the valve cannot be known prior to VSD closure.

At present, surgical planning is based on a patient's Z-score [22, 32]. The Z-score uses patient body surface area and the estimated PV diameter, from echocardiography (ECHO), as parameters to aid in designing an appropriate surgical procedure that will realize an acceptable maximum pressure gradient across the PV [20]. Although ECHO is the gold standard in pediatric cardiology, two-dimensional ECHO measurements are limited and can result in an inaccurate estimation of diameter. Accordingly, the first step during surgery, once the heart is opened, is to confirm the diameter of the PV with a Hegar dilator [21]. Assuming the diameter was estimated correctly with ECHO, the surgeon will follow through with the pre-operative surgical plan based on the Z-score. It is noteworthy, however, that the pressure drop across the PV is more dependent on overall valve geometry than the one-dimensional diameter measurement that is used in the Z-score.

When the Z-score-based surgical plan calls for the PV to be left intact, trans-esophageal ECHO, manual palpation, and/or needle-based transduction are used midoperatively to examine the maximum pressure gradient across the valve [2, 31, 37]. These checks are performed once the VSD is closed, the patient is removed from bypass, and the heart begins to beat on its own, but while the chest is left open. If an excessive pressure gradient is detected, then surgical modification of the PV is required. This subjects the patient to additional surgical trauma, prolonged time on bypass, and extended anesthesia. Each of these factors increases surgical risk [3, 6, 12]. Furthermore, midoperative measurements increase surgical costs and place additional stress on the surgeon. In addition, the midoperative pressure measurements can be inaccurate due to the traumatized state of the patient, resulting in abnormally high or low quantifications that can differ greatly from values measured only days after surgery.

If the flaws in current surgical planning practices lead to unnecessary sacrifice of the PV, then the patient is put at risk for late complications associated with FPI. Even if the valve is spared, the patient is put at risk for complications associated with prolonged surgery. Here we present
new methods for predicting the maximum pressure gradient across the PV after the VSD has been closed. Unlike the conventional Z-score, the proposed methods rely on patient-specific, time-varying anatomical information from computed tomography (CT) data, which is then used to drive computational fluid dynamics (CFD) simulations. Those simulations have the potential to increase surgical quality, decrease operation time, decrease healthcare costs, and ultimately to improve surgical outcomes.

2. Methods
   a. Patient data acquisition

Patient was imaged pre-operatively with a GE Medical Systems LightSpeed VCT CT scanner (GE) at Saint Joseph's Hospital and Medical Center (Phoenix, AZ). The patients were given a 20ml bolus of VISI 320 contrast agent and anesthetized. Data were acquired at 80KV and 214.80mAs and was stored as DICOM format images with the following parameters: 512 x 512 image matrix, 0.313 x 0.313 mm pixel dimensions, 0.625 mm slice spacing. Ten cardiac phases, spaced equally over the course of the heart cycle, were acquired for each patient. An average heart rate of 100 beats per minute was observed during the scans, and the time interval between phases was 0.06 s. Preoperative transvalvular velocities in the RVOT were measured with trans-esophageal ECHO, and post-operative velocities in the same region were measured with transthoracic ECHO. Velocity measurements were used to estimate pressure gradients across the PV, according to clinical convention, through Bernoulli’s equation at steady state:

$$\Delta P = m \frac{dv}{dt} + \frac{1}{2} \rho \Delta v^2 + \rho g \Delta h + R_{\text{viscous}},$$

Where \(\Delta P\) is the pressure gradient across the pulmonary valve and \(v\) is the downstream flow velocity. It is noteworthy that pressure gradients estimated in this way quantify the maximum instantaneous gradient (MIG), which represents the maximum pressure gradient that is present across the PV at any one point in time. Accordingly, the CFD simulations that were performed in this study (described later in Subsection 2.c), were also used to quantify MIG in order to facilitate comparison to clinical data. MIG differs from the other standard metric for quantifying pressure gradients across the PV, the peak-to-peak value, which is based on cardiac catheterization data. The peak-to-peak value represents the difference between the maximum pressures that are measured upstream and downstream of the valve, which occur at different points in time. Both metrics are used routinely in clinical practice to evaluate pressure gradients across the PV. All patient data involved in this study were acquired under institutional review board (IRB) approval and were anonymized according to the standards of the Health Insurance Portability and Accountability Act (HIPAA).
b. Segmentation and reconstruction
Each of the ten cardiac phases for a given patient were segmented and reconstructed into three-dimensional (3D) models with Mimics software (Materialise Inc, Leuven, Belgium) to create time-varying anatomical representations of the RVOT. Each dynamic anatomical model included the RV, the RVOT, and the main pulmonary artery (MPA) with its Left (LPA) and Right (RPA) branches extending till they bifurcated into smaller arteries. Segmentation was accomplished with thresholding and region growing and 3D reconstruction was performed with grey value interpolation to minimize partial volume effects. To simulate VSD closure, a division between the two ventricles was created prior to reconstruction into 3D by connecting the boundaries of the septal wall around the VSD. The simulated closure was created from inferior to superior, and connected on the medial side of the PV annulus. The modified 3D anatomical models were also separated into RV and RVOT components, under physician supervision. The boundary between the RV and RVOT was identified just prior to the inlet of the PV annulus.

![Figure 2: 3D reconstruction of the Pulmonary Artery (Green) & Right Ventricle (Purple)](image)

Care was taken to ensure that the annulus itself was left intact in each model. RV model volumes were calculated at each time phase, and changes in those volumes were used along with a patient's average heart rate to scale a standard RVOT flow waveform from literature [29]. RVOT flow waveforms were then represented as discrete Fourier series, up to the first 7 harmonics, and used to prescribe boundary conditions for CFD as described next in Subsection 2.c. As a point of reference, the maximum decrease in RV volume between a pair of phases was 6,005.9 mm$^3$, which was observed in the patient when RV blood volume decreased from 24,963.9 mm$^3$ to 18,958.0 mm$^3$. 
c. CFD simulation
Anatomical patient models of the RV and RVOT at peak systole were imported into Geomagic Studio software (Geomagic Inc., NC, USA) for post-processing. The models were sectioned off at the RVOT inlet and immediately prior to the bifurcation of each of the LPA and RPA into smaller arteries. The surface normal to the RVOT was extruded by 5 diameters, while the surface normal to the LPA and the RPA was extruded by 15 diameters. This ensured a fully developed outflow boundary condition. Ansys Workbench 14.0 utility was used in order to analyze the problem, as it provides support for coupling between Ansys Mechanical and Ansys Fluent as part of a Fluid Structure Interaction (FSI) solution. Separate mesh elements were created within the Mechanical and Fluent software packages. A quad dominant surface mesh was created in Ansys Mechanical with 153,784 elements. The minimum element size for the mesh was fixed at 0.27 mm to ensure that the mesh was compatible for large deformation FSI studies. The Ansys Fluent mesh was created using a hexahedral core dominant method with tetrahedral surface elements. The mesh had 192,667 nodes, and 704,497 corresponding mesh elements.

Figure 3: Smoothened Pulmonary Artery using Geomagic

FSI simulations were conducted in ANSYS Workbench 14.0 software (ANSYS Fluent Inc, Lebanon, NH, USA) on a dual quad core Mac Pro computer with 16GB RAM. The vessels were assumed to be elastic with an elastic modulus defined at 48,574 KPa and a Poisson’s ratio of 0.49. The wall density was fixed at 1030 kg/m$^3$ with a thickness of 1 mm. Fixed supports were provided to the geometry at the inlet and two outlets (LPA & RPA) in order to keep the geometry in place in Ansys Mechanical during FSI simulation. Blood was modeled as an
incompressible Newtonian fluid with a viscosity of 3.71e-3 Pas and a density of 1060 kg/m$^3$. A pressure-based, segregated parallel solver was used to solve for the Navier Stokes equations. A node-based, second-order accurate upwind discretization scheme was applied for the momentum equations while the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was used to define the pressure-velocity coupling. In order to simulate Pulsatile conditions, discrete Fourier series representations of the velocity waveforms were imposed at the inlet. An adaptive time-stepping method was used with a maximum time-step size of 10 ms and a minimum time-step size of 0.01 ms. Analyses of the FSI solutions were performed in CFD Post – which is a post-simulation analysis software included within Ansys.

3. Results

The FSI simulations showed a maximum instantaneous gradient (MIG) pressure of 38mmHg in the MPA, which are similar to the pressures, recorded using transthoracic ECHO post-operatively in the same region. The highly elevated simulated pressure gradients agree well with clinical expectations, since VSD closure alone causes significant increases in flow through the RVOT and pressure drop across the PV. The strong similarity between pressure gradient values simulated under steady and pulsatile flow conditions also parallels previous studies that have investigated transvalvular pressure gradients [36].

![Figure 4: Velocity streamlines representing flow velocities at peak systole.](image-url)
The MIG flow velocity in the MPA at peak systole was recorded at 3.7 m/sec. High flow velocities in the MPA region are expected because of the stenosis in the RVOT region which we have not dealt with. Our conditioning of the data in the lab was only virtual surgery to close the VSD. The MIG flow velocities and Pressure gradients recorded at 38mmHg are similar to the post-operative ECHO data recorded by transthoracic ECHO. This is a good indication of our simulation representing flows similar to clinical data acquisition by ECHO.

Wall displacement measurements are important for to validate the entire simulation. 3D reconstruction of the systolic segment of the heart wave was carried out from data acquisition.
carried out in step 2.a. In order that the simulation is a true representation of the artery physiology, wall displacement calculated between the starting segment of the heart wave and the systolic segment, should be in agreement with the values obtained by simulation. Displacement values were recorded at 70% (approximately 0.7 mm) of the target value (1 mm) at the critical MPA region.

Figure 7a: Wall Displacements on the surface of the Pulmonary Artery (front view)

Figure 8: Wall Displacements on the surface of the Pulmonary Artery (rear view)
4. Discussions

Computational Fluid Dynamic (CFD) simulations can be a great tool to study flow profiles to represent various heart pathologies. Recent advancements in simulation software have made it possible to simulate the rather complex problem of Fluid Structure Interaction (FSI) which is a true representation of natural phenomena for anatomical structures such as arteries. Earlier studies at our lab focused on methods that used simulation methods on rigid bodies. However, rigid bodies are not representative of flows through elastic and deformable structures such as arteries and vasculature in general. Carrying out a FSI simulation requires a complex setup between mechanical software (to handle deformation and energy of wall structures) and fluid simulation software that simulates fluid flow according to the scaled patient specific input flow profile. FSI simulations also require a significant amount of computational resources as well as time as compared to rigid body simulations that are mainly dealing with fluid phenomena in geometries.

Establishing the correct material properties for the deforming mechanical analysis proved to be a challenge during our simulation. Material property values were borrowed from various sources in literature; however it was very tough to find values associated with young subjects as well as for our specific case of tetralogy of Fallot.

Even though there are several limitations, the methods used here present a promising framework for improving TOF repair planning and improving long-term patient outcomes. A clinician can make better decisions if he has better tools to assess critical readings for velocity & pressure. CFD simulations can provide the clinician insight about the severity of the congenital defect, to which he can make recommendations and decisions for treatment. The goal of our experiment at the lab was to develop a tool that can enable the clinician to be able to make a decision to save the PV in cases where minor modifications to the RVOT region will successfully lower velocity and pressure measurements after VSD closure, such that the PV can sustain itself during the normal heart cycle.
References


