Virtual surgical modification for planning tetralogy of Fallot repair

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ABSTRACT

Goals for treating congenital heart defects are becoming increasingly focused on the long-term, targeting solutions that last into adulthood. Although this shift has motivated the modification of many current surgical procedures, there remains a great deal of room for improvement. We present a new methodological component for tetralogy of Fallot (TOF) repair that aims to improve long-term outcomes. The current gold standard for TOF repair involves the use of echocardiography (ECHO) for measuring the pulmonary valve (PV) diameter. This is then used, along with other factors, to formulate a Z-score that drives surgical preparation. Unfortunately this process can be inaccurate and requires a mid-operative confirmation that the pressure gradient across the PV is not excessive. Ideally, surgeons prefer not to manipulate the PV as this can lead to valve insufficiency. However, an excessive pressure gradient across the valve necessitates surgical action. We propose the use of computational fluid dynamics (CFD) to improve preparation for TOF repair. In our study, pre-operative CT data were segmented and reconstructed, and a virtual surgical operation was then performed to simulate post-operative conditions. The modified anatomy was used to drive CFD simulation. The pressure gradient across the pulmonary valve was calculated to be 9.24mmHg, which is within the normal range. This finding indicates that CFD may be a viable tool for predicting post-operative pressure gradients for TOF repair. Our proposed methodology would remove the need for mid-operative measurements that can be both unreliable and detrimental to the patient.

Keywords: tetralogy of Fallot, congenital heart disease, surgical planning, computational fluid dynamics, image processing

1. INTRODUCTION

For many years, a primary goal in treating congenital heart disease has been to keep patients alive long enough to reach adulthood. The short-term surgical success of current procedures for treating congenital heart defects (CHD) has resulted in an ever-growing adult CHD population. Doctors are now becoming increasingly concerned with post-surgical complications in young to mid-aged adults with CHD. These complications often arise from the very surgical procedures that were initially designed to save these patients’ lives. There is now a new push in the medical community to address these concerns by developing new and better surgical techniques. Tetralogy of Fallot patients represent a population that could potentially benefit from the modification of existing techniques.
1.1 Tetralogy of Fallot

TOF is present in 4 of every 10,000 births, making it the predominant cyanotic heart defect in newborns. This pathology, represented in Figure 1, is characterized by four specific lesions: a large ventricular septal defect (VSD), an obstructed right ventricular outflow track (RVOT), right ventricular hypertrophy, and an overriding aorta (Ao). 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 naturally occurring RVOT (involving the pulmonary artery) and the VSD that leads to the left ventricle (LV) and eventually the left ventricular outflow track (involving 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.

Figure 1. CT images of a TOF case in which the LV and RV are connected (a) and the RVOT is obstructed (b).

Ventricular pressure rises more quickly on the left side of the heart as compared to the right side during the cardiac cycle. This phenomenon causes blood to flow to the RV from the LV, and ultimately through the pulmonary artery, when a VSD is present. Only when RVOT obstruction is significant will blood flow tend towards the Ao. When blood flow favors the path 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 needed to force blood to the lungs.

1.2 Surgical repair methods

Depending on the size and/or cyanotic nature of the infant, a palliation procedure may be preformed to aid in directing additional blood to the lungs. Regardless, TOF patients require a complete surgical repair within their first few years. This complete surgical repair involves closure of the VSD and opening of the obstructed RVOT, which may include surgical manipulation of the pulmonary valve.

Ideally, no surgical manipulation of the PV is required. The pressure gradient across the valve is low enough when the VSD is closed that the valve can adapt to new conditions as the patient grows. Leaving the PV intact is preferable since alterations to the valve may result in PV insufficiency, which is associated with right ventricular dysfunction, arrhythmias, and sudden death. However, if the pressure gradient is too high across the valve, then the patient is at risk for acute RV failure due to excessive afterload. A high gradient, after VSD closure, calls for
surgical manipulation of the PV. One current problem in the operating room is deciding when it is appropriate to manipulate the PV, since the actual post-operative pressure drop is unknown prior to VSD closure.

At present, surgical planning is based on a patient’s Z-score\(^7,12\). The Z-score uses patient body surface area and the estimated PV diameter, from ECHO, as parameters to aid in designing an appropriate surgical procedure\(^13\). Although ECHO is the gold standard in pediatric cardiology, measurements in a two-dimensional plane are limited and can result in an incorrect estimation. Therefore, the first step during surgery, once the heart is opened, is to confirm the diameter of the PV with a Hegar dilator\(^14\). Assuming the diameter was estimated correctly with the ECHO, the surgeon will follow through with the pre-operative surgical plan. It should be noted that once the valve has been surgically altered, little can be done by the surgeons to address the PV pressure.

Assuming the PV is left intact, transesophageal ECHO, manual palpation, and/or needle-based transduction can be used mid-operatively to examine the pressure gradient\(^15,16,17\). This can only be done once the VSD is closed, the patient is removed from bypass, and the heart begins to beat on its own. This occurs while the chest is left open. If a high pressure gradient persists, further 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\(^18,19\). In addition, mid-operative pressure measurements can be flawed, due to patient trauma, resulting in abnormally high or low estimations of the pressure gradient across the valve. These estimations can differ greatly from measurements that are taken only days after surgery. Furthermore, mid-operative measurements increase costs and place additional stress on the surgeon.

In this paper, a new method for predicting the PV pressure gradient after VSD closure is proposed. This method uses patient-specific time-varying anatomical models to drive computational fluid dynamics (CFD) simulations. The ability to predict this pressure gradient well could facilitate improved surgical planning and eliminate the need for mid-operative PV gradient measurements. This methodology has the potential to increase surgical quality, decrease operation time, decrease healthcare costs, and ultimately to improve surgical outcomes, as proposed in Figure 2.

Figure 2. Benefits of the proposed patient-specific surgical planning methodology for TOF repair.

2. MATERIALS AND METHODS

2.1 Patient data collection

This study involved pre-operative medical image data from a TOF patient taken with a GE Medical Systems CT scanner (model: LightSpeed VCT). The scan took place at Saint Joseph’s Hospital and Medical Center (Phoenix, AZ). Data acquisition occurred at 80KV and 214.80mAs and was stored in DICOM format (512 x 512 pixel plane, .313 x .313 mm pixel size, .625mm slice spacing). The DICOM file contained 10 cardiac phases that were equally spaced throughout time. The patient was given 20ml of a VISI 320 contrast bolus agent and anesthetized. An average heart rate of 100 beats per minute was observed during the scan. The time interval between phases was calculated as .06s for this DICOM set.

2.2 Segmentation and reconstruction

The 10 cardiac phases were segmented and reconstructed with Mimics (Materialise Inc, Leuven, Belgium) to create time-varying anatomical models of the RVOT, including the pulmonary artery bifurcation and RV. Segmentation was accomplished through region growing and 3D reconstruction was performed with grey value interpolation to minimize partial volume effects. To simulate the VSD closure, a division between the two ventricles was made by
linking the septal wall around the VSD. This process was applied going from inferior to superior; making sure the simulated VSD closure connected up to the medial side of the PV annulus. The modified anatomical models were also separated into RV and RVOT model components. Separation was executed just prior to the inlet of the PV annulus, as shown in Figure 3. Care was taken to ensure that the annulus itself was left intact. RV model volumes were calculated at peak systole to enable simulation of the maximum pressure gradient present during one cardiac cycle. Peak systole was identified based on the pair of sequential phases that corresponded to the greatest RV volume decrease. The maximum decrease in volume between a pair of phases was 6005.93mm$^3$, where RV blood volume decreased from 24,963.93mm$^3$, in phase two, to 18,958mm$^3$ in phase three. The RVOT geometric information, from phase two, was then used in the CFD simulation.

![Figure 3. 3D anatomical model from cardiac phase 2.](image)

**2.3 CFD simulation**

CFD simulations were performed based on the following parameters: RV volume decrease = 6005.93mm$^3$, RVOT time phase = 2, inter-phase time interval = .06s. The anatomical RVOT model was imported into Geomagic Studio (Geomagic Inc, NC) for post-processing. The model was sectioned off at the edge of the RVOT, proximal to the annulus, and immediately prior to the bifurcation of the main pulmonary artery. The model was then imported into Gambit (ANSYS Fluent Inc, Lebanon, NH) and surfaces were extruded normal to the inlet and outlet to impose fully developed boundary conditions. The vessel lumen was then discretized into approximately 465,000 tetrahedral mesh elements comprising 86,709 nodes, as shown in Figure 4.

The CFD simulation was solved in Fluent (ANSYS Fluent Inc, Lebanon, NH) using a second-order-accurate upwind scheme. The model was assumed to be rigid and a no-slip boundary condition was imposed at the walls. The pressure-velocity coupling was defined using the Semi-Implicit Method for Pressure-Linked Equations algorithm. The change in RV volume at peak systole and corresponding ejection ratio were used to specify the inlet boundary parameters. A flat velocity profile of 1.16 m/s was imposed at the extruded inlet of the RVOT. The convergence criterion was set to 1E-6. Finally, the velocity and pressure maps from the CFD solution were analyzed using Tecplot (Tecplot Inc, Bellevue, WA).
3. RESULTS

The velocity magnitude and pressure maps from the RVOT CFD simulation are shown in Figures 5 and 6, respectively. The pressure difference between the sectional slices at the inlet and outlet were averaged to obtain a pressure drop of 9.24mmHg across the RVOT, which is near the upper limit of the normal range $^{20, 21, 22, 23}$. The distance between the inlet sectional slice and the annulus was 2.62mm and the distance between the outlet sectional slice and the annulus was 8.64mm.
TOF is a complex and severe congenital heart defect characterized by the inability to pump sufficiently oxygenated blood to the body. This pathological insufficiency is the result of both an obstructed RVOT and a VSD. The only way to correct this condition is to close the VSD and force blood towards the lungs, through the RVOT. Unfortunately, this can create an excessive pressure drop across the PV. Surgeons must then address that problem by opening the PV, which can lead to other complications. One current challenge with TOF repair is determining when PV manipulation is appropriate. The method presented in this paper addresses this challenge directly.

However, there are a number of shortcomings inherent to our current study. The first and most obvious deficiency is that this process has only been executed on a single patient. We will address this shortcoming in future work. Next, our CFD simulations are hindered by the fact that patient-specific velocity profiles are not available from CT data to be used as boundary conditions. This could be addressed through the acquisition of additional MR data for each patient, but it is unlikely that additional medical imaging scans would be economically viable in practice. Lastly, our CFD simulations were executed for a single time phase and under the assumption of a static anatomy. To fully understand the complex flow dynamics in the RVOT, time-varying simulations with wall motion will be required. The incorporation of surgeons directly into our workflow will also be required to ensure that virtual anatomical modifications are realistic.

Despite these shortcomings, we have demonstrated that our method is feasible. The implications of a fully functional tool in this context would be significant. First, such a tool would allow surgeons to better understand a specific patient’s disease state, and plan accordingly. Next, there would be no need to rely on a mid-operative measurement that is both inherently unreliable and dangerous to the patient. Lastly, surgical decisions would be made outside of the operating room based on better information. Each of these changes would represent an improvement over the current state-of-the-art.
5. CONCLUSIONS

We have developed a method for simulating the pressure gradient present across the PV after partial TOF repair. Although this method is executed entirely \textit{in silico}, it is based on a collection of relevant \textit{in vivo} data and is more patient-specific than the generic Z-score currently used in surgical planning. Initial results demonstrate that our approach can estimate the PV pressure gradient within the normal expected range. Specifically, a pressure drop of 9.24mmHG was calculated across the PV for the case that we examined.

Our findings are promising, but a great deal of future work is required. We need to apply our approach to a sufficiently large patient database and refine our computational methods to improve accuracy. Perhaps most challenging is the longer-term goal of demonstrating conclusively to the surgical community that computational tools such as image processing and CFD do in fact allow surgeons to perform more effectively. Nevertheless, our proposed methods for improved surgical planning represents an important step towards achieving improved outcomes for TOF patients.

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REFERENCES


