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SURGEM: A solid modeling tool for planning and optimizing pediatric heart surgeries☆

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HIGHLIGHTS

- We describe solid modeling challenges faced while developing a surgery planning tool.
- We support three surgeries: (1) DORV, (2) Fontan procedure and (3) Stenosis repair.
- DORV and Stenosis repair procedures utilize a simple sketch based interface.
- For Fontan, the surgeon specifies endpoint locations by clicking.
- More direct and precise control allows quick exploration of number of surgical options.

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ABSTRACT

Approximately 1% of children are born with a moderate to severe congenital heart defect, and half of them undergo one or more surgeries to fix it. SURGEM, a solid modeling environment, is used to improve surgical outcome by allowing the surgeon to design the geometry for several possible surgical options before the operation and to evaluate their relative merits using computational fluid simulation. We describe here the solid modeling and graphical user interface challenges that we have encountered while developing support for three surgeries: (1) repair of double-outlet right ventricle, which adds a graft wall within the cardiac chambers to split the solid model of the unique ventricle, (2) the Fontan procedure, which routes a graft tube to connect the inferior vena cava to the pulmonary arteries, and (3) stenosis repair, which adds a stent to expand a constricted artery. We describe several solutions that we have developed to address these challenges and to improve the performance, reliability, and usability of SURGEM for these tasks.

1. Introduction

Approximately 1% of children born have a moderate to severe congenital heart defect (CHD) [1]. More than half of these children undergo at least one invasive surgery in their lifetime [2]. There are more than 40 different types of CHD, and many involve performing delicate changes to the geometry and topology of the cardiovascular structure. Often, the surgeon faces the problem of evaluating several topological options, such as whether one should implant a graft inside the heart or use an external baffle, compounded with the need to optimize the various geometric parameters such as the location and angle of the connection where a baffle is attached to an artery. The outcome of the surgery (probability of survival, quality of life, and chances of avoiding subsequent surgeries) depends sig-

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Fig. 1. Dr. Kirk Kanter from Children's Healthcare of Atlanta is using SURGEM with a pen tablet to visualize the patient's cardiovascular anatomy and plan the heart surgery.

nificantly on these choices and optimizations. To assist the surgeon in these delicate surgical planning activities, we have developed an interactive solid modeling environment called SURGEM (short for SURGEry Modeler). It supports loading a detailed triangle mesh which is extracted from medical imaging, such as Cardiac Magnetic Resonance (CMR), and which represents the boundary of the solid model of the cavity of the patient's heart and of the abutting vasculature. SURGEM lets the surgeon inspect this virtual model and modify its geometry and topology interactively using various input modalities, which include 3D input with a 6 DoF tracker in each hand or simply using a stylus to draw curves or drag points on a touch sensitive tablet (Fig. 1).

Finally, SURGEM allows the surgeon to export the resulting solid models for off-line Computational Fluid Dynamic (CFD) analysis. The results of this analysis can help the surgeon in selecting the optimal corrective option for the surgery and in understanding an option's sensitivity to the variations of geometric parameters. This sensitivity analysis is important to predict the robustness of the course chosen and thus anticipate the consequences of the expected discrepancy between the planned model and the physical model that will inevitably result from the operation [3].

Intuitive SURGEM tools for freely bending and twisting the boundary of the solid model without altering its connectivity have been described elsewhere [4,5]. These were based on smooth space warps that the surgeon controls either directly though a different screw model controlled with each hand [6] or with a virtual ribbon held at each end by a different hand [4].

In this paper, we report on novel and more challenging tools that support designing and performing topological changes and that require more complex processing and optimization of the geometry.

Specifically, we describe, in geometric and algorithmic terms, the solid modeling and graphical user interface challenges that we have encountered while developing support for three specific types of heart surgeries:

1. The **Double Outlet Right Ventricle (DORV)** repair adds an internal graft wall (cut out from a developable baffle surface, i.e. a surface that can be flattened without stretching) to split the solid model of the unique ventricle into two solids and hence creates a bi-ventricular circulation.
2. The **Fontan** procedure adds a graft (tubular baffle, possibly with a bifurcation) to connect the inferior vena cava to the pulmonary arteries,
3. The **Stenosis** repair inserts a stent to expand a constricted artery into a tube of a circular cross-section of a chosen diameter.

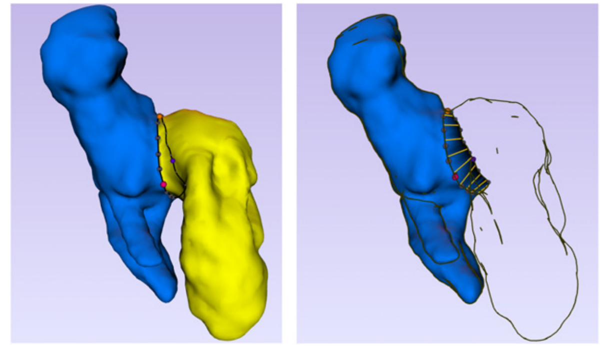

Fig. 2. The model of the pre-operation DORV anatomy (left) shows a heart with pulmonary atresia and the aorta arising from the RV. A suture loop (black) drawn on it by the surgeon using SURGEM is shown (the hidden portion of the suture loop lying on the back wall is shown with its control points, made visible through the yellow surface) and was used to separate the surface of the heart into the yellow and blue parts. Optimally, the yellow surface is made transparent (right) to reveal the baffle (developable surface highlighted by yellow lines) that has been inserted to separate the ventricles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We describe, in the subsequent subsections, these challenges and the practical solutions that we have developed to address them and to improve the performance, reliability, and usability of SURGEM for these tasks.

2. Double-outlet right ventricle surgery

2.1. Objectives

The DORV intraventricular repair surgery targets children born with a heart where the two ventricular chambers and arterial outlets are not properly separated: all outlets from the heart arise from the right ventricle. Throughout the paper, we use the term *ventricle* to refer to the solid model bounded by the interior surface of the heart. The objective of the repair is to recreate the normal partitioning of the two ventricular chambers (which we will refer to as the RV (right ventricle) and LV (left ventricle)) and the great arteries so as to restore proper routing of blood flow. This might be accomplished, for example, by placing a Teflon (PTFE) *baffle* inside the ventricle and by suturing it to boundary surface along a *suture loop* to direct blood from the LV to the aorta. Fig. 2 shows a typical configuration before surgery (left) with a unique ventricle and after surgery (right) where the heart has been split in two parts (RV and LV) by the inserted baffle.

While editing the geometry and position of the baffle, the surgeon wishes to achieve the following *objectives*: (1) Minimize the difference between the volumes of the solid models of the LV and RV models created by the surgery. (2) Ensure that the shape of the baffle and the tracing of the suture loop are not conflicting with any physical constraints or surgical practices.

We designed the DORV intraventricular repair planning interface to make the specification of the baffle easy and to quickly provide feedback on the volumes of the LV and RV resulting from the split.

From a usability perspective, we want to satisfy the following *goals*: (1) Provide a visualization environment that is simple to operate and allows the surgeon to control the view and clearly see the boundary of the RV along with the suture loop drawn on it, (2) Provide a straightforward to learn, natural to use, and effective paradigm through which the surgeon can quickly design and then carefully adjust the shape of the baffle, and (3) Provide real-time visual feedback to guide these careful adjustments.

From a solid modeling perspective, our *challenges* are: (1) To ensure that the shape of the baffle is a developable surface, because, while the PTFE material used for the baffle is slightly stretchable in