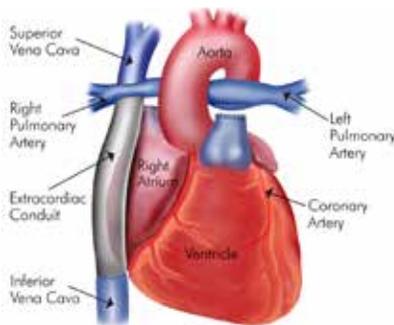


“Using accurate simulation in conjunction with skilled surgery will increase the effectiveness of these procedures and provide the young patients with better quality of life.”

Hearts Content



^ Heart after correction with Glenn and TCPC surgical procedures

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computational fluid dynamics to determine the optimal connection points based on the patient's cardiovascular anatomy, improving surgical effectiveness and resulting in a better quality of life for these children.

The long-term prognosis for babies born with single-ventricle heart defects

can depend on the location of vascular connections made during corrective surgery. **Shanghai Children's Medical Center** uses simulation to individualize this surgery. Researchers employ

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In a normal heart, the left ventricle pumps oxygenated blood to the body and the right ventricle pumps deoxygenated blood to the lungs. But about two out of every 1,000 babies are born with only a single ventricle. The oxygenated and the deoxygenated blood blend in the ventricle, and the mixture is pumped throughout the body, causing symptoms that include shortness of breath, low energy and a blue color in the extremities. This condition places such a heavy burden on the single ventricle that, without surgical correction, most children born with this disorder will die from heart failure within one year.

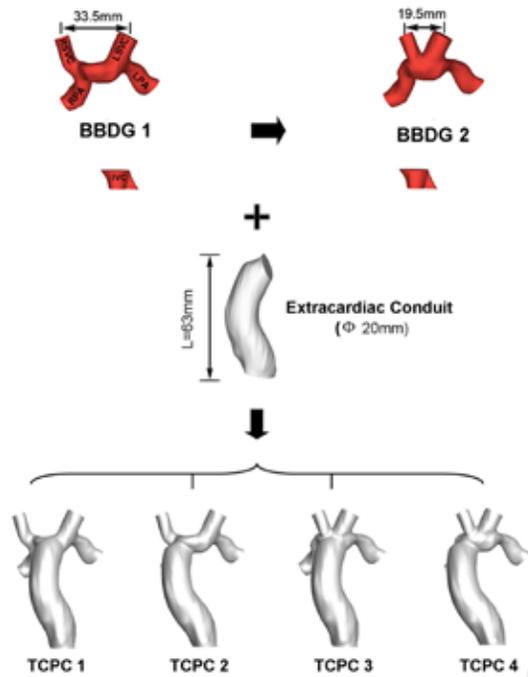
Correcting single ventricle defects normally involves reconfiguring the circulatory system to ease the burden on the ventricle. The ventricle still pumps blood to the body, but the blood returning from the body travels directly to the lungs via blood vessel connections for reoxygenation, before reaching the malformed heart's single pumping chamber.

The surgery is performed in a staged approach. The first stage, required in most but not all babies born with this defect, balances the blood flow so that an equal amount of blood travels to the body and lungs (Norwood procedure). In the second stage, called a bidirectional Glenn procedure, the vessels that drain blood from the head and upper body — the left and right superior vena cava (LSVC and RSVC) — are disconnected from the heart and sutured directly to the pulmonary artery (PA), which provides blood to the lungs. This removes some of the work done by the single ventricle. In the third stage, called the total cavopulmonary connection (TCPC) or Fontan procedure, the vessel returning blood from the lower half of the body — the inferior vena cava (IVC) — is disconnected from the heart and connected directly to the PA.

Clinical studies have found a wide variation in the long-term survival rate and post-operative quality of life of patients receiving these procedures. One reason for this disparity is that surgeons have the flexibility to connect the LSVC, RSVC and IVC to different points on the PAs. Which connection point will work best for a particular patient depends on the patient's heart structure and other variables that affect flow patterns in the veins. These flow patterns, in turn, have a major impact on the efficiency of the pulmonary system and the burden that is placed on the single ventricle.

TAKING PATIENTS' INDIVIDUAL ANATOMY INTO ACCOUNT

Until recently, surgeons have not had a method to determine the effects of different connection points on the patient's long-term health. Researchers at Shanghai Children's Medical Center use computational fluid dynamics (CFD) to perform virtual operations that take each patient's unique heart and blood vessels into account while evaluating



▲ Connection points from the large veins to the pulmonary artery were varied in the four different models developed for this study (front view shown on top and back view on bottom).

different sites to connect vessels to the PA. Researchers can then compare power losses and energy efficiency across the flow domain to determine the configuration that will maximize energy efficiency for that specific patient. To calculate energy efficiency, clinicians divide the total energy leaving the flow domain across the two outlets by the sum of energy entering the system across the three inlets.

In a recent example, researchers performed magnetic resonance imaging (MRI) on a five-year-old boy who had been born with a single ventricle, and had already undergone the Glenn procedure, and whose doctors were planning to perform a TCPC. His MRI images were imported into Materialise Mimics® software for 3-D reconstruction of his vascular anatomy, which was used to perform virtual operations based on these configurations. First, a second Glenn procedure was performed virtually by moving the connection sites of the LSVC and RSVC vessels closer to the PA. Then two different virtual TCPC operations were performed on each of these two models with different connection points for the IVC. The result was four different geometrical models, each based on different attachment alternatives, for the Glenn and TCPC surgeries.

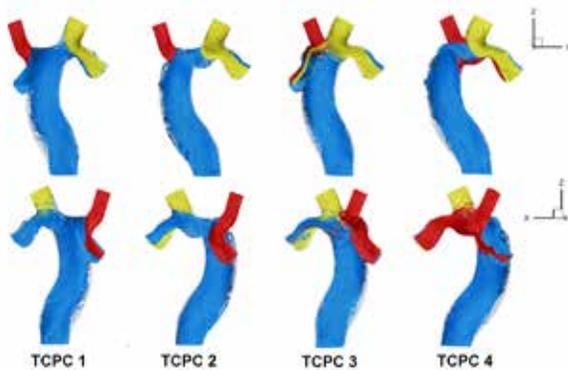
The researchers exported the four models as STL files that they then imported into ANSYS Workbench. A tetrahedral mesh was generated in the central connection area, and five boundary-fitted prism layers were created at the near-wall regions to improve the resolution with which fluid motion could be determined in this critical area.

Mass flow rates measured by the MRI on each vessel entering the PA were imposed as boundary conditions. They set a static pressure boundary condition at the outlet of the left pulmonary artery (LPA) and set five different static pressures at the outlet of the right pulmonary artery (RPA) to vary the relative flow rates between the LPA and the RPA. The flow rates were varied (40:60, 45:55, 50:50, 55:45 and 60:40) because different levels of vascular resistance of the LPA and RPA lead to this degree of disparity in patients. The team calculated the power loss in each simulation based on the static pressure, velocity and flow rate on the cross-sections of each of the five vessels.

DETERMINING THE IDEAL SURGERY

The results showed that the power loss was the lowest and the energy efficiency the highest in the TCPC 2 configuration, while TCPC 4 provided the largest power loss and the lowest energy efficiency. TCPC 1 and TCPC 3 fell in between. The variation in the relative pulmonary flow rates (LPA:RPA) did not affect the relative ranking of the different TCPC surgical options; however, it did significantly affect the relative differences between these options. For example, the value power loss reached its lowest level at an LPA:RPA flow ratio of 50:50 in TCPC 1 and TCPC 3. However, in TCPC 2 and TCPC 4, the flow domain power loss kept decreasing as the RPA flow ratio increased.

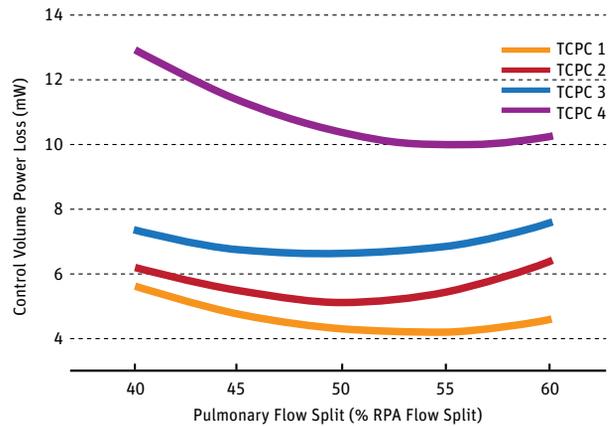
The flow pattern results helped explain why the different designs performed as they did. For example, the results



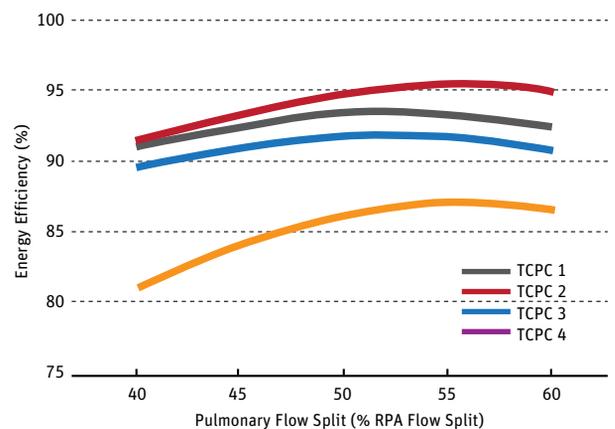
▲ Velocity flow streamlines for the four different models (front view shown on top and back view on bottom) showing direction of flow. Each inlet is represented by a different color.

showed that the particular connections used in TCPC 1 caused interaction between the IVC and LSVC streams, producing turbulence that wasted power. However, when the connection was moved in TCPC 2, there was no turbulence in this area. Researchers concluded that the streams from the LSVC and RSVC should not interact with the IVC in order to avoid turbulence and resulting power loss.

Based on the simulation results, Shanghai Children's Medical Center researchers recommended that the TCPC 2 surgical configuration be performed on the patient. Once researchers optimized the surgical procedure, they printed a



▲ Power loss for the different geometries and flow splits



▲ Energy efficiency for the different geometries and flow splits

3-D model of the recommended surgical geometry as a guide for the surgeon. At the patient's 5-year and 10-year follow-ups, he showed no signs of cardiac failure and displayed normal physical capacity. The latest echocardiogram showed no obstructions in the reconfigured areas of the circulatory system and normal cardiac function. Both sides of the branch pulmonary arteries were well developed. While it is not yet practical to perform simulation on every patient, one of the goals of the research team is to reduce the time and effort required for simulation in order to make this possible in the future. Another goal is improving the accuracy of the simulation by using a transient simulation with boundary conditions controlled by a user-defined function (UDF) to model the variations in inlet flow and velocity during the pulmonary cycle.

It is hoped that using accurate simulation in conjunction with skilled surgery will increase the effectiveness of these procedures and provide these young patients with better quality of life. ▲