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# A New System for Surgery



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## Virtual surgery could help doctors treat complex congenital heart defects.

Medical researchers adopt best practices from every possible discipline to keep patients from dying and improve the quality of their lives. A team from Politecnico di Milano in Italy is working with a network of researchers from around the world to apply systems modeling to help physicians make surgical decisions for children born with a heart condition called hypoplastic left heart syndrome (HLHS). This is a congenital heart condition that results in only one functioning ventricle. Medical advances over the last two decades have allowed successful palliation and survival for some, but these children must undergo at least three surgeries, multiple interventions and a lifetime of abnormal physiology as their hearts function with only two chambers instead of the normal four. Many children do not survive after every stage of the surgery since their physiology remains in a tenuous state.

Multidomain modeling becomes critical when considering biofluid dynamics in reconstructive pediatric cardiac

surgery, in which a systems approach to predict the results of surgery is both appropriate and appealing. Because there is a wide spectrum of possible surgical treatments to repair a complex heart defect, patient-specific multidomain modeling can help considerably in choosing the best treatment to ensure optimal blood flow for the patient, ultimately improving quality of life.

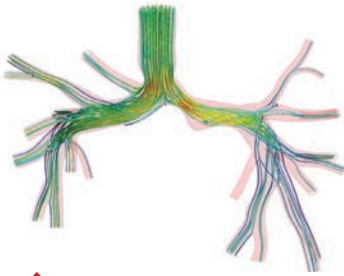
Politecnico di Milano participates in a collaborative cardiovascular team for the nonprofit Transatlantic Network, a group that pools a critical mass of competence and skills to advance medical knowledge. Network partners provided a 3-D reconstruction of the pre-operative anatomy of a patient, including detailed pulmonary branches from magnetic resonance (MR) images. A lumped parameter network (LPN), which simplifies the description of the remaining circulation, was built based on the MR-measured flows and catheterization pressure tracings available for that patient. The LPN took the form of a nonlinear ordinary differential equation (ODE) system. Researchers created virtual reconstructions of the different surgical options while maintaining the pre-operative anatomy of the

pulmonary vasculature. These 3-D models could then be coupled with the LPN and fluid dynamics results calculated with ANSYS Fluent software to determine blood flow distribution across the arteries and energy losses at the surgical connections.

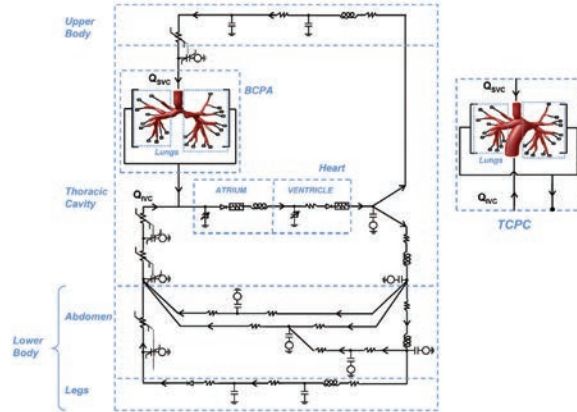
The research team carried out simulations by coupling 3-D and LPN models through user-defined functions. An explicit Euler method was used for the solution of the ODE system for the LPN with a fixed time-step of  $10^{-4}$  seconds. The exchange of information in terms of pressures and flows took place at the interfaces between the LPN and the CFD model, physically located at the inlet/outlet cross sections of the 3-D model (superior vena cava, inferior vena cava [IVC], left pulmonary artery and right pulmonary artery). The transient Navier–Stokes equations in the 3-D rigid-walled domains were solved with Fluent. Second-order upwinding for momentum and standard discretization for pressure were chosen. The team completed simulations using an Intel® Core™ 2 Duo (3 GHz) processor with a 64-bit operating system, taking three days to complete the 48,000 time steps, corresponding to a physical process of 4.8 seconds, or two respiratory cycles, each of them equal to about four cardiac cycles.

## SURGERIES REQUIRED FOR CHILDREN BORN WITH SINGLE-VENTRICLE HEARTS

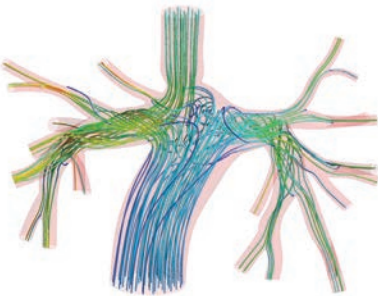
SURGERY	AGE OF CHILD	PURPOSE
Norwood	A few days	Connect functioning ventricle to rest of circulation system
Bidirectional Cavopulmonary Anastomosis (BCPA)	Four to six months	Increase blood flow to lungs
Total Cavopulmonary Connection (TCPC)	Two to three years	Reroute venous return directly to lungs, achieving normal sequence of blood flow (de-oxygenated blood flows to lungs, oxygenated blood to body)



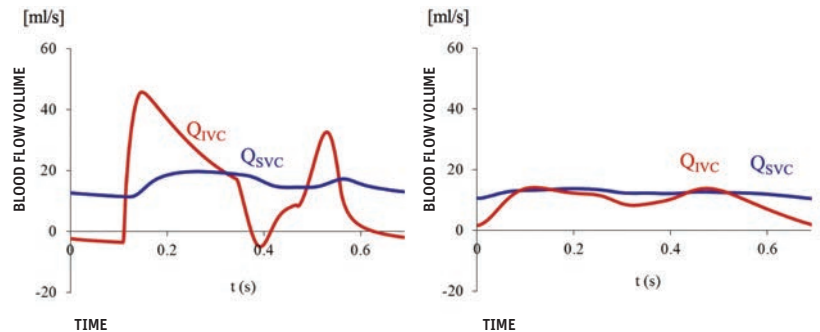
Pathlines color-coded by velocity magnitude at BCPA surgery site. Pathlines simulate the injection of contrast medium in superior vena cava and allow assessment of blood distribution from the upper body into pulmonary arteries.



Pre-operative 3-D model of stage 2 BCPA coupled with lumped-parameter model of circulation (left); post-operative 3-D model of stage 3 TCPC (right). The model on the right is coupled with the same lumped-parameter model of circulation for prediction of post-operative hemodynamics. Patient anatomy courtesy Lucile Packard Children's Hospital, Palo Alto, Calif., U.S.A.



Pathlines color-coded according to velocity magnitude at TCPC surgery site. They simulate injection of contrast medium in the superior and inferior vena cavae and allow assessment of blood distribution from the upper and lower body into pulmonary arteries.



IVC: Inferior vena cava SVC: Superior vena cava

Inlet flows after BCPA (left) and TCPC (right) operations. The change in blood volume flow in IVC on the right is affected by coupling the CFD 3-D model with the LPN; it would be impossible to predict this without use of a multidomain model. The LPN delivers more realistic boundary conditions for the CFD model.

Many potential benefits arise from the application of in silico simulation techniques to this field. For example, using simulation results to chart the blood volume flow over time in the two vena cavae after specific surgeries clearly shows how the pulsatility of the IVC flow after bidirectional cavopulmonary anastomosis (available from the LPN model only, mean value = 12.95 mL/s) can be predicted to significantly dampen down after total cavopulmonary connection (TCPC, mean value = 9.57 mL/s).

Without use of a multidomain approach, a 3-D stand-alone model of the TCPC would have completely missed this feature. Therefore, the flow model provides the surgeon with a flow prediction that accounts for the interaction between surgical technique and patient variability.

A further future benefit is that this method could be applied to educate and train young doctors. The ability to simulate a number of pathophysiological scenarios (for example, the effects of drug administration or exercise) as well as to

visualize complex fluid surgical treatments shows enormous potential for training students before they start to apply their skills in the operating room. 🚨

The study is part of the work under way within the five-year Transatlantic Network project Multi-Scale Modeling of Single Ventricle Hearts for Clinical Decision Support, funded by the Foundation Leducq, Paris, France. [www.fondationleducq.org/nivel2.aspx?idsec=1180](http://www.fondationleducq.org/nivel2.aspx?idsec=1180).