Integration of in-silico and in-vivo data for patient-specific outcome assement in univentricular circulation

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Hypoplastic Left Heart Syndrome (HLHS) is a congenital condition which can severely impair health conditions. In subjects affected by HLHS, the left ventricle is underdeveloped or not functional at all, so that it can not support systemic circulation. This is one example of the so-called univentricular condition, in which only one ventricle is functional, and the clinical management must provide for both pulmonary and systemic circulation, taking account of the severe physiologic impairment. Not earlier that 30 years ago comfort care was the only option for HLHS; now, instead, there are a number of therapeutic options available for families, although the optimal treatment approach is still under debate.

HLHS represents 2–3% of all congenital heart diseases. The natural history of HLHS is of such a gravity that, without treatment, it would be responsible for no less than 25–40% of all neonatal cardiac deaths (Murdison KA et al. Circulation 1990), since it is fatal within a few weeks from birth in 95% of cases.

Starting from the 1980s, the best clinical practice treatment is given by the use of the right ventricle to drive systemic circulation. This is achieved after a series of surgical operations, gradually preparing the patient, until the final configuration: the Total Cavopulmonary Connection (TCPC), i.e., the connection in which the venae cavae (issuing deoxygenated blood in the right atrium, in the healthy subject) are anastomosed to the pulmonary arteries, thereby shunting the heart.

A multidisciplinary approach is required, due to the complexity of the disease and individual peculiar features, so that it can not be assumed that a standard HLHS anatomy exists. The surgical treatment of HLHS, as well as of all the pathologies leading to univentricular circulation, requires careful planning in order to optimize the mechanical power exerted by the functional ventricle, avoiding power dissipations as much as possible.

In the framework of a collaboration between ISS (Italian National Institute of Health) and the Bambino Gesù Children's Hospital in Rome (OPBG), we obtained a patient-specific model of the central venous and pulmonary compartments, starting from diagnostic MRI data after follow-up of a HLHS subject, previously operated on at the OPBG, and to calculate the flow field associated to the obtained numerical model by means of Computational Fluid Dynamics (CFD). The individual variations in the presentation of the disease call for a fine-scale knowledge of the flow field ensuing from the surgery, therefore a personalized assessment of the clinical outcome is mandatory.

A numerical model of the patient's circulation was obtained. The inlet sections of the blood compartment were the inferior (IVC) and superior vena cava (SVC); the outlet sections were the left pulmonary artery (LPA) and the two branches (RPA_{inf} and RPA_{sup}) of the right pulmonary artery, after the first bifurcation. The boundary conditions were set according to clinical data.

CFD results (Fig. 1) show that the morphology of the calculated flow field was highly dependent on the closeness of the IVC and SVC anastomoses to the right pulmonary bifurcation: this entailed a complex flow field, with a marked deviation of the pathlines' direction. Considering ideal particles flowing in the model through either of the two outlet sections belonging to the RPA, it was found that these particles had been released in both cases by the IVC as well as by the SVC. This finding is clinically relevant, in that the IVC flow (carrying hepatic factors from the liver) contributes to either pulmonary branch of the RPA: it must be emphasized that the hepatic factors are essential for the physiological growth of the vessels, hence the personalized assessment of the outcome enabled to verify that such important requisite was satisfied. Similarly, ideal particles travelling through the left PA's outlet showed that both IVC and SVC contributed to the pulmonary flow.

The power lost in the connection was found to be 4.357 mW, which compares favourably with previously reported results (Liu Y et al. 2004). The hydraulic efficiency of the connection was found to be high (94%).

We intend to continue the long-standing collaboration between ISS and OPBG, analyzing patient data in support of this surgery. This will eventually lead to the creation of an atlas of reconstruction surgeries, addressing also other diseases than the HLHS.

Population health and health sector benefits – Albeit not a frequent disease, HLHS represents a very serious condition. The surgical treatment is similar to other congenital cardiocirculatory pathologies and calls for a personalised approach, involving clinicians as well as bioengineers. This collaborative activity is geared towards minimizing the known long-term morbidities of univentricular conditions, i.e., declining exercise capacity already from early adolescence on, and liver disease (Nakano et al, Eur J Cardiothor Surg 2015). The presented activity will form the basis for disseminating patient-specific practices, showing that surgical planning as well as personalized outcome assessments are useful in the management of complex health conditions and, when optimised, can limit the need for organ transplantation frequently presented by the univentricular patients, in the long term.

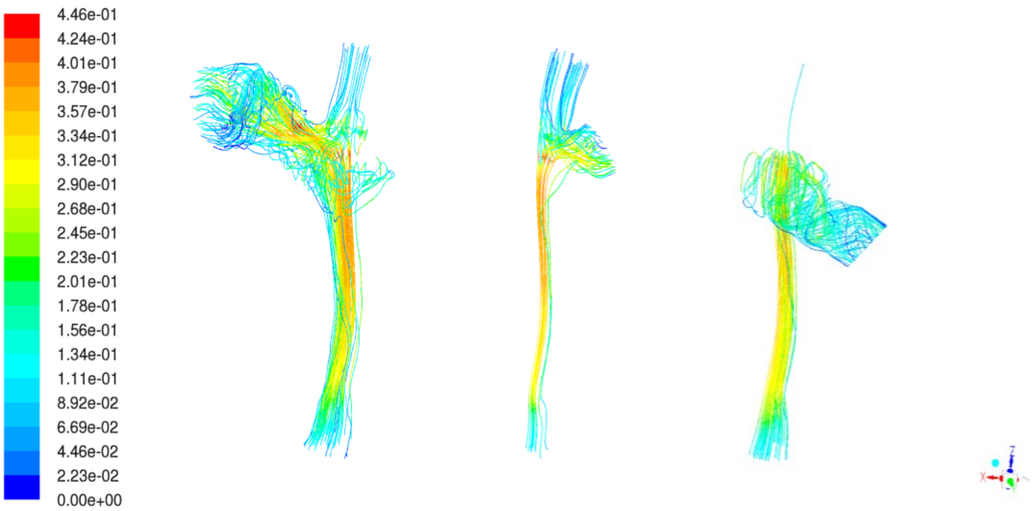

Figure 1 – Pathlines showing the contribution of IVC and SVC flows to each outlet section (from left to right: LPA, RPA_{sup}, RPA_{inf}*) of the pulmonary arteries*