Copernicus: A cloud-based HPC platform to support systemic-pulmonary shunting procedures

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Congenital heart diseases (CHDs) account for nearly one-third of all congenital birth defects. Since the prevalence of CHDs cannot be altered, interventions and resources must be focused to improve survival and quality of life. The modified Blalock Taussig shunt (mBTS), a common palliative operation performed on patients with cyanotic heart diseases, is unfortunately associated with significant mortality with the most threatening complications being over-shunting and shunt thrombosis. The proposed experiment aims to realize an application to support surgical planning using advanced numerical means, presented in an interactive and effective manner.

The challenge: creating innovative solutions to support surgery for congenital heart disease

InSilicoTrials Technologies and RBF Morph are innovative SMEs that offer a portfolio of software and services to clinics and medical research. To expand their business, the SMEs joined forces under the FF4EuroHPC project with RINA Consulting, CINECA and Fondazione Toscana Gabriele Monasterio to tackle the challenging field of CHDs. CHDs are a significant health problem, being the seventh leading cause of death for children under one year of age in 2017. Although the prevalence of CHDs cannot be changed, interventions and resources can focus on improving the survival rates and quality of life of those affected.

A common palliative operation for CHD is mBTS, which provides blood flow from the systemic circulation to the lungs. However, despite its simple concept, the mBTS procedure is associated with significant morbidity and mortality, with over-shunting and shunt thrombosis being the most serious and life-threatening complications. The criteria for determining shunt size, length, and position remain a matter of debate, as a shunt diameter that is too small can lead to shunt thrombosis due to high wall shear stress, while a shunt that is too large may cause pulmonary overflow, decreased diastolic pressure, and reduced systemic perfusion.

Computational simulation can help support medical decisions and improve surgical outcomes by modelling the effects of different shunt sizes and positions. However, it requires considerable computing power and expertise to provide accurate results in a short time. By combining the expertise of all organizations involved, and with the fundamental tools provided by the HPC environment, this FF4EuroHPC experiment creates an opportunity to generate new business opportunities for the partners in the sphere of advanced medical modelling.

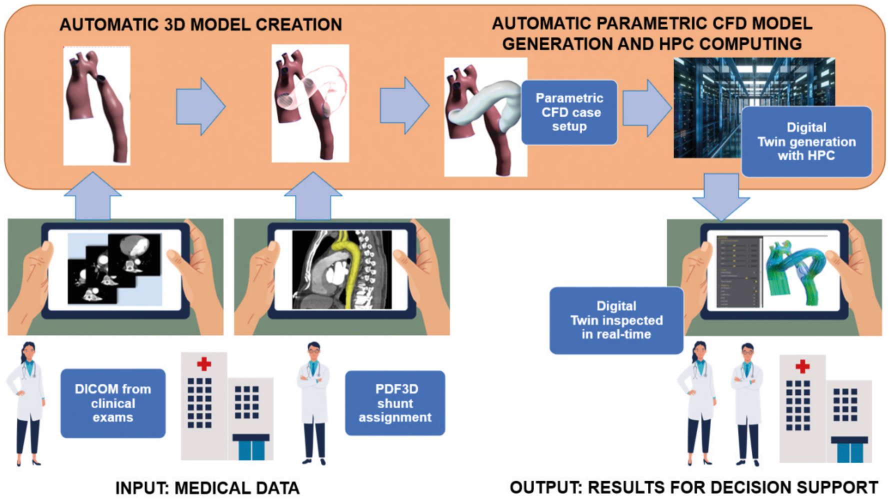

Fig. 1. The Copernicus concept: the process starts and ends in the hands of the medical staff. The creation of the medical digital twin is powered by high fidelity CAE, mesh morphing, and HPC.

The solution: development of a medical digital twin to simulate the surgical intervention

This experiment faced a significant challenge in creating a cost-effective decision support web application called "Copernicus" to assist surgeons in their approach to mBTS medical interventions. Simulating the impact of such surgery on blood flow requires complex computational fluid dynamics calculations on high-performance systems. However, these calculations are still far from being used in clinical practice during preoperative planning due to the specialized knowledge required to perform them.

To overcome these problems, Copernicus generates a medical digital twin (MDT) of the patient's vascular district through a reduced order model (ROM), which condenses the complex and expensive preloaded calculations. This allows the size and positioning of the shunt implant to be varied interactively in a geometrically parameterized process. Medical personnel can thus inspect the patient's MDT and observe how the planned intervention will affect the fluid dynamics of the impacted area.

The platform's dedicated user interface enables the medical team to make surgical decisions more efficiently. By using the HPC, the time required to perform the demanding preloaded analysis that supports the MDT is significantly reduced. This acceleration is crucial as important decisions regarding mBTS preparations have to be made in a short time, usually within two days, in the case of complicated morphologies. Validation through retrospective clinical data has improved the readiness level of the Copernicus platform, enabling business exploitation with minimal additional effort. By harnessing HPC, ROM, and the power of interactive visualization, the Copernicus platform provides an innovative and effective tool to improve medical decision making in the treatment of CHDs.

The Copernicus concept is explained in Fig. 1 with the medical part shown in green at the bottom of the diagram, and the CAE shown in orange at the top. Using a tablet, medical personnel inspect the image data stored in DICOM, the data interchange standard for biomedical imaging. Once approved, the geometry enters the computer aided engineering (CAE) part where automatic AI-powered segmentation allows the aortic arch district to be extracted. The segmentation results are then displayed to the surgeon who assigns an initial shunt placement according to current best practice.

The CAE part defines the prosthetic geometrical model with the shunt placement and lateral parameterization. This parametric model is then used to define hundreds of variations (i.e. possible surgical scenarios). Thanks to HPC all variations are calculated and then distilled into a reduced order model that is the engine of the interactive surgery MDT. The MDT can be inspected by the medical team so that the initial assumption provided for placement can be refined to achieve the best compromise for the patient. It is worth noting that, from the perspective of the medical personnel, this approach is displayed as an augmentation of the data available on the original patient image data.

The technical implementation of Copernicus is depicted in Fig. 2. The orange section summarizes the pre-processing steps. The starting point is the segmentation of the CT image stored in the DICOM file. The aortic arch is automatically extracted and is ready to be displayed to the surgeon. It will be used in CAE as the surface of the relevant vessels. Once the surgeon's input is received (an automatic process), the CAD SpaceClaim tool allows the input data to be transformed into a CAD Boundary Representation (BRep) model of the patient's vascular district with the shunt positioned according to the proposed hypothesis solution.

The CAE model, i.e. a CFD model, is then generated using the Ansys Fluent meshing with watertight geometry technology. RBF Morph software is then used to make the geometry and positioning of the shunt parametric (Fig. 3). The positions of the insertion points on the vessels can be changed along with their angles and the size and length of the shunt. The configuration of the RBP (ROM builder preprocessing)

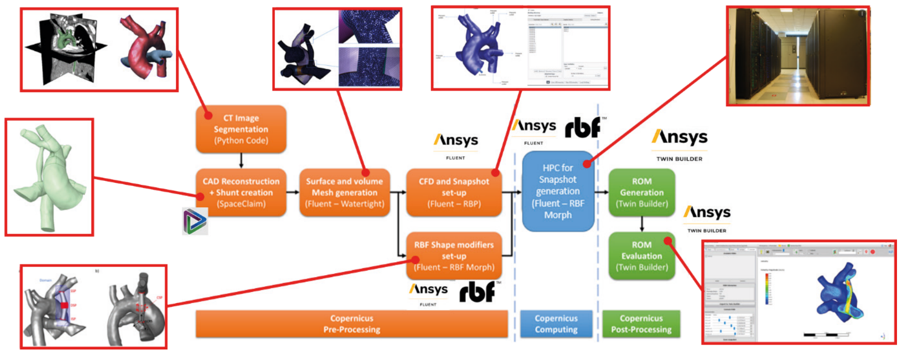

Fig. 2. The implementation of the Copernicus solution in detail: from the DICOM medical image to the interactive medical digital twin.

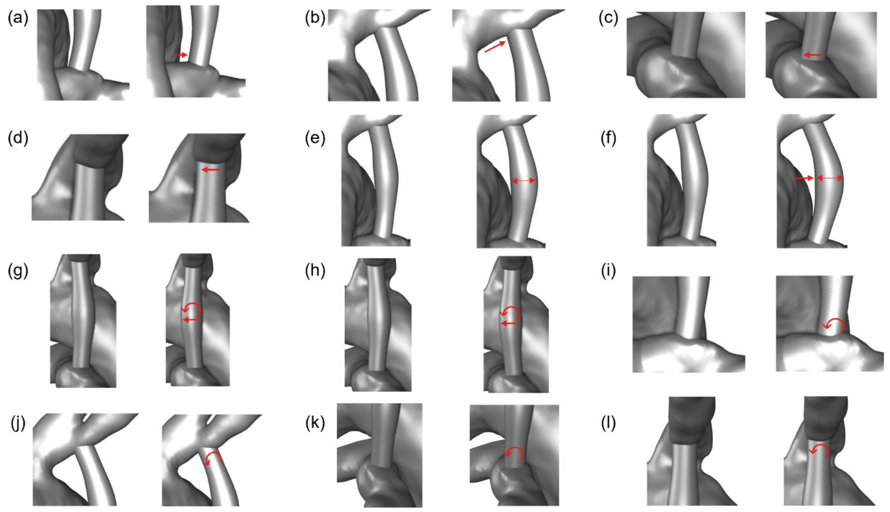

Fig. 3. Shunt shape and placement.

extension to the Fluent solver is conducted so that the solver, coupled with RBF Morph, is ready to calculate and store the CFD simulation results as snapshots, ready to be processed for data compression. The next step is performed on the HPC cluster where Ansys Fluent in combination with RBF Morph enables the creation, solution, and storage of all required snapshots (150 in the current workflow). Once the HPC runs are complete the post-processing phase can begin (Fig. 2).

Ansys Twin Builder is used to generate reduced order models from the snapshots; both geometry variation and flow solutions are captured by using POD (proper orthogonal decomposition); the number of modes stored allows the prescribed accuracy to be achieved.

The interactive ROM representative of the MDT is now ready to be inspected by the medical team using Twin Builder's ROM visualization tool.

The success story presented in this article was developed during the first tranche of FF4EuroHPC Project. FF4EuroHPC supports the competitiveness of European SMEs by funding business-oriented experiments and promoting the uptake of advanced HPC technologies and services. The experiment is an end-user-relevant case study demonstrating the use of cloud-based HPC (high-performance computing) and its benefits to the value chain (from end-user to HPC-infrastructure provider) for addressing SME business challenges that require the use of HPC and complementary technologies such as HPDA (high performance data analytics) and AI (artificial intelligence). The successful conclusion of the experiment created a success story that can inspire the industrial community.

A solution with the potential to disrupt the medical field and save lives

The proposed Copernicus solution has the potential to have a significant impact on the clinical field by enabling surgeons to make informed decisions about CHD treatment with greater accuracy and speed, leading to a reduction in post-operative complications and recurrences, and ultimately a reduction in hospitalization costs.

The Copernicus solution represents a promising opportunity for the partners involved to expand their activities and contribute to the advancement of medical modelling.

In the era of the precision medicine, the ability to more accurately provide the biomarkers of patients, using more clinical data, imaging, and other variables enables the healthcare system to guide diagnosis and treatment more precisely. The concept of the medical digital twin, and its related virtual representation of a patient, therefore, is the approach to achieve this. In fact, such an approach is able to reduce the costs to the health system and increase the safety of interventions for the operators and the patients by developing ad-hoc, patient-specific procedures with the added benefit of also safely harnessing different virtual therapeutic and treatment scenarios.

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