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A VIRTUAL TEST BENCH FOR HEMODYNAMIC EVALUATION OF AORTIC CANNULATION IN CARDIOPULMONARY BYPASS

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Introduction

Cardiopulmonary bypass (CPB) is a common practice in cardiac surgery. In this technique, venous blood is directed from the venous system to a heart-lung machine and then returned to the aorta through an inserted arterial cannula. Among the perioperative and postoperative complications, a reduction of cerebral perfusion, resulting in neurological complications, is observed, linked to the reduction of blood flow from the aortic arch to the carotid artery. Related to the altered flow conditions induced by the arterial cannula, a second major complication is an increased risk of thromboembolic events, caused by the mechanical activation of platelet aggregation pathways, induced by the highly disturbed flow patterns. Thus, the study of the effect of cannulation and its influence on the described mechanisms is of high clinical relevance and could allow the optimization of therapeutic performances. Currently, there is very little guidance for the surgeons regarding optimal clinical use parameters. In this study, we implemented a computational fluid dynamics (CFD) model to numerically assess the fluid dynamics generated by the arterial cannula. Mesh morphing techniques based on radial basis functions (RBF) are used to explore clinical use parameters that influence surgery performances. As an example of the parameters that can be analysed with the developed benchmark, the cannula insertion angle is considered and its effect on flow dynamics-related thromboembolic risk and supra-aortic arteries perfusion is evaluated.

Methods

A three-dimensional computer-aided design (CAD) geometry of an ostensibly healthy human thoracic aorta including subclavian, carotid and brachiocephalic arteries was reconstructed from 4D PC-MRI images. A CAD model of outflow cannula with a straight tip (Sorin Group) was selected and positioned 2 cm below the orifice of brachiocephalic artery, according to the clinical practice, using the open source software Vascular Modelling ToolKit (VMTK, www.vmtk.org). The finite volume method was applied to perform numerical simulations under steady flow conditions. Blood was assumed as an isotropic, incompressible, homogeneous, Newtonian viscous fluid, with a specific mass value equal to 1060 kg/m^3 and a constant dynamic viscosity value equal to 3.5 cP. The arterial walls were assumed rigid with no-slip condition. A steady volume flow rate of 4.5 L/min is imposed at the inlet section and stress-free conditions were imposed at the outlet sections. No flow from the left ventricle was simulated, imitating the in vivo situation during cross-clamping. The prescribed volumetric flow rate implies a Reynolds number of $8 \cdot 10^3$ in the cannula tip, thus to simulate a real case it is necessary to adopt a turbulent model. A standard *k-ω* model was adopted. The general purpose CFD code Fluent (ANSYS Inc., USA) was used on hybrid hexahedral-tetrahedral computational mesh-grids, generated using ICEM-CFD (ANSYS Inc., USA). The fluid domain was divided into about $1.1 \cdot 10^7$ cells. To automatically update the existing mesh in consequence of modifications of the arterial cannula angle of insertion, a mesh morphing technique was adopted. In detail, the tool RBF Morph, whose implementation is based on radial basis functions and it is available for ANSYS Fluent, was used (http://www.rbf-morph.com). Three cannula insertion angles relative to the aortic arch wall normal were considered: 30°, 35° and 40° (Figure 1). To evaluate the mechanical activation of platelets and the consequent risk for thromboembolic events, the Lagrangian-based model of shear-induced platelet activation proposed by Grigioni et al. was applied [1]. The model takes into account for the cumulative load history sustained by platelets moving along a generic fluid path to define the Platelet Activation State (PAS):

$$PAS = \int_{t_0}^{t} Ca \left[\int_{t_0}^{\phi} \tau(\xi)^{b/a} d\xi + \frac{PAS(t_0)^{1/a}}{C} \right]^{a-1} \tau(\phi)^{b/a} d\phi \tag{1}$$

Where a, b and C are experimentally-calibrated constants [2] and τ is the shear stress.

Results

The cannula insertion angle greatly influenced the perfusion of carotid artery: the flow rate percentage was of 13.40%, 1.50% and 0.45% of the inflow for insertion angle of 30°, 35° and 40°, respectively. Particle trajectories visualization (Fig. 1) put in evidence the presence of complex flow patterns in the aortic arch. In particular, increasing the insertion angle, a rotating structure develops right downstream of the cannula tip. Color-coding with respect to PAS values shows that particles moving near the cannula wall are activated at higher levels, independently of the cannula insertion angle. In conclusion, a computational framework for the exploration of optimal clinical use parameters has been developed. The developed tool can also help the design and optimization of the arterial cannula, exploring the effect of shape modifications on clinically relevant parameters used as measure of performance. In future, a cerebral autoregulation model will be integrated in the framework.

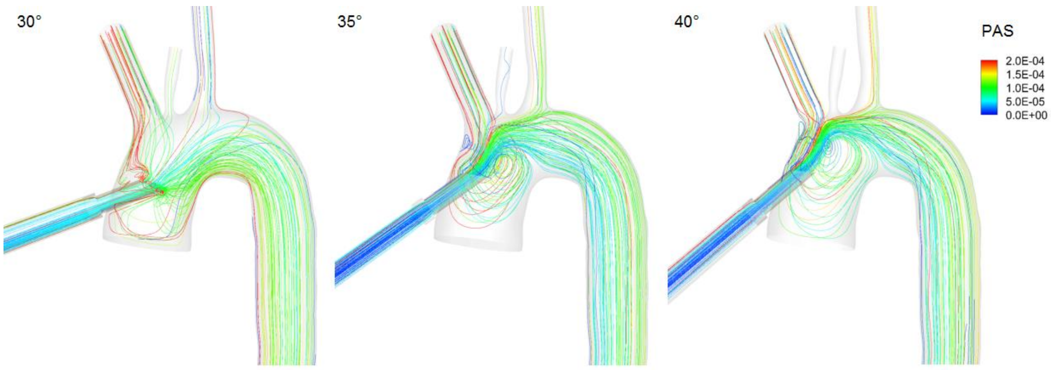

Figure 1. Trajectories of platelet-like particle sets, color-coded with respect to local PAS value.

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