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CFD analysis of different arterial cannulation site during Heart Surgery with Cardioplumnonary Bypass

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Abstract

To assess, using a patient-specific computational fluid dynamics (CFD) analysis, hemodynamic characteristics of four different arterial cannulation sites routinely used during cardiopulmonary bypass (CPB). The arterial cannula was a standard 22 Fr diameter rigid cannula with a straight tip. A 3D real aorta model was generated from CT images using segmentation and reverse engineering techniques. The 22 Fr cannula was modeled and inserted at four common cannulation sites along the aortic vessel perpendicular to it. Each cannulation site was assigned to a clinical case-scenario characterized by the location of the arterial cannulation site: case 1, in the ascending aorta, 2 cm above the ST junction; case 2, in the aortic arc between the origin of the first two epi-aortic vessels (EAV) i.e brachiocephalic trunk and left common carotid artery; case 3, in the right subclavian artery; case 4, in the right common femoral artery. The assumption of identical boundary conditions was chosen for all simulations in order to enhance the only effects of arterial cannulation site onto blood flow distribution and Shear Stress indexes over the aortic vessel and its major branches. The flow was delivered through the cannula assuming the ascending aorta below the cannulation site was cross-clamped, as during open heart surgery.

Keywords: CFD, CBP, Cannula

1. Introduction

Cardiopulmonary Bypass (CPB) allows for temporary replacement of the pumping function of the heart and respiratory function of the lungs during open heart surgery (Morrow et al. 2008 and Niles et al. 2001). CBP does it by diverting blood flow through a circuit that drains venous blood from the right atrium, before pulmonary circulation, and returns it oxygenated to the systemic pressure with adequate perfusion pressure in the aortic vessel. The CPB circuit consists of:

- Venous cannulas: generally inserted into the superior and inferior vena cava
- A venous drainage line
- A reservoir for venous blood
- A series of mechanical pumps
- A heat exchanger
- An oxygenator
- An arterial drainage line
- An arterial cannula for the reinfusion of the blood into the native vascular system (i.e. the aorta or its major branches)

After the connection patient-to-CBP via arterial and venous cannulae, is established, the extracorporeal circulation is initiated. A cross clamp is applied onto the ascending aorta, well below the arterial cannulation site. The heart is arrested and the surgeon can operate into a bloodless field while CBP ensure adequate organ perfusion to the whole body. Operation time can go from two to seven-eight ours depending by the complexity of the surgery and its complications. According to patient's anatomy and the operation to be performed, especially the arterial cannula, can be positioned in different areas along the aortic vessel or its main branches. Cannulas are generally made of PVC and are reinforced with a metal coil to avoid kinking and potential malperfusion.

It seems easy to guess that the position of the CBP outflow cannula (arterial cannula) could play an important role in blood flow distribution to the body and eventually led to organ malperfusion during open heart surgery. However the correlation between blood flow distribution and different arterial cannulation site used during open heart surgery has never been quantified yet. We conducted a computational fluid dynamics (CFD) analysis using a patient-specific aorta model, to compare the hemodynamic characteristics of four different arterial cannulation sites routinely used during cardiopulmonary bypass (CPB) for heart surgery.

2. Methods

A 3D real aorta model was generated from Computer Tomography images using segmentation and reverse engineering techniques (de Moraes et al. 2011, Pham and Hieu 2008) (Figure 1).

The assumption of identical boundary conditions for all simulations was chosen in order to analyze the only effects in blood flow distribution and hemodynamics of the arterial cannula's site: a flow rate of 5 l/min was set at the inlet of the cannula; open boundary conditions were set in the outputs ; no-slip conditions were set on the walls from the native aorta because no flow was consedered, as it was cross-clamped.

A 22 Fr standard rigid cannula with a straight tip was modeled by means of commercial CAD software (Figure 2) using reverse engineering techniques.

Figure 1. Aortic Model

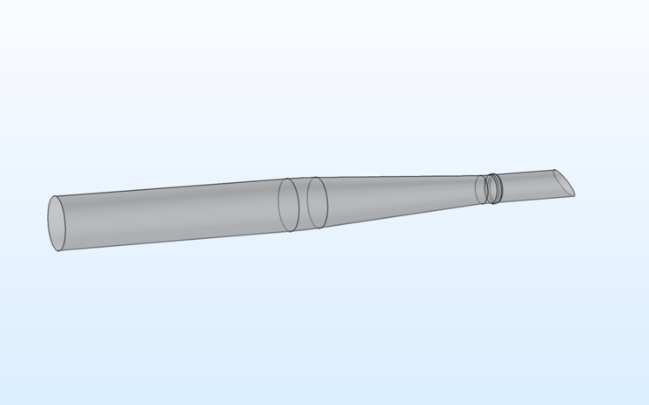


Figure 2. Cannula Model

Since the aorta is a large vessel and blood can be approximated as a Newtonian and incompressible fluid, we consider a density of 1,060 kg/m^3 (Cutnell and Johnson 1998) and a viscosity of 0.0035 Pa·s (Caruso et al. 2015).

The Computational Fluid Dynamics simulations were done using COMSOL 5.6 (COMSOL Inc, Stockholm, Sweden). The meshes had boundary layers and tetrahedral and triangular elements, with a total number of elements variable from 130000 to 150000, according to the geometry was optimized by analyzing the error trend as a function of simulation time (Figure 3).

The Pardiso solver was employed to solve the Navier- Stokes equations, choosing the P1-P1 discretization and a step of 0.001. The flow was considered as laminar, and 3D Navier-Stokes equations were used as governing laws (Gramigna 2015).

The incompressible condition gives:

$$\nabla . u = 0 \tag{1}$$

The governing equation used to solve the laminar model is:

$$\rho\frac{\delta u}{\delta t} + \rho(u.\nabla)\mathrm{u} = \nabla.\{-pI + \mu[\nabla\mathrm{u} + (\nabla\mathrm{u})^{T}]\} \qquad (2)$$

where ρ is the fluid density, u is the fluid velocity, p is the pressure, I is the unit diagonal matrix and μ is the viscosity (Gramigna et al. 2015). Each cannulation site was assigned to a clinical case-scenario characterized by the location of the arterial cannulation site: case 1, in the ascending aorta, 2 cm above the ST junction; case 2, in the aortic arc between the origin of the first two supra-aortic vessels (SAV) i.e brachiocephalic trunk and left common carotid artery; case 3, in the right subclavian artery; case 4, in the right common femoral artery.

Four cases were simulated:

- Case 1: Ascending Aorta
- Case 2: Aortic Arch
- Case 3: Right Subclavian artery
- Case 4: Right Common Femoral Artery

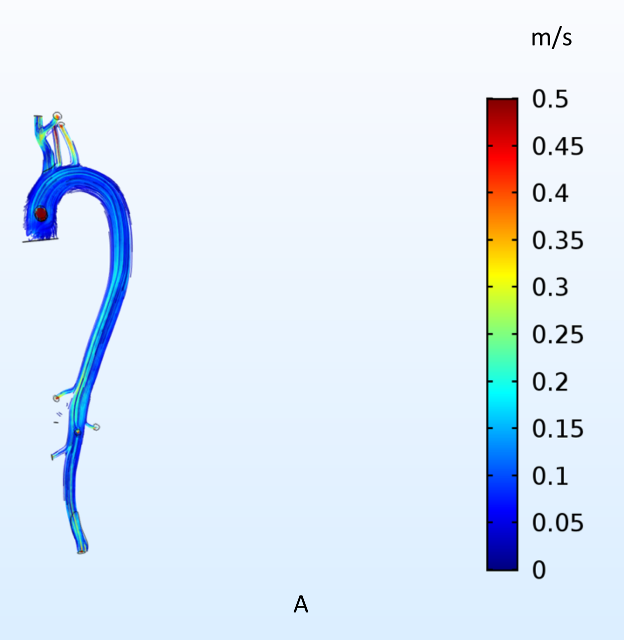
The aim of our study was to compare the hemodynamic characteristics of four different arterial cannulation sites routinely used during cardiopulmonary bypass (CPB) in terms of blood flow distribution to the aortic vessel and its major branches, flow pattern and shear-stress wall values (WSS). The CFD analysis allowed us to get data on a clinical scenario (hemodynamic changes depending on the location of the arterial cannulation site, during open heart surgery) that because of its nature is otherwise almost impossible to study in vivo (Caruso et al. 2015, Kaufmann et al 2009, Kaufmann et al. 2014).

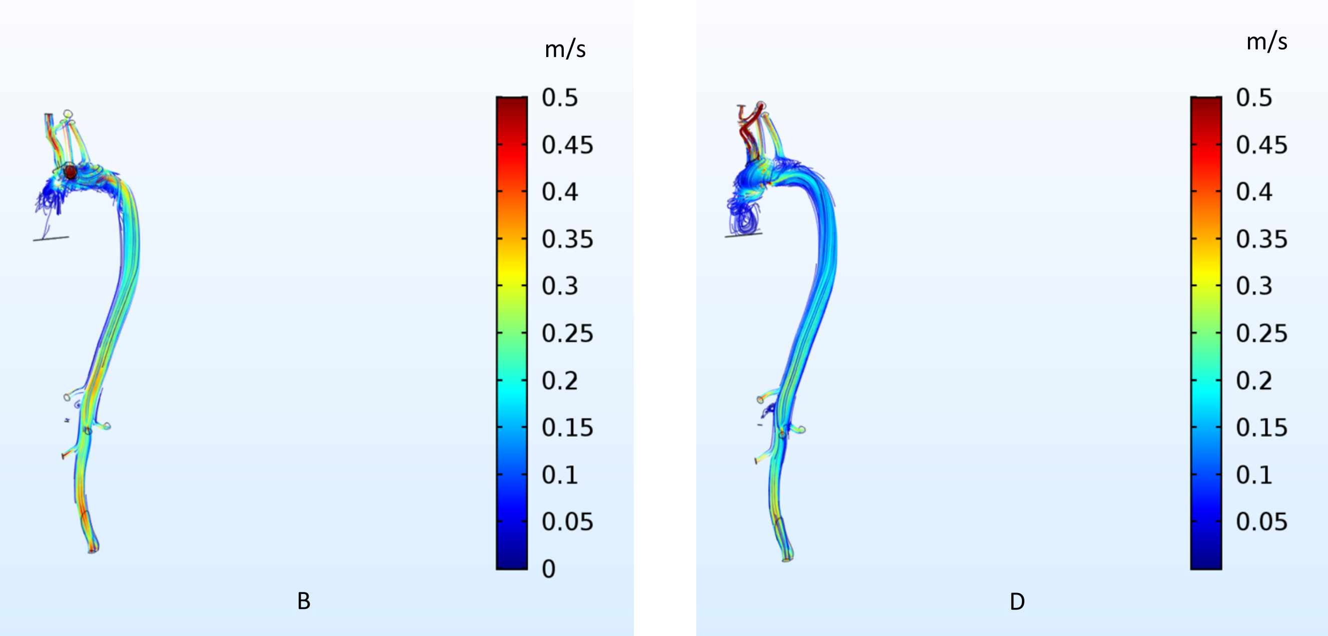
Figure 3. Mesh

3. Results

Blood flow velocity, flow distribution and Wall Shear Stress (WSS) along the aorta and its major branches were calculated for all the four configurations.

As for speed flow and pattern: case 1 has got a linear flow distribution and an homogeneous velocity never higher than 0,25 m/s (Fig. 4A). In case 2 we had higher velocity with peaks at 0.35 m/s in the istmic and abdominal regions together with a fast turbulent flow recirculation in the ascending aorta (Fig. 4B). The pattern was similar in the case 3 with the negative add on of peak velocity of 0.5 m/s in the bracheocefalic trunk (cannulation site) (Fig. 4C). Case 4 had the same highest peak velocity in the femoral artery and abdominal aorta with turbulent flow recirculation in the ascending aorta. High peak velocities were noted in this configuration also in the three epi-aortic vessels (EAV) (Fig. 4D).





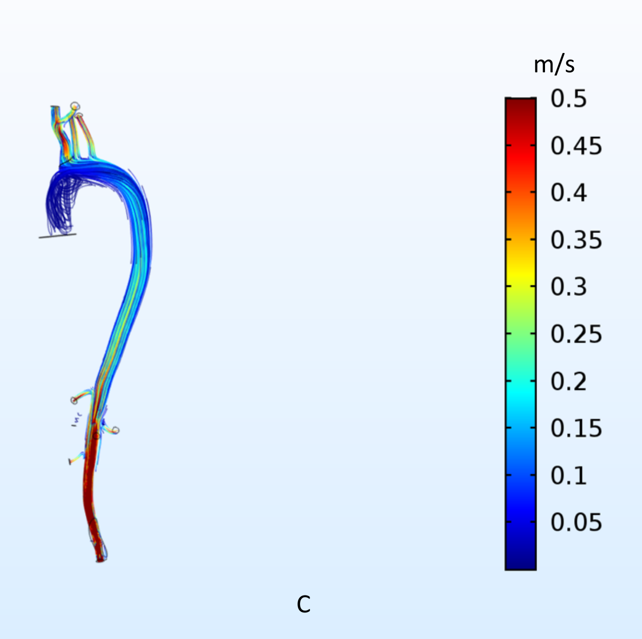


Figure 4 flow velocity streamlines along the aortic vessel and its main branches. Case 1 (A), case 2 (B), case 3 (C) and case 4(D).

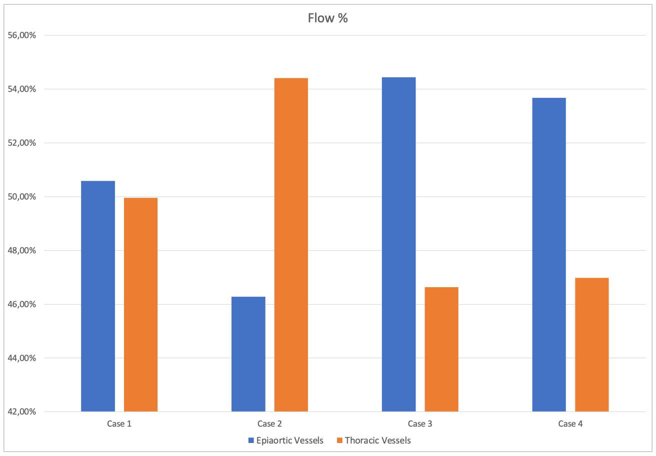


Figure 5. flow percentage distribution in epiaortic vessels (blue) and thoracic vessels (orange) for case 1, case 2, case 3 and case 4.

The wall shear-stress (WSS) value varied in the four case scenario (Fig. 6). Case 1 had the best WSS distribution (lowest and homogeneous along the aorta); followed closed by case 2. Case 3 and 4 showed highest WSS into the Bracheocefalic trunk and femoral artery, respectively (Fig.5 C-D).

Moreover, figure 5 reports the percentage of blood flow distribution during CBP in the thoraco-addominal district and in the EAV). The best balanced flow distribution belongs to case 1 (50,58% in the EAV and 49,42% in the Thoraco-abdominal district).

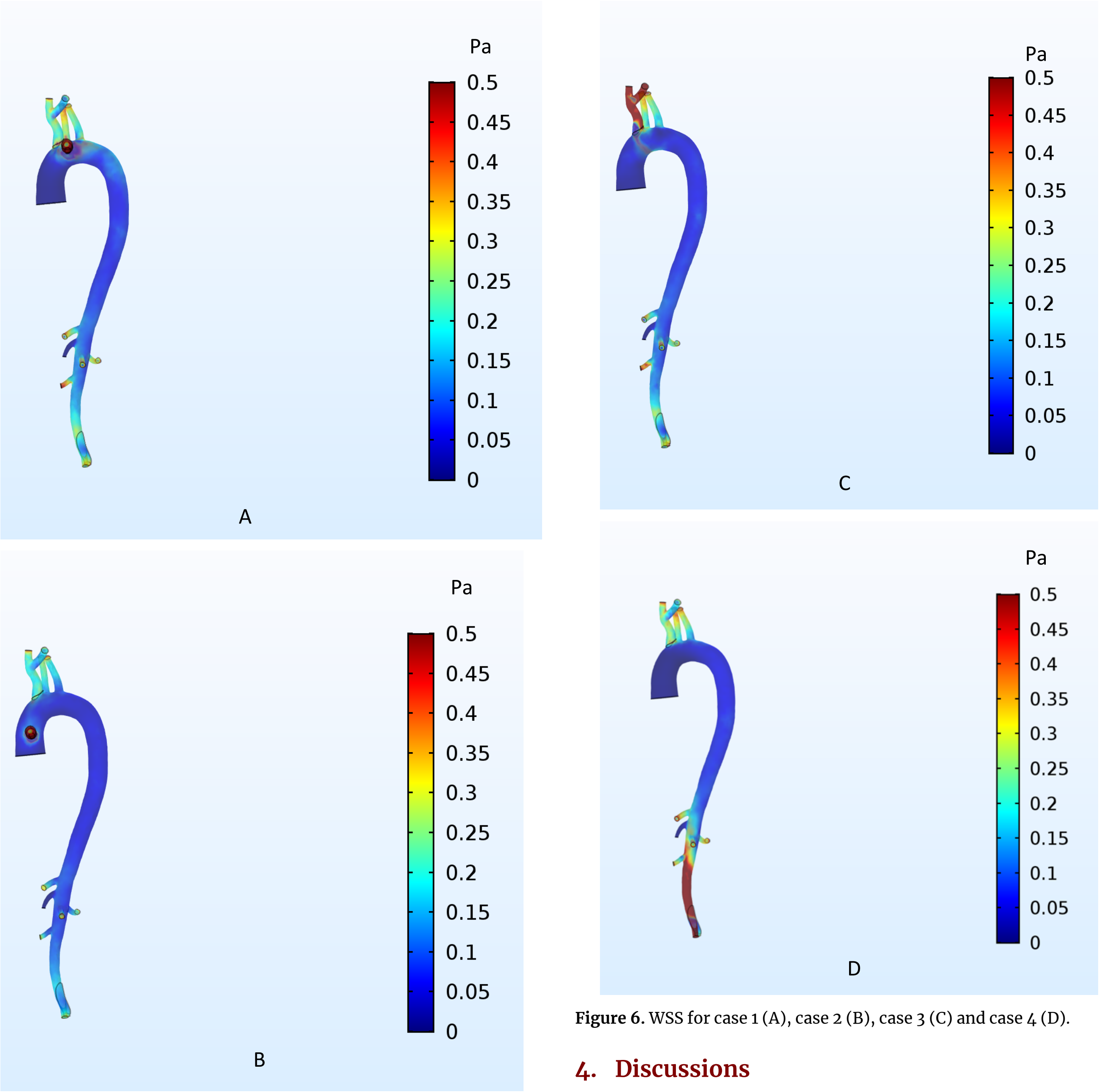


Figure 6. WSS for case 1 (A), case 2 (B), case 3 (C) and case 4 (D).

4. Discussions

The CFD analysis allowed to quantify the blood flow pattern and its distribution to the body during open heart surgery depending on the location of the arterial cannula along the aortic vessel. Our data suggest that case 1, i.e. arterial cannulation site at the ascending aorta, 2cm above the ST-junction, has got the best hemodynamic behavior: linear flow pattern, no high peak flow velocity, low WSS and balanced flow distribution between the upper and the lower body. This is encouraging giving that case 1 is the "standard" cannulation site historically used during CPB. Our study showed that despite old, that cannulation site should be always preferred by the surgeon, if possible, because gives the best CBP hemodynamic profile.

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