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In silico study of the dynamic interaction between extracorporeal circulation and native circulation

Abstract: An in silico investigation of modelled Extracorporeal Life Support (ECLS) via a femoral arterial cannula revealed the existence of both a defined separation zone between the opposing flows (ECLS, native flow) and different ranges dependent on flow distribution. The interaction between pulsating native circulation and constant ECLS flow is dynamic. A transient simulation model was developed to investigate the dynamic influence on this fluid mechanical interaction.

The in silico model is based on a CT-generated 3D model derived from a life-sized silicon aorta. A geometric standard cannula (16Fr) is inserted femoral. Inlet boundary conditions such as the temporal flow profile of a subject from the left ventricle (native circulation) and the flow from the femoral cannula are varied such that during transient simulations the summed flow (total perfusion) is 5.5 l/min. The outlet pressure boundary conditions at the branching arteries are selected such as to model the downstream vascular system.

Transient simulations revealed the dynamic effects of different flow fractions (Heart – ECLS) on the flow. Stationary simulations show a separation zone between the two flows, the position of which respectively the ECLS-range, oscillates dependent of the native circulation. Furthermore, it was noted that a raised pulse was impedimental to ECLS. This can be partly compensated by increasing the length of cannula inserted. At the same time the ECLS supply for the brain can improve at the cost of performance post-bifurcation. Increasing the ECLS fraction to above 50% flow led to retrograde flow combined with blood suction from the femoral artery.

The EMPAC project model has been further developed to include investigation of the dynamic effects of blood flow. This has made it possible for the first time to analyse in detail and evaluate the temporal effects of both opposing flows streams. A subsequent investigation explains whether aortic elasticity plays a significant role.

Keywords: ECLS, Femoral-arterial cannulation, Competing circulations, Computational Fluid Dynamics, Transient simulation.

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1 Introduction

At 38.5%, cardio-vascular diseases continue to be the most common single cause of death in Germany [1]. The most common reason for cardiac arrest is acute myocardial infarct. Loss of muscle performance or cardiac arrhythmia means the heart is unable to eject enough blood to the body. Should resuscitation after initial treatment for heart failure fail to restore cardiac sufficiency, the circulation requires restitution with Extracorporeal Life Support (ECLS) Systems. However, when the heart recovers and restores circulation, it works against the external artificial perfusion of ECLS, which in turn hinders fully cardiac recovery.

The serious medical condition of patients receiving ECLS clearly makes any sort of experimentation unethical. Systematic investigation of the complex physiology of such patients has hitherto been largely based on animal experimentation [2, 3] and mock circulatory loops (MCL). However, numerical simulation (in silico) is increasingly used to investigate blood supply during ECLS or Extracorporeal Membrane Oxygenation (ECMO) [4]. The EMPACs working group has developed a modified MCL (in vitro) that incorporates various elements of the human vascular system. In addition, a 3D simulation of MCL has been developed that, with the aid of computational fluid dynamics (CFD), circumvents technical measurement

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problems by offering post-processing options, and has proven suitable for investigating extreme physiological situations.

Confirming the findings of Stevens et al. [5], a separation zone between two flow systems (native and ECLS with femoral artery cannulation) could be identified, too. This separation zone exemplifies one of the difficulties with ECMO/ECLS, described in the literature as Harlequin Syndrome and characterised by upper body hypoxia [6, 7]. The different range of the separation zone dependent on the relative flow contributions from the left ventricle (LV) and ECLS were demonstrated, highlighting the difficulty in providing proximal aortic vessels with sufficient oxygenated blood.

ECLS flow is constant whereas the native circulation is pulsatile, and the investigation of dynamic effects on fluid mechanical interactions in this system requires such simulation modelling.

2 Materials and methods

In silico Finite Element Methods (FEM) and Computational Fluid Dynamics (CFD) are a relatively new addition to more traditional in vitro and in vivo experimental methods in medical research. They have proven excellent for the systematic testing of medical products such as heart valves, blood pumps, oxygenators and also ECMO / ECLS cannulas [5, 8, 9, 10], as these methods overcome limitations of conventional methodologies, and enable the qualitative and quantitative visualisation of previous unmeasurable parameters. They also allow the ethical investigation of extreme clinical situations.

2.1 Arterial anatomy model

The basis for in both the in vitro and in silico models is a silicone model of the arterial vascular system by United Biologics© (United Biologics, 2871 Pullman St, Santa Ana, CA 92705, USA). Computer tomography (CT) was used to scan the aorta caudo-cranially. The CT scan was run as base with tube voltage 90 kV, 80 m/As/ref, layer thickness 6 mm and pitch of 1.0. Mimics Innovation Suite by Materialise© (Materialise HQ, Technologielaan 15, 3001 Leuven, Belgium) was used for subsequent segmentation and processing. Finally, a 3D CAD model of the fluid volume was generated.

2.2 Simulation model

The simulation model consisted of the 3D CAD model of the atrial anatomy and a 16 French standard cannula using different insertion lengths, meshed fluid volume and physiological boundary conditions.

The solid volume of a geometrically standard 16 Fr cannula was inserted at lengths of 35 mm and 185 mm into the left superficial femoral artery. Boolean Subtraction was used to create the final fluid volume for both variants.

Tetrahedral elements were used for meshing. A prismatic layer including compression in direction to the wall provided adequate resolution in the boundary layer. The higher mesh quality (y+ Parameter < 10) was confirmed by a mesh check.

The Windkessel effect usually causes damping of fluctuation in blood pressure during the cardiac cycle. However, in this study, the aorta was assumed to be rigid. As with Dwyer et al. [11], there was no interaction between the compliance of the aorta and the stroke volume to afford net storage of blood during the systole. The major physiological boundary conditions applied are listed below:

- Duration: 3 Heart cycle
- Domain: Reference pressure = 90.0 mmHg
- Inlet: Velocity (t) from MRI
- Outlets: Opening
- Walls: no slip
- Fluid: Dynamic viscosity (non-Newtonian)
- Turbulence model: Shear stress transport (SST)

2.3 Variations

Flow fraction and pulse were varied during the simulation series.

Both volume flows (LV and ECLS) were varied in 25% complimentary steps such that for transient simulations the combined flow rate (total perfusion) through the arterial systems was 5.5 l/min.

Based on MRI flow measured at a pulse rate 70 bpm for individual recording intervals, intermediate values were interpolated for the subsequent simulations. Flow was then normalized to before pre-determined rate of 5.5 l/min. Captured data was thereafter transformed to a pulse of 110 bpm.

3 Results

Transient simulations showed the dynamic effect of the different flow fractions from the heart and ECLS on the overall flow situation within the arterial vascular system.

3.1 Separation zone

As already established for static simulations, a separation zone (SZ) formed between both flows, the position of which (i.e. the range of ECLS blood) oscillated, dependent on pulsation of the native blood circulation.

A clearly defined separation zone was also identifiable via Doppler ultrasound in EMPACs-MCL. In this separation zone the velocity of both fluid components drops to zero.

3.2 Impact of the pulse

An increased pulse reduced the ECLS fraction in the renal arteries and distal to the bifurcation. ECLS flow can only extend its range during diastole when the effect of LV flow is less. Increased pulse decreased the diastolic interval and thus also ECLS range.

The ECLS volume oscillates with the cardiac cycle within an identical region which with each cycle moves further into the aorta. At a pulse rate of 70 bpm it reaches to above the renal artery; at 110 bpm, this it reaches the renal artery after the third cycle.

3.3 Impacts of the incorporation length

At low LV flow, the longer insertion length ensured the ECLS fraction in contra-flow to the pulsatile LV flow reached the left carotid artery. A weak concentration of ECLS blood was even detectable as far as the brachio-cephalic trunk. However, longer cannula insertion negatively influenced supply post-bifurcation. This could be compensated by increased LV flow. Nevertheless, the increase resulted in a reduction in velocity at the extremities.

At a higher pulse rate (110 bpm) the greater insertion length provided better supply to the renal arteries due to ECLS. In contrast, the ECLS fraction in the internal iliac arteries was drastically reduced.

3.4 Impacts of the LV-flow

Both flows are complimentary, in other words increased LV flow drove the increasingly weaker ECLS flow further back so that the ECLS fraction in the renal arteries was significantly reduced. Increased insertion length delays this reduction.

Increasing LV flow increasingly improved perfusion of the left superficial femoral artery. With reduced LV blood was sucked out of the left side extremities. At 50% LV fraction a partial flow reflux occurred above both the bifurcation and in the cannulated left superficial femoral artery. Perfusion arising from increased LV flow or antegrade flow occured only during systole.

LV flow has a significant effect on ECLS range until the end of the third cardiac cycle.

4 Conclusion

Both simulation models (EMPACs research group) can be used to verify the complex haemodynamic processes in ECLS, thereby improving individual patient treatment.

EMPAC's previous simulation model has been extended to include the dynamic effects of the integrated circulation and risk-free simulation of potentially dangerous extreme physiological situations. This makes it possible for the first time to analyse and evaluate the temporal effects of the two competing circulations in detail.

Currently, verification via ultrasound and MRT is being done on an identical in vitro model. Future studies are needed to determine whether elasticity of the aorta plays a significant role.

Author Statement

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