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Three-dimensional computational model of a blood oxygenator reconstructed from micro-CT scans

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ABSTRACT

Cardiopulmonary bypass procedures are one of the most common operations and blood oxygenators are the centre piece for the heart-lung machines. Blood oxygenators have been tested as entire devices but intricate details on the flow field inside the oxygenators remain unknown. In this study, a novel method is presented to analyse the flow field inside oxygenators based on micro Computed Tomography (μCT) scans. Two Hollow Fibre Membrane (HFM) oxygenator prototypes were scanned and three-dimensional full scale models that capture the device-specific fibre distributions are set up for computational fluid dynamics analysis. The blood flow through the oxygenator is modelled as a non-Newtonian fluid. The results were compared against the flow solution through an ideal fibre distribution and show the importance of a uniform distribution of fibres and that the oxygenators analysed are not susceptible to flow directionality as mass flow versus area remain the same. However the pressure drop across the oxygenator is dependent on flow rate and direction. By comparing residence time of blood against the time frame to fully saturate blood with oxygen we highlight the potential of this method as design optimisation tool.

In conclusion, image-based reconstruction is found to be a feasible route to assess oxygenator performance through flow modelling. It offers the possibility to review a product as manufactured rather than as designed, which is a valuable insight as a precursor to the approval processes. Finally, the flow analysis presented may be extended, at computational cost, to include species transport in further studies.

1. Introduction

According to the National Health Service (NHS [19]) and Health and Safety Executive (HSE [10]), up to 25,000 people die of Chronic Obstructive Pulmonary Disease (COPD) every year and the disorder affects over a million individuals in Great Britain. In addition up to 400 people develop Acute Respiratory Distress Syndrome (ARDS) with a mortality rate of over 50%. Improving treatment techniques have a direct social and individual impact in saving lives, increasing life expectancy and reducing cost to the public health services. Two different methods are clinically approved and are used to transfer oxygen into the blood:

- Mechanical ventilation, mainly controlled by pressure and/or volume (Chatburn et al. [4]), transfers oxygen into the lungs of the patient for the gas exchange. Often the ventilation pressure and oxygen concentration are set very high to overcome the impaired lung function. A potentially resulting barotrauma, volutrauma and oxygen toxicity may prevent or slow down the lung recovery.
- Extra Corporeal Membrane Oxygenation (ECMO) is bypassing the cardiopulmonary cycle by oxygenating the blood outside the patient by pumping blood through a bed of micro-porous Hollow Fibres Membranes (HFM). For details on the development of ECMO, the reader is referred to Haworth [8].

For the last decade ECMO devices based on HFM prevailed and has brought a new branch of studies, where the oxygenator itself is investigated. The oxygenator is one of the centre pieces of the ECMO circuit and the development of hollow fibres with membranes or micro porous walls is advancing rapidly with novel materials and coatings. The effort to optimize the HFM-assembly concentrates to reduce the pressure drop across the device, to minimize haemolysis, decrease the priming volume of blood, and increase biocompatibility and lifetime of HFM oxygenators.

Computational fluid dynamic (CFD) models are used to study blood flow path, heat exchange, pressure drop, stress analysis,

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mass transfer of oxygen and carbon dioxide, different convection-diffusion models, blood stagnation, thrombogenicity, etc. These models use either a homogeneous porous media to describe the fibre bundle in bulk or a heterogeneous approach to model single fibre arrangements. The rheology is usually implemented as Newtonian flow field or more realistically described as shear thinning fluid. Non-Newtonian shear thinning numerical models for blood are well known and described by Johnston et al. [11] or Marcinkowska-Gapińska et al. [15].

For example Gartner et al. [6] and Pelosi et al. [20] use a porous media approach to model thrombogenic depositions and study the thrombogenic potential of oxygenators. Zhang et al. [25] predict blood-gas exchange and pressure drop with a Newtonian flow field through a porous media. A comparison of different porous media models is presented by Khanafer et al. [13] with a set porosity ($\Phi = 0.75$). Hormes et al. [9] present a novel diffusivity model to predict the O_2 and CO_2 mass transfer and partial pressure, which is validated by comparing the numerical solution with a purpose built oxygenator. The oxygenator and the CFD model use a uniform distribution of fibres.

Commonly the same partial pressure P_{O_2} is applied at the fibre surface for convection and diffusivity. Taskin et al. [23] presented a novel model to describe gas exchange as profile on the fibre surface. The study is comparing a single and multi fibre approach with uniform fibre distribution.

A study by Nagase et al. [18] presented mass transfer correlations based on the theory for heat transfer across a tube bank and concluded that the mass transfer performance of membrane oxygenators is attributable to the hollow fibre arrangement. The layouts considered are uniformly arranged staggered or squared (in-line) fibres.

An oxygenator cross-section modelled with individual fibres in two dimensions is compared to the porous media approach by Mazaheri and Ahmadi [16]. To avoid computational costly simulations of individual fibres, novel porous models are developed to integrate the fibre distribution for a better local process mapping (Low et al. [14], Zhang et al. [25]) and an attempt to "adjust" the porosity based on fibre orientation is described by Bhavsar et al. [3].

But all off these models have been developed with the assumption of a uniform distribution of fibres either staggered, squared or crossed (3D) or simplified with a porous media approach. Although a good agreement between numerical predictions and experimental results has been reported in the literature by Consolo et al. [5] and Pelosi et al. [20], the porous media approach is inherently unable to capture and characterize the intricate details on the flow field within the fibre bundles.

Imaging modalities can be used as a diagnostic tool to investigate the micro-structural components in an oxygenator and, when combined with CFD, can even provide information on the localised functional behaviour (flow/oxygenation) of the device. In this paper we demonstrate a method for building a full-scale, image-based, three-dimensional computational model of a blood oxygenator. All individual fibres are reconstructed from the images of a μCT scan and CFD is performed using a Non-Newtonian fluid model to investigate the local flow field inside the device.

2. Prototypes and methods

The common method of extra-corporeal oxygenating blood is achieved by pumping ambient air or through the core of HFM's whereas the blood is flowing on the outside of the fibres. Molecular diffusion increases the oxygen level in the red blood cells and removes carbon dioxide from the venous blood.

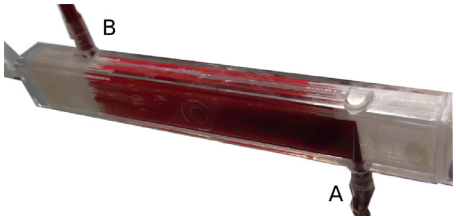

Fig. 1. Image of an oxygenator prototype (SRD3083), courtesy of Haemair Ltd. For this experiment, blood flows from the inlet A to the outlet B.

2.1. Prototypes

Two manually assembled oxygenators are used for experimental evaluation. The blood samples, outdated packed cells, are sourced from the Welsh Blood Service [24] which is accredited by the Medicines and Healthcare products Regulatory Agency [7]. The experiments are conducted by Haemair Ltd. and follow their standard of operation procedure SOP2007v04. One of the prototypes is depicted in Fig. 1. The core of the oxygenator is built with folded mats of hollow fibres produced by Membrana GmbH [17]. The fibres are state of the art ('OXYPLUS®') and have an outer diameter of approximately 380 µm and a nominal wall thickness of 90 µm. The fibre wall is highly porous ($\geq$ 55%) to allow molecular diffusion but blocking any fluid. For more details see Membrana GmbH [17]. Resin seals both ends of the oxygenator around the fibres, forcing the blood to flow between inlet and outlet (Fig. 1). Ambient air is pumped through the hollow core of the fibres. The nominal outer dimensions of the enclosure is 10 × 20 × 100 mm. Both prototypes are built to support flow along the fibres and to prevent cross-flow between the fibres at the same time, to minimize clotting and haemolysis. Additionally a virtual idealised geometry is used to set up the CFD model. Size, volume and fibre count are comparable to the real world devices. The fibres in the virtual device are uniformly arranged to exploit symmetry and simplify meshing. The virtual model is used for comparison and to test the numerical solution. For all devices the key characteristics are listed in Table 1.

2.2. Reconstructed geometry

μCT scans were performed on both prototypes using a Nikon XT H 225 with a voxel size of 22 µm. The source voltage and current were set to 55 kV and 174 µA, respectively. The exposure time for each radiograph was 2 s, with 720 radiographs being collected over 360 °.

A complete set of reconstructed two-dimensional images was computed with ~1500 × 1000 pixels and a displacement in z-direction of ~30 µm. The images captured from the μCT scan show the fibres and their arrangement in great detail (see Fig. 2). The warp thread in OXYPLUS® mats is a polyethylene terephthalate (PET) multifilament yarn (33 dtex[1]) with 24 filaments. The threads, with an estimated diameter of ~70 µm± 10, are woven into the fibre bundle every 10 mm to keep the fibres at a minimum distance and hence allow blood flow in-between. Due to the small size of the threads, we assumed that any pressure drop or mixing affects can be neglected for this study. To verify that the fibres remain in a straight line (in z-direction, see Fig. 4) throughout the device a visual inspection was conducted on a 3D compilation [22] of the μCT images (see Fig. 2) as well as overlaying 2 images from the opposite ends. A cross-section image for each oxygenator (Fig. 3a and b) was used to recreate a full size real world three-dimensional geometry to run CFD-simulations. Both prototypes were manually

[1] Dtex (decitex) is a textile measuring unit for yarn. 1 dtex = 0.1 g/km.