MODELLING OF CELL-SCALE HAEMODYNAMICS IN THE MATERNAL INTERVILLOUS SPACE OF HUMAN PLACENTA

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Introduction

The human placenta is a vital organ where the mother supplies oxygen and nutrients to her fetus. The solute transport process relies on robust maternal blood flow in the highly heterogeneous intervillous space (IVS) akin to random porous media [1,2]. Because the IVS contains flow channels which are comparable in size with red blood cells (RBCs), the particulate nature of blood can lead to rheological behavior beyond the description of existing continuum models [3]. In this work, we model cellular blood flow across realistic IVS as a suspension of deformable RBCs in plasma, to enable a mechanistic understanding of the structure-function relationship between the IVS's architecture and haemodynamics.

Methods

3D IVS domains were reconstructed from synchrotron micro-CT image stacks of the human placenta tissue [4] (**Fig. 1a**). Cellular blood flow of designated feeding haematocrits (i.e. H_F, volume fraction of RBCs) in the reconstructed flow domain was simulated with our high-performance parallel blood flow simulator *HemeLB* (open source: https://github.com/hemelb-codes/hemelb) using the lattice-Boltzmann and immersed-boundary methods [5]. For comparison, homogeneous Newtonian flow with physiological blood viscosity and pure plasma flow with liquid water viscosity were also simulated.

Results

Preliminary flow simulations in a large IVS domain, either for homogeneous blood (**Fig. 1b**) or for dilute RBC suspension (H_F = 1%, **Fig. 1c**), recapitulate the exponential flow distribution reported for IVS flow [4]. Further simulations with homogeneous blood along three principal directions of a cropped cubic domain reveal a moderate degree of flow anisotropy (**Fig. 1d**). For semi-dilute RBC suspension (H_F = 10%, **Fig. 1e**), the flow resistance in the three directions are indeed different (despite similar patterns for the RBC residence time, **Fig. 1f**), evaluated by the apparent viscosity of the suspension relative to plasma viscosity (**Table 1**). The RBC deformability is also found to have a notable effect, with elevated viscosity for hardened cells.

RBC type	x-flow	y-flow	z-flow
Normal	2.66	2.71	2.87
Hardened	2.95	2.96	3.13

Table 1: Relative apparent viscosity for H_F = 10%.

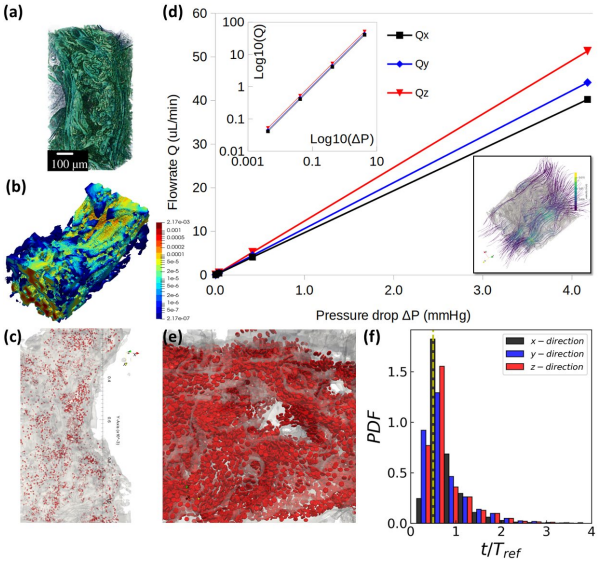

Figure 1: (a) 3D rendered placental tissue (about 0.2 mm^3) from synchrotron micro-CT [4]. (b) Simulation of homogeneous blood (assuming physiological viscosity η = 0.003 Pa s) across a reconstructed IVS domain from (a). (c) Dilute RBC flow (H_F = 1%) across the same IVS domain. (d) Flow-pressure relationship (inset for log-log scale) extracted from flows of homogeneous blood across the x-, y-, z- directions of a cubic IVS domain (bottom inset, about 0.03 mm^3) cropped from the large tissue volume in (a). (e) Semi-dilute RBC flow (H_F = 10%) across the same domain as in (d). (f) Distribution of normalised RBC residence time in the cubic domain.

Discussion

The cell-scale haemodynamics investigated here can help elucidate the elusive structure and function relationship in the IVS which may explain how impaired placenta architecture causes pregnancy pathologies.

References

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