Porous media flow models for maternal placental circulation

C.G. Ball[1], D. Grynspan[2], A. Gruslin[3]

1. Department of Pathology and Laboratory Medicine, University of Ottawa / Ottawa Hospital, Ottawa, Ontario, Canada
2. Department of Pathology and Laboratory Medicine, University of Ottawa / Children's Hospital of Eastern Ontario, Ottawa, Ontario,
3. Departments of Obstetrics and Gynecology and of Cellular Molecular Medicine, University of Ottawa / Ottawa Hospital, Ottawa, Ontario, Canada

Introduction

As we believe that abnormal flow patterns seen in the chorionic vessels is an earlier, more sensitive predictor of intra-uterine growth retardation (IUGR), we also surmise that these patterns become increasingly dominant in increasingly small fetal vessels. In this case, the villous circulatory bed may be the most proximate correlate of the factors that lead to IUGR. Accordingly, the effects of the intimately connected uteroplacental flow of the inter-villous space cannot be ignored.

Indeed, numerous approximations of uteroplacental blood flow and solute transport have been proposed as a means to uncover underlying pathophysiologic processes (of IUGR and other entities). In these efforts, analytical solutions or mathematical models are applied to approximate physical processes in the uteroplacental flow bed. These models, while intricate, cannot account for the presumed variations in intervillous flow mechanics that may be seen. We propose a method to study the flow physics in a maternal side of a placentone.

Porous Flow Models

These models are appealing; their apparent simplicity is deceptive. Inlets and outlets are modelled as flow sources and sinks, respectively; meanwhile, the villous tree is homogenised, and resistance to intervillous flow is applied.

The primary drawback to the models is related to the stated limitations of the homogenisation approximation. Homogenisation of the inhomogeneous villous tree requires complex statistical characterisation. Accounting for geometrical variation of key features (shown in Figure 1) is possible. Models do not yet incorporate fetal-placental flow; they cannot predict intra-placentone flow physics. Importantly this may force ignorance of the intimacy of the fetal and maternal flows.

Computational Predictions

Expected physiologic consequences of various flows in a placentone are well reasoned, and founded upon fundamentals of fluid mechanics. It has been argued that a pathological villous tree may result from deviant utero-placental blood flow. The predicted consequences may even be seen histologically.

Rigorous computational simulation of the fluid dynamics within a placentone is hindered, again, by the complexity of the villous tree. The intricate detail of the tree must be replicated (programmed) before flow around it can be simulated – this is no easy task. Verification of the accuracy of the simulated flow is an equally daunting task (qualitative verification is shown in Figures 3 and 4).

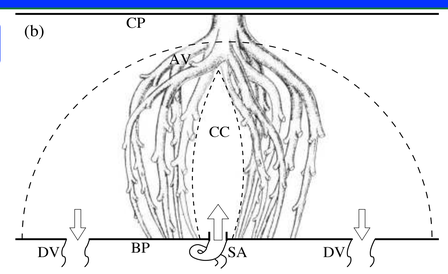

Fig 1. A schematic of the placentone at term, enclosed between basal (BP) and chorionic plates (CP), showing spiral arteries (SA), decidual veins (DV), central cavity (CC), and anchoring villli (AV) (modified from 1. and 3.)

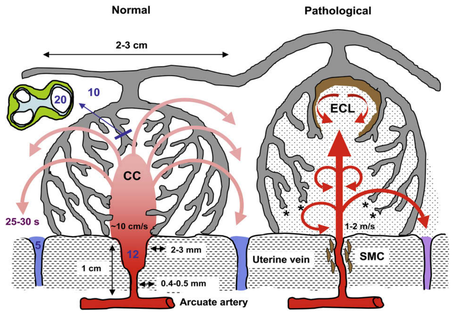

Fig 2. Diagrammatic representation of normal and pathologic alteration of the villous tree in response to altered spiral arterial in-flow (as predicted by 2.)

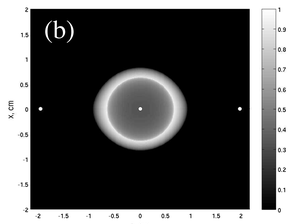

Fig 3. Computed intensity distribution of a tracer, numerically injected at the spiral artery source on the basal plate at 15s after introduction into a porous flow model (from 1.)

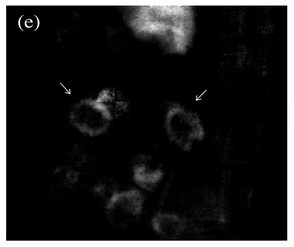

Fig 4. Method to verify the solution shown in Figure 3: Compare the radioangiographic film of a monkey uterus injected with radio-opque dye (from 1.)

Experimental Measurements

Placental experimentation has focussed predominantly on gross transport in the placenta, and on understanding of mediators. To our knowledge, there has been no experimental investigations into the precise detail of blood flow in the intervillous space, as drawn schematically in Figure 2.

Experimental measurement is unfortunately confounded by the observer effect. This is of particular concern in fluid mechanics where measuring sensors interact with the flow being studied. This is not an insurmountable challenge, however.

With particle image velocimetry (PIV), it is possible to measure fluid flows in a complex geometry using the methods described in 6. Briefly, a reflective-particle laden fluid is pumped through a geometry; laser-photographic tracking of the motion of these particles allows three-dimensional velocity fields within the entire geometry to be measured non-intrusively.

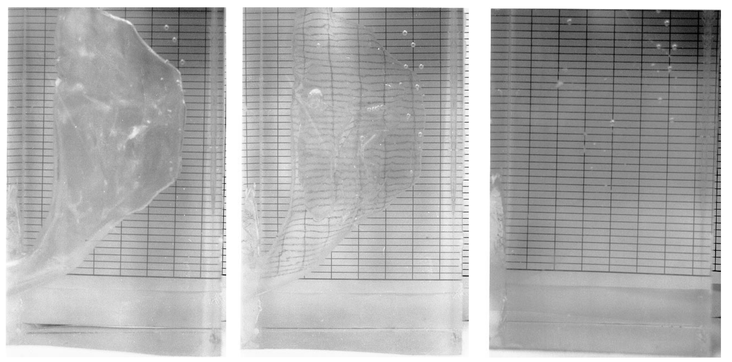

Fig 5. Gridlines seen through the complex geometry of a silicone nasal model when filled with air, water, and an refractive-index matched aqueous glycerine (as demonstrated by 6.)

Our Goals

1. Determine actual typical placentone and villous tree geometries from healthy and IUGR placentas.
2. Acquire/build scaled models of realistic idealised healthy and IUGR placentones
3. Measure the flow velocity fields within these geometries using methods similar to those described in 6.

References

1. Bernischke, K., Kaufmann, P, Baergen, R.N. Patholog of the human placenta. 5th ed. Springer; 2006.
2. Burton, G.J., Woods, A.W., Jauniaux, E., Kindom, J.C.P. (2009) Rheological and physiological consequences of conversion of the maternal spiral arteries for uteroplacental blood flow during human pregnancy. Placenta. 30:473—482.
3. Chernyavsky, I.L., Jensen, O.E., Leach, L. (2010) A mathematical model of intervillous blood flow in the human placentone. Placenta. 31:44—52.
4. Chernyavsky, I.L., Leach, L., Dryden, I.L., Jensen, O.E. (2011) Transport in the placenta: Homogenizing haemodynamics in a disordered medium. Phil. Trans. R. Soc. A. 369:4162—4182.
5. Erian, F.F., Corrsin, S., Davis, S.H. (1977) Maternal, placental blood flow: A model with velocity-dependent permeability. J. Biomechanics. 10:807—814.
6. Hopkins, L.M., Kelly, J.T., Wexler, A.S., Prasad, A.K. (2000) Particle image velocimetry measurements in complex geometries. Experiments in Fluids. 19:91—95.