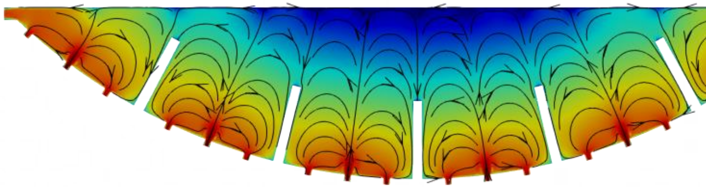
Placental haemodynamics: Transport effects at the organ scale

Adam Blakey (he/him)
Penny Gowland, Paul Houston,
Matthew Hubbard, George Hutchinson,
Lopa Leach, and Reuben O'Dea



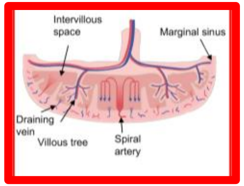
PGR Retreat 2023
26^{th} May 2023

University of Nottingham
UK | CHINA | MALAYSIA

Today's talk

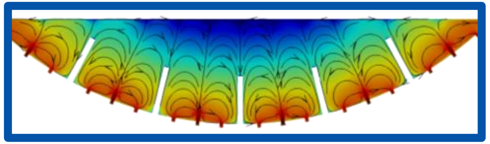
01

Introduction



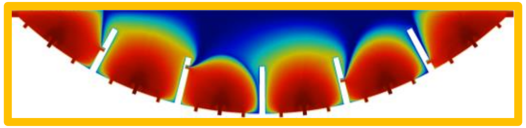
02

Blood flow



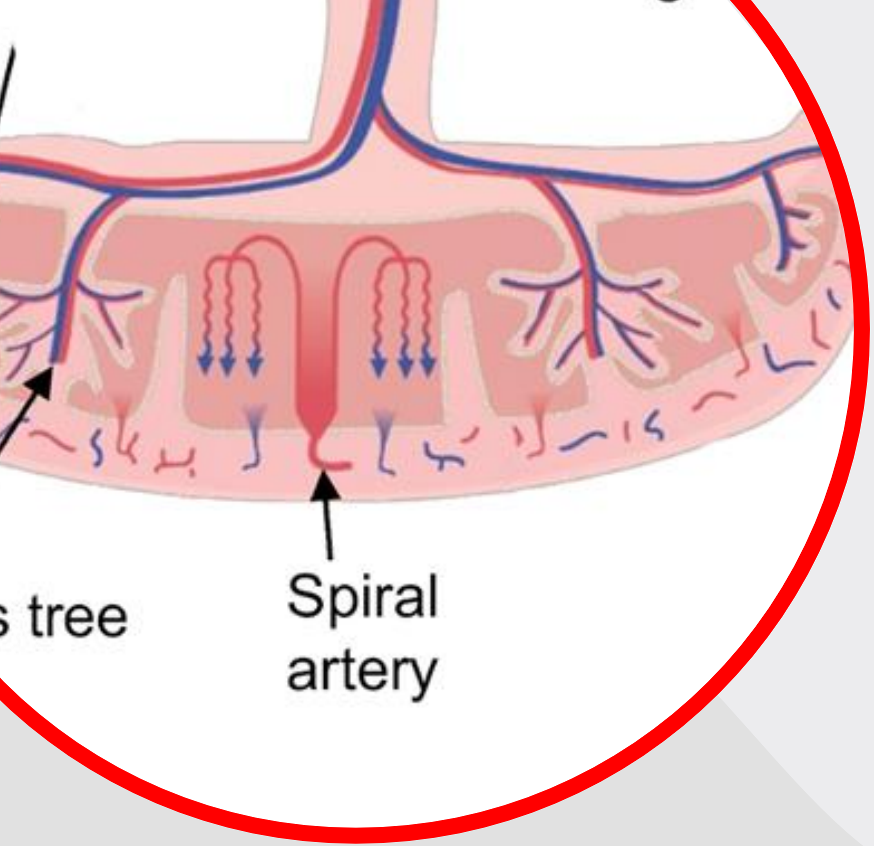
03

Nutrient transport



04

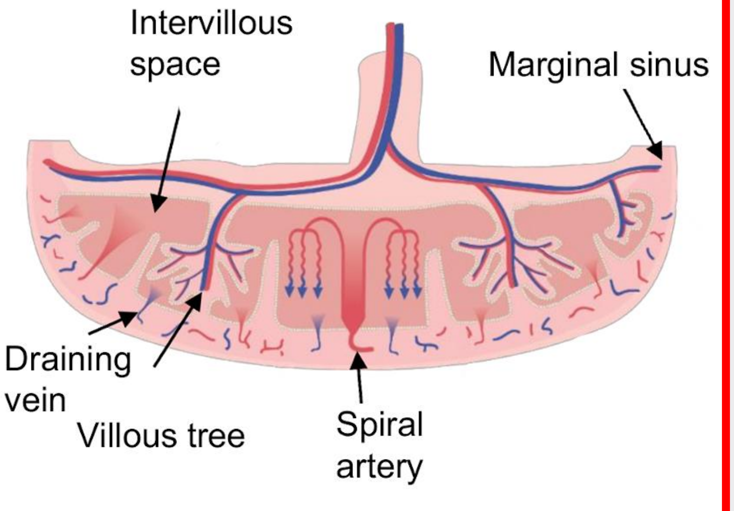
In progress



01

Introduction

What is a placenta?



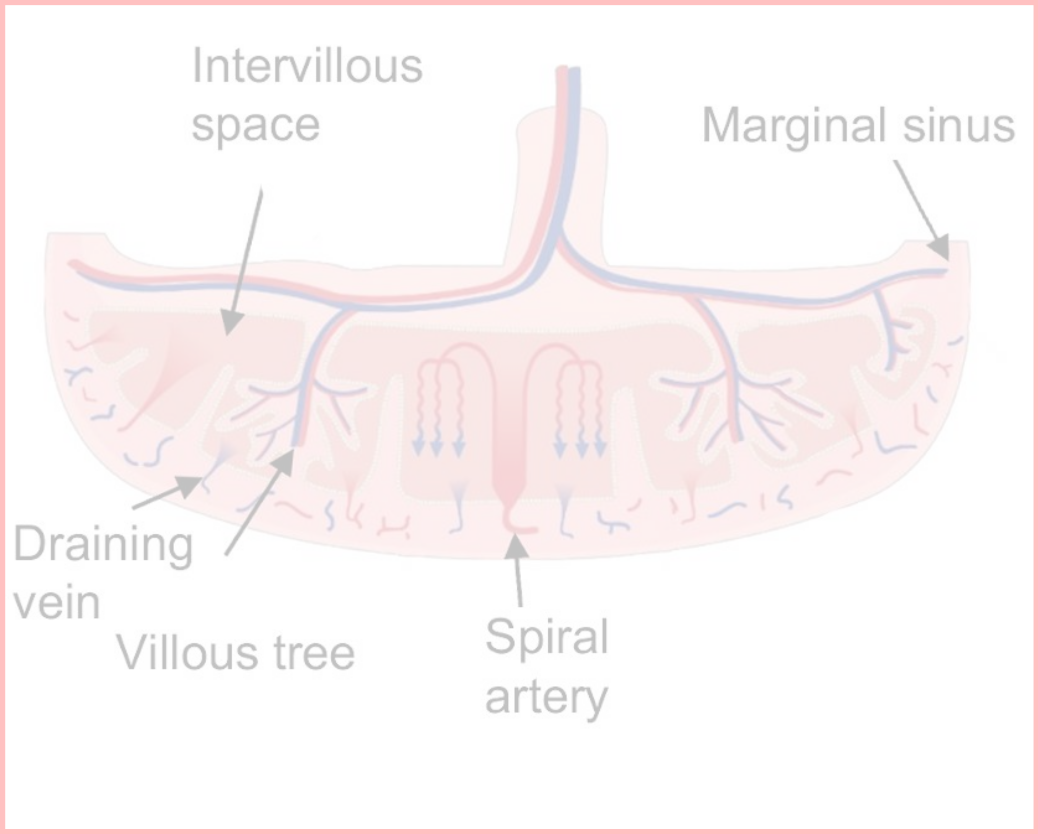
Modified from [Dellschaft et al., 2020]

- Provides nutrients and oxygen to foetus
- Removes waste products
- Vital to fetal development

What is a pla

Provides nutrients and oxygen to

products
velopment



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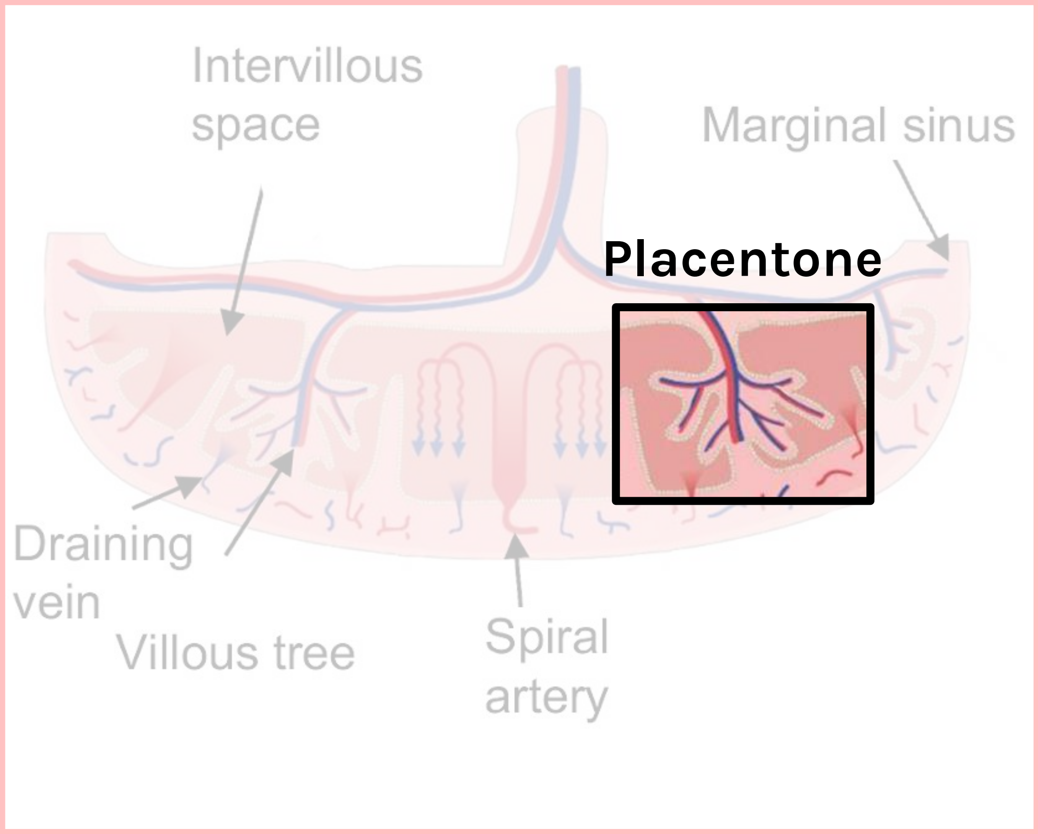

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What is a placenta?

Viewer discretion is advised

What is a placenta?

[Lopa Leach]

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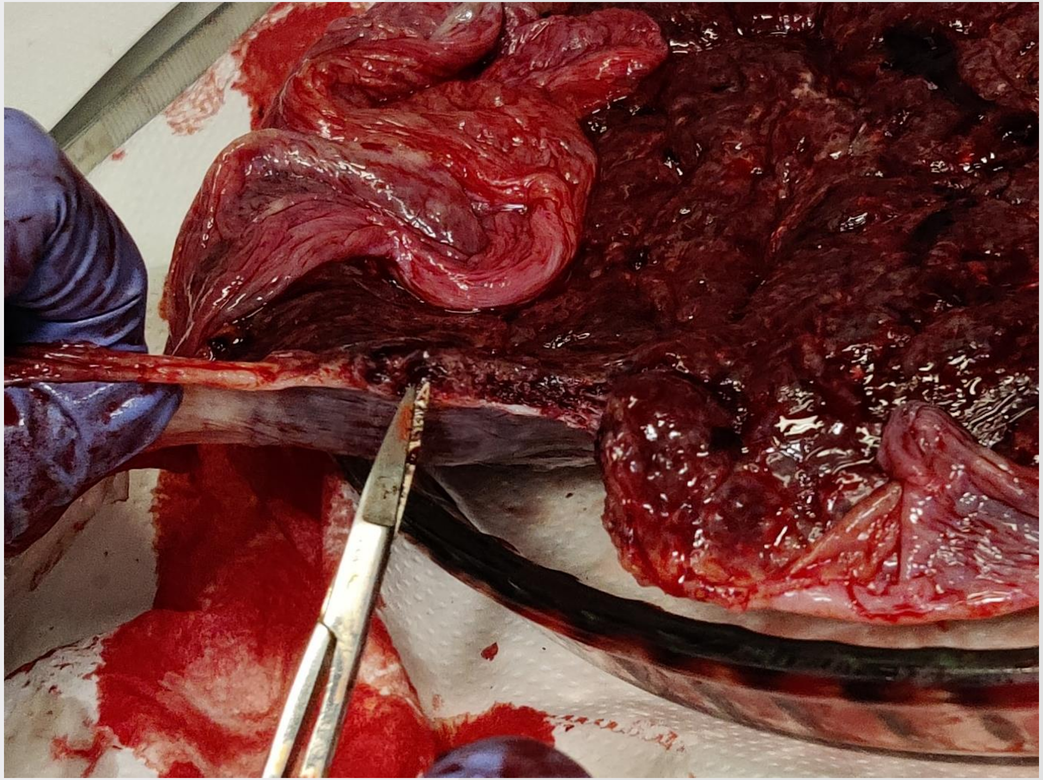
What is a placenta?



[Lopa Leach]

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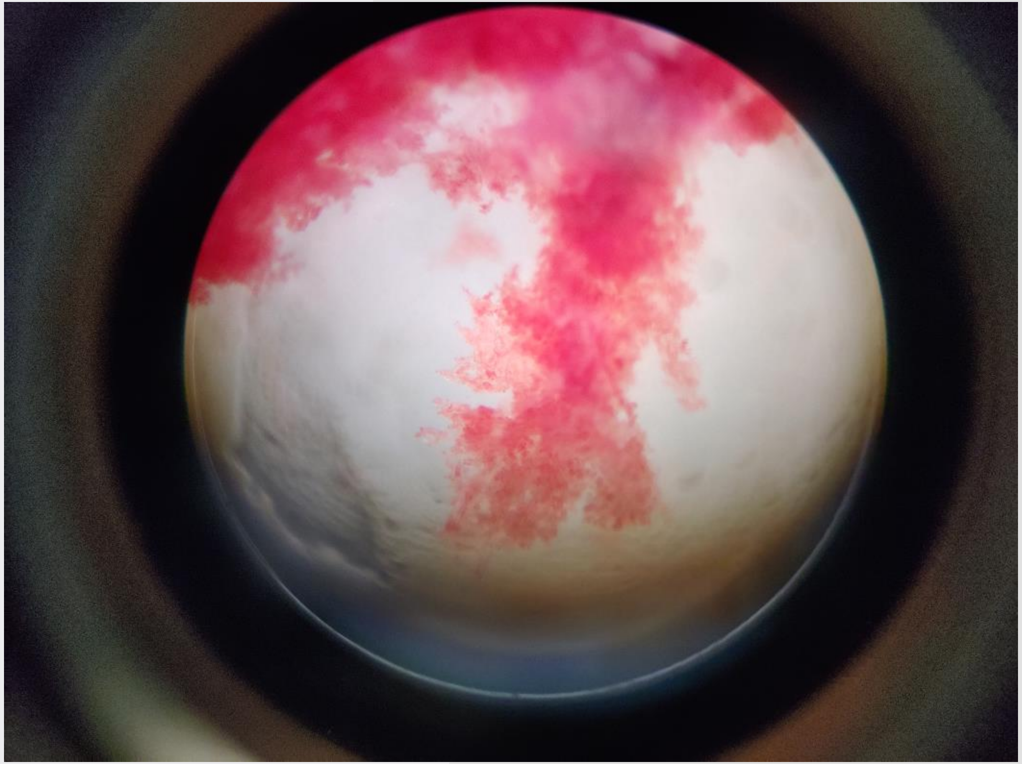
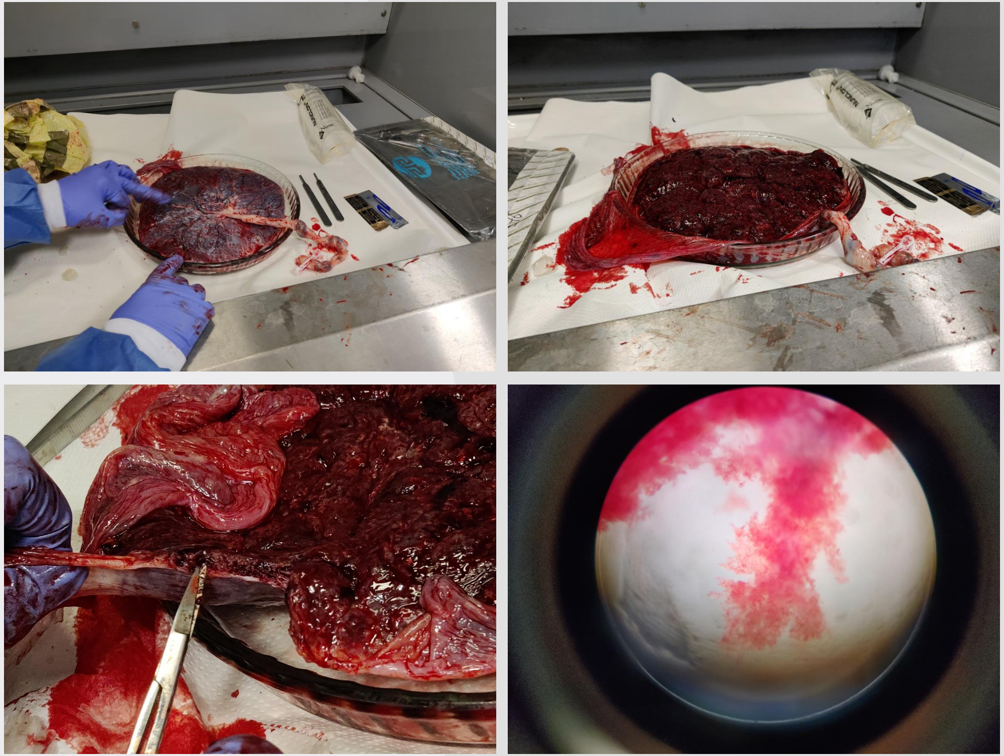


[Lopa Leach]

What is a placenta?



[Lopa Leach]

Inter-disciplinary Work

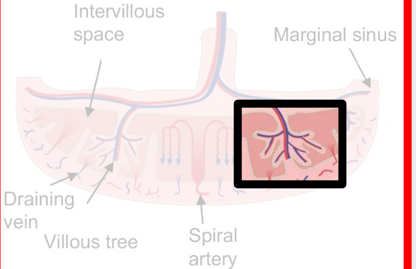
MATHS
Modelling and prediction

SCI COMP
Computational tools

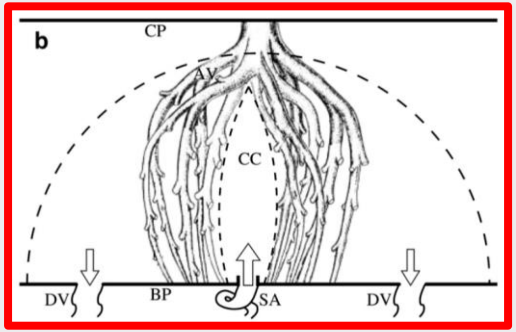
BIOLOGY
Perfusion experiments

PHYSICS
MRI data

Maternal flow equations



[Dellschaft et al., 2020]



[Chernyavsky et al., 2010]

- Homogenise tree structure
  ➔ porous medium
- Incompressible flow
- Navier-Stokes & Brinkman

Brinkman:

$$-\nabla^2 \boldsymbol{u} + \frac{1}{\mathrm{Dr}} \boldsymbol{u} + \nabla p = f_{\mathrm{B}}$$
$$\nabla \cdot \boldsymbol{u} = 0$$
$$\boldsymbol{u}_{\mathrm{wall}} = \boldsymbol{0}$$
$$\boldsymbol{u}_{\mathrm{neumann}} \equiv \left(\nabla \boldsymbol{u} - p\underline{\boldsymbol{I}}\right) \cdot \boldsymbol{n} = \boldsymbol{0}$$

Navier-Stokes:

$$-\nabla^2 \boldsymbol{u} + \mathrm{Re}\, \nabla \cdot (\boldsymbol{u} \otimes \boldsymbol{u}) + \nabla p = f_{\mathrm{NS}}$$
$$\nabla \cdot \boldsymbol{u} = 0$$
$$\boldsymbol{u}_{\mathrm{inlet}} = \frac{(R^2 - r^2)}{R^2} \hat{\boldsymbol{y}}$$
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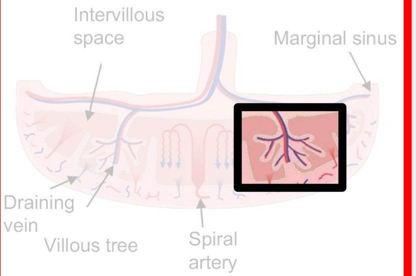
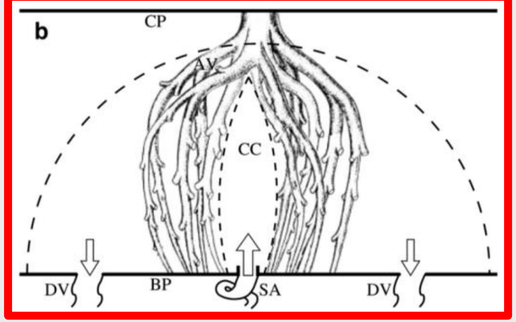
Maternal flow equations



[Dellschaft et al., 2020]



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Navier-Stokes-Brinkman:

$$-\nabla^2 \boldsymbol{u} + \mathrm{Re}\, \nabla \cdot (\boldsymbol{u} \otimes \boldsymbol{u}) + \frac{1}{\mathrm{Dr}} \boldsymbol{u} + \nabla p = f$$

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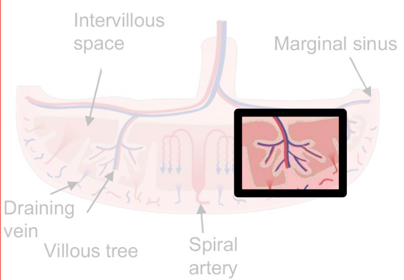
Maternal flow equations



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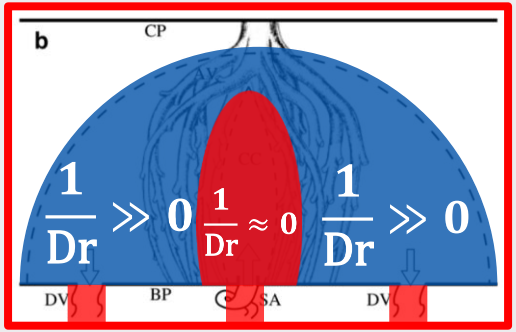

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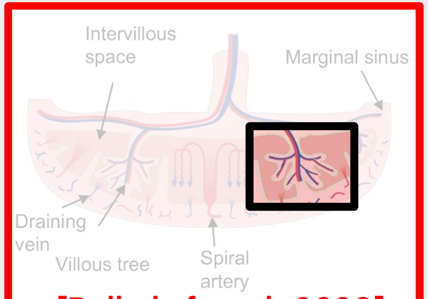

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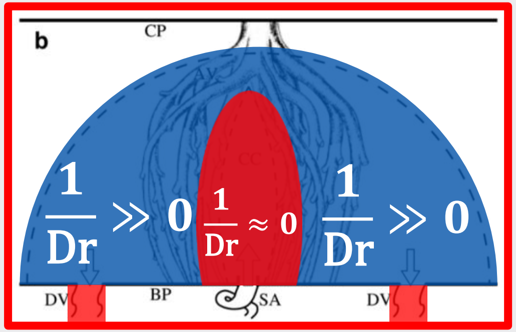

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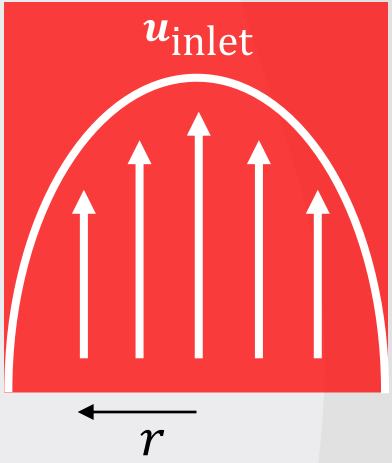

Navier-Stokes-Brinkman:

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DGFEM discretisation

Find $\forall \boldsymbol{u}_h, p_h \in \boldsymbol{V}_h \times Q_h$ s.t.

$$A(\boldsymbol{u}_h, \boldsymbol{v}_h) + B(\boldsymbol{v}_h, p_h) - B(\boldsymbol{u}_h, q_h) + C(\boldsymbol{u}_h, \boldsymbol{v}_h) = F(\boldsymbol{v}_h) - G(q_h),$$

$\forall \boldsymbol{v}_h, q_h \in \boldsymbol{V}_h \times Q_h$.

[Cliffe et al., 2010]

Navier-Stokes-Brinkman:

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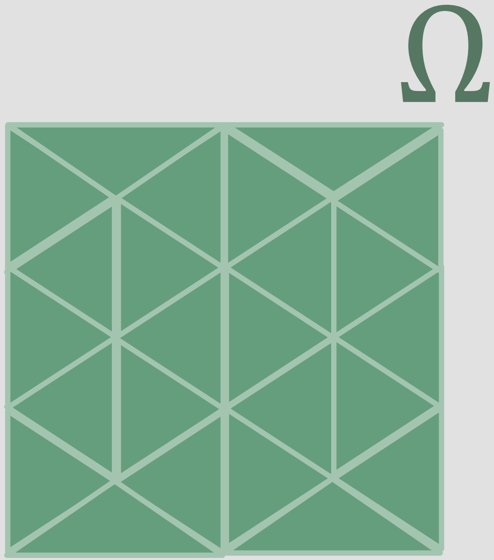
$$A(\boldsymbol{u}, \boldsymbol{v}) = \int_\Omega \boldsymbol{\nabla}_h \boldsymbol{u} : \boldsymbol{\nabla}_h \boldsymbol{v} - \int_{F \cup \Gamma_D} \{\{\boldsymbol{\nabla}_h \boldsymbol{v}\}\} : [\![\boldsymbol{u}]\!] + \{\{\boldsymbol{\nabla}_h \boldsymbol{u}\}\} : [\![\boldsymbol{v}]\!] + \int_{F \cup \Gamma_D} \sigma [\![\boldsymbol{u}]\!] : [\![\boldsymbol{v}]\!] + \frac{1}{\mathrm{Dr}} \int_\Omega \boldsymbol{u} \cdot \boldsymbol{v}$$

$$B(\boldsymbol{u}, q) = -\int_\Omega q \boldsymbol{\nabla}_h \cdot \boldsymbol{v} + \int_{F \cup \Gamma_D} \{\{q\}\} [\![\boldsymbol{v}]\!]$$

$$C(\boldsymbol{u}, \boldsymbol{v}) = -\int_\Omega (\boldsymbol{u} \otimes \boldsymbol{u}) : \boldsymbol{\nabla}_h \boldsymbol{v} + \int_{F \cup \Gamma_D} \mathcal{H}(\boldsymbol{u}^+, \boldsymbol{u}^-, \boldsymbol{n}) [\![\boldsymbol{v}]\!]$$

$$F(\boldsymbol{v}) = \int_{\Gamma_D} \sigma \boldsymbol{g}_D \cdot \boldsymbol{v} - \int_{\Gamma_D} (\boldsymbol{g}_D \otimes \boldsymbol{n}) : (\nabla_h \boldsymbol{v})$$

$$G(q) = \int_{\Gamma_D} q\, \boldsymbol{g}_D \cdot \boldsymbol{n}$$



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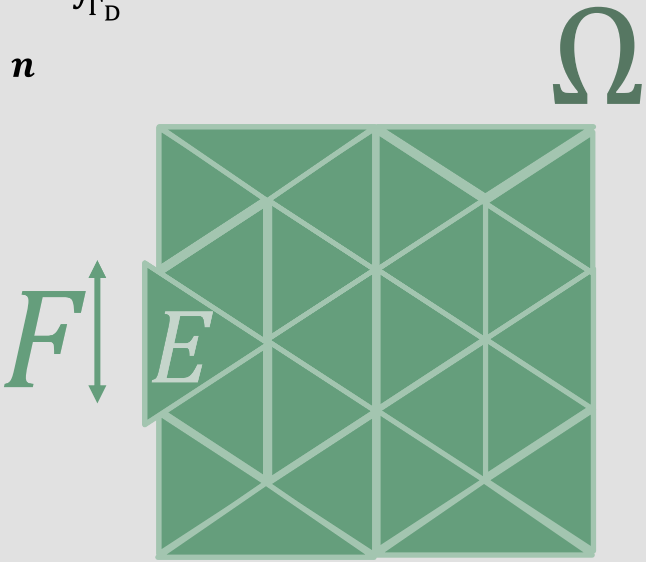

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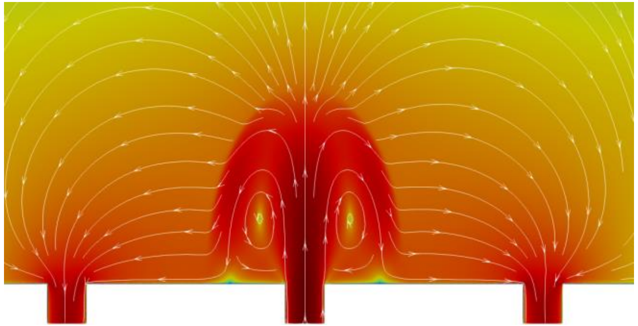
[Cliffe et al., 2010]

DGFEM motivation

- Stable for large variation in parameters



Navier-Stokes

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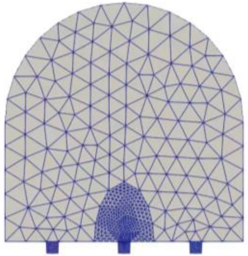
DGFEM motivation

- Stable for large variation in parameters
- Moving meshes and hyperbolic term



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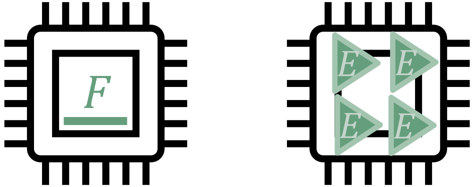
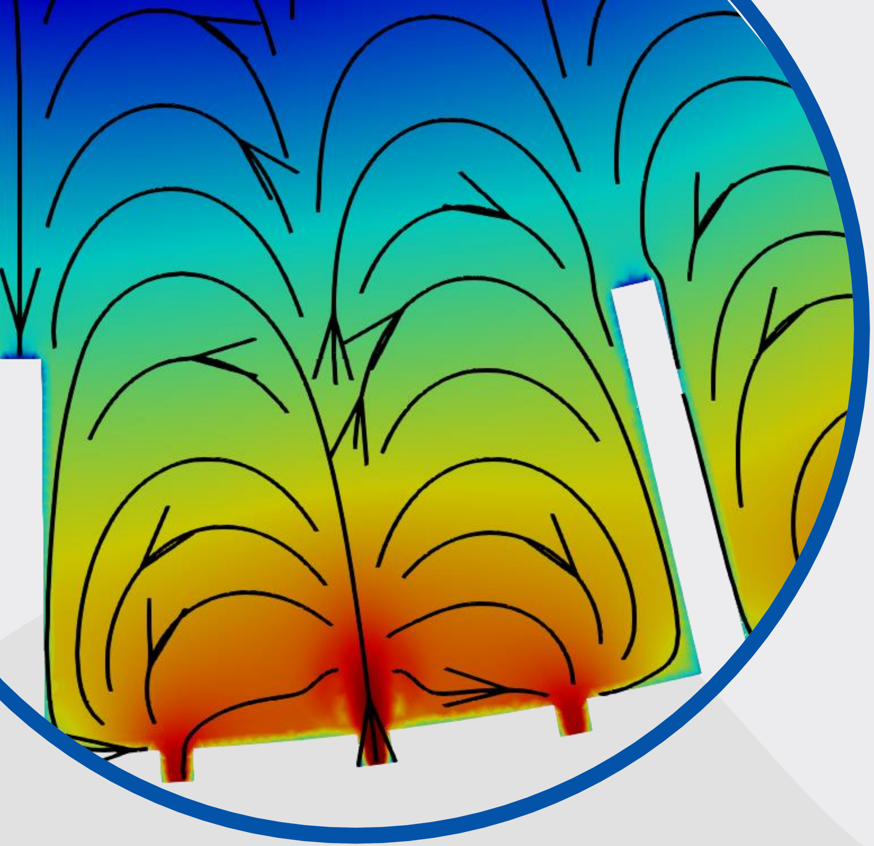
DGFEM motivation

- Stable for large variation in parameters
- Moving meshes and hyperbolic term
- More parallelisable

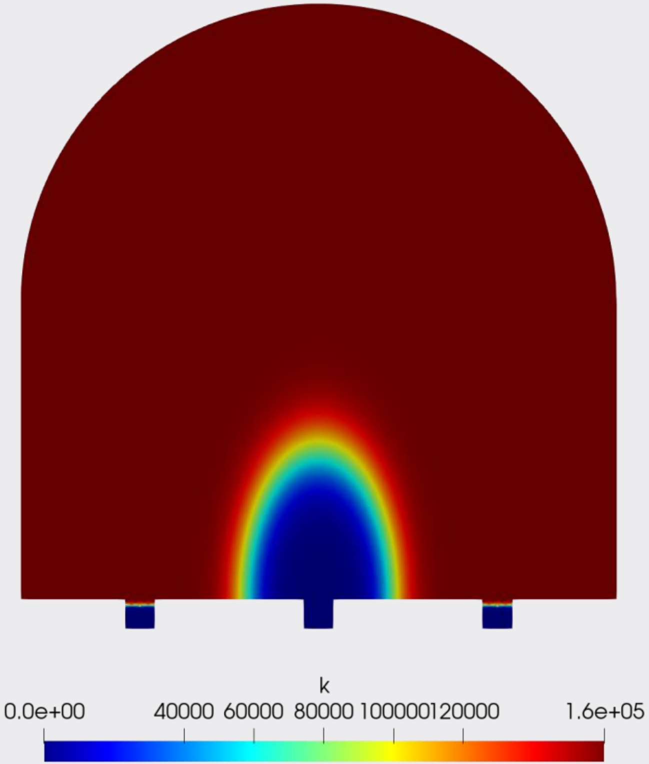




02

Blood flow

Single placentone

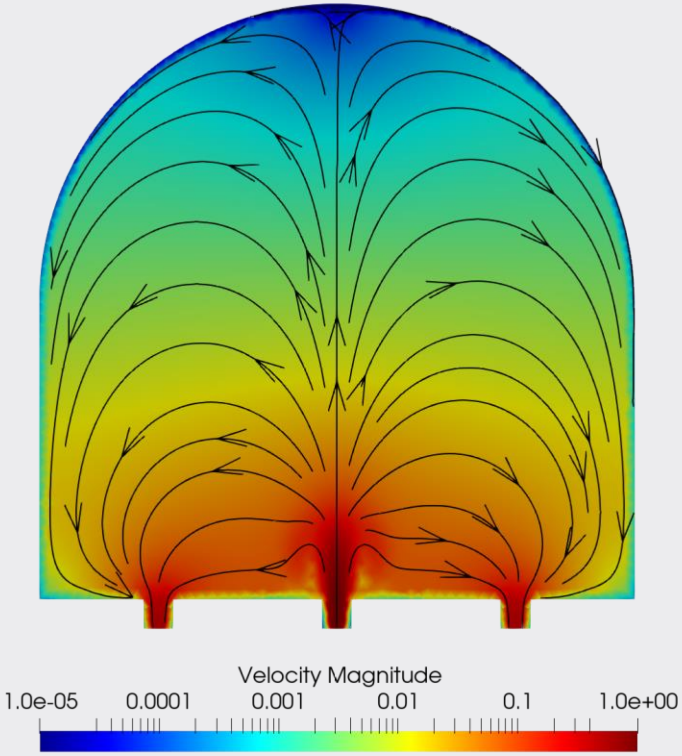


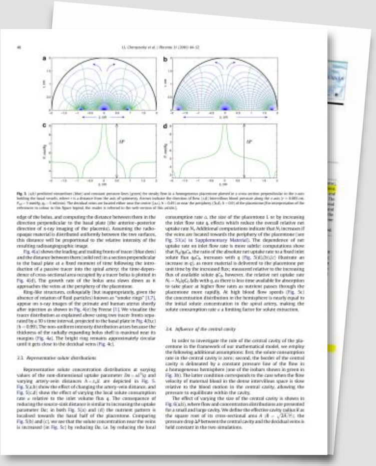
$$Re = 1 \times 10^3$$

$$\frac{1}{Dr_{max}} = 1.6 \times 10^5$$

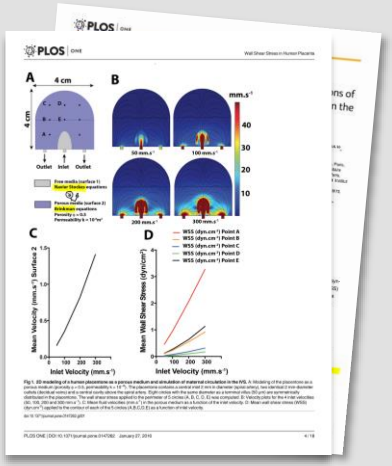
Single placentone

- Qualitatively matches other models
- Assumes no ‘spilling’
- Exponential fluid slow down





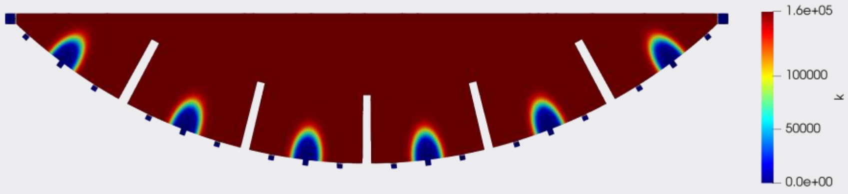
[Chernyavsky et al., 2010]

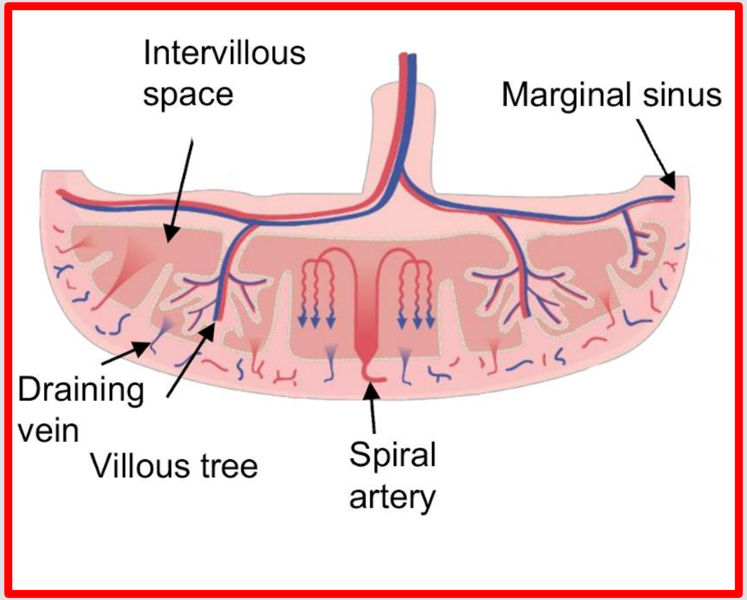


[Lecarpentier et al., 2016]

2D slice of whole placenta

- Agree with placentone simulations
- Show ‘spilling’
- Include marginal sinuses





[Dellschaft et al., 2020]

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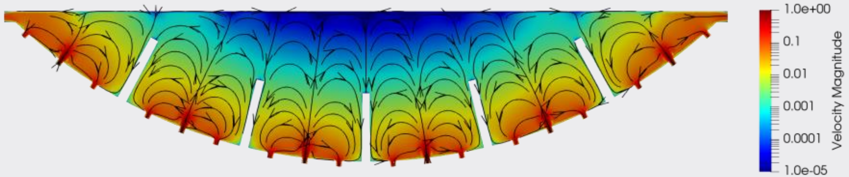

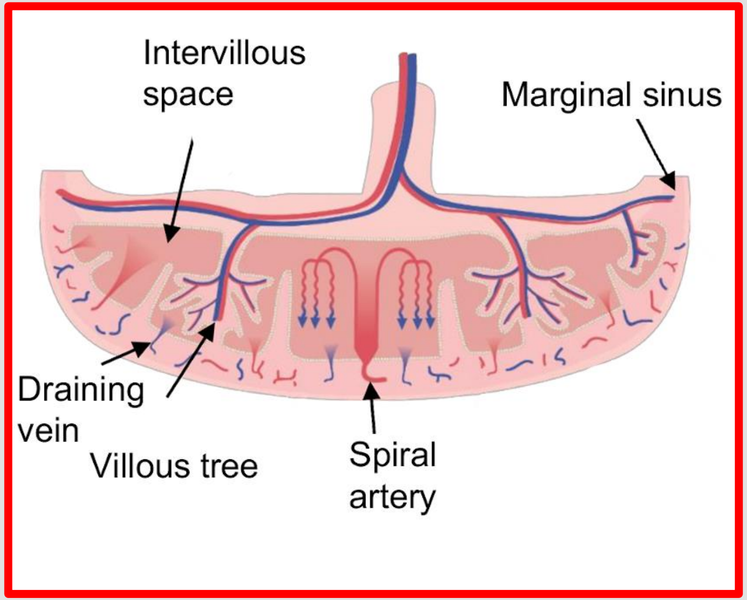

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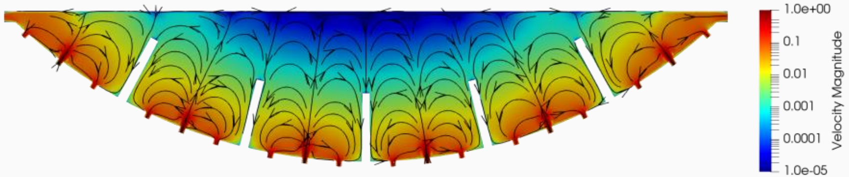

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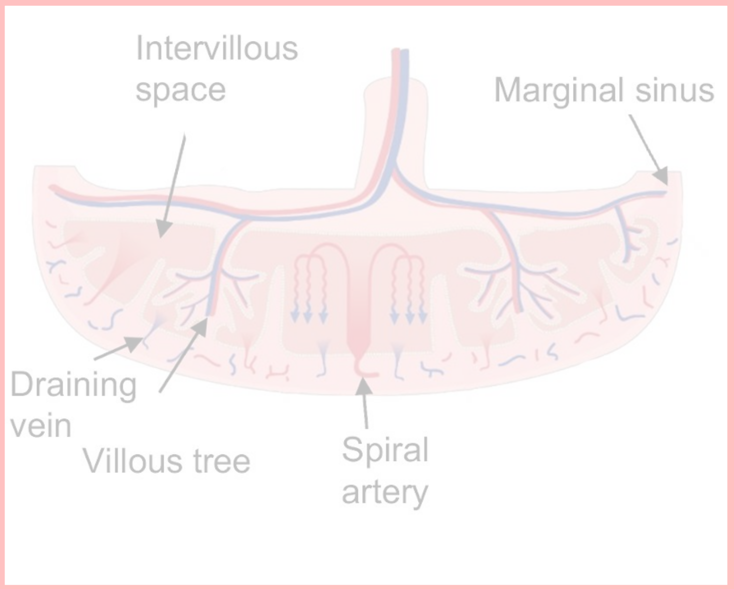

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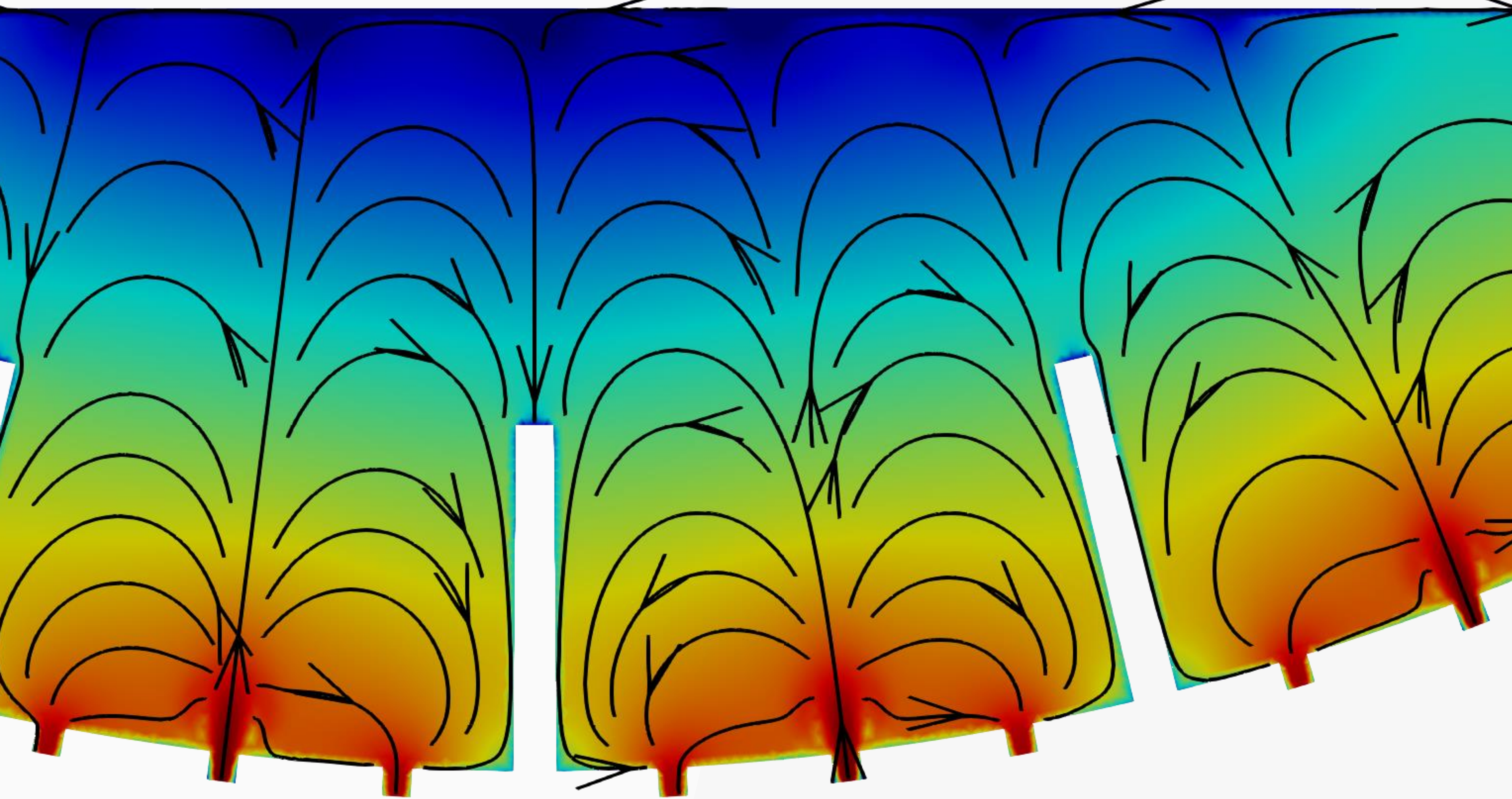
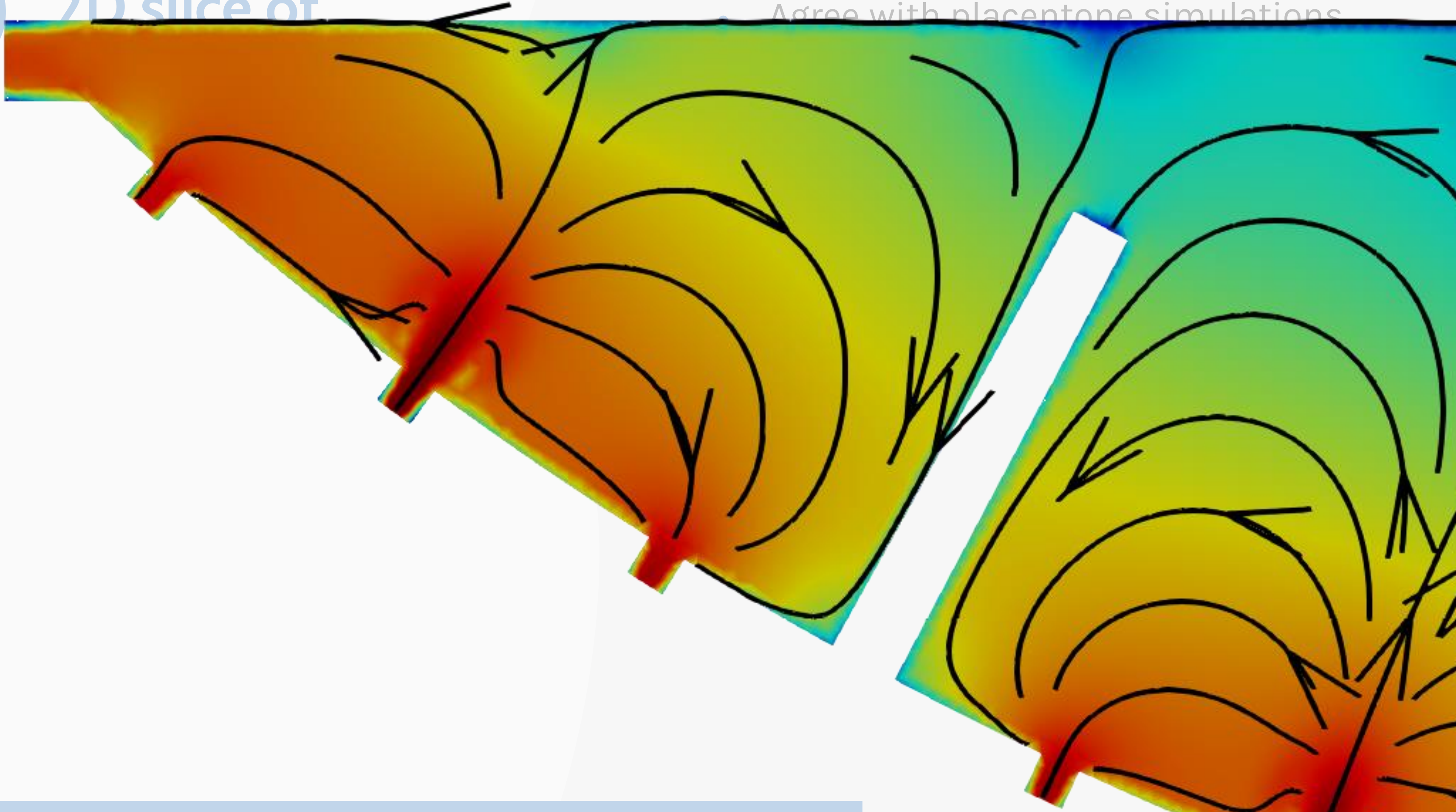


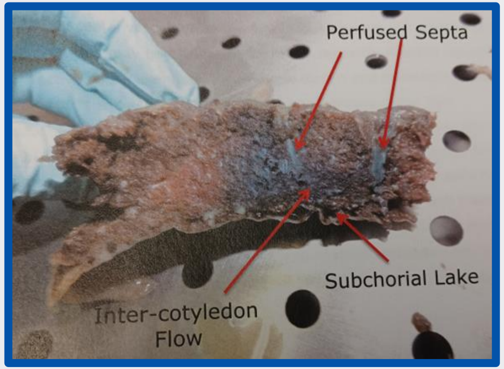
2D slice of

- Agree with placentone simulations



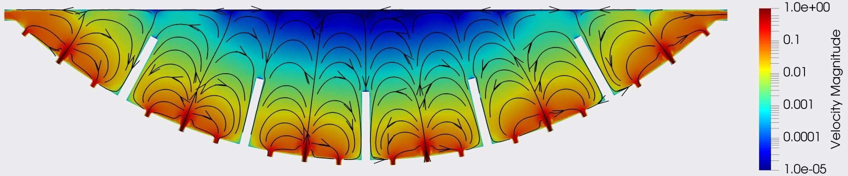
Septal veins

[Lopa Leach]

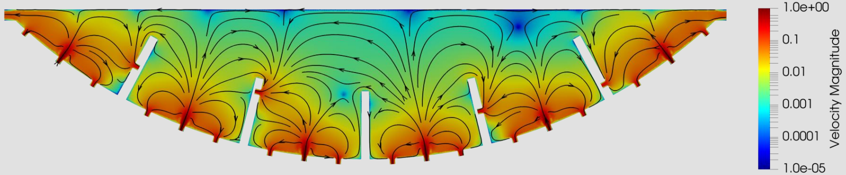


- Reduces slow-moving blood
- Geometrically more accurate
- Uniformity of exchange

No septal veins

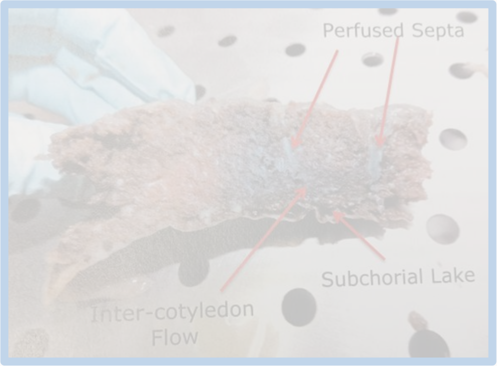


With septal veins



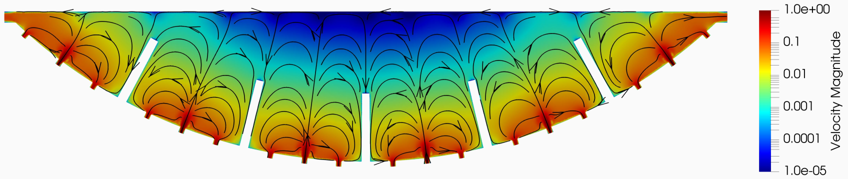
Septal veins

[Lopa Leach]

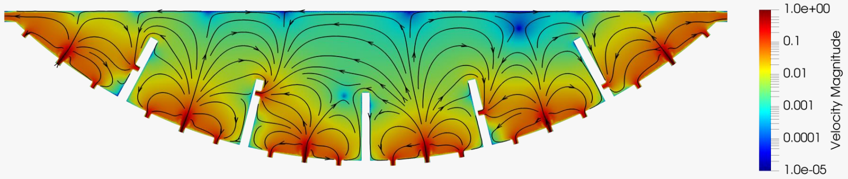


- Reduces slow-moving blood
- Geometrically more accurate
- Uniformity of exchange

No septal veins



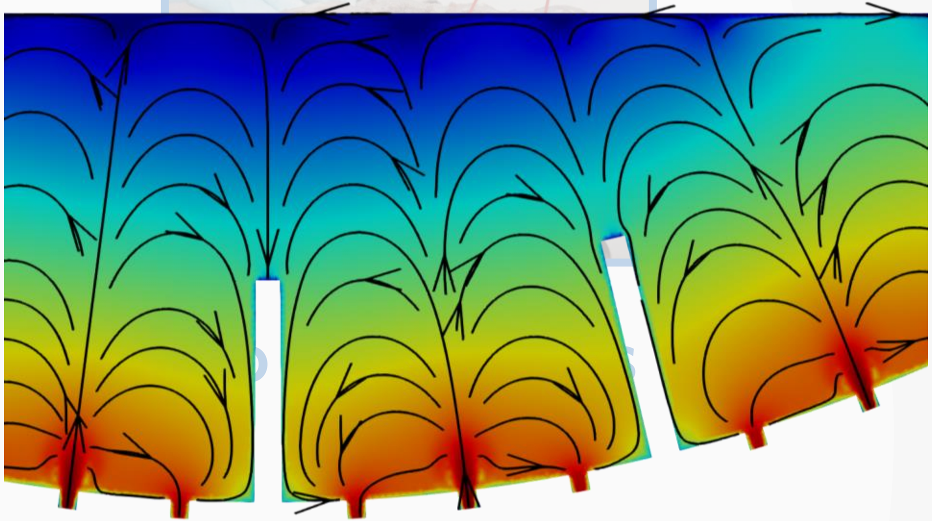
With septal veins

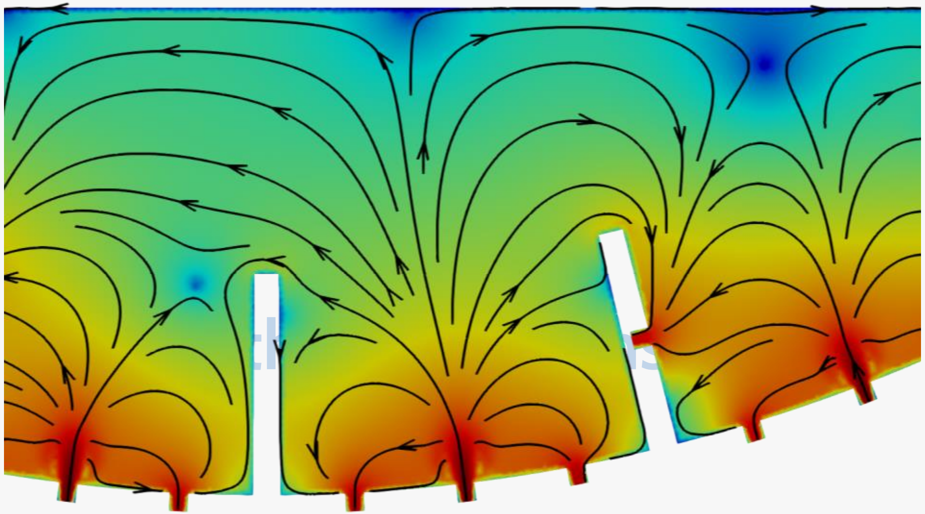


Septal veins

[Lopa Leach]

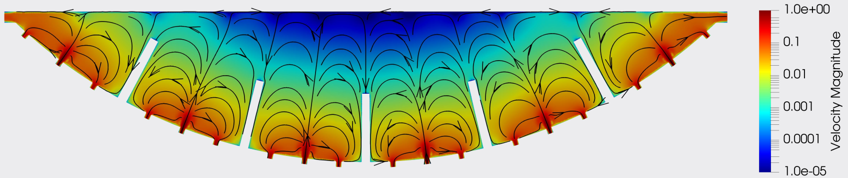
- Reduces slow-moving blood
- Geometrically more accurate
- Uniformity of exchange

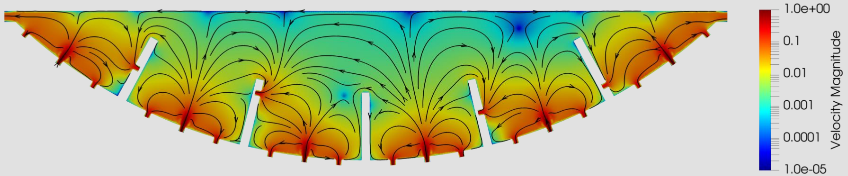




Flux transport

$$\int \boldsymbol{u} \cdot \boldsymbol{n} \, \mathrm{d}x$$





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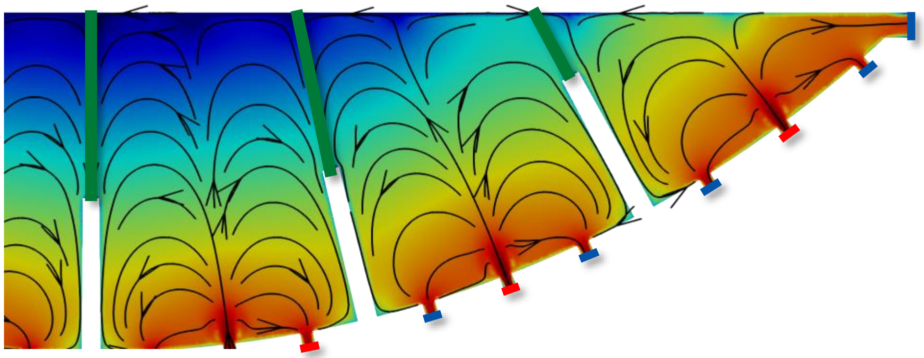

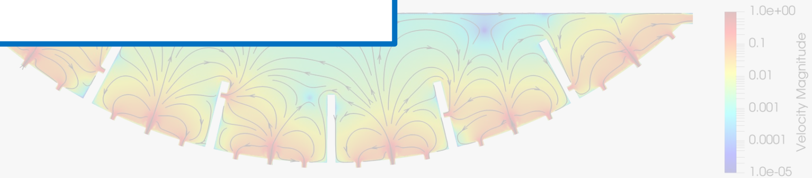

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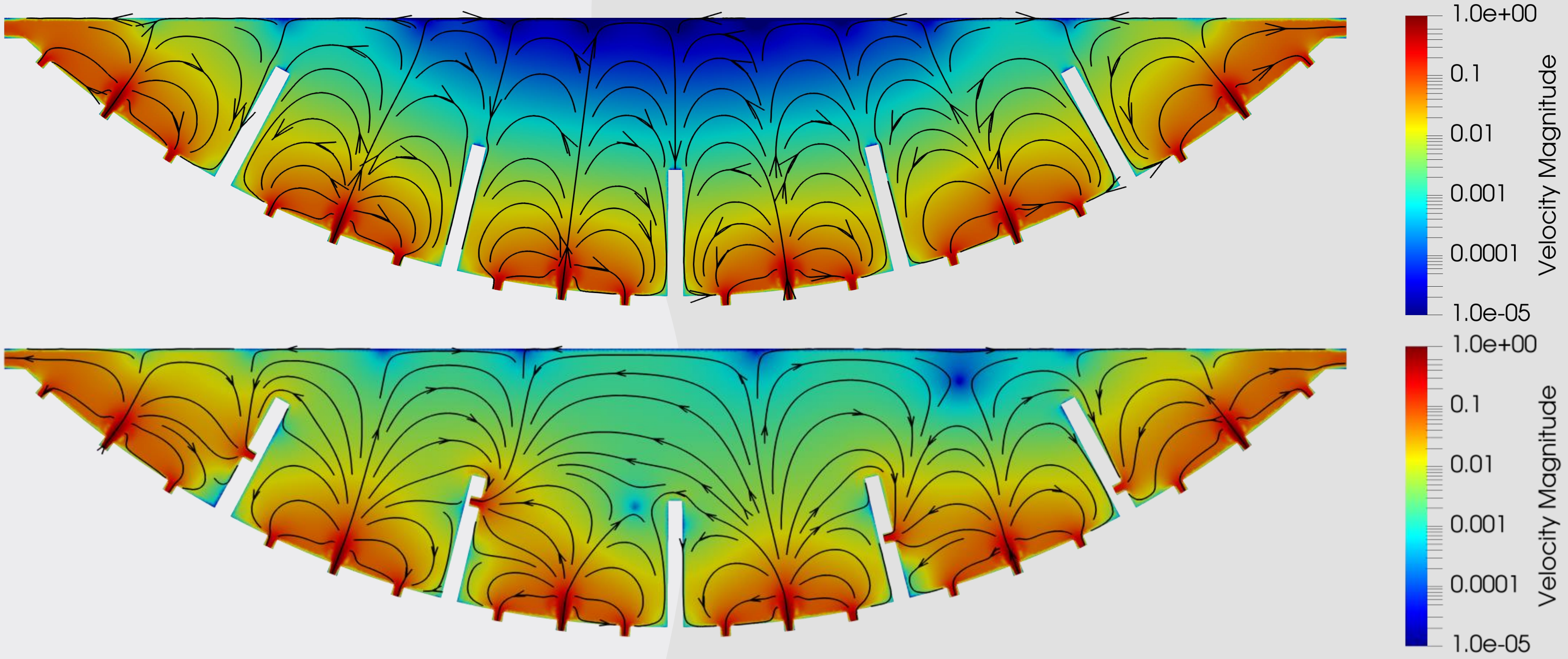

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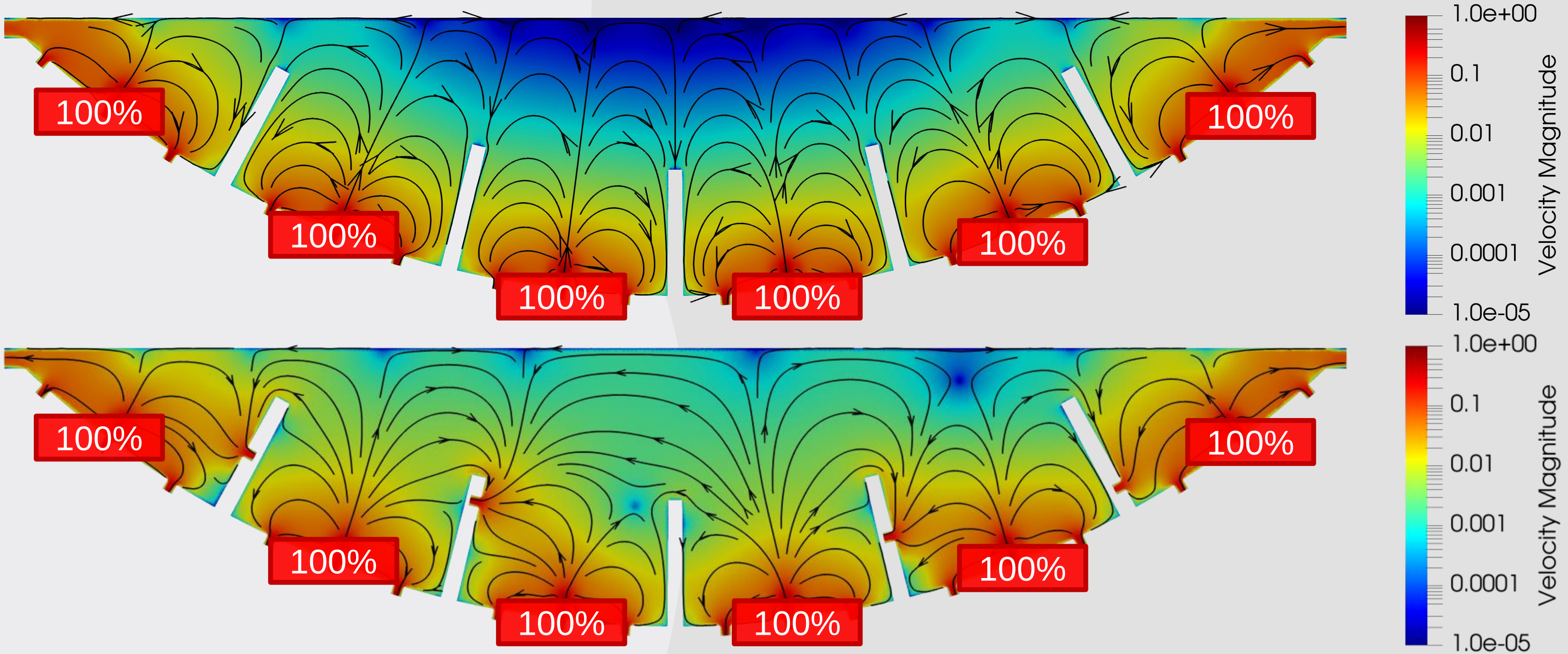

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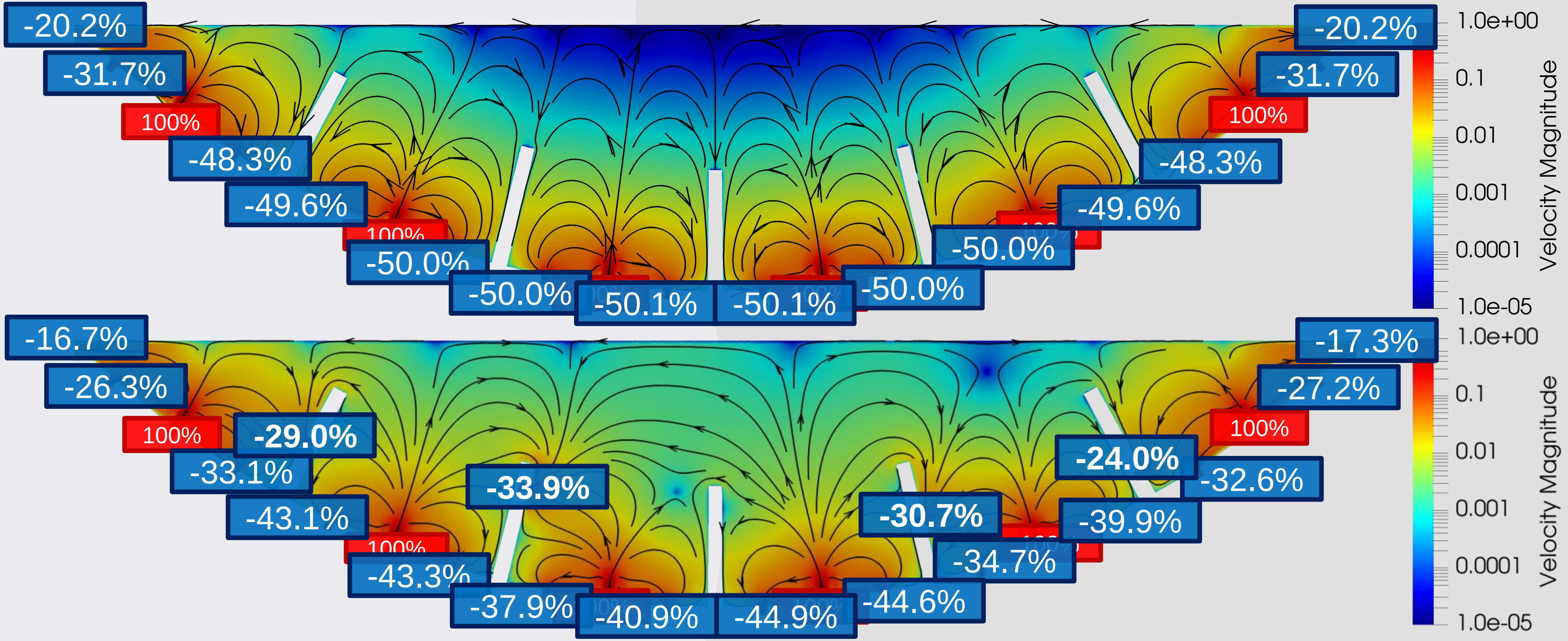
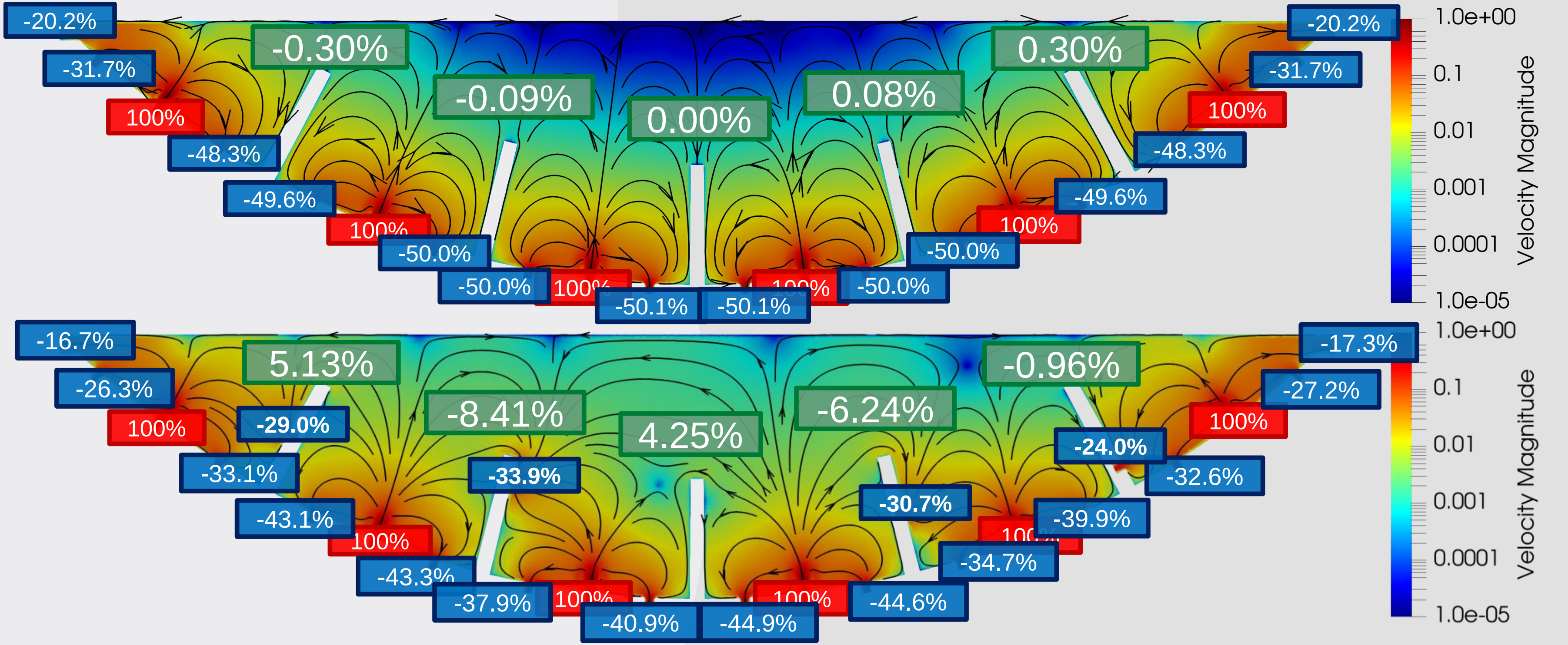
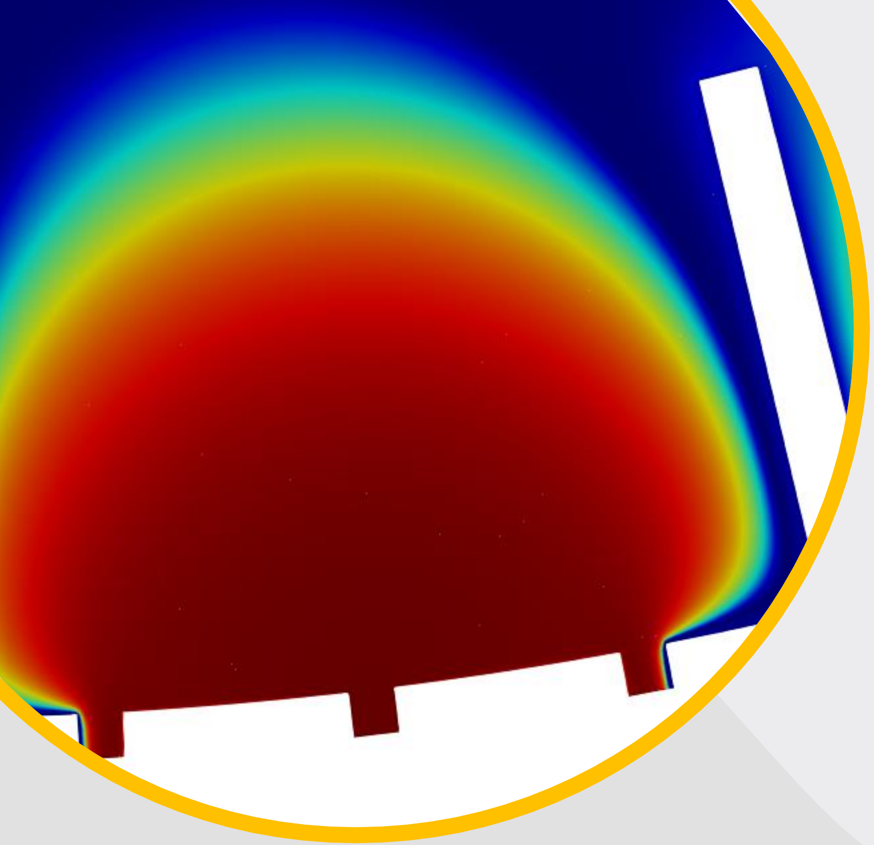


Flux transport

$$\int \boldsymbol{u} \cdot \boldsymbol{n} \, \mathrm{d}x$$





03

Nutrient transport

Nutrient transport

Reaction-advection-diffusion:

$$\frac{\partial c}{\partial t} - \frac{1}{\mathrm{Pe}}\nabla^2 c + \nabla\cdot(\boldsymbol{u}c) + \mathrm{Dm}\ c = f$$

$$c_{\mathrm{inlet}} = 1$$

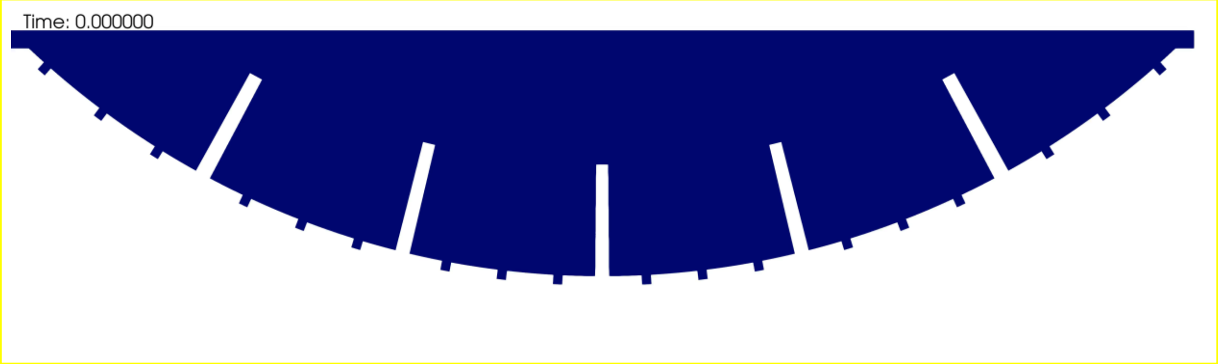
$$c_{\mathrm{neumann}} \equiv \boldsymbol{n}\cdot(\mathbf{u}\nabla c) = 0$$

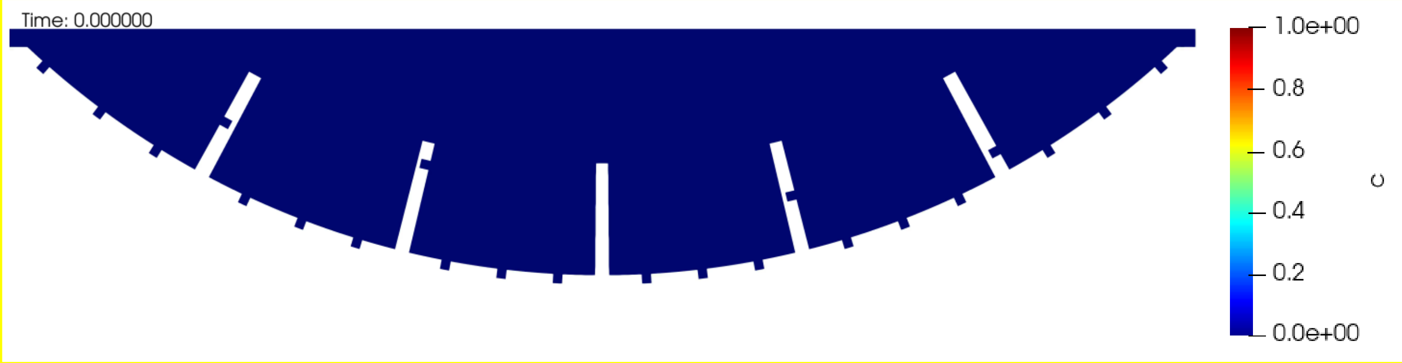
Oxygen parameters:

$$\frac{1}{\mathrm{Pe}} \approx 4.17\times 10^{-7}$$

$$\mathrm{Dm}_{\mathrm{max}} \approx 6.67\times 10^{-3}$$

Nutrient transport





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04

In progress

Next steps

VALIDATION

Compare to MRI data:
particle simulations

3D

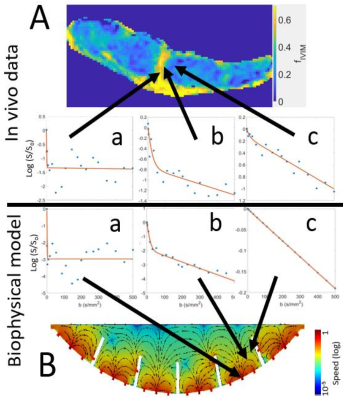
Limited 3D simulations:
comparison to 2D

MESH MOVEMENT

Moving boundaries:
utero-placental pump

Next steps

VALIDATION



[George Hutchinson, and Penny Gowland]

Compare to MRI c…
particle simulati…

…H MOVEMENT

…ving boundaries:
…o-placental pump

Compare to MRI c

particle simulati

SH MOVEMENT

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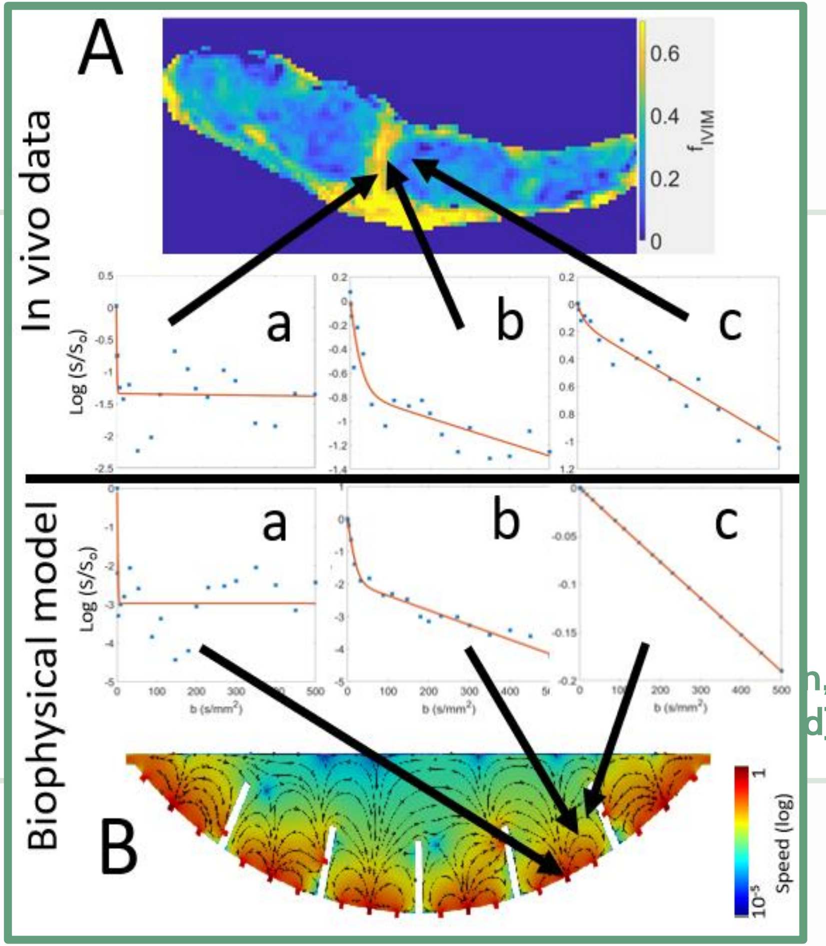
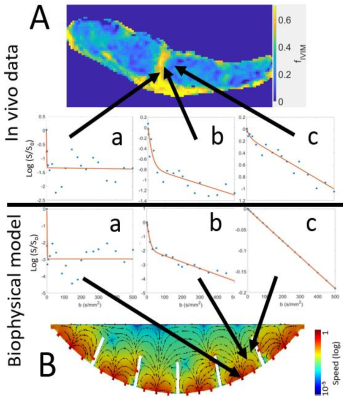


Next steps

VALIDATION



[George Hutchinson, and Penny Gowland]

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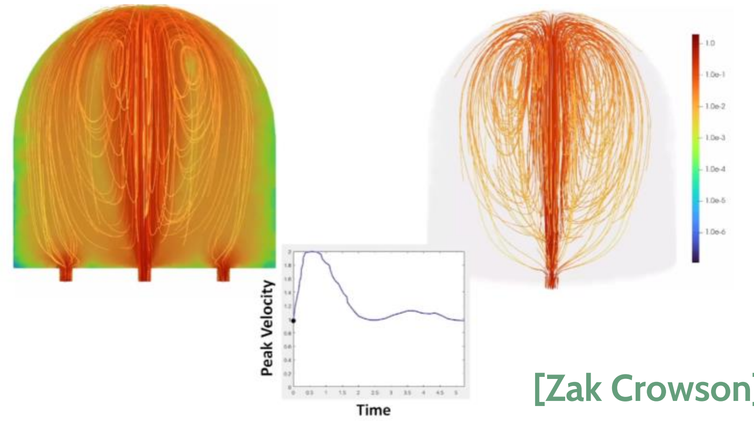

[Zak Crowson]

VALIDATIO
Compare to MRI
particle simulati

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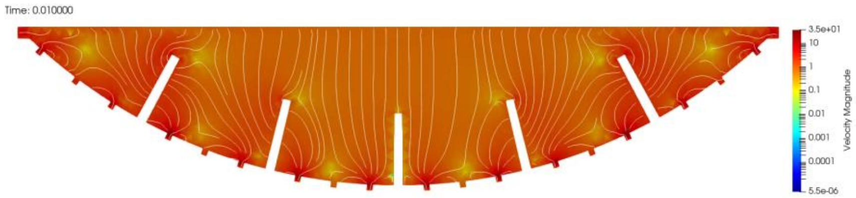

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Compare to MRI c
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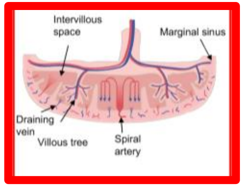
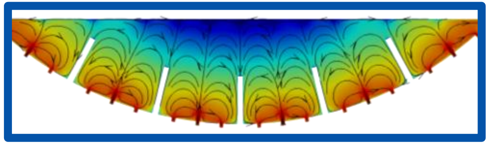
Summary

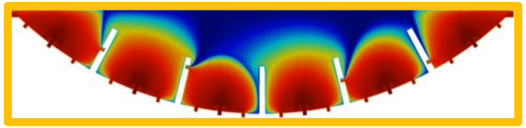
01 Introduction



02 Blood flow



03 Nutrient transport



04 In progress

University of Nottingham
UK | CHINA | MALAYSIA

Questions?

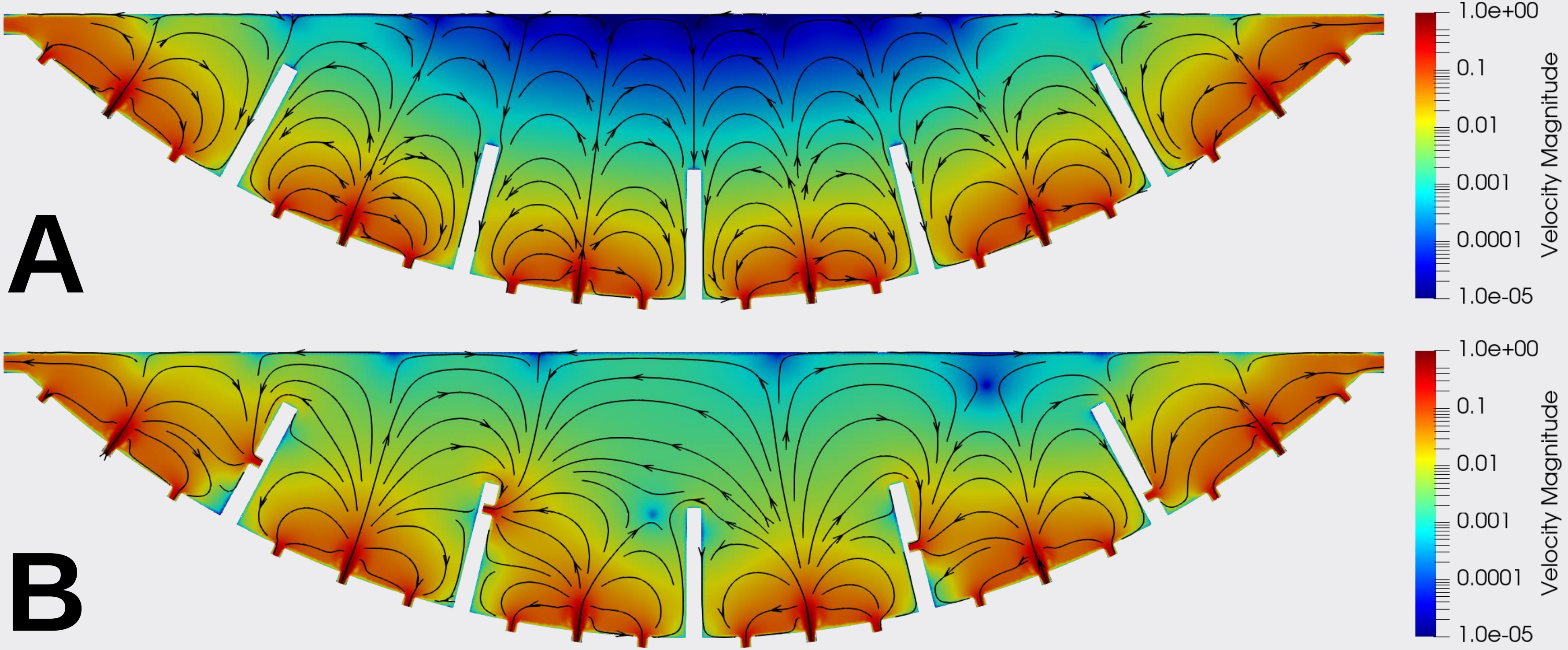
Thanks for your attention!

https://adam.blakey.family
@amblakey
adam.blakey@nott.ac.uk

05

Additional material

Side-by-side flow with and without septal veins



Nondimensionalised equations with parameters

Navier-Stokes + Darcy:

$$-\nabla^2 \boldsymbol{u} + \mathrm{Re}\, \nabla \cdot (\boldsymbol{u} \otimes \boldsymbol{u}) + \frac{1}{\mathrm{Dr}} \boldsymbol{u} + \nabla p = f$$

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\boldsymbol{u}_{\mathrm{inlet}} = \frac{(R^2 - r^2)}{R^2} \hat{\boldsymbol{y}}$$

$$\boldsymbol{u}_{\mathrm{wall}} = \mathbf{0}$$

$$\boldsymbol{u}_{\mathrm{neumann}} \equiv \left(\nabla \boldsymbol{u} - p \underline{\boldsymbol{I}} \right) \cdot \boldsymbol{n} = \mathbf{0}$$

$$\mathrm{Re} = 1 \times 10^3$$

$$\frac{1}{\mathrm{Dr}_{\mathrm{max}}} = 1.6 \times 10^5$$

$$\frac{1}{\mathrm{Pe}} \approx 4.17 \times 10^{-7}$$

$$\mathrm{Dm}_{\mathrm{max}} \approx 6.67 \times 10^{-3}$$

Reaction-advection-diffusion:

$$\frac{\partial c}{\partial t} - \frac{1}{\mathrm{Pe}} \nabla^2 c + \nabla \cdot (\boldsymbol{u} c) + \mathrm{Dm}\, c = f$$

$$c_{\mathrm{inlet}} = 1$$

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$$\mathrm{Re} := \rho L U / \mu$$

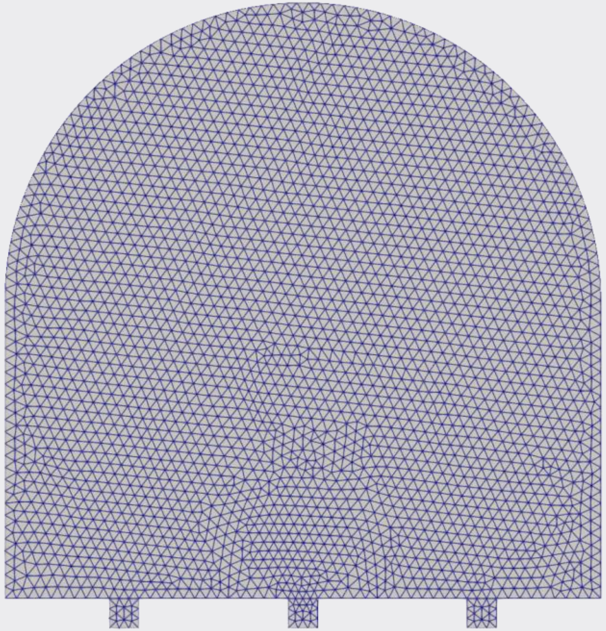
$$\mathrm{Dr} := k / L^2$$

$$\mathrm{Pe} := U L / D$$

$$\mathrm{Dm} := R L / U$$

Single placentone

- Qualitatively matches other models
- Assumes no 'spilling'
- Exponential fluid slow down



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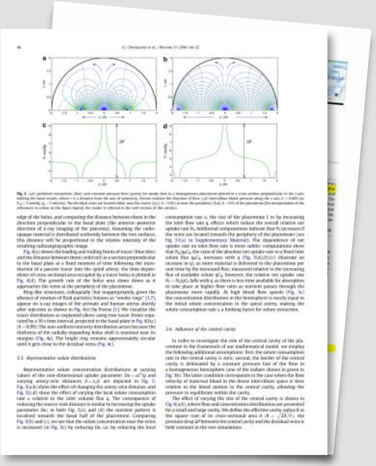
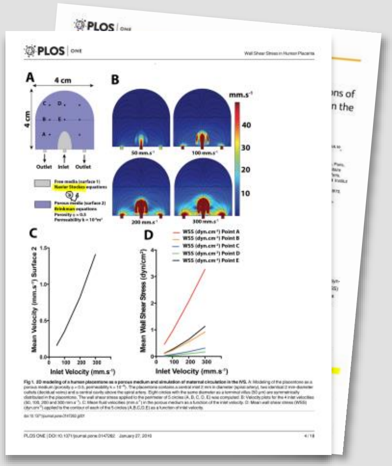


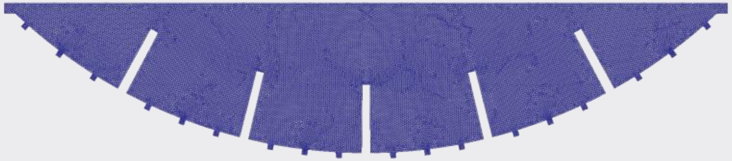
[Chernyavsky et al., 2010]



[Lecarpentier et al., 2016]

2D slice of whole placenta

- Agree with placentone simulations
- Show ‘spilling’
- Include marginal sinuses



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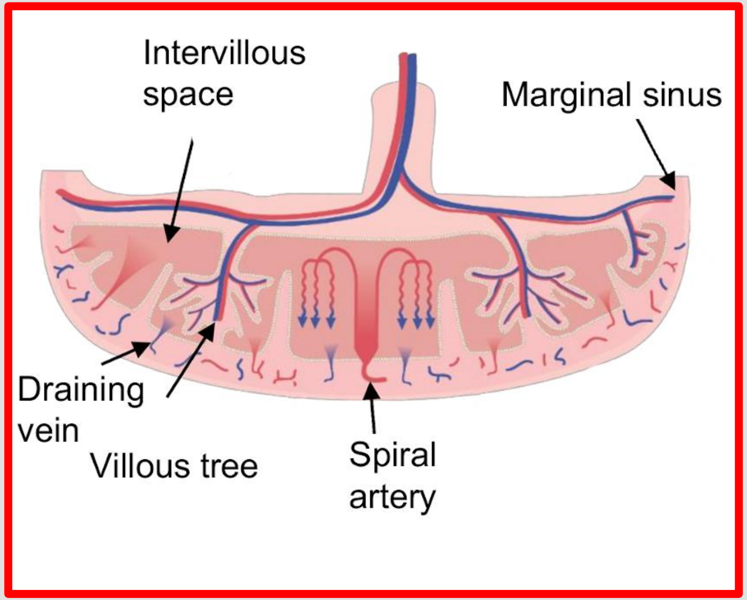

[Dellschaft et al., 2020]