AI-supported Modelling of Brain tissue as Soft Multiscale Multiphysics (Poroelastic) medium

January 21, 2022

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- Objective: simulation of poroelastic media such as **Brain tissue** (providing a digital twin).

Multiscale Multiphysics media (poroelastic)

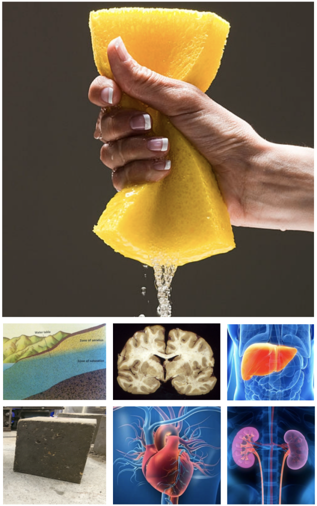

Figure 1: Poroelastic media

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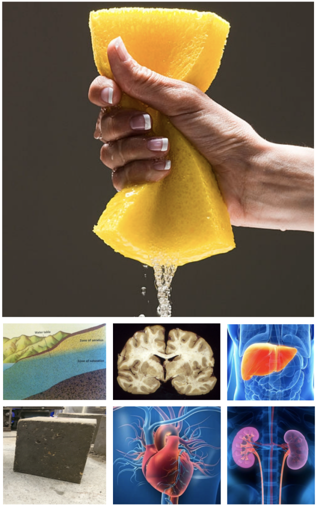

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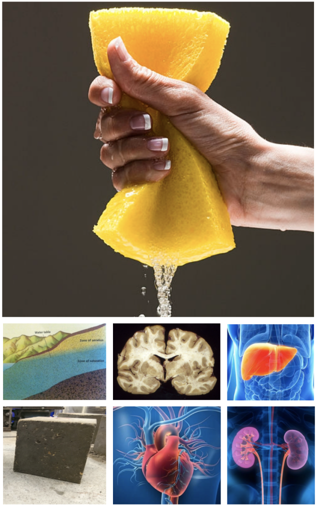

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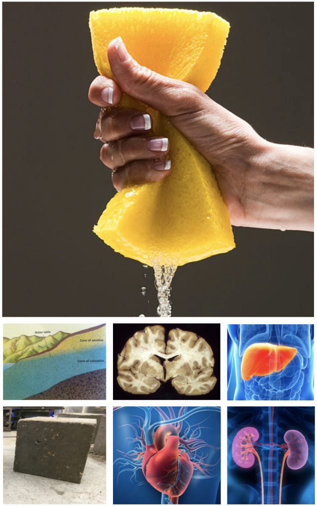

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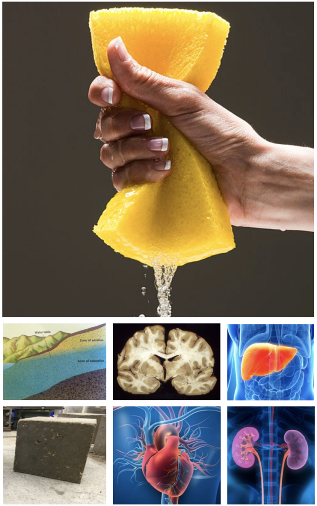

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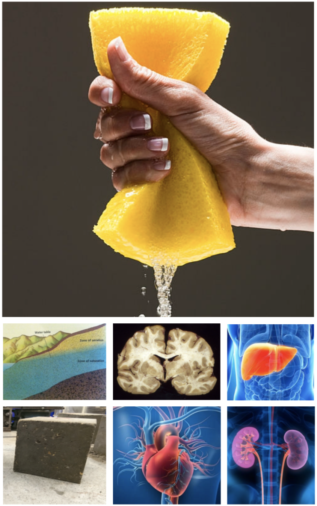

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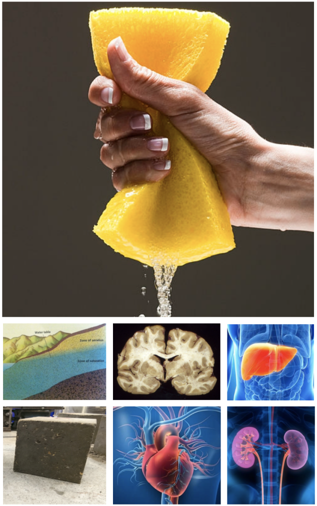

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- Rate/history dependent
- Sponge deformation causes fluid flow/percolation and vice versa

The problem

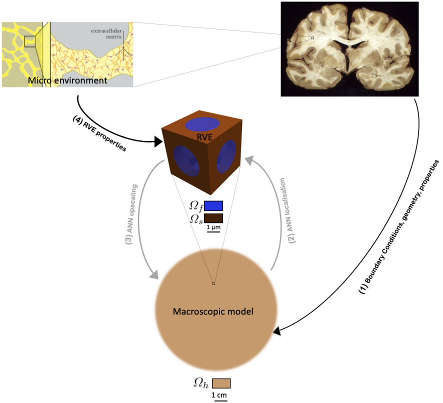

Figure 2: Outline of the problem

- Brain is a soft poroelastic/poro-inelastic tissue.

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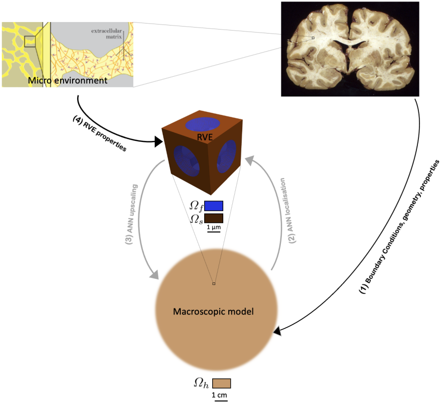

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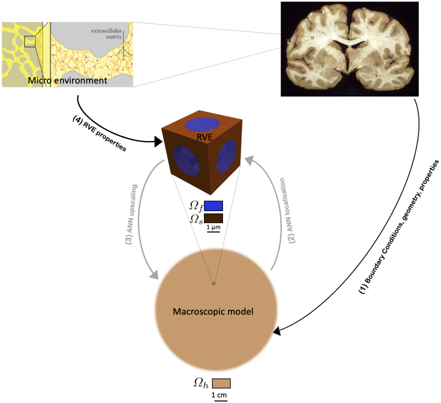

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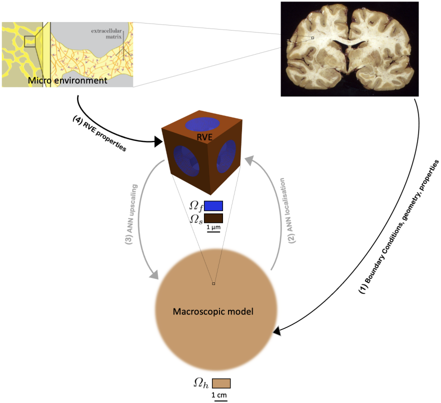

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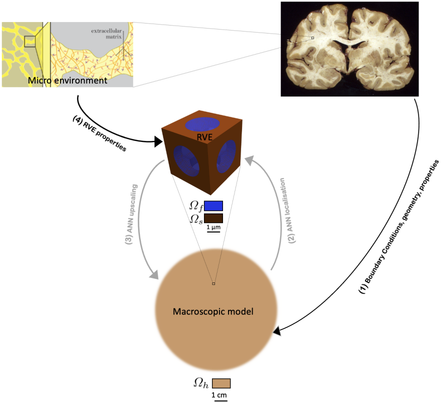

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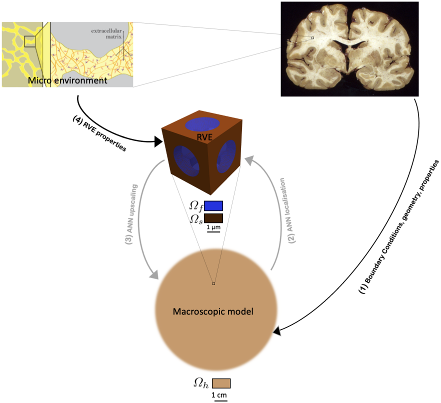

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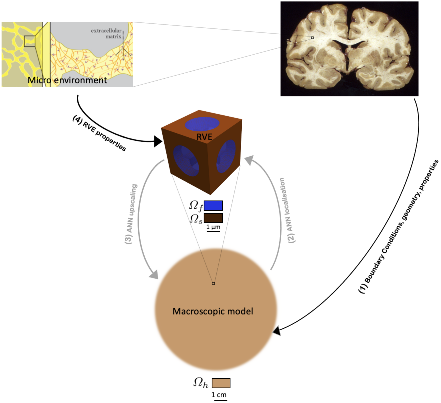

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- Paths (4) is to reach appropriate RVE based on microscopic images.

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- Such (mostly) microscopic changes are not obvious at macroscopic level while they have significant effects in material response.
- Thus: considering solid deformation is crucial even if we are only interested in fluid diffusion for drug delivery :)

model1

remodelling based

$$
\begin{aligned}
0 = &\int_{\partial\mathcal{B}} \Delta \boldsymbol{t}_s \cdot \delta \boldsymbol{u}^{(0)}\,\mathrm{d}S \\
&- \int_{\mathcal{B}} \left(\tilde{\mathbb{C}} : \Delta\boldsymbol{\varepsilon}^{(0)} - \tilde{\boldsymbol{\alpha}}\Delta p^{(0)}\right) : \nabla_{\boldsymbol{x}}\,\delta\boldsymbol{u}^{(0)}\,\mathrm{d}V \\
&+ \int_{\mathcal{B}} \left(\frac{1}{M}\Delta\dot{p}^{(0)}\right)\,\delta p^{(0)}\,\mathrm{d}V \\
&+ \int_{\partial\mathcal{B}} (\mathbf{K}\Delta\nabla_{\boldsymbol{x}} p^{(0)}) \cdot \boldsymbol{n}\,\delta p^{(0)}\,\mathrm{d}S \\
&- \int_{\mathcal{B}} (\mathbf{K}\Delta\nabla_{\boldsymbol{x}} p^{(0)}) \cdot \nabla_{\boldsymbol{x}}\,\delta p^{(0)}\,\mathrm{d}V \\
&+ \int_{\mathcal{B}} (\tilde{\boldsymbol{\alpha}} : \Delta\dot{\boldsymbol{\varepsilon}})\,\delta p^{(0)}\,\mathrm{d}V \\
&\quad \forall\ \delta\boldsymbol{u}^{(0)},\ \delta p^{(0)}.
\end{aligned}
$$

$$
\begin{aligned}
\nabla_{\boldsymbol{y}}^2 \mathbf{W}^{\mathbf{T}} - \nabla_{\boldsymbol{y}}\boldsymbol{P} + \mathbf{I} &= \mathbf{0} \quad \text{in } \Omega_f \\
\nabla_{\boldsymbol{y}} \cdot \mathbf{W}^{\mathbf{T}} &= \mathbf{0} \quad \text{in } \Omega_f \\
\mathbf{W} &= \mathbf{0} \quad \text{on } \Gamma \\
\langle \boldsymbol{P} \rangle_f &= \mathbf{0}
\end{aligned}
$$

with 7 solid problems

$$
\begin{aligned}
\nabla_{\boldsymbol{y}} \cdot (\mathbb{C}\xi_{\boldsymbol{y}}(\mathcal{A})) &= \mathbf{0} \quad \text{in } \Omega_s \\
(\mathbb{C}\xi_{\boldsymbol{y}}(\mathcal{A}))\boldsymbol{n} + \mathbb{C}\boldsymbol{n} &= \mathbf{0} \quad \text{on } \Gamma \\
\langle \mathcal{A} \rangle_s &= \mathbf{0}
\end{aligned}
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\end{aligned}
$$

where

$$(\tilde{\mathbb{C}}, M, \tilde{\boldsymbol{\alpha}}, \mathbf{K}) = ANN\,(\textit{microscale properties}(\textit{passive effects}, \textit{active effects}))$$

pros: non-formulated/structured passive and active changes, easier to develop
cons: B.C.s, complex to use

model2

ALE based

$$
\begin{aligned}
0 = &+ \int_{\Omega_h} \Delta \mathbf{P}_E : \nabla_{\boldsymbol{X}} \delta \boldsymbol{u}^{(0)} dV - \int_{\partial\Omega_h} \Delta \boldsymbol{t} \cdot \delta \boldsymbol{u}^{(0)} dS \\
&- \int_{\Omega_h} \Delta (\hat{\mathbf{G}}^{(0)} \mathbf{K} (\hat{\mathbf{F}}^{(0)})^{-T} \nabla_{\boldsymbol{X}} p^{(0)}) \cdot \nabla_{\boldsymbol{X}} \delta p^{(0)} dV \\
&+ \int_{\partial\Omega_h} \Delta (\hat{\mathbf{G}}^{(0)} \mathbf{K} (\hat{\mathbf{F}}^{(0)})^{-T} \nabla_{\boldsymbol{X}} p^{(0)}) \cdot \boldsymbol{N}_e \delta p^{(0)} dS \\
&+ \int_{\Omega_h} \Delta \langle \mathbf{G}^{(0)T} : \nabla_{\boldsymbol{Y}} \dot{\boldsymbol{u}}^{(1)} \rangle_s \delta p^{(0)} dV \\
&- \int_{\Omega_h} \Delta (\hat{\mathbf{G}}^{(0)T} : \nabla_{\boldsymbol{X}} \dot{\boldsymbol{u}}^{(0)}) \delta p^{(0)} dV
\end{aligned}
$$

where

$$
\begin{aligned}
\hat{\mathbf{F}}^{(0)} &= \langle \nabla_{\boldsymbol{X}} \boldsymbol{u}^{(0)} + \nabla_{\boldsymbol{Y}} \boldsymbol{u}^{(1)} \rangle_s + \mathbf{I} \\
\hat{\mathbf{G}}^{(0)} &= \det \hat{\mathbf{F}}^{(0)} (\hat{\mathbf{F}}^{(0)})^{-1} \\
\nabla_{\boldsymbol{Y}} \boldsymbol{u}^{(1)} &= ANN \left(\nabla_{\boldsymbol{X}} \boldsymbol{u}^{(0)}, p^{(0)} \right)
\end{aligned}
$$

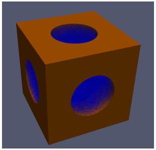
$$
\begin{aligned}
\mathbf{0} &= \nabla_{\boldsymbol{Y}} \cdot \mathbf{P}^{(0)} && \text{in} \quad \Omega_s \\
\mathbf{0} &= \left(\mathbf{P}^{(0)} + p^{(0)} \mathbf{G}^{(0)T} \right) \cdot \boldsymbol{N}, && \text{on} \quad \Gamma
\end{aligned}
$$

where

$$
\mathbf{P}^{(0)} = \frac{\partial \Psi^{(0)}}{\partial \mathbf{F}^{(0)}}
$$

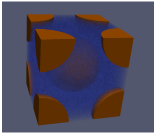
pros: compatible with energy-based techniques (Hyperelasticity, phase-field fracture/cut, growth etc.), more accurate, more stable numerically, B.C. etc.
cons: it was very difficult to develop and formulate :)

Why starting from microstructure?



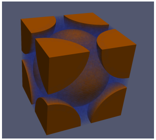
fluid pressure cube

Uniaxial cube



fluid pressure separate spheres

Uniaxial separate spheres



fluid pressure joined spheres

Uniaxial joined spheres

Energy distribution

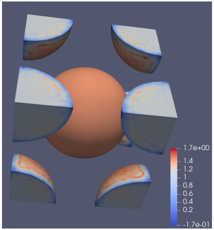


Figure 3

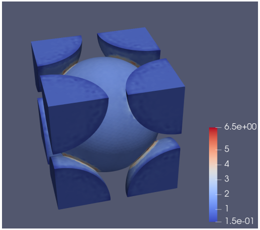


Figure 4

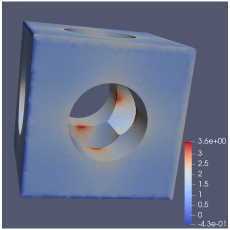


Figure 5

The RVE should reasonably match the tissue's ultrastructure.

Some results

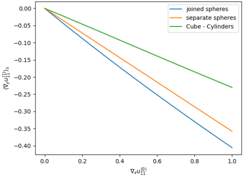


Figure 6

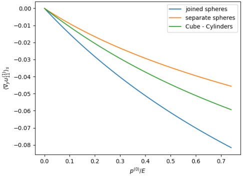


Figure 8

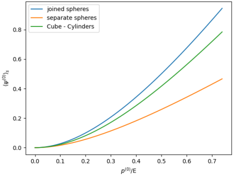


Figure 10

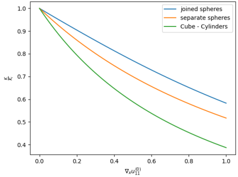


Figure 7

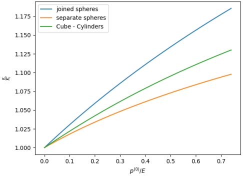


Figure 9

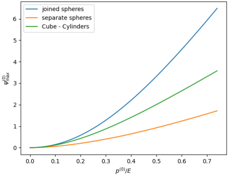
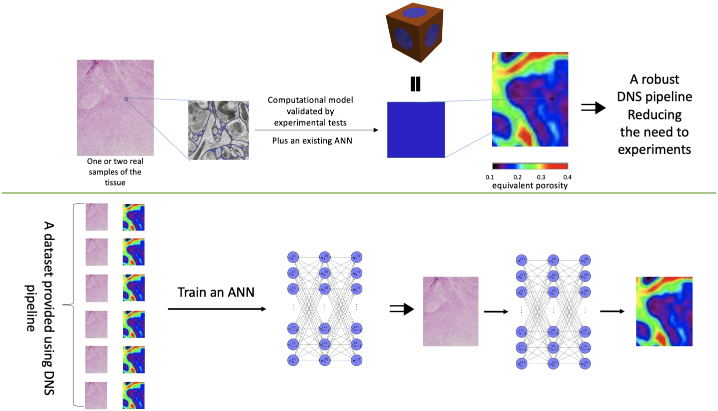


Figure 11

Potential work package



Concluding remarks

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- appropriate RVE geometry and properties (at least a good understanding) could be achieve using microscopic images (cryo-EM?)
- The importance and considerable influence of RVE geometry is shown in terms of both average quantities and energy concentration.
- Using some experimental results from the literature, together with our simulations we highlighted the importance of considering solid deformation and FSI features to reach a realistic prediction of fluid diffusion in brain tissue.

Thank you for your attention

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