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Using Salomé to reproduce the structure and to observe the diffusion of water molecules in biological tissue

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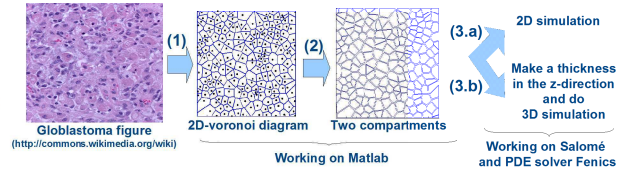
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Introduction

Diffusion magnetic resonance imaging (DMRI) can give useful information on cellular structure and its structural changes [1]. Salomé [2] is used to reproduce some complicated shapes in d -dimensions ($d=2,3$) that are used to represent the natural structures of various biological tissue. The meshes representing these shapes are used as inputs to a finite element code that we built upon FENICS C++ [3]. Results were obtained for a model of glioblastoma (cerebral tumor) as a Voronoi diagram which was used to observe the convergence of the apparent diffusion tensor in long-time limit to the effective diffusion tensor computed by homogenization theory [4].

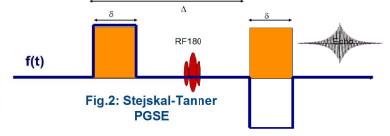
Problem formulation

- (1) The black points in the glioblastoma image are extracted to create a 2D Voronoi diagram by Matlab.
- (2) The common segments of two adjacent Voronoi cells are thickened to create extra-cellular space (Fig.1) in which the interior compartment contains cells, and the exterior compartment is between the cells.
- (3) Simulation

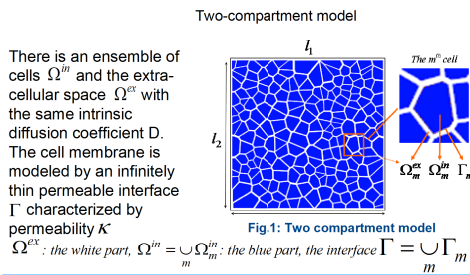


(3.a) Generate the triangular mesh from step 2 using Salomé and perform simulation for 2D using our finite element code.

(3.b) Make a thickness in the z-direction, create one layer, repeat this layer and put a thickness between two layers to create multi-layer structure, generate the tetrahedral mesh and do simulation for 3D.



The DMRI signals from which we define the apparent diffusion tensors are obtained by solving Bloch-Torrey equation for a Stejskal - Tanner PGSE sequence (Fig.2) and the effective infinite time diffusion tensors are obtained by solving Laplace equation on the same domain Ω which contains a representative sample of the cellular structure $\Omega = \prod_{k=1}^d [a_k, b_k]$ ($a_k < b_k$).



Bloch-Torrey PDE and the apparent diffusion tensor D^A

$$\frac{\partial M(\vec{x}, t)}{\partial t} = -i\gamma f(t) (\vec{g} \cdot \vec{x}) M(\vec{x}, t) + \nabla \cdot (D \nabla M(\vec{x}, t))$$

with initial conditions are the uniform distribution

$$D \nabla M^{in}(\vec{x}, t) \cdot \vec{n}^{in}(\vec{x}) = -D \nabla M^{ex}(\vec{x}, t) \cdot \vec{n}^{ex}(\vec{x}) = \kappa (M^{ex}(\vec{x}, t) - M^{in}(\vec{x}, t)), \vec{x} \in \Gamma,$$

$$[M(\vec{x}, t)]_{\vec{x}_i=a_i} = [M(\vec{x}, t)]_{\vec{x}_i=b_i} \exp(i(\vec{g} \cdot \vec{e}_i) \gamma l_k \int_0^{\Delta} f(s) ds), \left[\frac{\partial M(\vec{x}, t)}{\partial x_k} \right]_{\vec{x}_i=a_i} = \left[\frac{\partial M(\vec{x}, t)}{\partial x_k} \right]_{\vec{x}_i=b_i} \exp(i\gamma (\vec{g} \cdot \vec{e}_i) l_k \int_0^{\Delta} f(s) ds)$$

$$\vec{g} = \vec{q} / \gamma \quad \Psi(\vec{q}, t) = \int_{\Omega} M(\vec{x}, t) d\vec{x} \quad \ln \Psi(\vec{q}, t) = \vec{q}^T D^A \vec{q} \int_0^{\Delta} f(s) ds + O(\|\vec{q}\|^4)$$

Laplace's equation and the effective diffusion tensor D^{eff}

$$\nabla \cdot (D \nabla v_j(\vec{x})) = 0$$

$$D \nabla v_j^e(\vec{x}) \cdot \vec{n}^{in}(\vec{x}) = -D \nabla v_j^i(\vec{x}) \cdot \vec{n}^{ex}(\vec{x}) = \kappa (v_j^e(\vec{x}) - v_j^i(\vec{x})), \vec{x} \in \Gamma$$

$$[v_j(\vec{x})]_{\vec{x}_i=a_i} = [v_j(\vec{x})]_{\vec{x}_i=b_i} - (\vec{g} \cdot \vec{e}_i) l_k$$

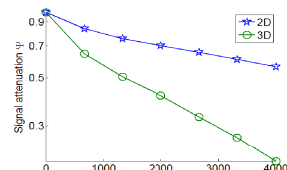
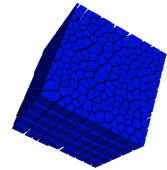
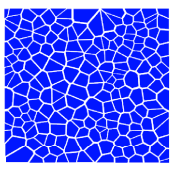
$$\left[\frac{\partial v_j(\vec{x})}{\partial x_k} \right]_{\vec{x}_i=a_i} = \left[\frac{\partial v_j(\vec{x})}{\partial x_k} \right]_{\vec{x}_i=b_i} \quad D_{jk}^{eff} = [D_{jk}^{eff}]_{j=1, d, k=1, d}$$

$$D_{jk}^{eff} = D \int_{\Omega} \nabla v_j \cdot \vec{e}_k d\vec{x}$$

\vec{e}_k is the unit vector in the k^{th} direction

Results

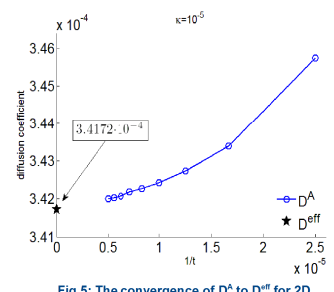
We simulated on 2D and 3D voronoi cells in the box $[-25 \mu m; 25 \mu m]^d$ (Fig.2 and Fig.3) by taking the same intrinsic diffusion coefficient $D=3 \cdot 10^{-3} \mu m^2 / \mu s$ for interior and exterior compartments. The permeability of the inter-compartment interface was $\kappa = 10^{-5} \mu m / \mu s$. Seven b-values were taken from 0 to 4000 to get a curve of signal attenuation from which we obtain the tensor D^A .



The signals in both 2D and 3D were obtained at $\delta = \Delta = 10ms$ in Fig.4. The computation for 7 b-values costs about 11 minutes for 2D with the mesh-size of 8565 vertices and 1.5 hours for 3D with the mesh-size of 49035 vertices.

$$b\text{-value} = \gamma^2 \vec{g}^T \delta^2 (\Delta - \delta/3)$$

Fig.5 shows the convergence of the apparent diffusion coefficient D^A to the effective diffusion coefficient D^{eff} in 2D for $\delta = 20ms$ and $\Delta = 20 \cdot 180ms$.



The computation for each D^A computed from 7 b-values costs between 20 minutes to 50 minutes.

Conclusion and future works

A Voronoi diagram was created to observe the diffusion in glioblastoma in both 2D and 3D. Preliminary results showed that Salomé gives good meshes for this application. More realistic shapes are currently under development such as random cylinders to approach the structure of the human cerebral grey matter.

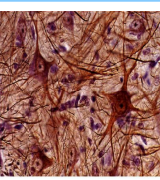


Fig.6: Human visual cortex (Le Bihan et al. PNAS 2006)

References

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