A Bi-Exponential Model for Cerebral Perfusion Imaging Using IVIM

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MRI technique designed to extract microvasculature parameters

😊 Non-invasive
Diffusion (tissue)… is what remains after removing the diffusion (tissue) component from the MRI signal.

\[ S = S_0 (1 - f_{IVIM}) F_{Diff}(b) + S_0 f_{IVIM} F_{IVIM}(b) \]

\[ F_{IVIM} = e^{-bD^*} \]

Dw-PGSE pulse sequence

Easy to implement

Quantitative

Discrepancies

Le Bihan D., 1988, Radiology.
PROJECT OBJECTIVES

- Establish IVIM as a robust cerebral perfusion technique
  - Preclinical testing – Neurospin
  - Numerical simulations – INRIA, Neurospin
  - Validation on human subjects – University of Illinois at Urbana-Champaign
- Characterize microvasculature (aging, pathologies)
\[ \Delta = 14 \text{ ms} \]

- **Mono-exponential**
- **Bi-exponential**

![Graph showing IVIM signal vs. b-value (s/mm²) with data points and fit lines for mono-exponential and bi-exponential models.](image)
METHODS: DATA ANALYSIS

\[
\frac{S}{S_0} = (1 - f_{IVIM})F_{Diff} + f_{IVIM}F_{IVIM}
\]

mono exponential model: \( F_{IVIM} = e^{-bD^*} \)

our model: \( F_{IVIM} = f_1 e^{-bD_1^*} + f_2 e^{-bD_2^*} \)

\[ AIC_c = N_b \ln(MSE) + \frac{2k(k + 1)}{N_b - k - 1} \]
### THE BI-EXPONENTIAL IVIM MODEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Delta = 14$ ms</th>
<th>$\Delta = 24$ ms</th>
<th>$\Delta = 34$ ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AIC_{cmono} - AIC_{cbl}$</td>
<td>15.00 ± 4.63</td>
<td>9.45 ± 4.34</td>
<td>3.18 ± 4.64</td>
</tr>
<tr>
<td>$D^*_1 (10^{-3}$ mm$^2$/s)</td>
<td>2.25 ± 1.58</td>
<td>4.28 ± 2.25</td>
<td>10.44 ± 5.91</td>
</tr>
<tr>
<td>$D^*_2 (10^{-3}$ mm$^2$/s)</td>
<td>23.92 ± 6.09</td>
<td>19.92 ± 2.30</td>
<td>23.16 ± 6.45</td>
</tr>
<tr>
<td>$f_{IVIM}$ (%)</td>
<td>9.37 ± 1.84</td>
<td>10.02 ± 2.05</td>
<td>9.53 ± 1.85</td>
</tr>
<tr>
<td>$f_2$ (%)</td>
<td>77.35 ± 11.54</td>
<td>81.86 ± 6.32</td>
<td>55.36 ± 26.79</td>
</tr>
</tbody>
</table>

\[
F_{IVIM} = f_{slow}e^{-bD^*_slow} + f_{fast}e^{-bD^*_fast}
\]

Fournet, G. et al., 2016, JCBFM, in press.
NUMERICAL SIMULATIONS OF MICROVASCULAR NETWORKS

Hypotheses:

- Segments = straight tubes
- Isochromat trajectory composed of N segments
- Different lengths, \( L_1 \ldots L_N \), for each segment in a trajectory
- Constant blood flow velocity, \( V \), in a trajectory

Solve the Bloch equations and compute the IVIM signal.
Library of simulated signals

Gaussian distributions

\[ L_{\text{mean}} = [8 - 150] \mu m \]
(2 \( \mu m \) step)
\[ \sigma_L = 0.5 \times L_{\text{mean}} \]

Gaussian distributions

\[ V_{\text{mean}} = [0.1 - 10] \text{ mm/s} \]
(0.1 mm/s step)
\[ \sigma_V = 0.5 \times V_{\text{mean}} \]

\[
F_{\text{IVIM/Sim}}(L_{\text{slow}}, V_{\text{slow}}, L_{\text{fast}}, V_{\text{fast}}) = f_{\text{slow}}F_{\text{Sim/low}}(L_{\text{slow}}, V_{\text{slow}}) + f_{\text{fast}}F_{\text{Sim/fast}}(L_{\text{fast}}, V_{\text{fast}})
\]

\[
F_{\text{IVIM}} = f_{\text{slow}}e^{-bD_{\text{slow}}^*} + f_{\text{fast}}e^{-bD_{\text{fast}}^*}
\]

\[ f_{\text{slow}}/f_{\text{fast}}: \text{found with the bi-exponential model fitting} \]
Simulation results are coherent with two pool model hypothesis
Two distinct blood flow velocities for the two pools
Vessel length cannot be determined with the parameters used
Estimating Capillary Lengths and Velocities

With short and long time data:

1. Estimate microvascular blood velocity (MBV) – 20-30 ms
2. Estimate microvessel segment length (MSL) – 400 ms

\[
MBV = \sqrt{\frac{6D_{\text{PGSE}}^*}{t_{\text{diff}}}} \\
MSL = \frac{6D_{\text{STEAM}}^*}{MBV}
\]

Cerjanic A. et al., ISMRM Annual Meeting 2015
Effect of different acquisition parameters on the IVIM outputs
  - Diffusion encoding time
  - Repetition time
  - ...

IVIM early biomarker for Alzheimer's disease?

Scan old and young volunteers – University of Illinois at Urbana-Champaign
ACKNOWLEDGMENTS

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5 different sites in Rhône-Alpes Region

Pôle Est Hospital
Louis Pradel, Lyon

Campus LyonTech La Doua

European Synchrotron Radiation Facility, Grenoble

Saint-Etienne Hospital

Cancer Center Léon Bérard, Lyon
Pipeline concept

Patient specific diagnosis

Biomechanics - *in vitro*

Understanding the thrombosis

Modelling - *in silico*
Numerical Simulation

*in vivo* - ICT - Virtual Stent

Stent Optimization

Deployment of stent for Patient specific diagnosis

http://www.thrombus-vph.eu
Decision Support System (DSS)

IN VIVO
Medical Imaging
Data of Patients

IN SILICO
Image Processing
Numerical simulation Modelling

IN VITRO
Biology and Biomechanics

DECISION SUPPORT SYSTEM
Data mining and Learning System

Sophisticated Thrombosis modelling

Prediction of the relevant treatment

http://www.thrombus-vph.eu
DSS and Care of the Patient

http://www.thrombus-vph.eu
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