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A Bi-Exponential Model for Cerebral Perfusion Imaging Using IVIM

Luisa CIOBANU

Inria
INVENTEURS DU MONDE NUMÉRIQUE

ILLINOIS

ANR

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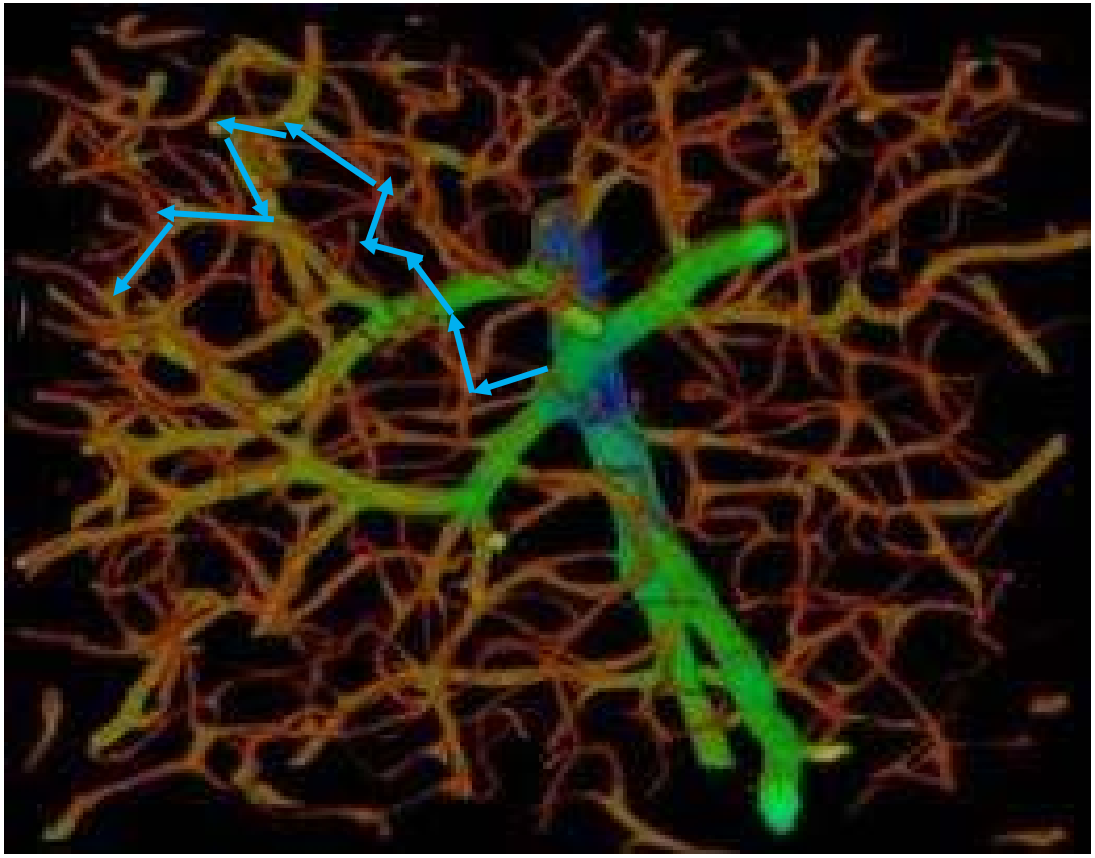
INTRAVOXEL INCOHERENT MOTION (IVIM) IMAGING

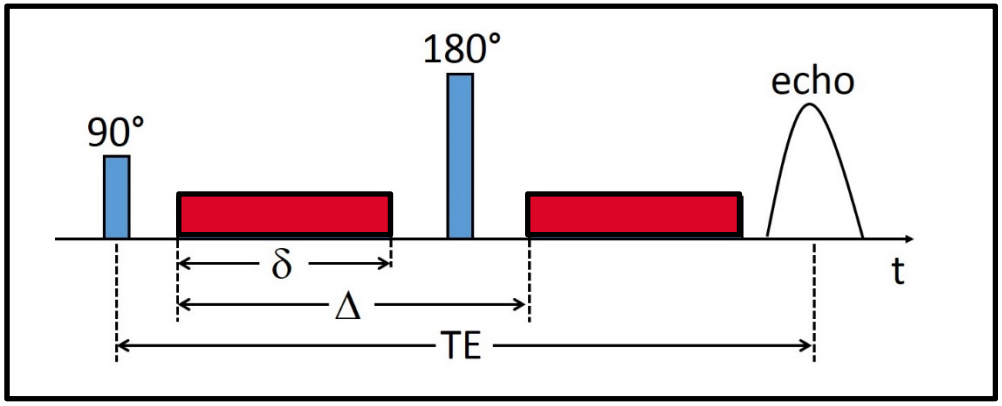
MRI technique designed to extract microvasculature parameters



☺ Non-invasive

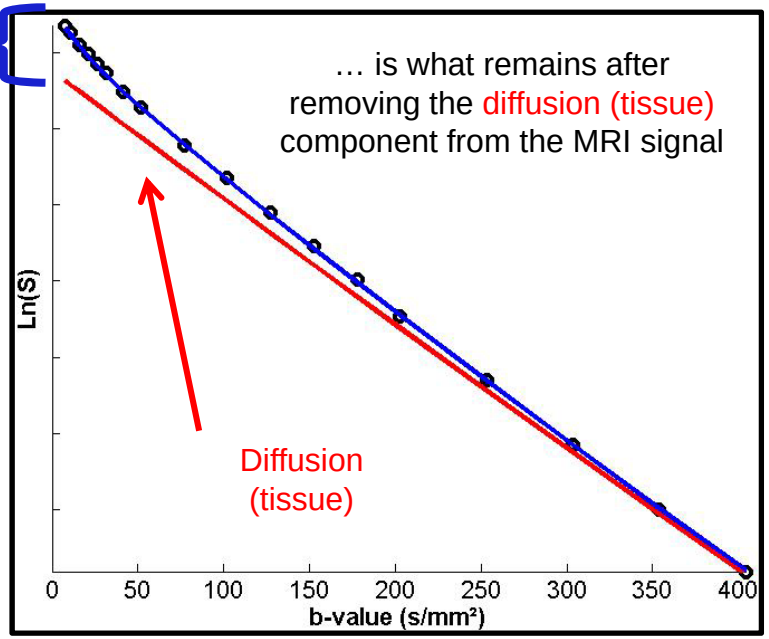
THE IVIM SIGNAL

☺ Easy to implement



Dw-PGSE pulse sequence

IVIM



Le Bihan D., 1988, Radiology.

☺ Quantitative

$$S = \underbrace{S_0(1 - f_{IVIM})F_{Diff}(b)}_{\text{diffusion component}} + \underbrace{S_0 f_{IVIM} F_{IVIM}(b)}_{\text{IVIM component only present at small b-values}}$$

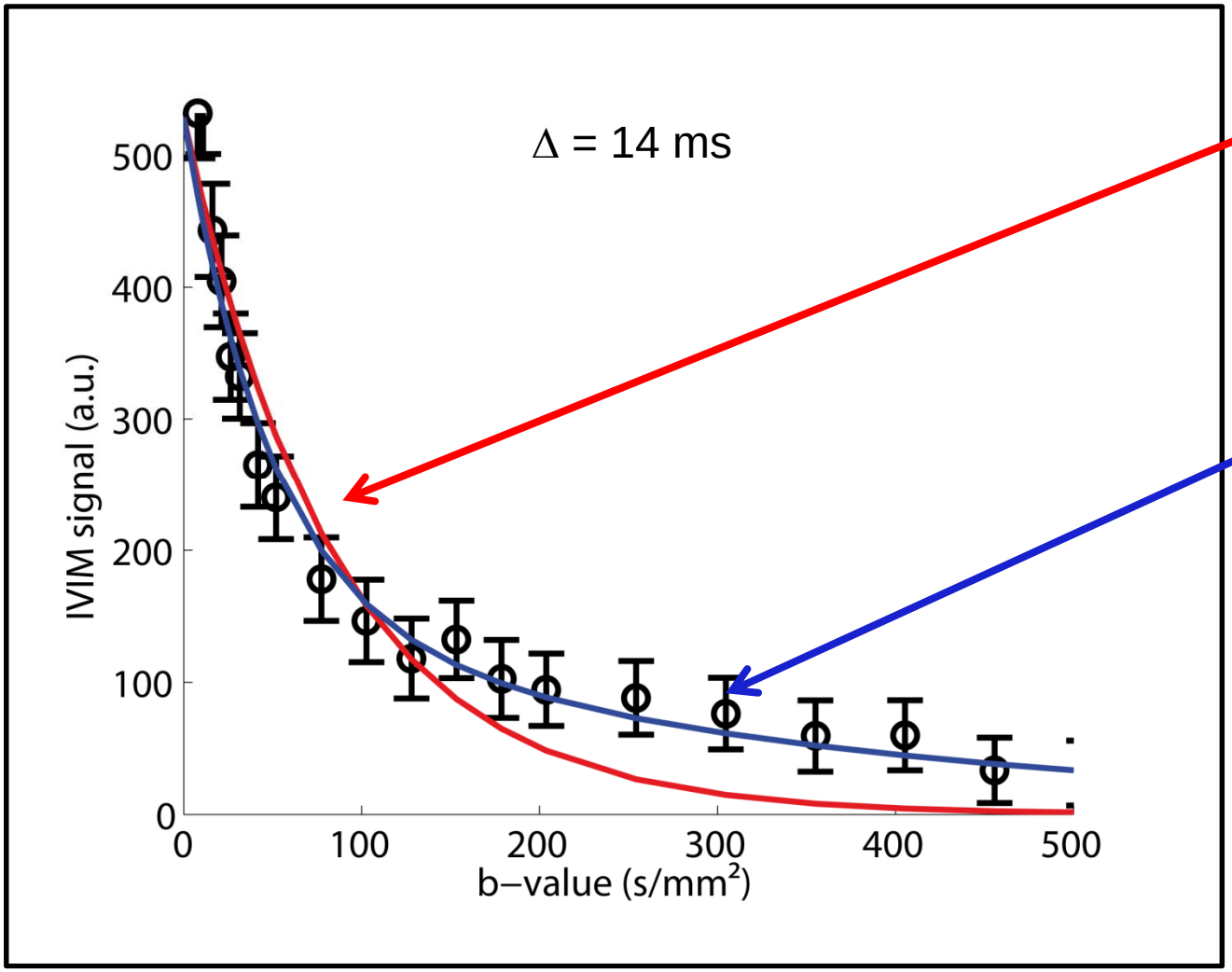
$$F_{IVIM} = e^{-bD^*}$$

☹ Discrepancies

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)

IVIM DATA

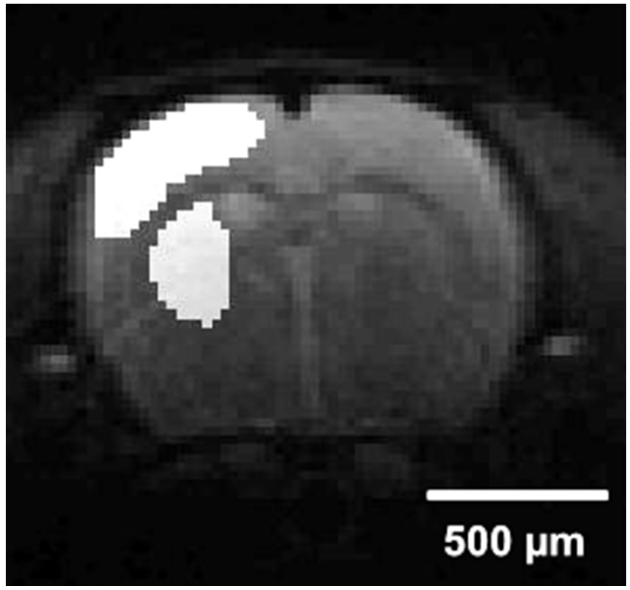

Δ = 14 ms
IVIM signal (a.u.)
0
100
200
300
400
500
b–value (s/mm²)
Mono-exponential
Bi-exponential

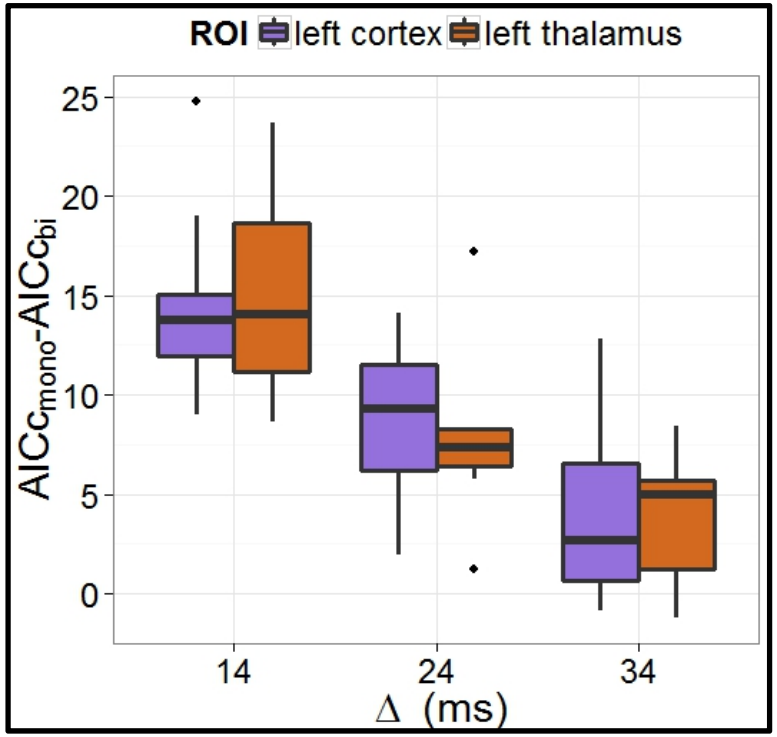
METHODS: DATA ANALYSIS

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

$$mono\ exponential\ model: \quad F_{IVIM} = e^{-bD^*}$$

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

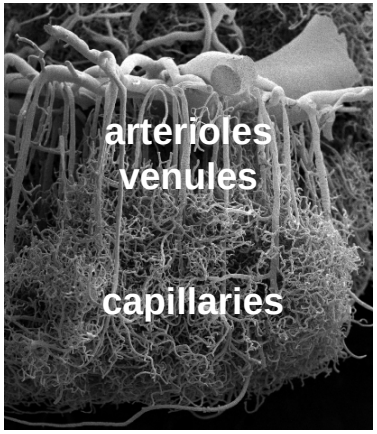




$$AIC_c = N_b \ln(MSE) + \frac{2k(k+1)}{N_b - k - 1}$$

THE BI-EXPONENTIAL IVIM MODEL

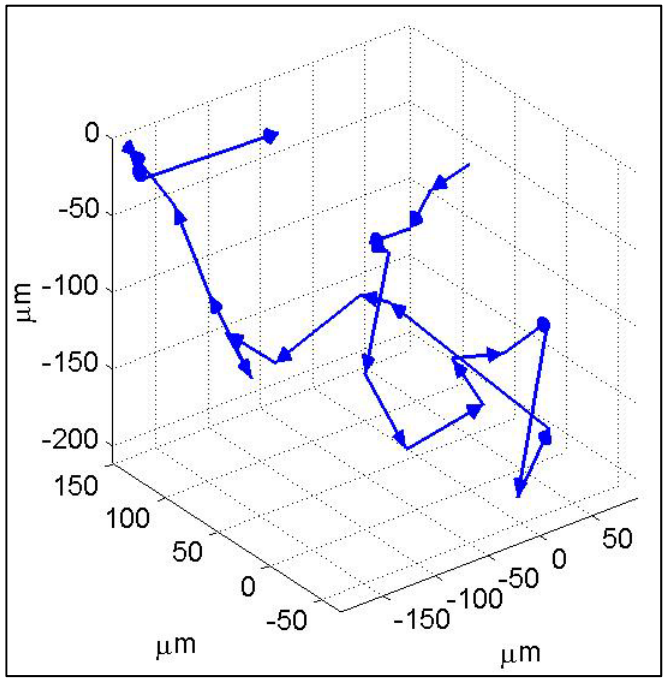
Parameter	Δ = 14 ms	Δ = 24 ms	Δ = 34 ms
AIC_{cmono}-AIC_{cbi}	15.00 ± 4.63	9.45 ± 4.34	3.18 ± 4.64
D^*_1 (10^{-3} mm²/s)	2.25 ± 1.58	4.28 ± 2.25	10.44 ± 5.91
D^*_2 (10^{-3} mm²/s)	23.92 ± 6.09	19.92 ± 2.30	23.16 ± 6.45
f_{IVIM} (%)	9.37 ± 1.84	10.02 ± 2.05	9.53 ± 1.85
f_2 (%)	77.35 ± 11.54	81.86 ± 6.32	55.36 ± 26.79



$$F_{IVIM} = f_{slow} e^{-bD^*_{slow}} + f_{fast} e^{-bD^*_{fast}}$$

Fournet, G. et al., 2016, JCBFM, in press.

NUMERICAL SIMULATIONS OF MICROVASCULAR NETWORKS



Hypotheses:

Segments = straight tubes

Segment orientations: uniform distribution in a unit sphere

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

Library of simulated signals

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

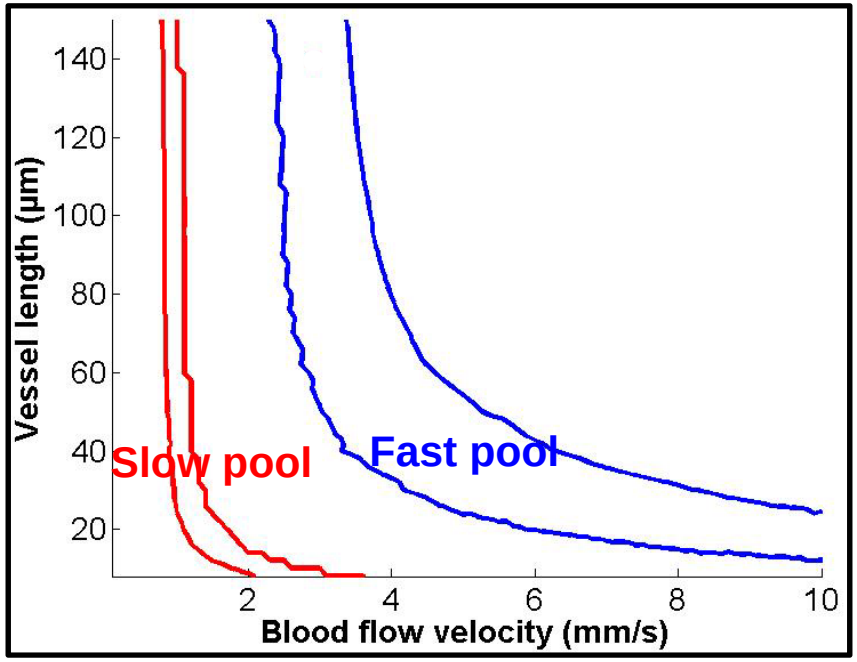
Gaussian distributions
$V_{mean} = [0.1 - 10]\ mm/s$
(0.1 mm/s step)
$\sigma_V = 0.5 \times V_{mean}$

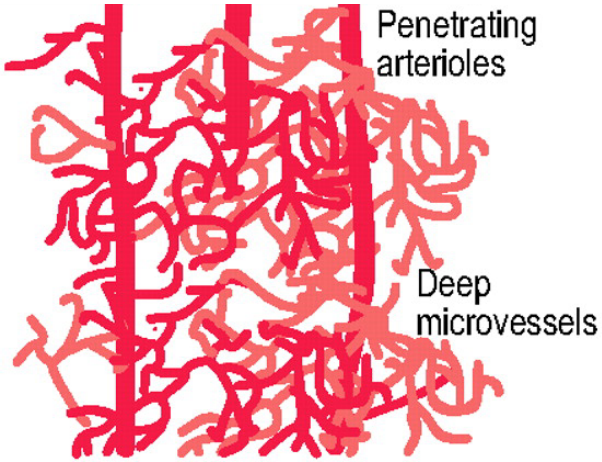
$$F_{IVIM/Sim}(L_{slow}, V_{slow}, L_{fast}, V_{fast}) = f_{slow} F_{Sim/slow}(L_{slow}, V_{slow}) + f_{fast} F_{Sim/fast}(L_{fast}, V_{fast})$$

$$F_{IVIM} = f_{slow} e^{-bD^*_{slow}} + f_{fast} e^{-bD^*_{fast}}$$

f_{slow}/f_{fast}: found with the bi-exponential model fitting

COMPARISON RESULTS





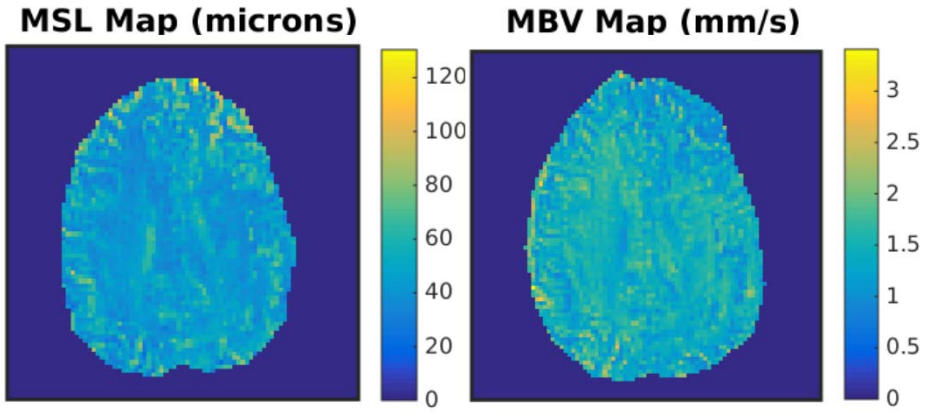
Vascular pool	Blood velocity (mm/s)
Slow	1.8
Fast	4.6

- 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



Short Diffusion Time (PGSE)	Long Diffusion Time (STEAM)

$$MBV = \sqrt{\frac{6D^*_{PGSE}}{t_{diff}}} \qquad MSL = \frac{6D^*_{STEAM}}{MBV}$$

Cerjanic A. et al. , ISMRM Annual Meeting 2015

WORK IN PROGRESS

- Effect of different acquistion parameters on the IVIM outputs
  - Diffusion encoding time
  - Repetition time
  - …
- IVIM early biomarker for Alzheimers disease?

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

ACKNOWLEDGMENTS

- Gabrielle Fournet
- Denis Le Bihan
- Boucif Djemai
- Erwan Selingue

NeuroSpin

- Jing Rebecca Li

Inria
INVENTEURS DU MONDE NUMÉRIQUE

- Brad Sutton
- Alex Cerjanic

ILLINOIS

ANR

NSF

NIH

Medical Imaging Research Center

Guy Courbebaisse, PhD, HDR
Scientific Researcher and Senior Project Leader

guy.courbebaisse@creatis.insa-lyon.fr
http://www.creatis.insa-lyon.fr/~courbebaisse
http://www.thrombus-vph.eu

Research Institute affiliated with INSA Lyon, University Claude Bernard Lyon 1, University Jean Monnet Saint-Etienne, CNRS (UMR 5220) and Inserm (U1206)

http://www.creatis.insa-lyon.fr

5 different sites in Rhône-Alpes Region

Pôle Est Hospital
Louis Pradel, Lyon

Creatis

Campus LyonTech La Doua

Saint-Etienne Hospital

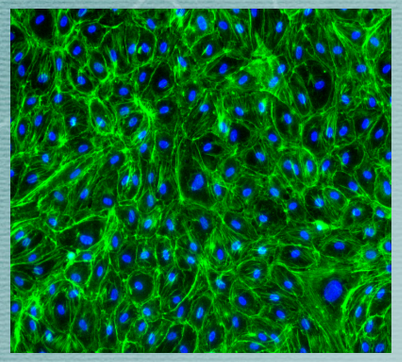
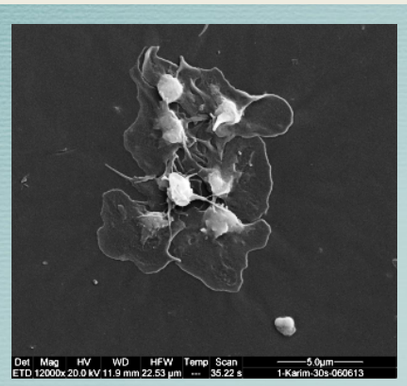
European Synchrotron Radiation
Facility, Grenoble

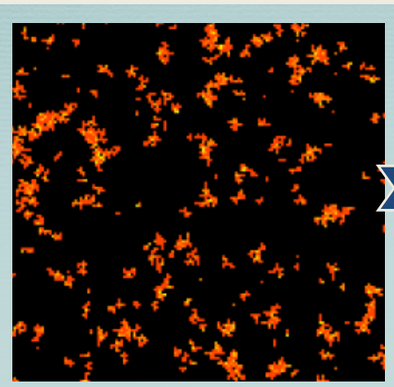
Cancer Center Léon Bérard, Lyon

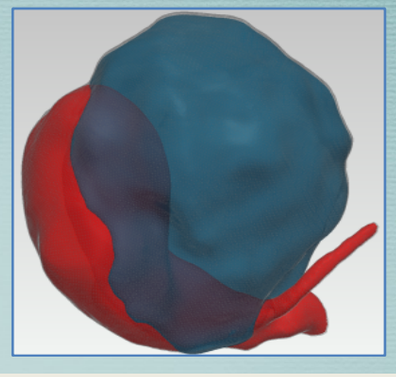
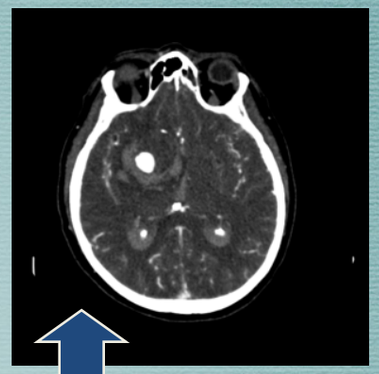
Pipeline concept

Patient specific diagnosis

http://www.thrombus-vph.eu

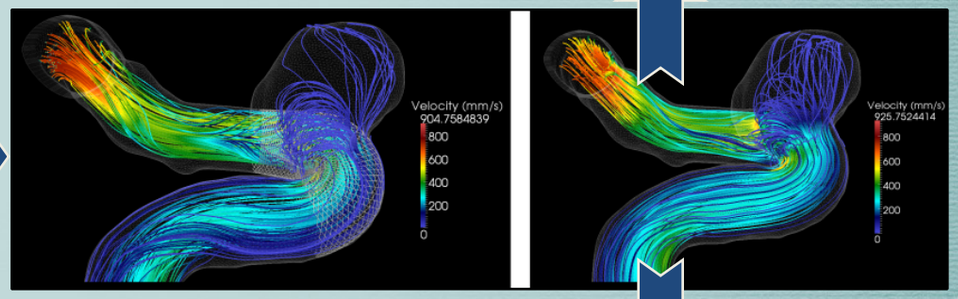


Biomechanics - *in vitro*

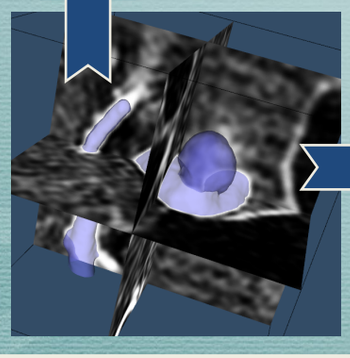
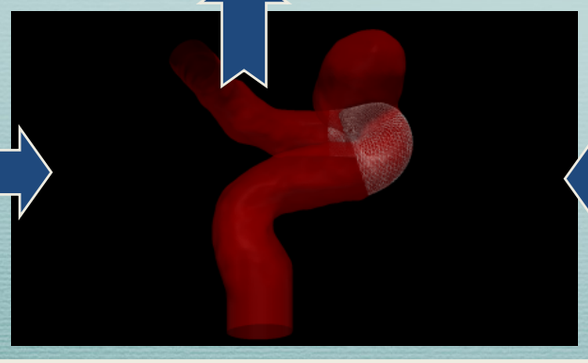
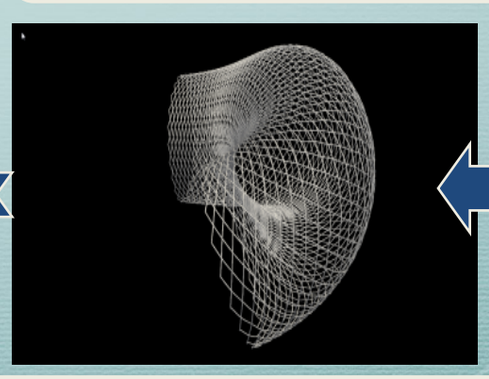
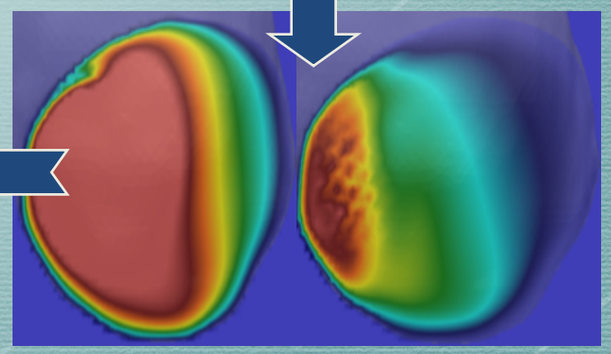
Understanding the thrombosis

Modelling - *in silico* Numerical Simulation



in vivo - ICT - Virtual Stent

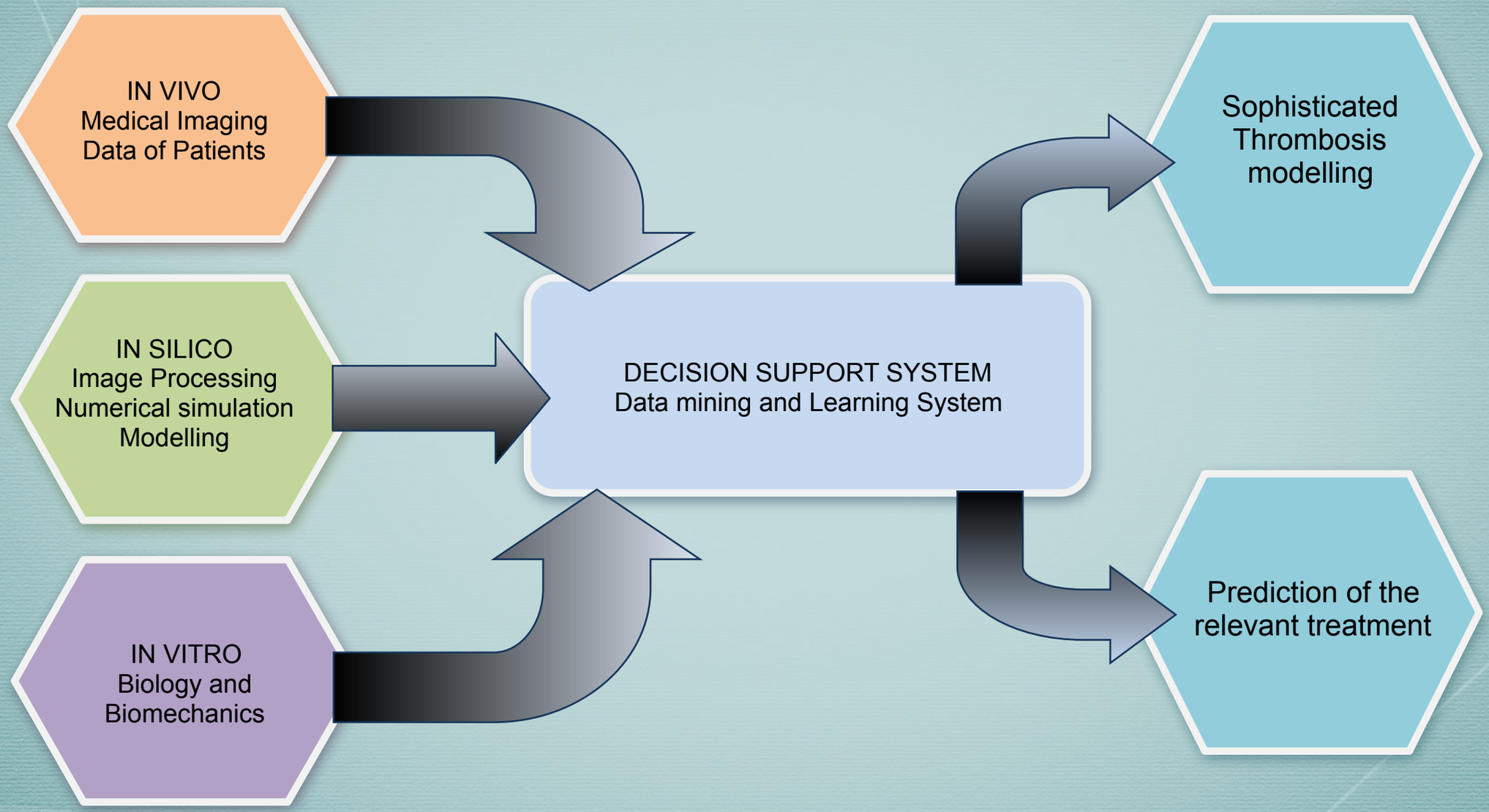
Stent Optimization

Deployment of stent for Patient specific

Decision Support System (DSS)

http://www.thrombus-vph.eu



DSS and Care of the Patient

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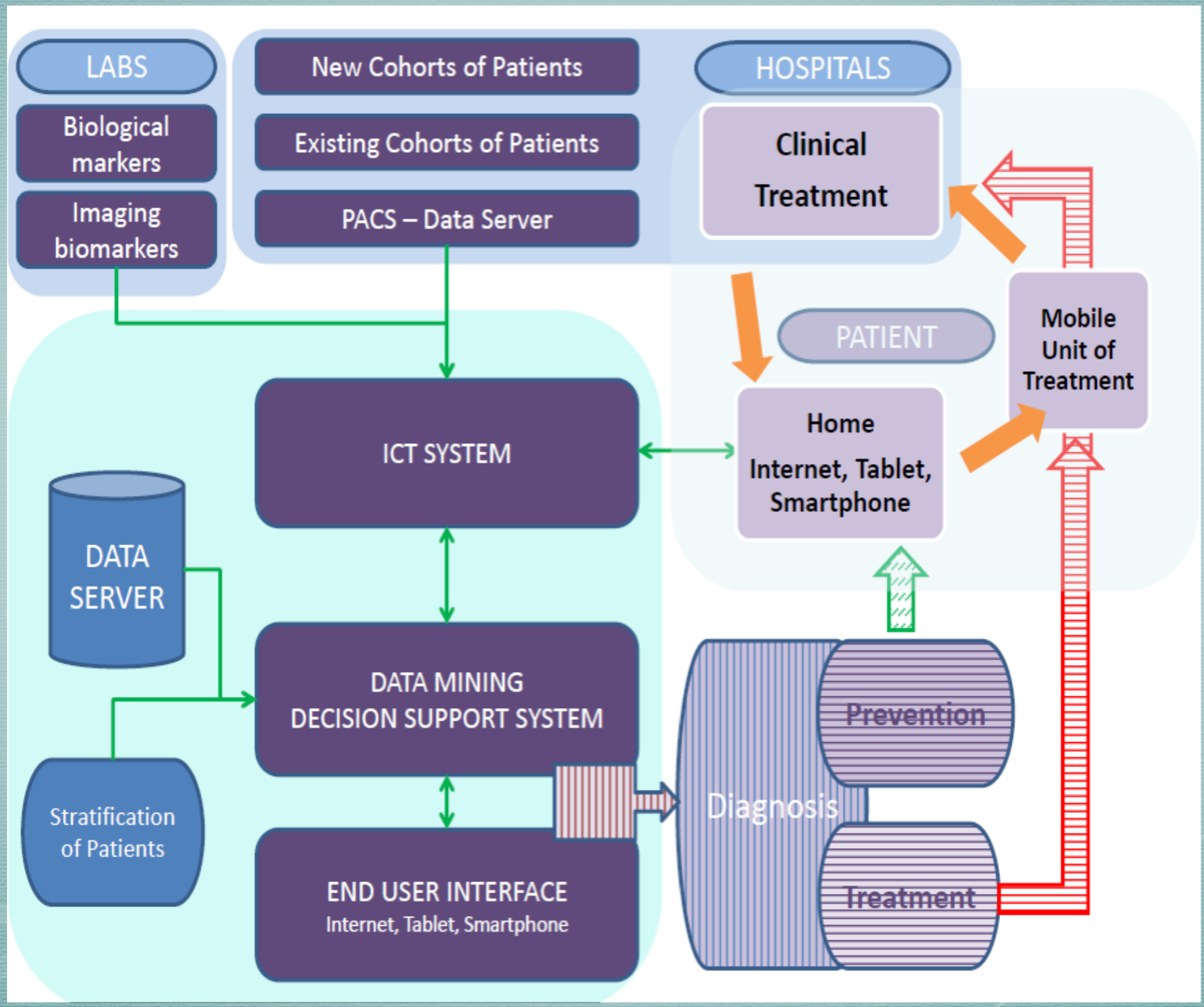

Medical Imaging Research Center

Guy Courbebaisse, PhD, HDR
Scientific Researcher and Senior Project Leader

guy.courbebaisse@creatis.insa-lyon.fr
http://www.creatis.insa-lyon.fr/~courbebaisse
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