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Wall Shear Stress Quantification in the context of 4D Flow MRI Simulation on Carotids

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Context

4D flow PC-MRI on carotids:

- Acquisition time: 8-20 min
- Resolution: [1,0x1,0x1,0 mm³; 30ms]

Technological constraint:

Measurements are subjected to:

$$SNR \propto \log \left(K \times \frac{T_{\text{acquisition}}}{N_{\text{voxels}}^3} \right)$$

with K a system and patient linked constant.

- ➔ Low reliability of biomarkers values
- ➔ Wall Shear Stress [Boussel et al., 2009]

MRI-Quantif project objective:

Enhance biomarkers estimation reliability in 4D flow PC-MRI

Contribution:

Estimate the Wall Shear Stress (WSS) Vector in 4D Flow MRI context

Strategy: Inverse problems theory

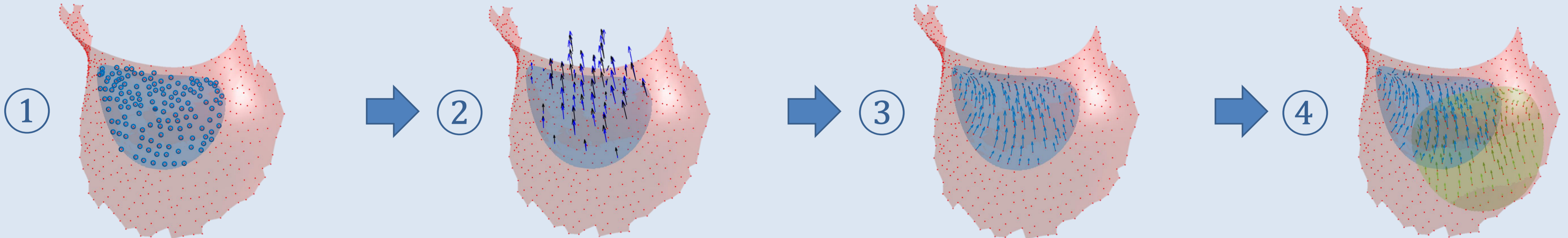


A priori knowledge on the vector field

State of the art

	Quantification without regularization	Quantification with regularization
Local Frame	Cylindrical frame [Barker et al., 2010]	Parabolic model [Petersson et al., 2012] Smoothing B-spline [Potters et al., 2014]
Whole domain	B-spline functions [Stalder et al., 2008] Sobel filters [Piatti et al., 2017]	5 th order polynomial [Köhler et al., 2001] Finite Element Model [Sotelo et al., 2016]

PaLMA (Parametric Local Morphology Algorithm)



- Fit a parametric surface around a point of interest in the local frame

$$z = S(x, y)$$

with S a third order polynomial

- Least-squares optimization

- Fit a "filtered" parametric model over the velocity data with a no-slip condition

$$\vec{V} = (z - S(x, y)) \times \vec{P}(x, y, z)$$

where \vec{P} is a 3D vector of 2nd order polynomials

- Least-squares optimization

- Compute the WSS on every points near the point of interest and repeat for all the vertices

$$\vec{\tau}_e = \mu(\nabla \vec{V} + \nabla \vec{V}^T) \cdot \vec{n}$$

- Projection of $\vec{\tau}_e$ on the surface

- Assess the WSS from the multiple estimations

$$\hat{\tau} = \operatorname{argmin}_{\vec{\tau} \in (\mathbb{R}^3)^3} \left\{ \sum \|\vec{\tau} - \vec{\tau}_e\|_H \right\}$$

with $\|\cdot\|_H$ the Huber norm of the vector norm

4D Flow MRI Simulation

- Application of a mean filter for the velocity
- Each voxel is divided into 216 smaller voxels
- Linear interpolation on this fine grid
- The filtered velocity is the mean of these 216 voxels
- Application of a centred Gaussian noise with a SNR of 20 dB (~ 4,5 % of the Venc) [Stalder et al., 2008]

$$\sigma = \frac{\sqrt{2}}{2} \times \frac{V_{\text{enc}}}{SNR}$$

Carotid N°1 Carotid N°2

Results

$$SER_{\text{mag}} = 10 \times \log_{10} \left(\frac{\sum_j \|\vec{\tau}_{CFD,j}\|_2^2}{\sum_j \|\|\vec{\tau}_{CFD,j}\| - \|\hat{\tau}_j\|\|_2^2} \right)$$

$$SER = 10 \times \log_{10} \left(\frac{\sum_j \|\vec{\tau}_{CFD,j}\|_2^2}{\sum_j \|\vec{\tau}_{CFD,j} - \hat{\tau}_j\|_2^2} \right)$$

r is the Pearson's correlation

$$\bar{\theta} = \operatorname{mean} \left(\cos^{-1} \frac{\vec{\tau}_{CFD} \cdot \hat{\tau}}{\|\vec{\tau}_{CFD}\| \|\hat{\tau}\|} \right)$$

$$\theta_m = \operatorname{mediane} \left(\cos^{-1} \frac{\vec{\tau}_{CFD} \cdot \hat{\tau}}{\|\vec{\tau}_{CFD}\| \|\hat{\tau}\|} \right)$$

Carotid	Time	Algorithm	SER_{mag} [dB]	SER [dB]	r [%]	$\bar{\theta}$ [°]	θ_m [°]
N°1	∇ t	[Potters et al., 2014]	3,61	3,12	71,1	28,7	17,7
		PaLMA	6,69	5,52	78,5	25,4	14,7
N°1	systole	[Potters et al., 2014]	3,48	2,99	58,8	23,2	16,2
		PaLMA	6,76	5,44	69,1	19,4	13,4
N°2	∇ t	[Potters et al., 2014]	2,04	1,76	71,9	45,7	30,5
		PaLMA	4,60	3,51	76,9	46,8	31,2
N°2	systole	[Potters et al., 2014]	1,78	1,61	72,1	29,3	18,9
		PaLMA	4,69	3,93	76,3	28,1	17,6

Table: Mean performance of both PaLMA and [Potters et al., 2014] computed over 20 MRI simulations on 2 carotids with a SNR of 20 dBs.

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Conclusion

- Fast Wall Shear Stress computation for carotids (less than 5 min per carotid)
- WSS quantification improvement for different metrics
- Possible filter adaptation if the MRI point spread function is known
- Possibility to improve the velocity model with fluid mechanics constraints such as incompressibility.