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

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2













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.

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

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] |

 $(\mathbf{4})$

Low reliability of biomarkers values Wall Shear Stress [Boussel et al., 2009] **Strategy:** Inverse problems theory



A priori knowledge on the vector field

PaLMA (Parametric Local Morphology Algorithm)

Sł

 $\left(3\right)$

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

Fit a "filtered" parametric model > over the velocity data with a noslip condition

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

Assess the WSS from the multiple estimations

Carotid N°1

1

z = S(x, y)

with *S* a third order polynomial

Least-squares optimization

 $\vec{V} = (z - S(x, y)) \times \vec{P}(x, y, z)$ where \vec{P} is a 3D vector of 2^{nd} order polynomials

Least-squares optimization

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

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

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

with $\|.\|_{H}$ the Huber norm of the vector norm

Région

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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
- \succ The filtered velocity is the mean of these 216 voxels

Application of a centred Gaussian noise with a SNR of 20 dB ($\sim 4,5$ % of the Venc) [Stalder et al., 2008]

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

$$\begin{aligned} \text{Results} \\ ER_{mag} &= 10 \times \log_{10} \left(\frac{\sum_{j} \left\| \vec{\tau}_{CFD,j} \right\|_{2}^{2}}{\sum_{j} \left\| \left\| \vec{\tau}_{CFD,j} \right\| - \left\| \hat{\tau}_{j} \right\| \right\|_{2}^{2}} \right) \\ SER &= 10 \times \log_{10} \left(\frac{\sum_{j} \left\| \vec{\tau}_{CFD,j} \right\| - \left\| \hat{\tau}_{j} \right\| \right\|_{2}^{2}}{\sum_{j} \left\| \vec{\tau}_{CFD,j} \right\| - \hat{\tau}_{j} \right\|_{2}^{2}} \right) \end{aligned} \qquad r \text{ is the Pearson's correlation} \\ \bar{\theta} &= mean \left(\cos^{-1} \frac{\vec{\tau}_{CFD} \cdot \hat{\tau}}{\left\| \vec{\tau}_{CFD} \right\| \left\| \hat{\tau} \right\|} \right) \\ \theta_{m} &= mediane \left(\cos^{-1} \frac{\vec{\tau}_{CFD} \cdot \hat{\tau}}{\left\| \vec{\tau}_{CFD} \right\| \left\| \hat{\tau} \right\|} \right) \end{aligned}$$

| Carotid | Time | Algorithm | $SER_{mag} [dB]$ | SER [dB] | <i>r</i> [%] | $\overline{oldsymbol{	heta}}$ [°] | $oldsymbol{	heta}_m$ [°] |
|---------|---------|------------------------|------------------|----------|--------------|-----------------------------------|--------------------------|
| 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 |
| | 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 |
| | 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 |

Keterences

[Barker et al., 2010] Barker A. J., Lanning C. et Shandas R. « Quantification of hemodynamic wall shear stress in patients with bicuspid aortic valve using phase-contrast MRI », Annals of Biomedical Engineering, 2010.

[Stalder et al., 2008] Stalder A. F., Russe M. F., Frydrychowicz A., Bock J., Henning J. et Markl M. « Quantitative 2D and 3D phase contrast MRI: Optimized analysis of blood flow and vessel wall parameters », MRM, 2008.

[Piatti et al., 2017] Piatti F., Pirola S., Bisseli M., Nesteruk I., Sturla F., Della Corte A., Redaelli A., Vorta E. « Towards the improved quantification of in-vivo abnormal wall shear stresses in BAV-affected patients from 4D-flow imaging: Benchmarking and application to real data », Journal of Biomechanics, 2017. [Petersson et al., 2012] Petersson S., Dyverfeldt P. et Ebbers T. « Assessment of the accuracy of MRI wall shear stress estimation using numerical simulations », JMRI, 2012. [Potters et al., 2014] Potters W. V., van Ooij P., Marquering H., vanBavel E. et Nederveen A. J. « Volumetric arterial wall shear stress calculation based on Cine Phase Contrast MRI », JMRI, 2015. [Köhler et al., 2001] Köhler U., Marshall L., Robertson M. B., Long Q. Xu X. Y. et Hoskins P. R. « MRI

measurement of wall shear stress vectors in bifurcation models and comparison with CFD predictions », JMRI, 2001.

[Sotelo et al., 2016] Sotelo J., Urbina J., Valverde I., Tejos C., Irarrazaval P., Andia M. E., Uribe S. et Hurtado D. E. « 3D quantification of wall shear stress ans oscillatory shear stress index using a finite-element method in 3D Cine PC-MRI data of thoracic aorta », IEEE Transactions on medical imaging, 2016.

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.

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.

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Carotid N°2