Visualization and Quantification of Blood Flow in the Human Aorta. From in vivo 4D Phase Contrast MRI to Subject-Specific Computational Hemodynamics

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Outline

In vivo 4D PC MRI measurements of healthy human aortic flows

- In vivo quantitative analysis of aortic helical blood flow

- Subject-specific models of aortic hemodynamics using individual not invasively measured flow conditions at boundaries:

- PC MRI measured flow rate waveforms as BCs

- 3D PC MRI measured velocity profiles as BCs (preliminary results)

SECTION I

Insight into the Physiological Relevance of Helical Blood Flow in the Human Aorta. An in vivo study

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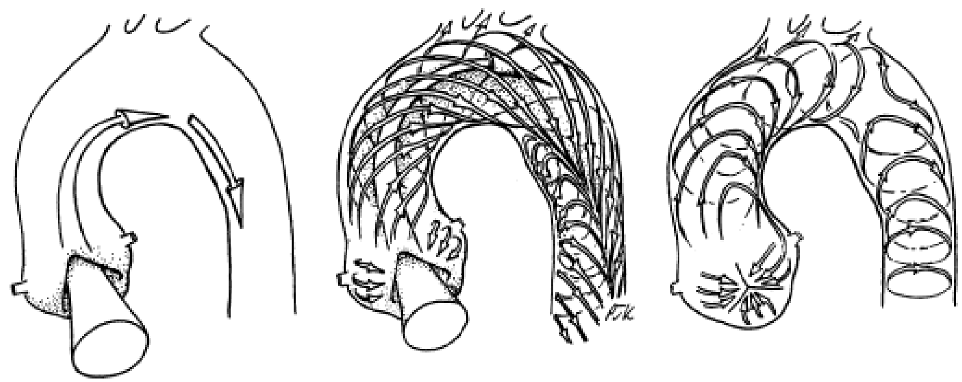
Background

Blood flow in the aorta is highly complex
In the past massive observations demonstrated

- that **helical flows** predominate in areas from the ascending aorta to the aortic arch
  (Segadal & Matre, 1987; Kilner et al., 1993; Chandran 1993)

- that this form of blood flow is a **basic pattern** for almost all the subjects no matter age and gender
  (Bogren & Buonocore, 1999; Houston et al., 2003)



Kilner et al. *Circulation* 1993

Reference Framework

It has been proposed that <u>energetic constraint</u> is but one consequence of the process of physiological evolution of helical blood flow in aorta, and that others remain to be discovered.

However, there is a relative paucity of quantitative data regarding helical blood flow dynamics in the human aorta.

<u>Qualitative Observations</u>

<u>NOT QUANTITATIVE</u>

Rationale, Aim, How

Rationale

Study of mechanistic relationship between physiological complexity and energy of aortic flow

Aim

Identify common features in physiological aortic bulk flow

How

In vivo aortic helical flow quantification in healthy humans by applying **4D PC MRI**

By using a Lagrangian representation of the aortic flow, we apply an index for helical flow quantification

Theoretical Remarks on Helicity

A better understanding of the role of pitch and torsion in blood flow development can be obtained through **helicity**, a scalar eligible to study relationships between complexity and energy.

Roughly speaking, **helicity gives measure of alignment of velocity and vorticity**

Like energy, **helicity influences evolution and stability of both turbulent and laminar flows** (Moffatt and Tsinober, 1992).

Helicity related to the **reduction** of non-linear processes responsible for transfer and redistribution of energy through various scales, and hence **energy dissipation**

Helical Flow Index - HFI

Morbiducci et al. *J Biomech 2007*
Morbiducci et al. *Ann Biomed Eng 2009*
Morbiducci et al. *Ann Biomed Eng 2010*
Morbiducci et al. *Biomech Mod Mechanobiol 2011*

begins with:

LAGRANGIAN ANALYSIS

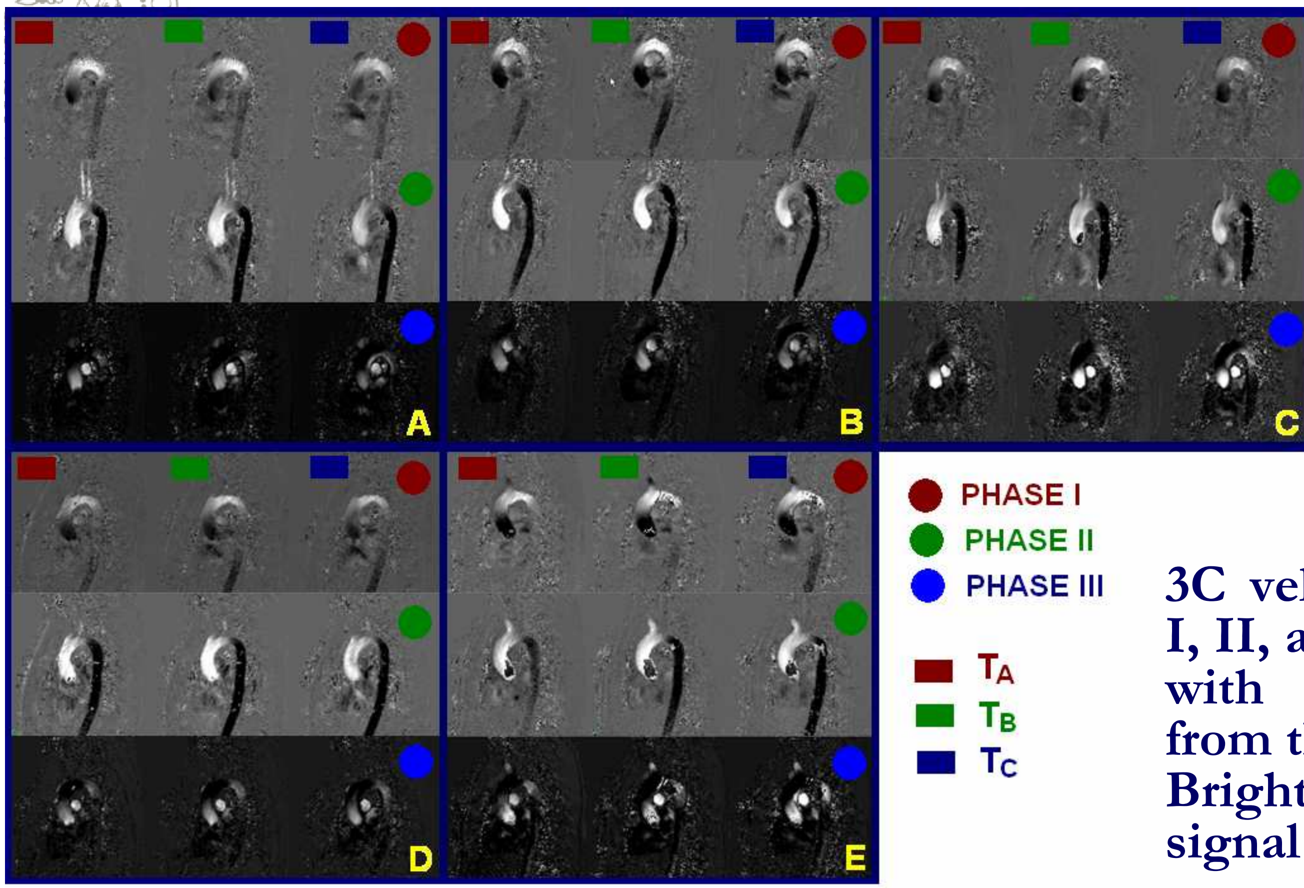
$H_v(\mathbf{s}; t) = \mathbf{V} \cdot (\nabla \times \mathbf{V}) = \mathbf{V}(\mathbf{s}; t) \cdot \boldsymbol{\omega}(\mathbf{s}; t)$

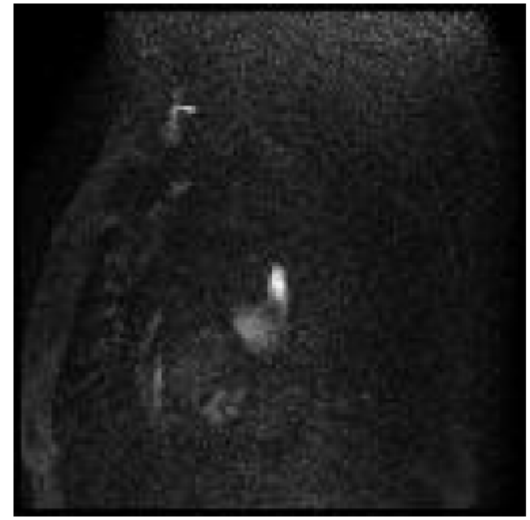
$$\mathbf{LNH}(\mathbf{s};t) = \frac{\mathbf{V}(\mathbf{s};t) \cdot \boldsymbol{\omega}(\mathbf{s};t)}{|\mathbf{V}(\mathbf{s};t)|\,|\boldsymbol{\omega}(\mathbf{s};t)|} \qquad -1 \leq \mathbf{LNH} \leq 1$$

ends up with:

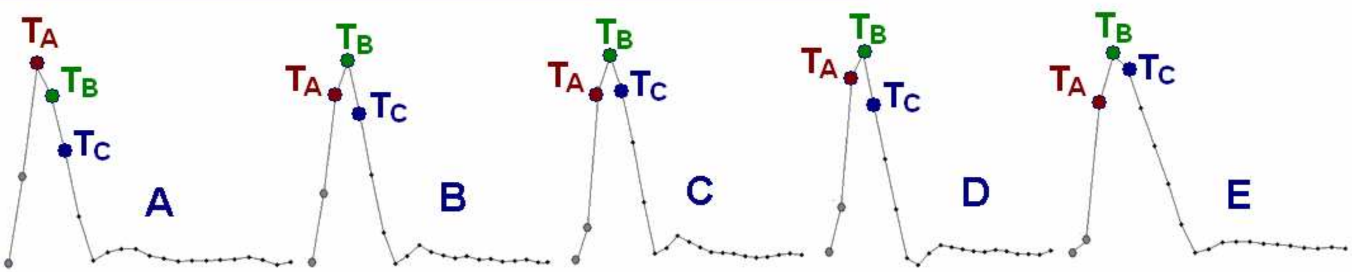
$$\mathrm{HFI} = \frac{1}{N_p}\sum_{k=1}^{N_p}\frac{1}{(t_k^{end} - t_k^{start})}\int_{t_k^{start}}^{t_k^{end}}|\mathrm{LNH}_k(\varsigma)|\,d\varsigma = \frac{1}{N_p}\sum_{k=1}^{N_p} hfi_k \qquad 0 \leq \mathbf{HFI} \leq 1$$

Results – Acquired PC MRI Data

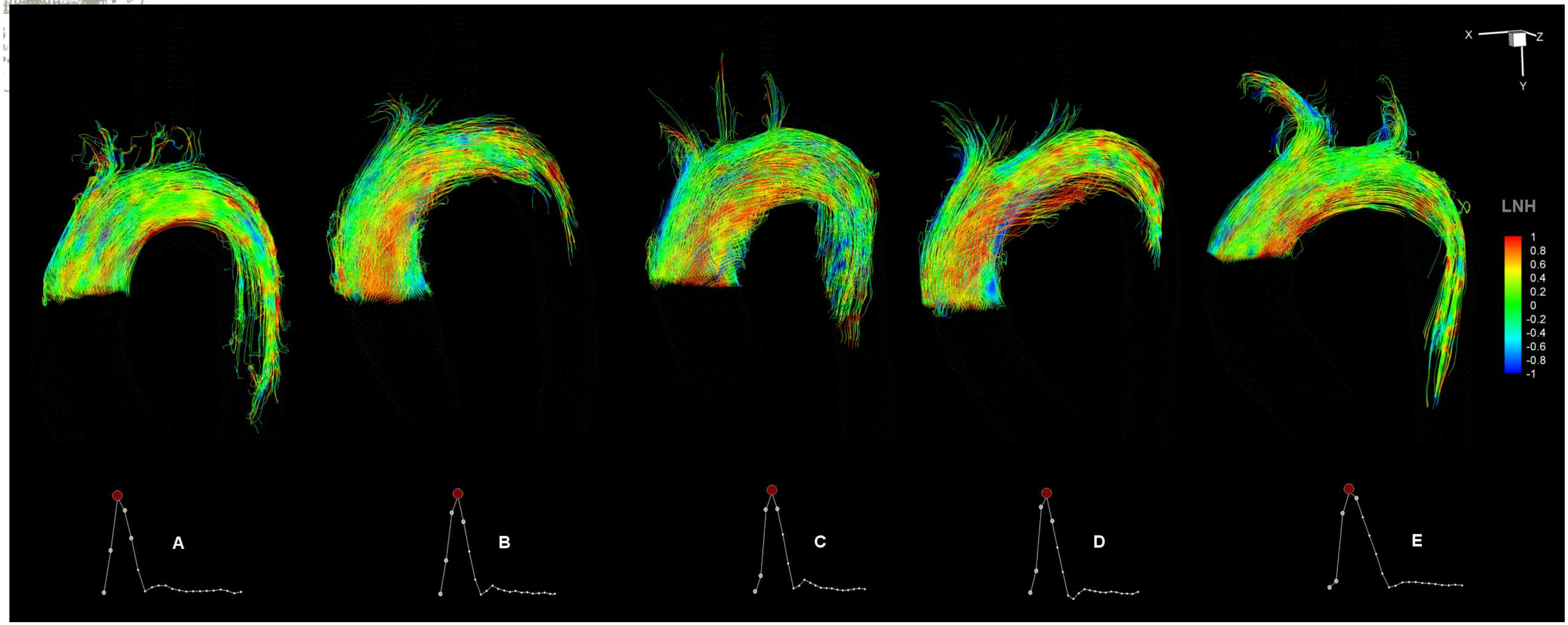




3C velocity map frames (phase I, II, and III) on a plane aligned with the aortic arch, viewed from the left.
Brightness is proportional to signal intensity

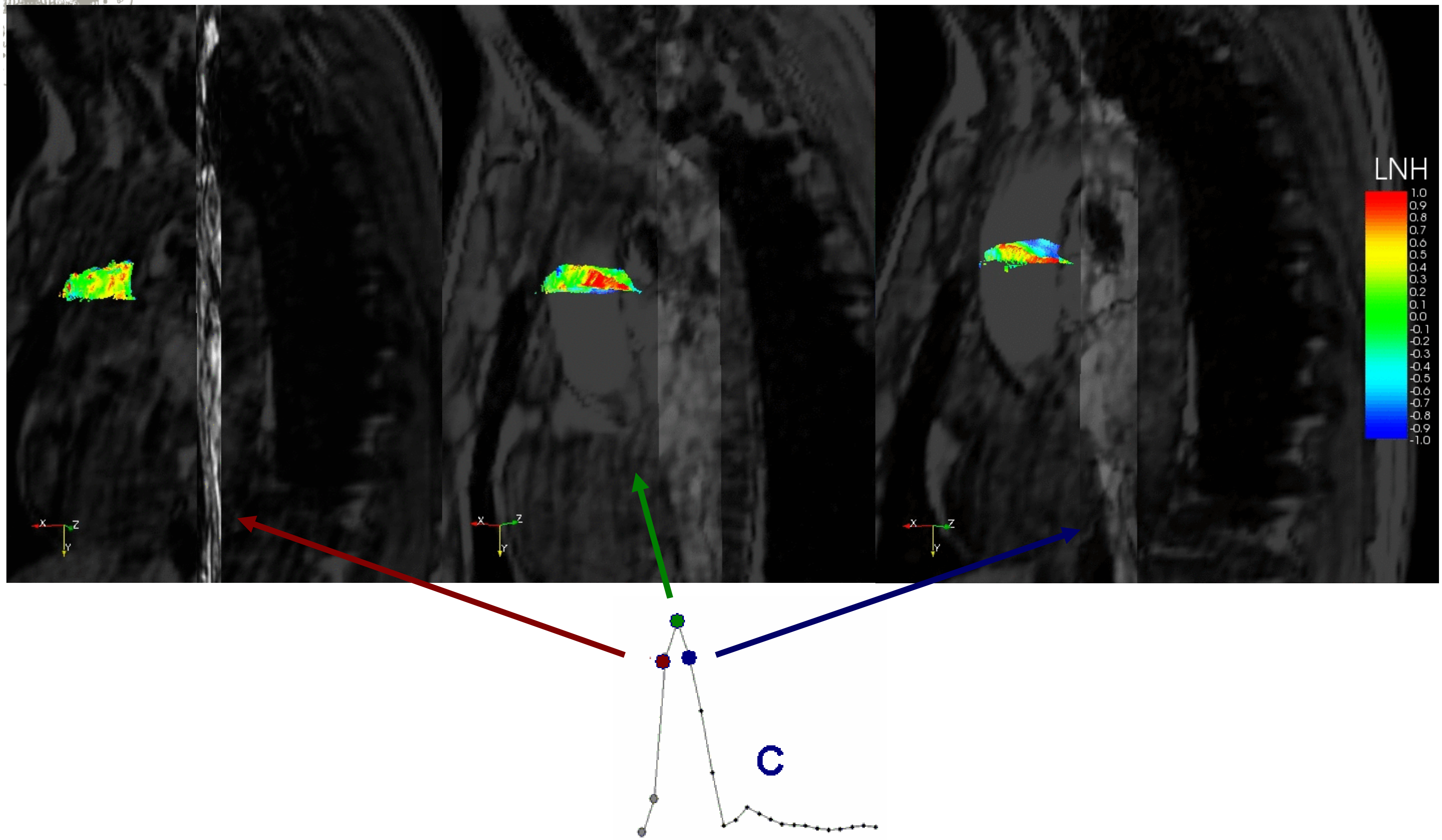


4D Evolution of the Aortic Flow – Lagrangian Analysis



Evolution of the particle set emitted after peak systole is strongly characterized by the onset of more coherent helical structures

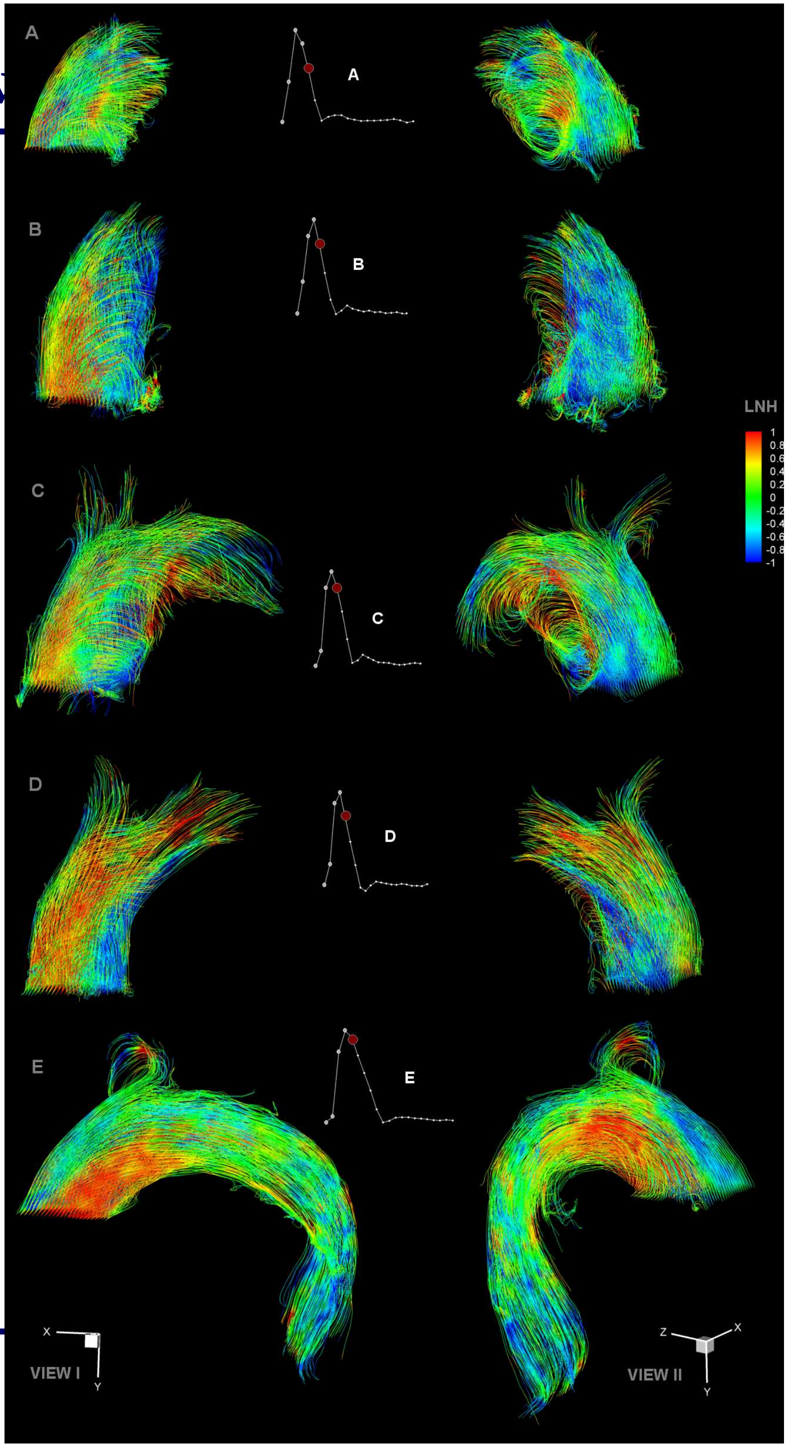
4D Evolution of the Aortic Flow – SUBJECT C



Morbiducci et al. *Biomech Mod Mechanobiol 2011*

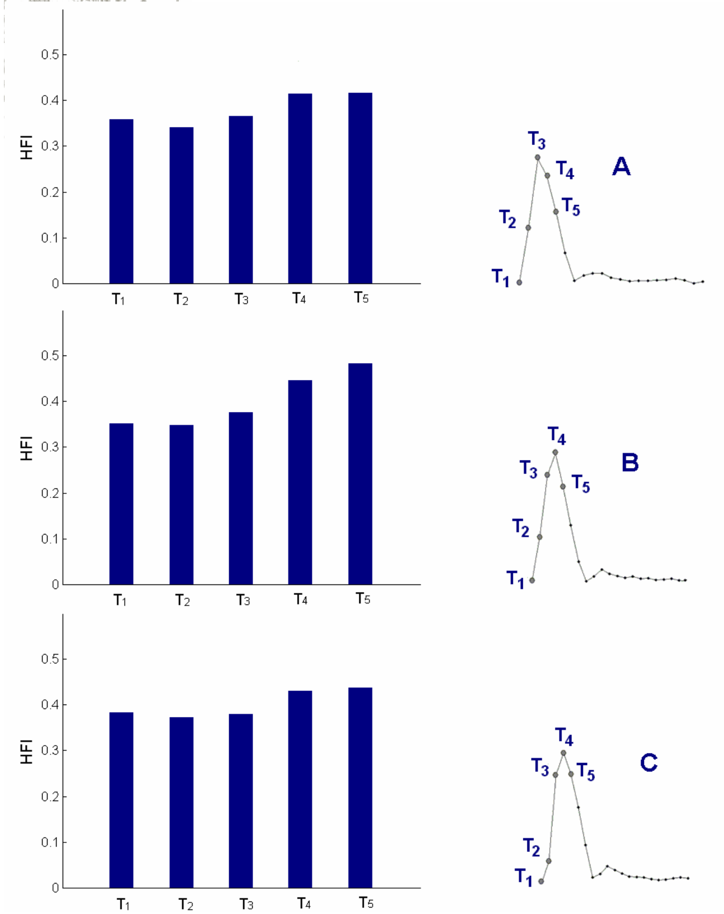
4D Evolution of the Aortic Flow

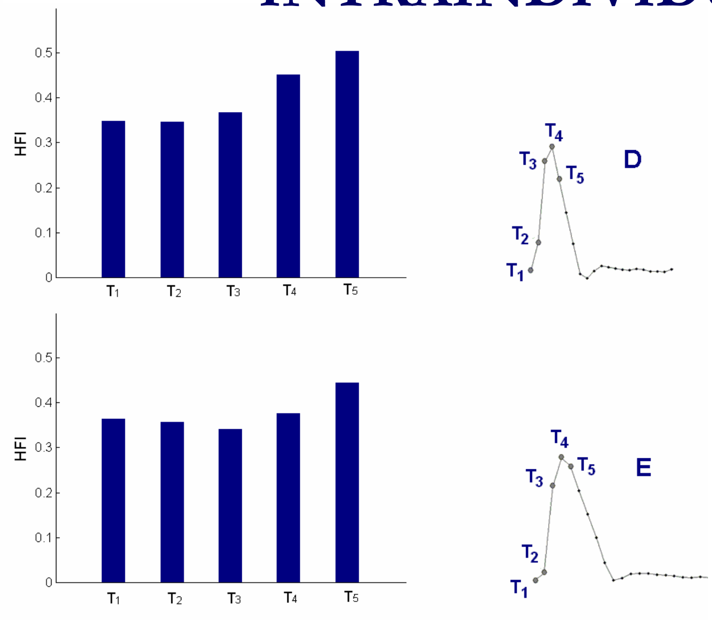
The flow deceleration phase is dominated by the fluid rotational momentum, resulting in coherent helical and bihelical patterns appearing in the ascending aorta.



Helical Flow – Quantitative Analysis I

INTRAINDIVIDUAL ANALYSIS





features common to all:

-particle sets emitted after peak-systole, highest helical content

- particle sets emitted during acceleration phase characterized by similar trends in HFI values

bulk flow helical content depends upon the evolution of the flow through the aorta

Morbiducci et al. *Biomech Mod Mechanobiol 2011*

Conclusion

There were two key findings of our study:

(i) intra-individual analysis revealed a statistically significant difference in the helical content at different phases of systole

(ii) group analysis suggested that aortic helical blood flow dynamics is an **emerging behavior** that is common to normal individuals.

Our results enforce the hypothesis that

helicity contribute to **optimize the naturally occurring fluid transport processes in the cardiovascular system, aiming at obtaining an efficient perfusion, avoiding excessive energy dissipation in the process of conveying blood flow in aorta**

SECTION II

On the Use of In Vivo Measured Flow Rates as Boundary Conditions for Subject-Specific Hemodynamic Models of the Human Aorta. Implications for Indicators of Abnormal Flow

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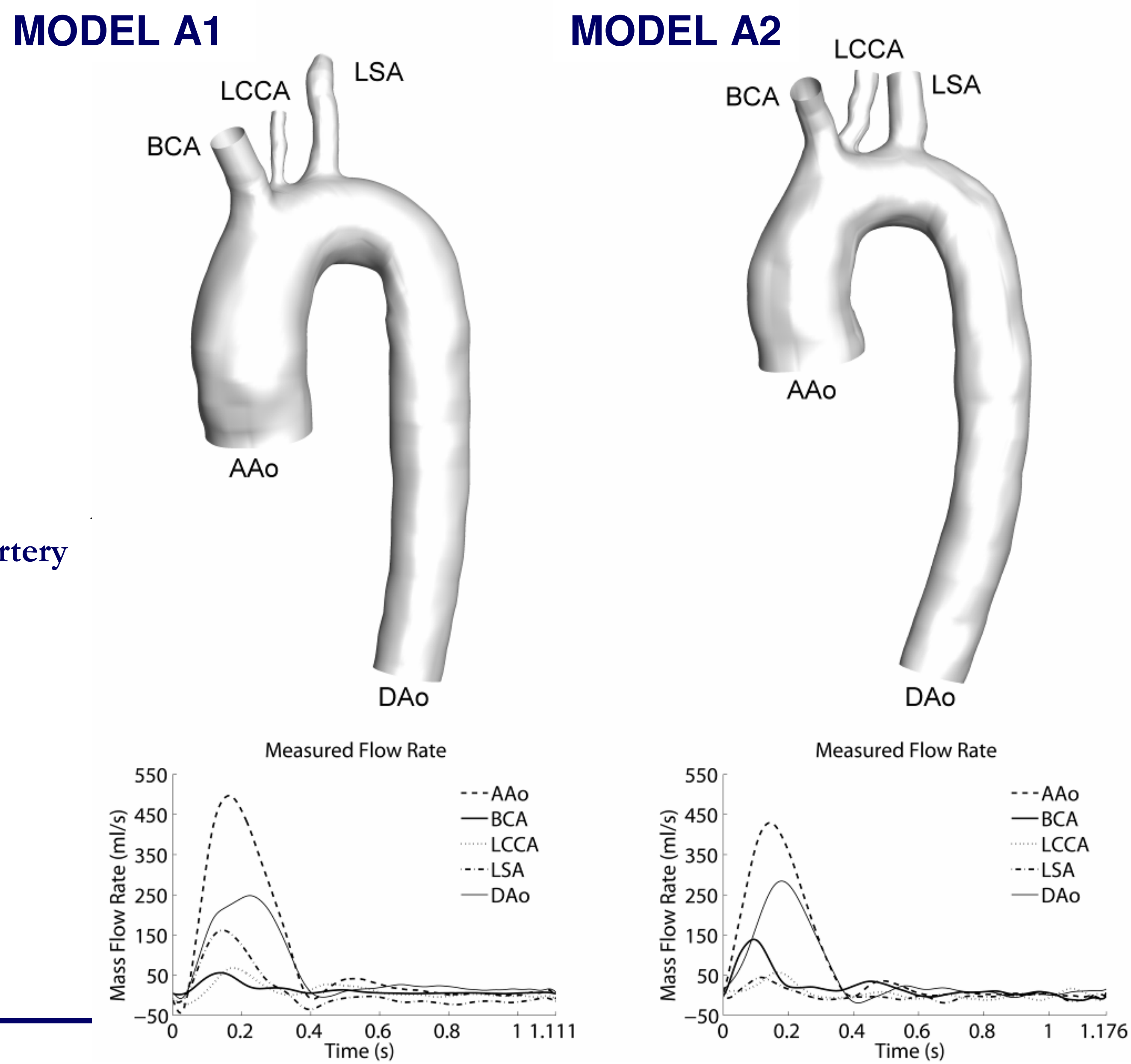
Aims

Aims

(1) to identify the individual, not invasively measured PC MRI-based BCs scheme that better **replicates** the measured flow rate waveforms;

(2) to describe the **impact that different strategies** of combining PC MRI-based BCs have **on WSS distribution**. The identification of a proper set of individual not-invasively measured BCs can eliminate potential sources of error and uncertainties in blood flow simulations in the human aorta.

Measured Flow Rate Waveforms



AAo – ascending aorta

DAo – descending aorta

BCA – brachiocephalic artery

LCCA – left common carotid artery

LSA – left subclavian artery

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Boundary Conditions

MFR: Measured Flow Rate Waveform

P: Stress free condition

COR: Constant Outflow Ratio (% of AAo inlet flow rate, measured)

Outlet Treatment Scheme	DAo	BCA	LCCA	LSA
I	P	COR	COR	COR
II	MFR	P	P	P
III	P	P	P	P
IV	MFR	COR	COR	P
V	MFR	MFR	P	P
VI	P	MFR	MFR	MFR

(*) flow rate at AAo inlet section prescribed in terms of flat velocity profile

WSS-based Descriptors of Abnormal Flow

TAWSS (Time Averaged WSS)

$$\text{TAWSS} = \frac{1}{T}\int_0^T |\,\mathbf{WSS}(s,t)\,|\,dt$$

OSI (Oscillating Shear Index)

$$\text{OSI} = 0.5\left[1 - \frac{\int_0^T |\,\mathbf{WSS}(s,t)\,|\,dt}{\left|\int_0^T \mathbf{WSS}(s,t)\,dt\right|}\right]$$

RRT (Relative Residence Time)

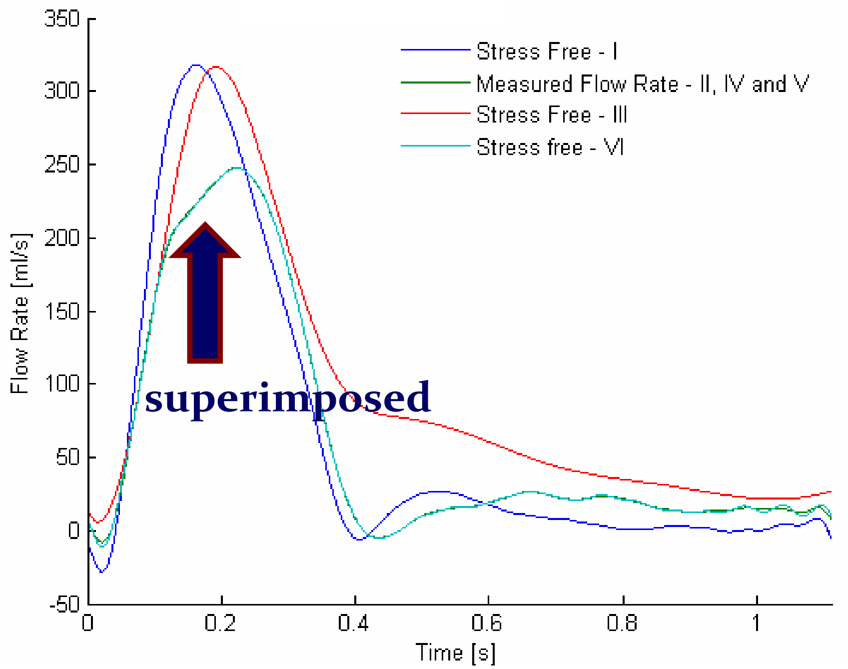
$$\text{RRT} = \frac{1}{(1-2\text{OSI})\text{TAWSS}} = \frac{T}{\left|\int_0^T \mathbf{WSS}(s,t)\,dt\right|}$$

Results – Computed vs Measured Flow Rates

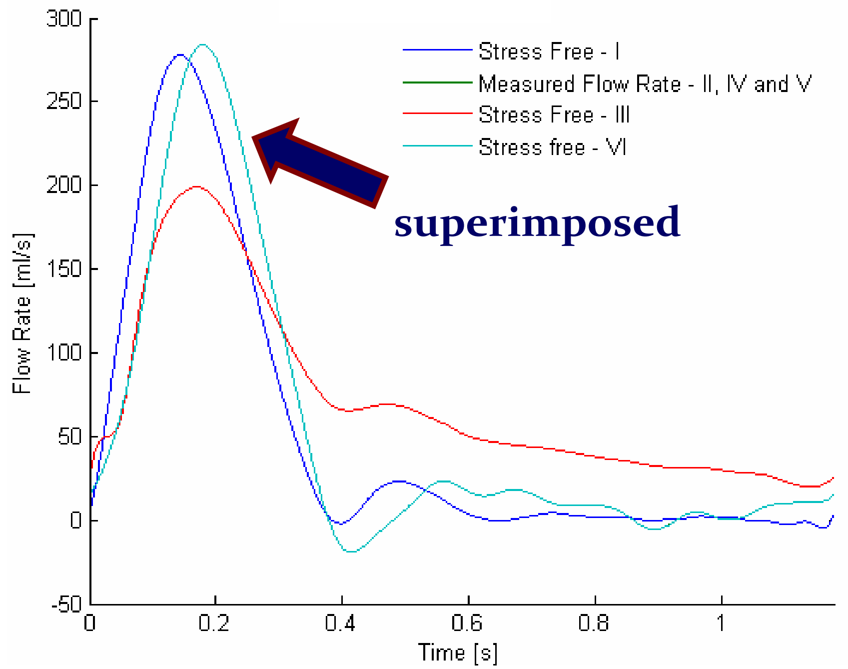
DAo – in-vivo *vs* in-silico Flow Rate

scheme VI (light blu, P at Dao, measured at BCA,LSA, LCCA)
- excellent agreement

Model A1



Model A2



Results – Computed vs Measured Flow Rates

In silico *vs* measured mean flow rates differences at DAo outlet section are maximized when BCs treatment scheme III (P at all outlets) is applied

↓

51% model A1 --- 34% model A2

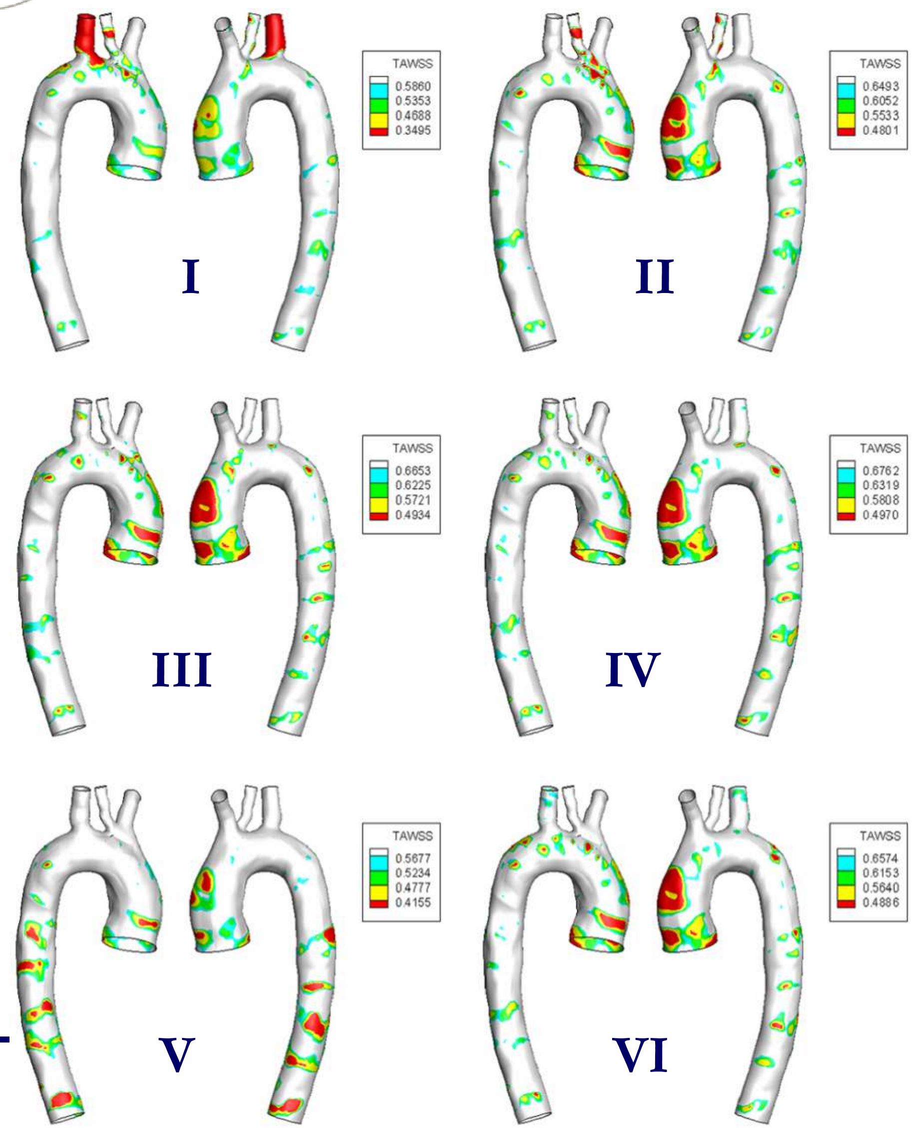
In silico *vs* measured diastolic flow rates differences at DAo outlet section are maximized when BCs treatment scheme I (measured COR) is applied

↓

49% model A1 --- 37% model A2

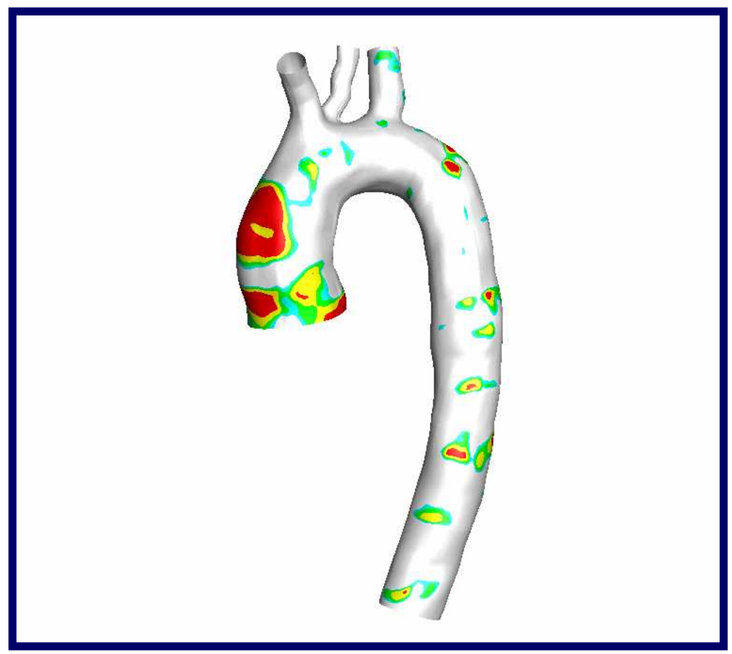
Results – WSS-based Hemodynamic Indicators

TAWSS



(1) Proximal outer arch curvature

(2) Focal regions on DAo



BC on DAo – **P**

TAWSS VI - MODEL A2

Results – WSS-based Hemodynamic Indicators

On regions exposed to low and oscillating WSS, the absolute percentage differences with respect to BCs scheme VI (P at Dao, measured at BCA, LSA, LCCA) are up to

	MODEL A1	MODEL A2
TAWSS	49%	138%
OSI	18%	32%
RRT	30%	44%

Conclusions

- Subject-specific hemodynamic simulation of aortic flow is feasible by using not invasively measured flow rate waveforms as BCs;

- Different schemes of BCs can influence WSS-based descriptors of disturbed flow:

    - they mainly affect descriptors value than their distribution;

It is recommended to prescribe time-varying outflow BCs based on in-vivo accurate measurements (for example VI).

SECTION III

On the Use of In Vivo 4D Velocity Profiles as Boundary Conditions for Image-Based Hemodynamic Models of the Human Aorta. Preliminary Study

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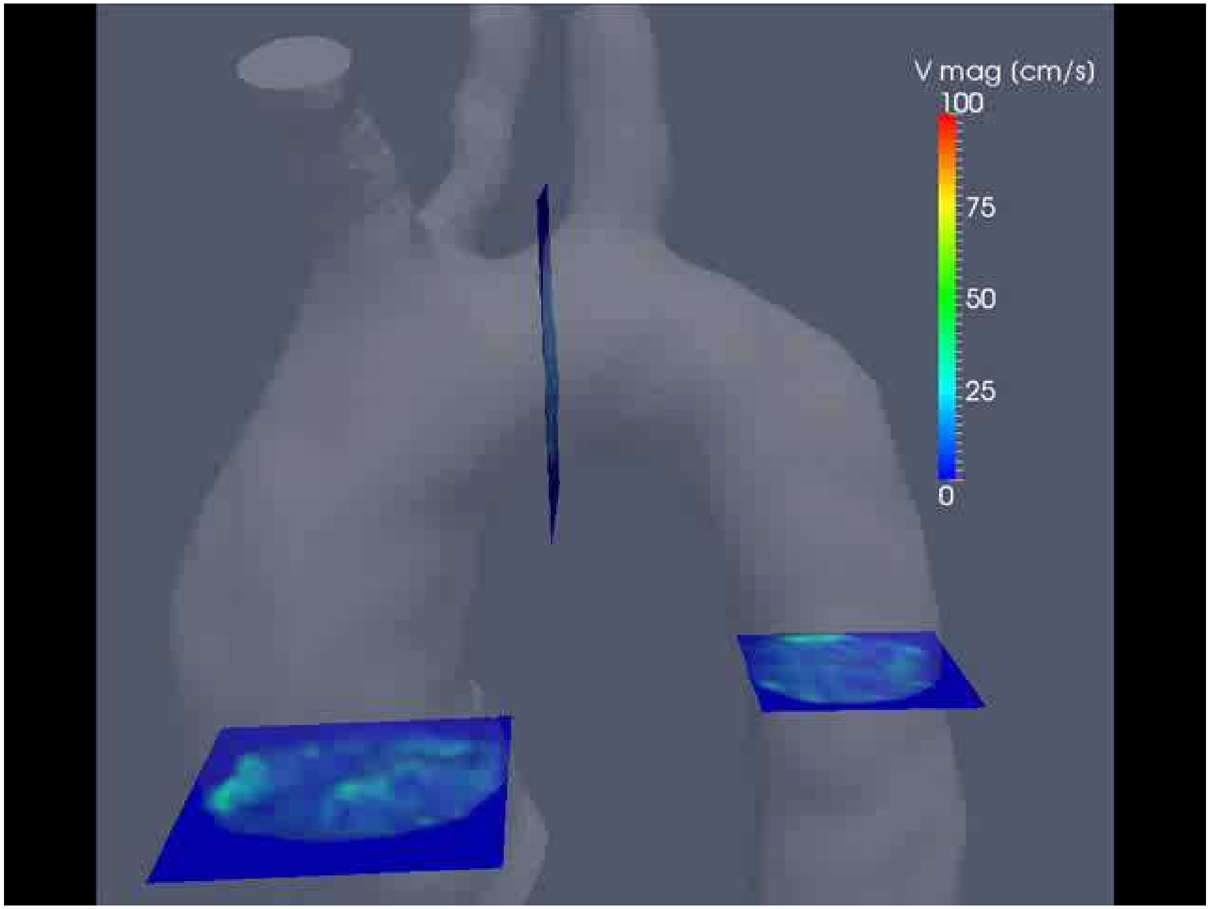
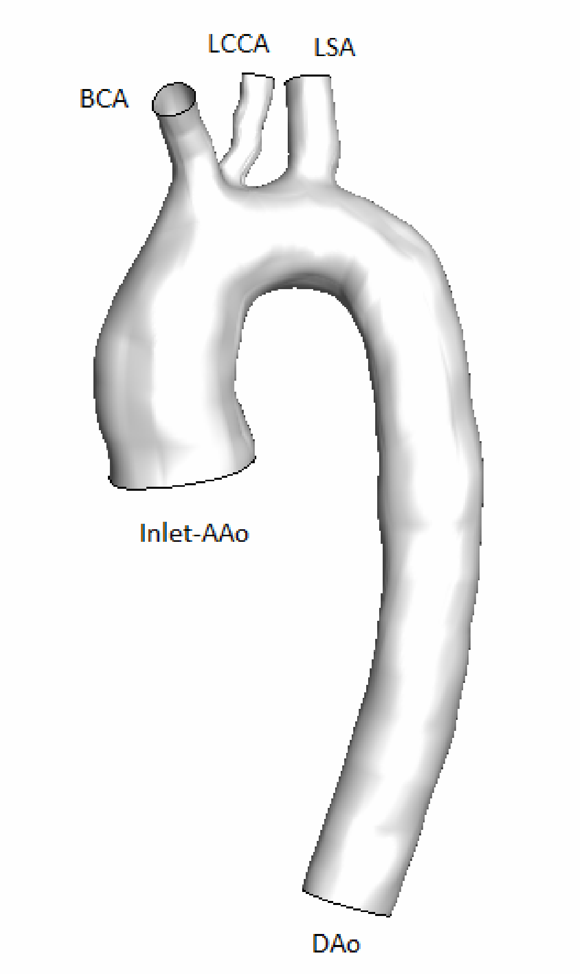
Methods

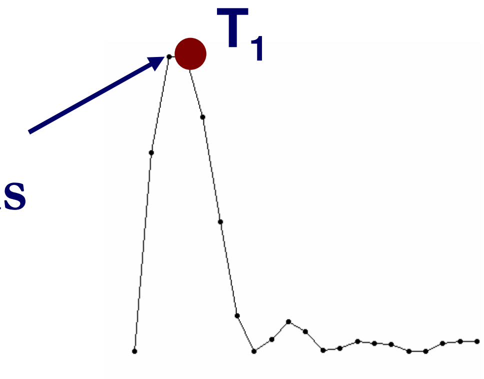
4D measured PC MRI Velocity profiles

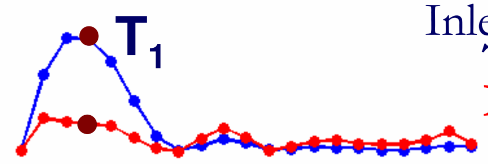




Methods – Inlet Boundary Conditions

Steady state analysis



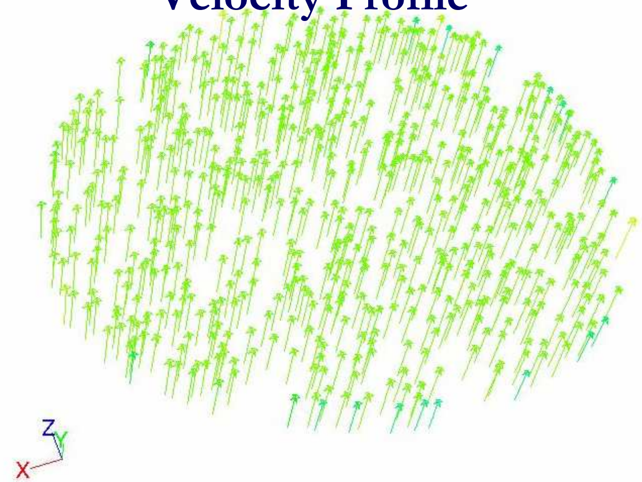


Inlet AAo section – Mean Velocity
THROUGH-PLANE
IN-PLANE

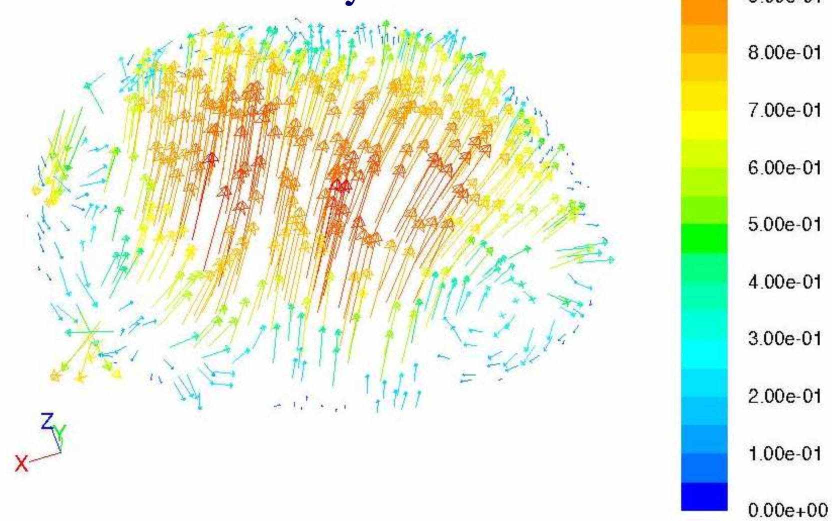
Inlet AAo section – Mean Helicity (absolute)

Prescribed BCs AAo Inlet Section

Flat Inlet Velocity Profile

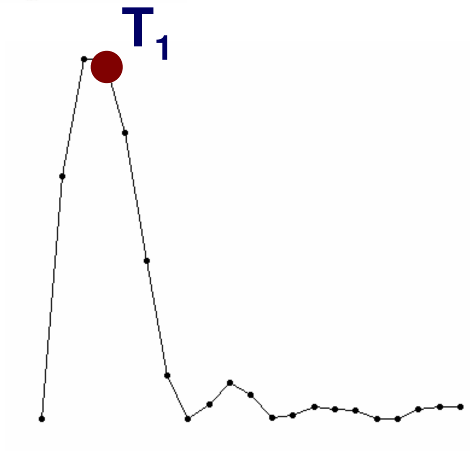


3D PC MRI Measured Inlet Velocity Profile



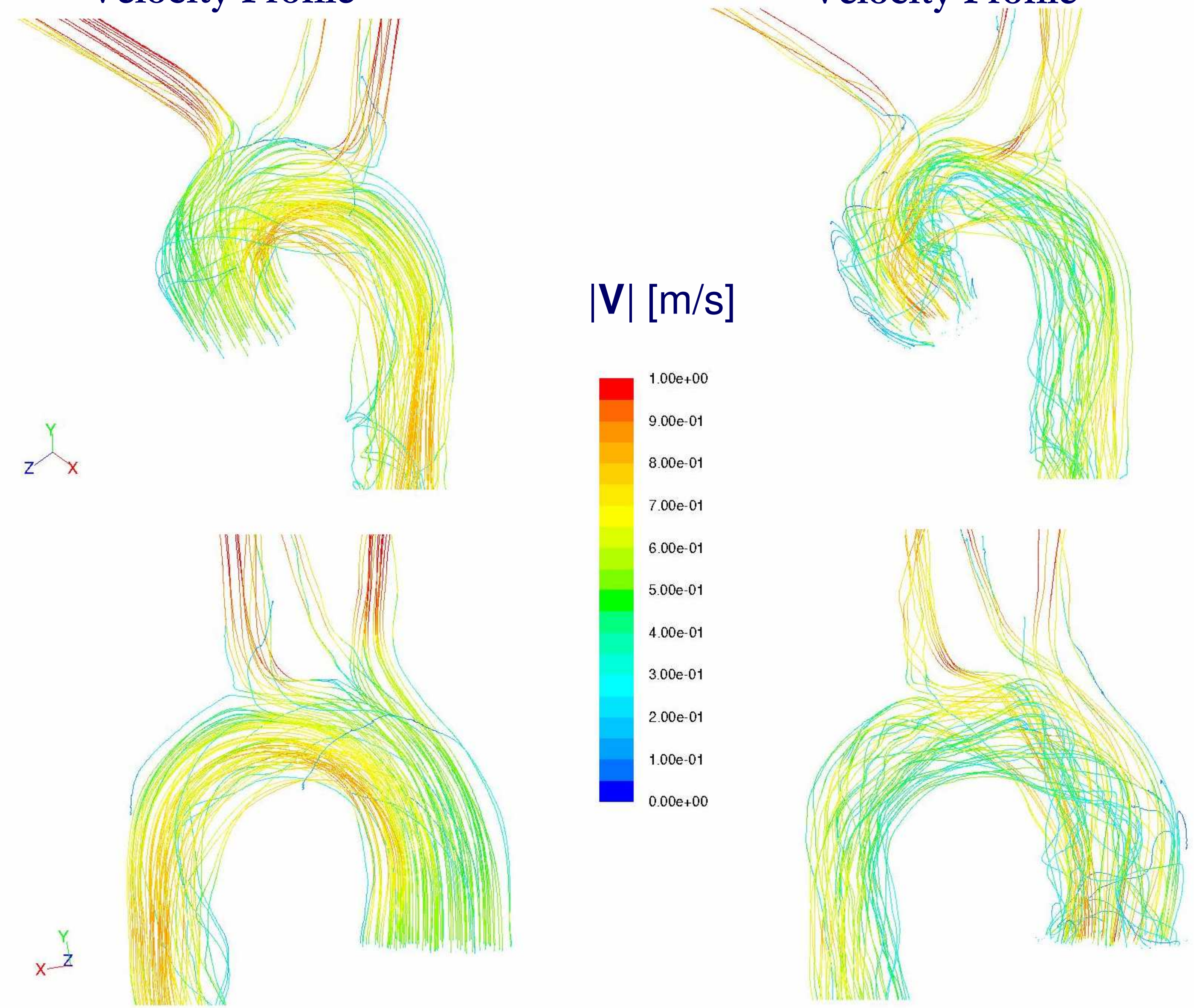
|V| [m/s]

Results – Streamlines at T_1

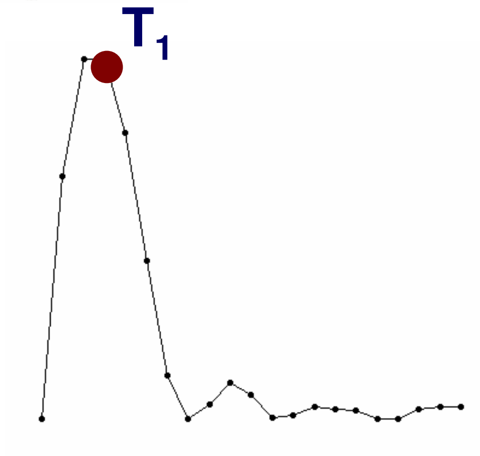


Flat Inlet
Velocity Profile

3D PC MRI Measured Inlet
Velocity Profile

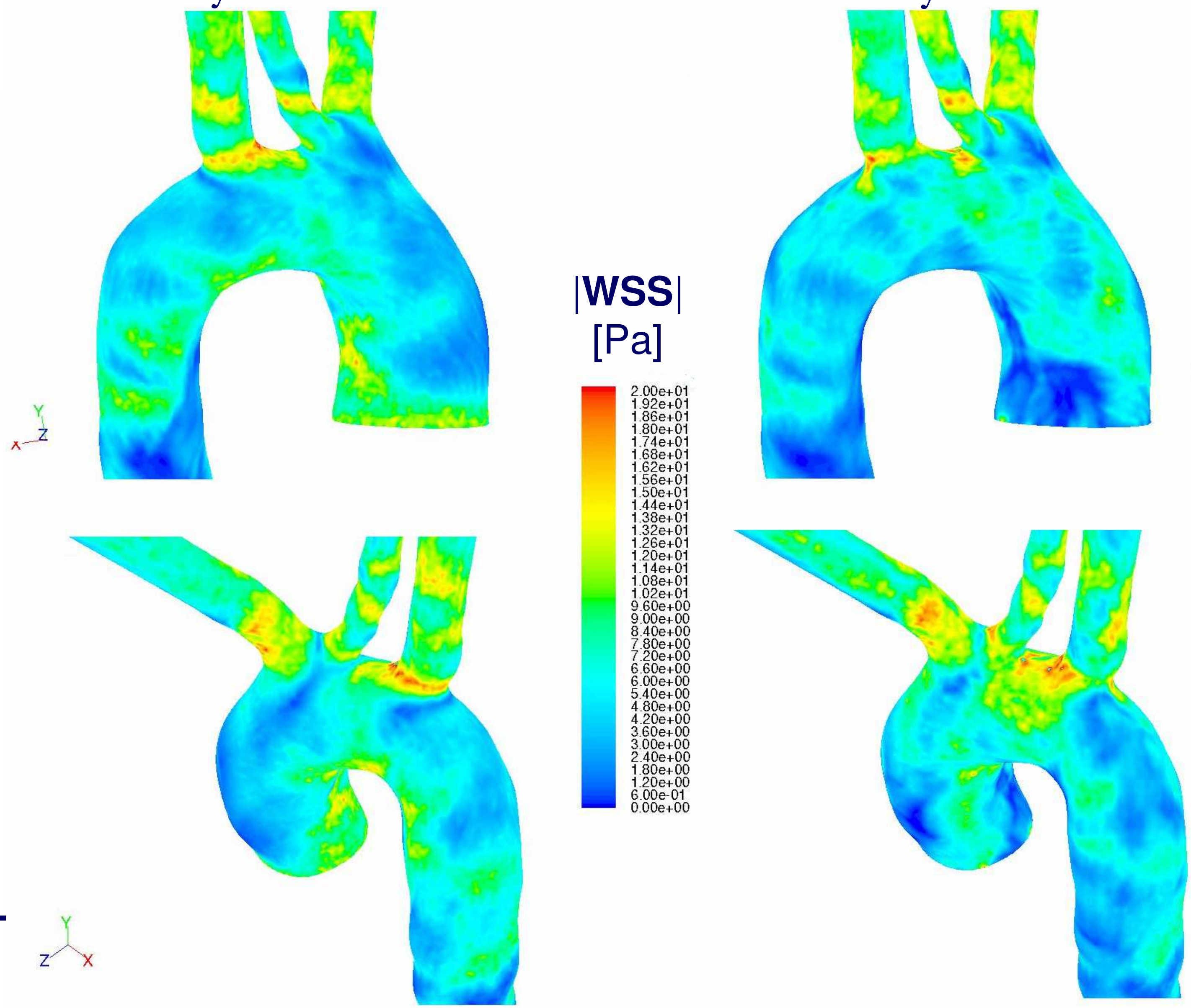


Results – WSS at T_1



Flat Inlet Velocity Profile

3D PC MRI Measured Inlet Velocity Profile



Conclusions [WORK IN PROGRESS]

From preliminary analysis

-Streamlines visualization highlights differences in bulk flow features

-Inlet velocity profiles influence WSS distribution at estrados, intrados and at osti

Future steps

-Pulsatile simulations: flat velocity profile vs 3D measured PC MRI profile as inlet BC

-Influence WSS & bulk flow

-Influence suvraortic vessels perfusion

Thank You for Your Kind Attention

Turin BioFluid Mechanics Ramblers

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