Modeling blood flow for clinical applications: technical side

Michele Conti

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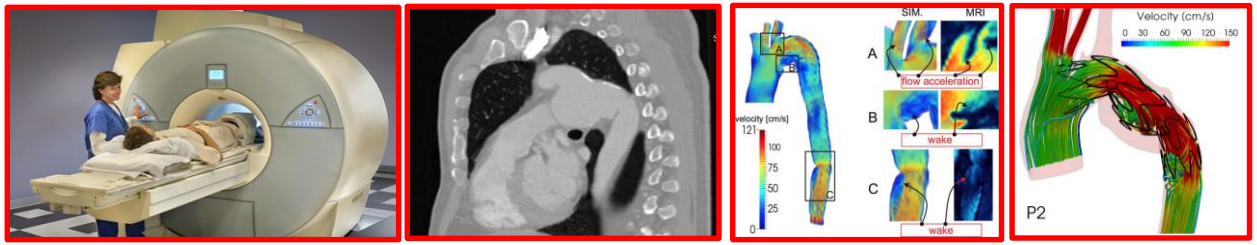
Credits: *Ferdinando Auricchio, Santi Trimarchi, Rodrigo Romarowski, Simone Morganti, Massimiliano Marrocco-Trischitta, UMCUtrecht (Prof. Moll), Francesco Secchi, Francesco Sardanelli*



Per quanto concerne i moderatori, relatori, formatori, tutor, docenti è richiesta dall'Accordo Stato-Regioni vigente apposita dichiarazione esplicita dell'interessato, di trasparenza delle fonti di finanziamento e dei rapporti con soggetti portatori di interessi commerciali relativi agli ultimi due anni dalla data dell'evento.
La documentazione deve essere disponibile presso il Provider e conservata per almeno 5 anni.

Dichiarazione sul Conflitto di Interessi

Il sottoscritto MICHELE CONTI in qualità di:

☐ responsabile scientifico ☐ moderatore ☐ docente
X relatore ☐ tutor

dell'evento "X CONGRESSO AIRMM - RISONANZA MAGNETICA IN MEDICINA 2019:
DALLA RICERCA TECNOLOGICA AVANZATA ALLA PRATICA CLINICA"
Milano, 28-29 marzo 2019

da tenersi per conto di **Biomedia srl Provider n. 148,**

ai sensi dell'Accordo Stato-Regione in materia di formazione continua nel settore "Salute" (Formazione ECM) vigente,

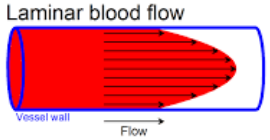
Dichiara

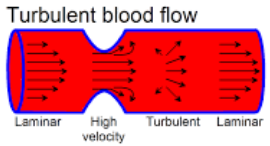
X che negli ultimi due anni NON ha avuto rapporti anche di finanziamento con soggetti portatori di interessi commerciali in campo sanitario

☐ che negli ultimi due anni ha avuto rapporti anche di finanziamento con soggetti portatori di interessi commerciali in campo sanitario (indicare quali):

_____ _____
_____ _____
_____ _____
_____ _____

Background and motivations





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Blood velocity

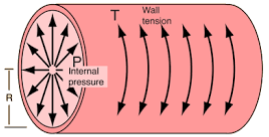
Aortic

Biomechanics

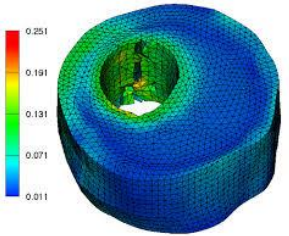
(Forces, displacements, stress, strain)

Blood pressure

Arterial wall compliance and material properties



Cylindrical Vessel
T = PR



Tools to measure aortic hemodynamics

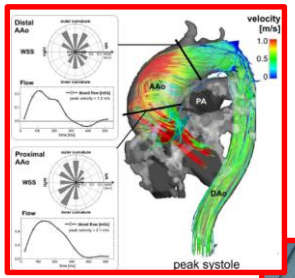
Computational fluid dynamics

Aortic hemodynamics

(blood velocity and pressure)

(4D-)MRI

In-vitro models and mock circulatory loop



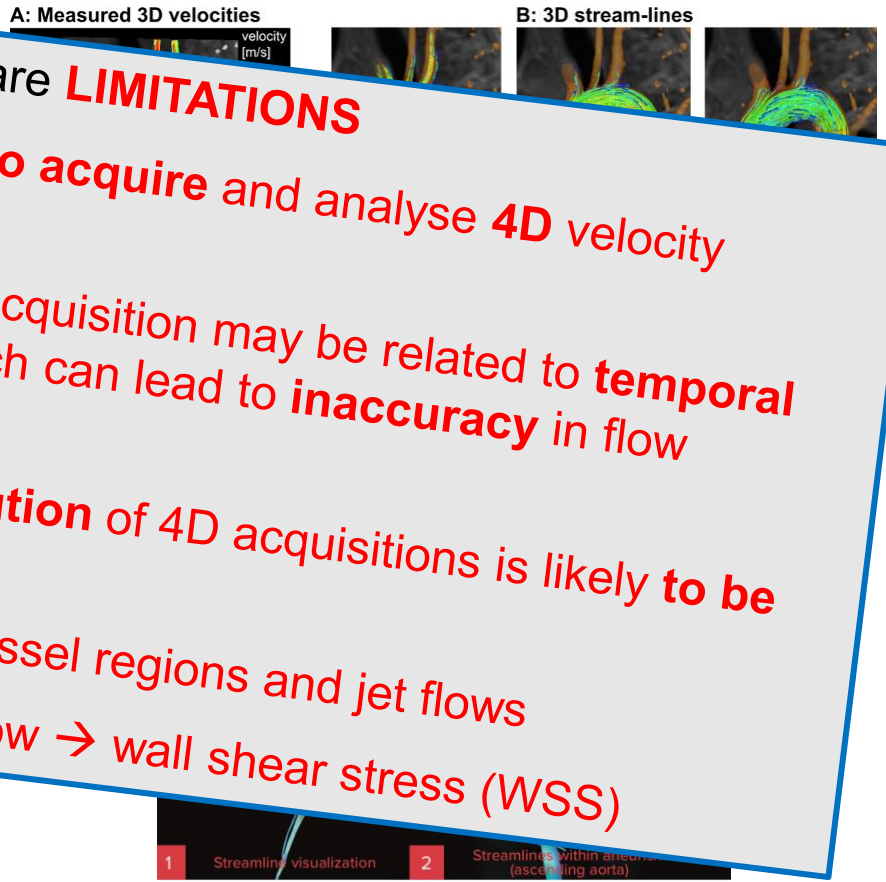
4D MRI*: measuring 3D flow in a non invasive manner

*Markl et al. Journal of Cardiovascular Magnetic Resonance 2011, 13:7

4D flow

BUT …there are **LIMITATIONS**

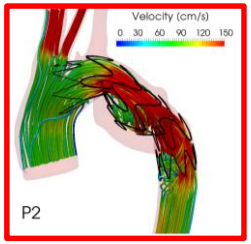
- **time** taken **to acquire** and analyse **4D** velocity datasets
- **aortic flow** acquisition may be related to **temporal blurring** which can lead to **inaccuracy** in flow acquisitions
- **spatial resolution** of 4D acquisitions is likely **to be suboptimal**
  - for small vessel regions and jet flows
  - Near wall flow → wall shear stress (WSS)



CAAS MR 4D flow, Pie Medical

Tools to measure aortic hemodynamics

Predire la rimodulazione dei **flussi post-TEVAR** partendo dai **dati pre-op.**



Computational fluid dynamics

MRI as:

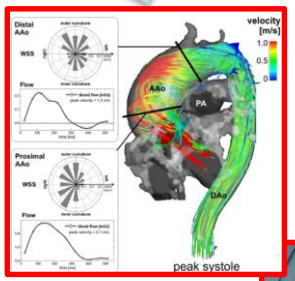
- Input to impose boundary consitions for the simulations
- Verification and validation

Aortic hemodynamics

(velocity and pressure)

(4D-)MRI

In-vitro models and mock circulatory loop



4D MRI*: measuring 3D flow in a non invasive manner

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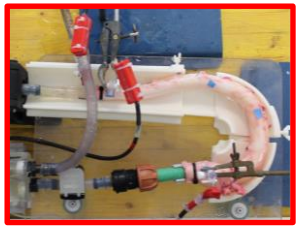
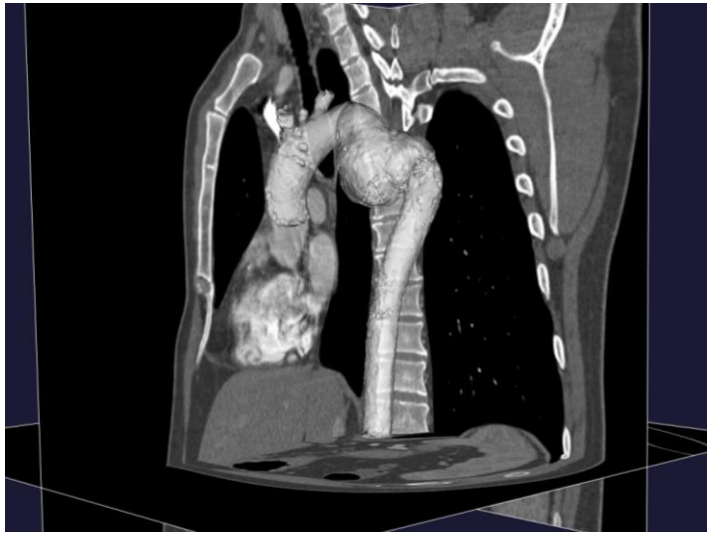
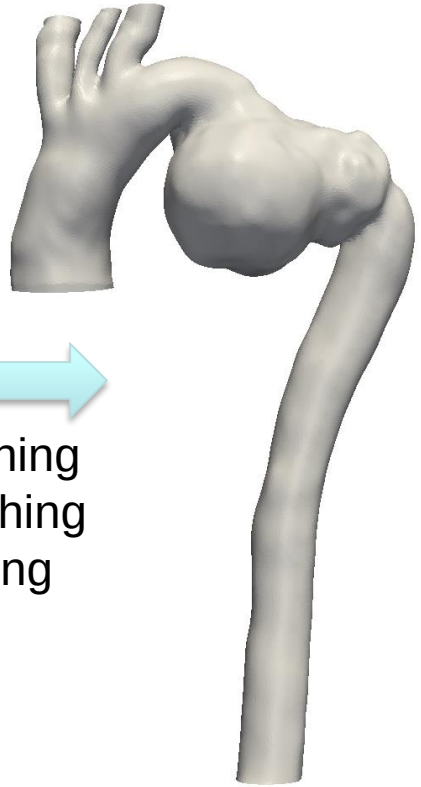


Geometry segmentation

Segmentation of the aorta from the root to the diaphragm + 3 supraortic vessels

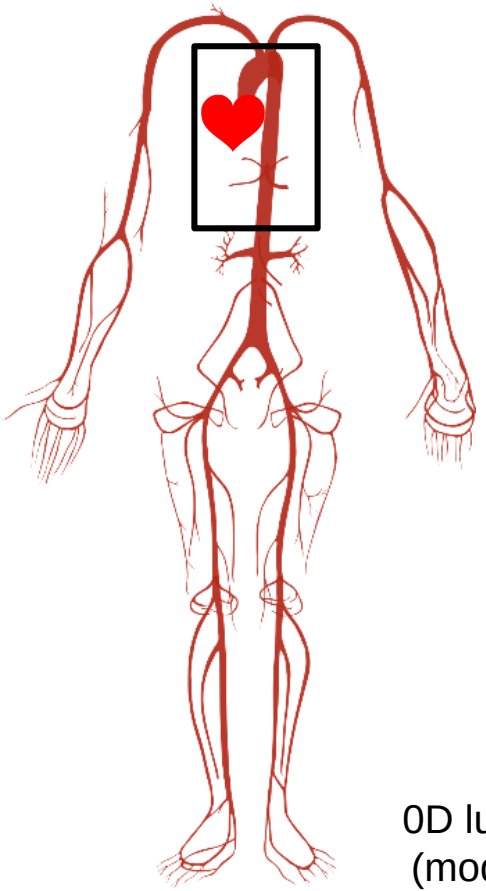


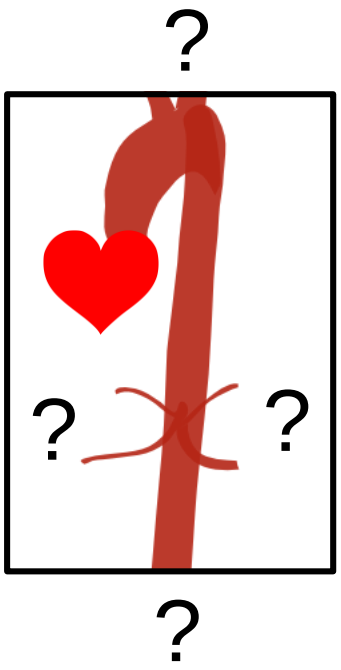
Smoothing
Remeshing
Clipping



1. Level set segmentation w/seeds manually chosen.
2. Colliding fronts algorithm propagation
3. Marching cubes at 0 level surface.

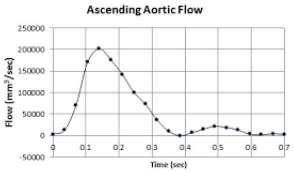
CFD simulations and in/outflow boundary conditions





Pressure/stress free

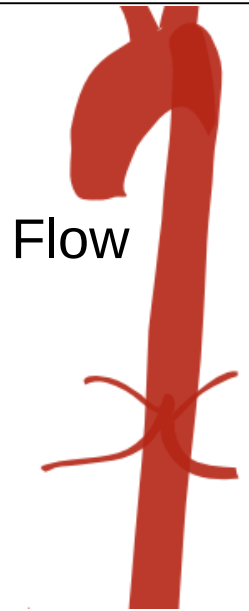
Velocity (e.g. from MRI)



0D lumped model – 3 Element Windkessel
(modeling systemic peripheral circulation)

CFD simulations and in/outflow boundary conditions: tuning

3WK



3WK

On the choice of outlet boundary conditions for patient-specific analysis of aortic flow using computational fluid dynamics

J. Biomec 2017

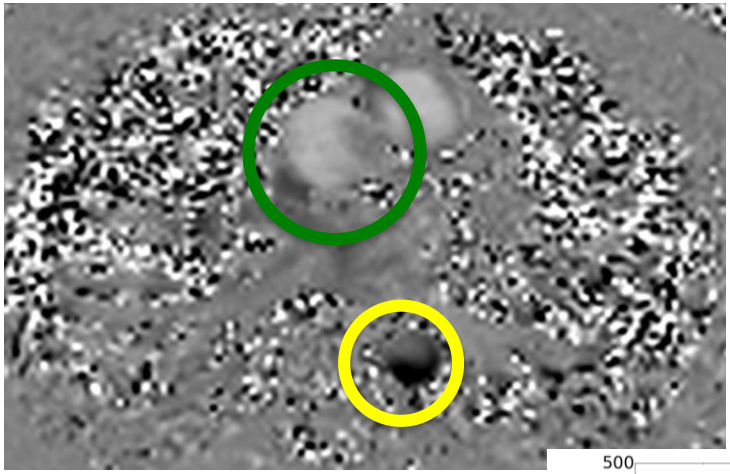
Flow in every boundary

Cuff pressure

Romarowski, R. M., Lefieux, A., Morganti, S., Veneziani, A., & Auricchio, F. (2018). Patient-specific CFD modelling in the thoracic aorta with PC-MRI–based boundary conditions: A least-square three-element Windkessel approach. International journal for numerical methods in biomedical engineering, 34(11), e3134.

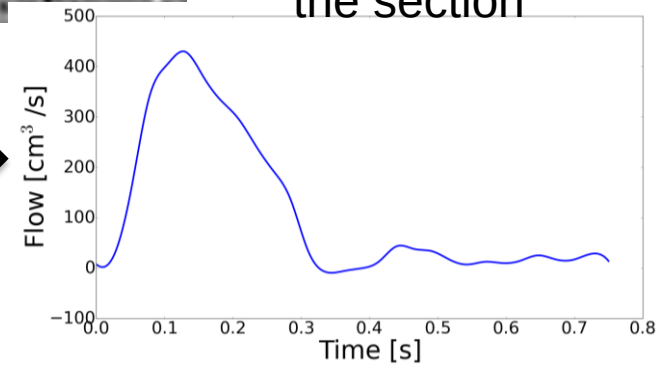
MRI processing

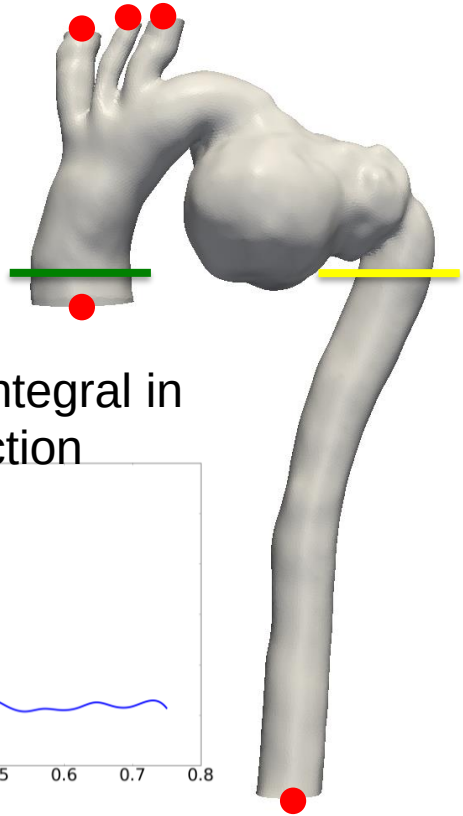
Extraction of the flow rates in all the vessels



PC-MRI: measure blood's velocity in a grayscale

Flow rate, integral in the section





MRI processing

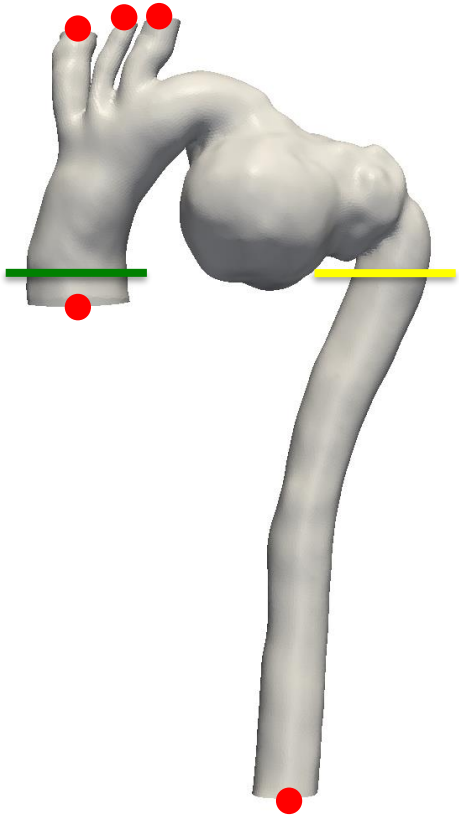
Comput Mech
DOI 10.1007/s00466-014-0976-6

ORIGINAL PAPER

Patient-specific analysis of post-operative aortic hemodynamics: a focus on thoracic endovascular repair (TEVAR)

F. Auricchio · M. Conti · A. Lefieux · S. Morganti · A. Reali · F. Sardanelli · F. Secchi · S. Trimarchi · A. Veneziani

the intervention. In particular, magnetic resonance imaging (MRI) was performed using a 1.5-T unit with 40-mT/m gradient power (Magnetom Sonata Maestro Class, Siemens, Erlangen, Germany) and a four-channel cardio-thoracic coil. Electrocardiographically-triggered free-breathing through-plane and in-plane phase-contrast (PC) sequences was performed for phase-velocity mapping of aortic and branches flow with following technical parameters: TR/TE = 4/3.2 ms, thickness 5 mm, velocity encoding from 150 to 350 ms, and temporal resolution 41 ms.



Journal of Biomechanics 46 (2013) 102–109

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Journal of Biomechanics

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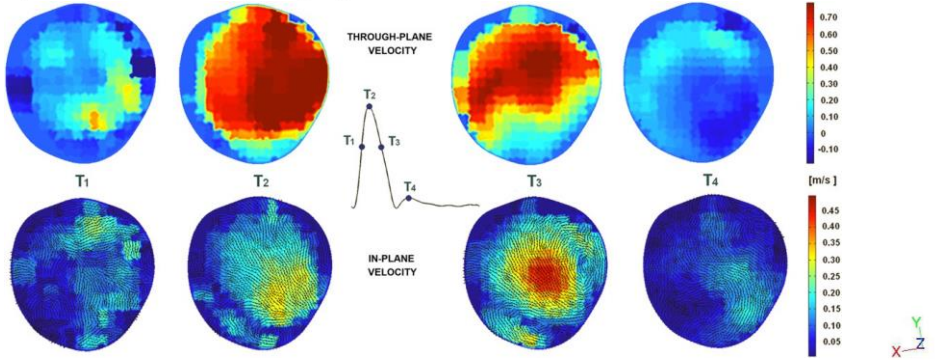
www.JBiomech.com

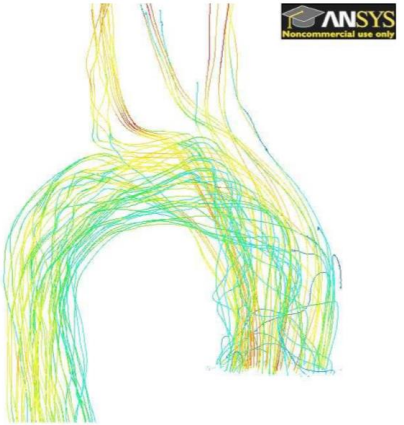
MRI process

Inflow boundary conditions for image-based computational hemodynamics: Impact of idealized versus measured velocity profiles in the human aorta

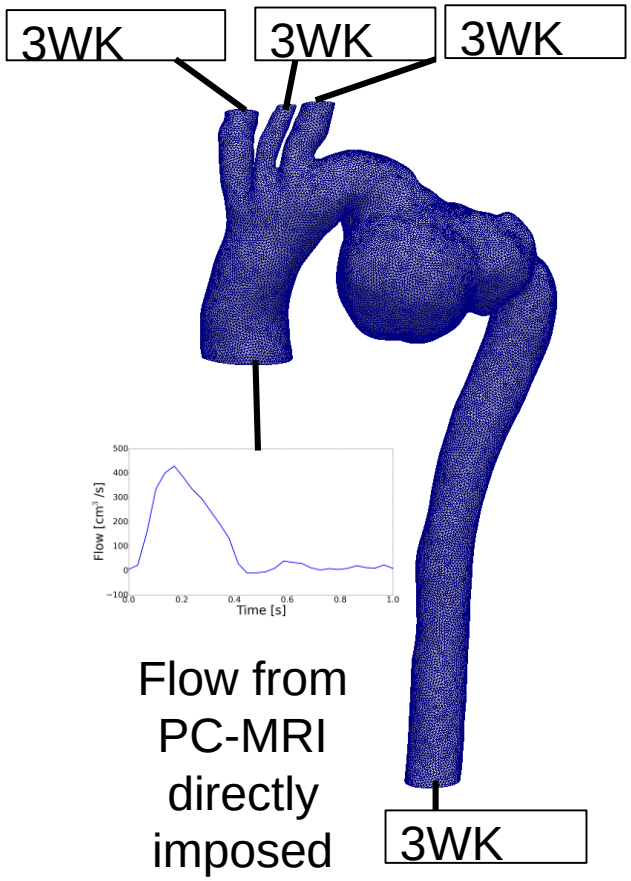
Umberto Morbiducci [a,*], Raffaele Ponzini [b], Diego Gallo [a], Cristina Bignardi [a], Giovanna Rizzo [c]

[a] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Turin, Italy
[b] CILEA HPC, Milan, Italy
[c] IBFM, Research National Council, Milan, Italy





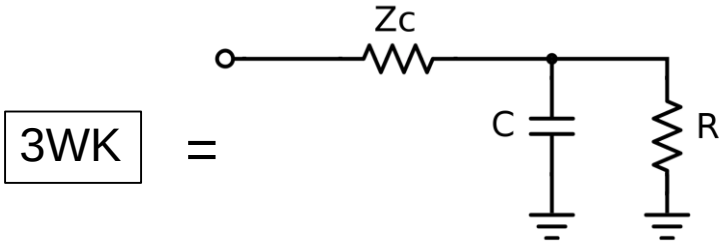
Calibration of BCs (I)



Flow from PC-MRI directly imposed

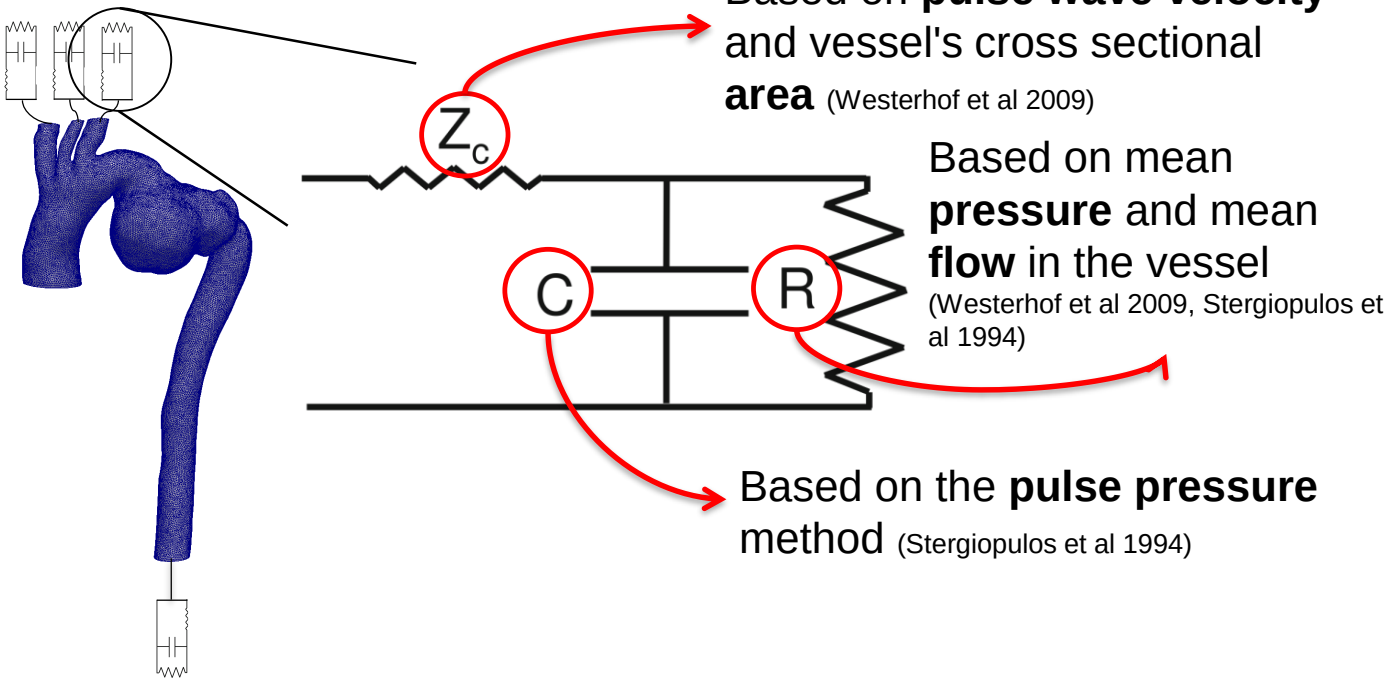
Q: Why 3WK in outputs having the real flow ?

A: Simulation less sensitive to noisy acquisitions



Each model element is tuned in a patient specific way

Calibration of BCs (II)



Based on **pulse wave velocity** and vessel's cross sectional **area** (Westerhof et al 2009)

Based on mean **pressure** and mean **flow** in the vessel (Westerhof et al 2009, Stergiopulos et al 1994)

Based on the **pulse pressure** method (Stergiopulos et al 1994)

NO INVASIVE MEASUREMENTS NEEDED!!!

iCardioCloud experience → database

Patient	Pathology	Details		CT	MRI	Mesh	Sim/s
P001	Aneurysm	Aneu post istmo on the inferior max diam 55mm	Pre				
			Post				
			Follow up				
P002	Aneurysms	3 separate saccular lessions	Pre				
			Post				
			Follow up				
			Follow up 2				
P003	Dissection	tl and fl clearly separated by flap	Pre				
			Post				
			Follow up				
P004	Dissection	aneurysm post type b partially clotted, both lumen visible fl 9ml/beat vl 45ml/beat	Pre				
			Post				
			Follow up				
P005	Dissection	type b dissection with aneurysm both in TA and AA. Max diam 71mm in AA	Pre				
			Post				
			Follow up				
P006	Aneurysm	dilat desc proximal 41mm dilat desc distal 100mm	Pre				
			Post				
			Follow up				

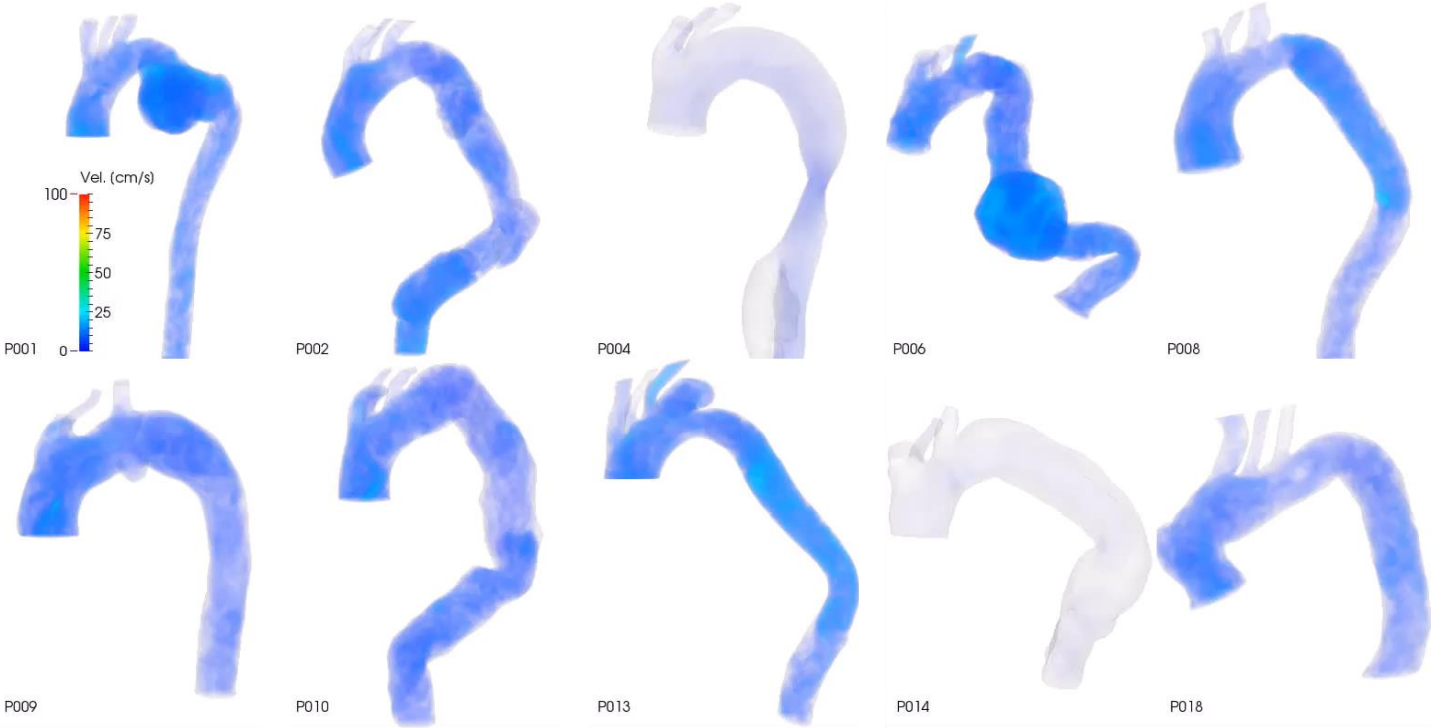
▪ ▪ ▪

Done
To be done
Can't be done
No data avail.

21 patients

- 10 aneurysms
- 7 dissections
- 1 penetrating arch ulcer
- 1 healthy
- 1 unknown (yet)

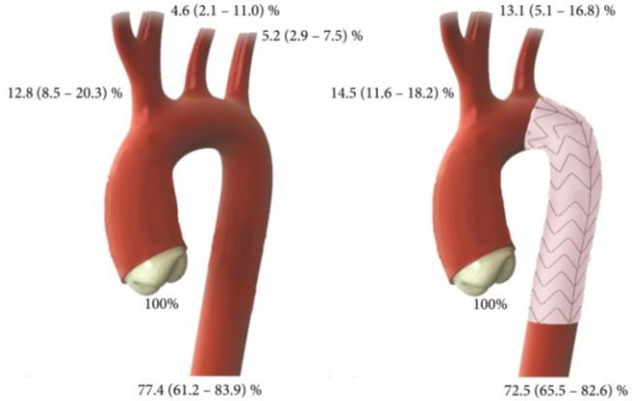
iCardioCloud experience → database

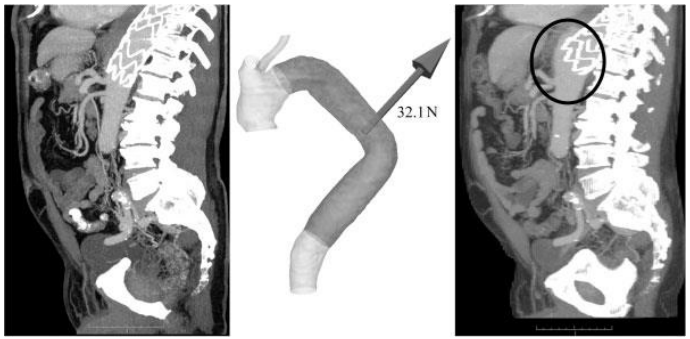


21 Patients: data assimilation challenge

iCardioCloud: CFD post-TEVAR

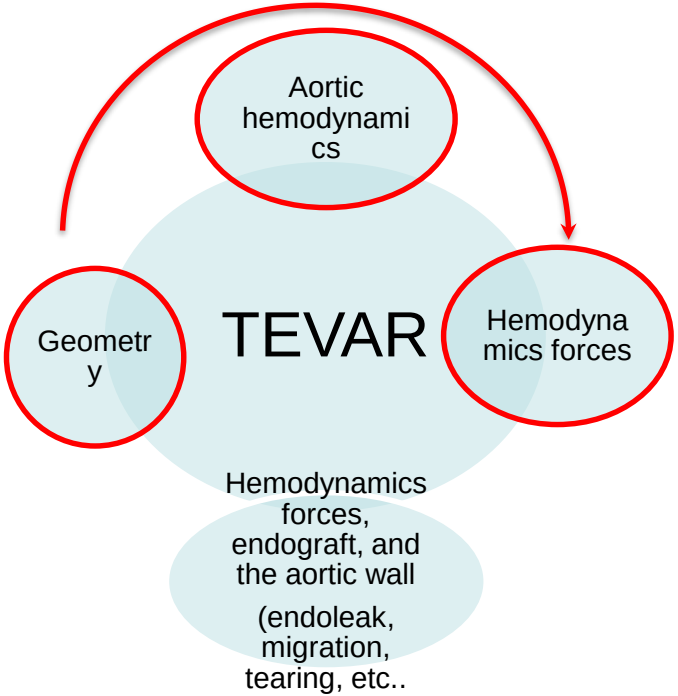
- **Four patients** were included.
- Following TEVAR in proximal landing zone 2, the **mean flow in the left common carotid artery (LCCA) increased almost threefold**, from 0.21 (0.12–0.41) L/min to 0.61 (0.24–1.08) L/min (.294%).
- The surface area of the LCCA had not yet increased commensurately and therefore maximum flow velocity in the LCCA increased from 44.9 (27.0–89.3) cm/s to 72.6 (40.8–135.0) cm/s (.62%).
- **One** of the patients presented with **Type Ib endoleak** at 1-year follow-up. The **displacement force** in this patient measured 32.1 N and **was directed dorsocranial, perpendicular to the distal sealing zone.**
- There was a linear correlation between the surface area of the stent graft and the resulting displacement force (p. 0.04).

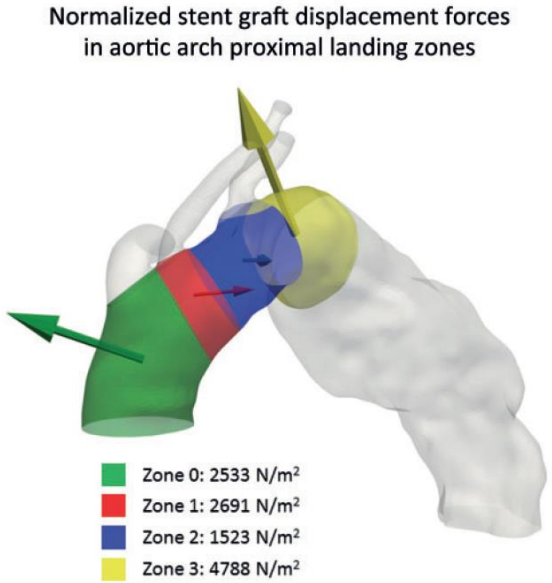




van Bakel, T. M., Romarowski, R. M., Morganti, S., van Herwaarden, J. A., Moll, F. L., de Beaufort, H. W., ... & Trimarchi, S. (2018). Blood Flow after Endovascular Repair in the Aortic Arch: A Computational Analysis. *AORTA*, *6*(03), 081-087.

Hemodynamics, forces, geometry



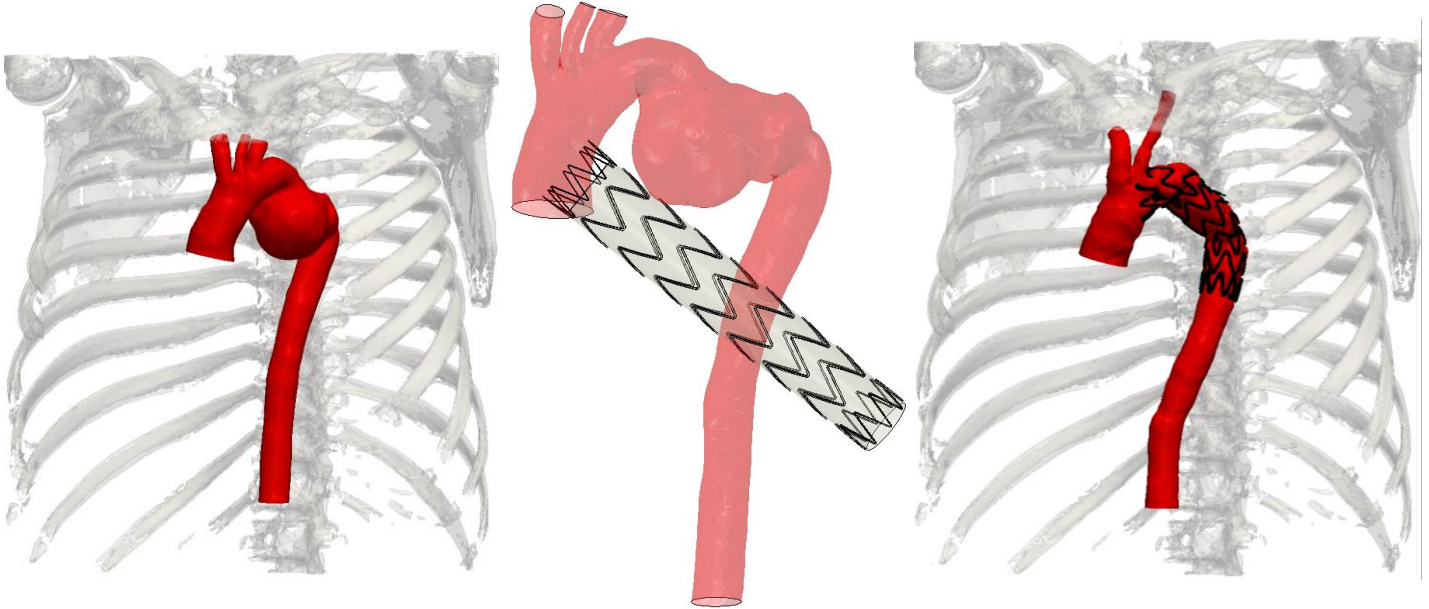


Marrocco-Trischitta, M. M., van Bakel, T. M., Romarowski, R. M., de Beaufort, H. W., Conti, M., van Herwaarden, J. A., ... & Trimarchi, S. (2018). The Modified Arch Landing Areas Nomenclature (MALAN) improves prediction of stent graft displacement forces: proof of concept by computational fluid dynamics modelling. European Journal of Vascular and Endovascular Surgery, 55(4), 584-592.

Marrocco-Trischitta, M. M., Romarowski, R. M., de Beaufort, H. W., Conti, M., Vitale, R., Secchi, F., ... & Trimarchi, S. (2018). The Modified Arch Landing Areas Nomenclature identifies hostile zones for endograft deployment: a confirmatory biomechanical study in patients treated by thoracic endovascular aortic repair. European Journal of Cardio-Thoracic Surgery.

Procedure planning of endovascular surgery: key issues

Pre-operative → *Planning & Surgery* → *Post-operative*



Realistic Simulation

Romarowski, R. M., Conti, M., Morganti, S., Grassi, V., Marrocco-Trischitta, M. M., Trimarchi, S., & Auricchio, F. (2018). Computational simulation of TEVAR in the ascending aorta for optimal endograft selection: A patient-specific case study. *Computers in biology and medicine*, *103*, 140-147.

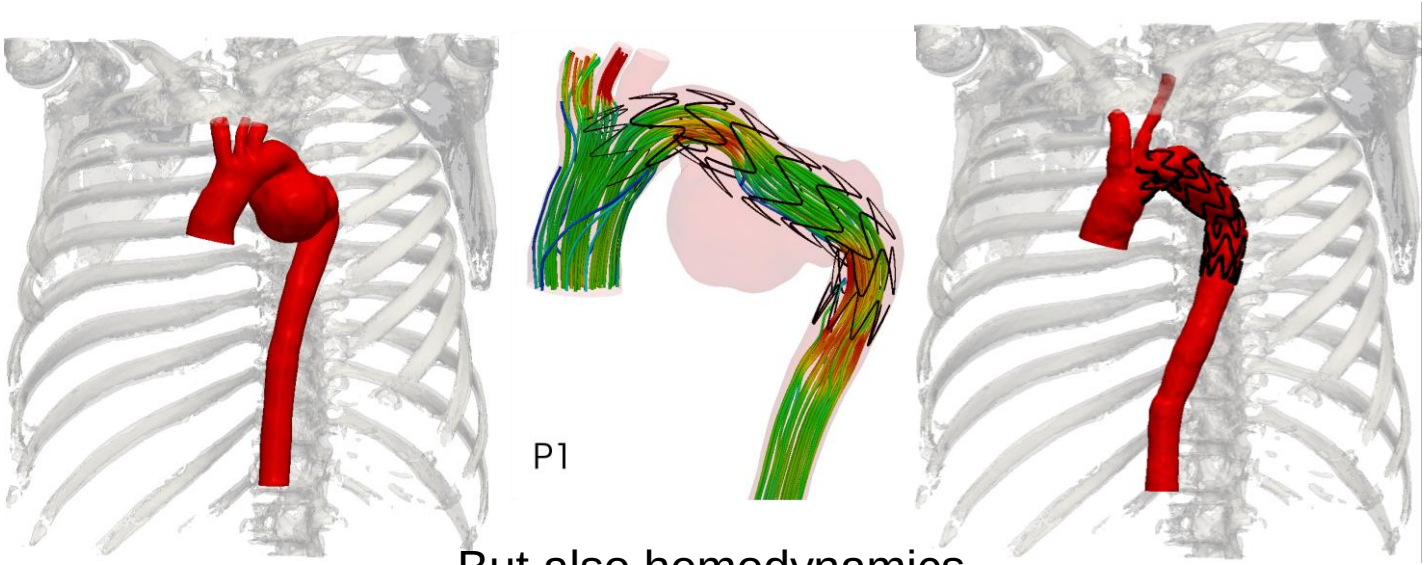
Auricchio, F., Conti, M., Marconi, S., Reali, A., Tolenaar, J. L., & Trimarchi, S. (2013). Patient-specific aortic endografting simulation: from diagnosis to prediction. Computers in biology and medicine, 43(4), 386-394.

TODAYMORROW

Procedure planning of endovascular surgery: key issues

Pre-operative → *Planning & Surgery* → *Post-operative*

Not only endograft apposition



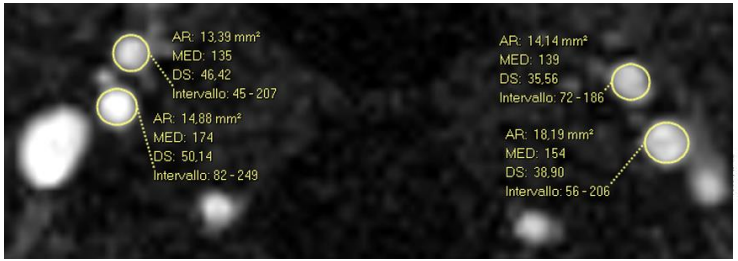
But also hemodynamics

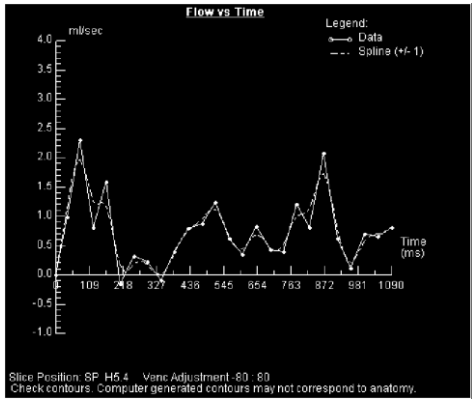
Realistic Simulation

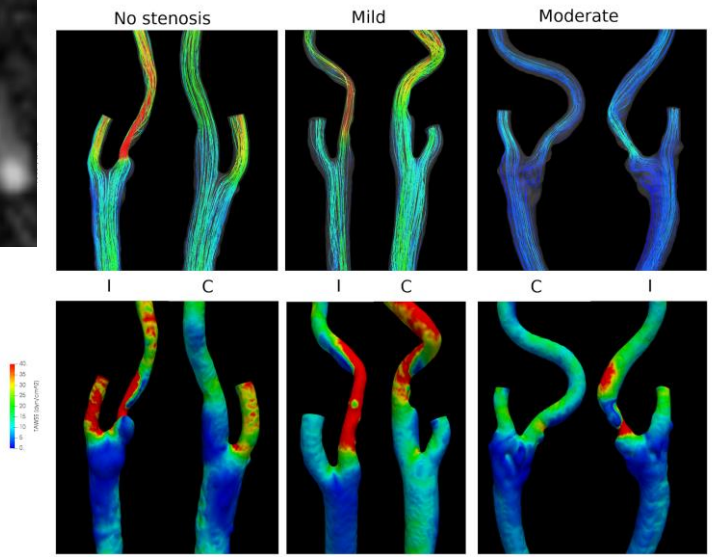
TODAYMORROW

Similar analyses for carotid artery

PC-MRI + CFD



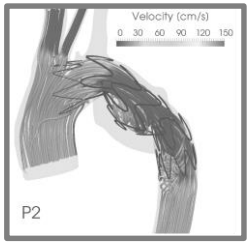




Italian Minister of Health (MoH) by the project ‘Impact of carotid endarterectomy and stenting on hemodynamics, fluid-structure interaction, autonomic modulation, and cognitive brain function’

Tools to measure aortic hemodynamics

Predire la rimodulazione dei **flussi post-TEVAR** partendo dai **dati pre-op.**



Computational fluid dynamics

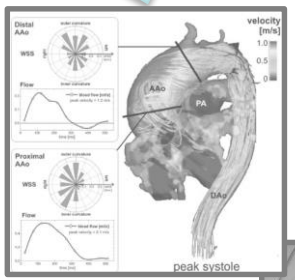
MRI come:
- Input per condizione al contorno delle simulazioni
- Validazione delle simulazioni

Aortic hemodynamics

(velocity and pressure)

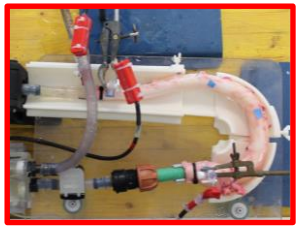
(4D-)MRI

In-vitro models and mock circulatory loop

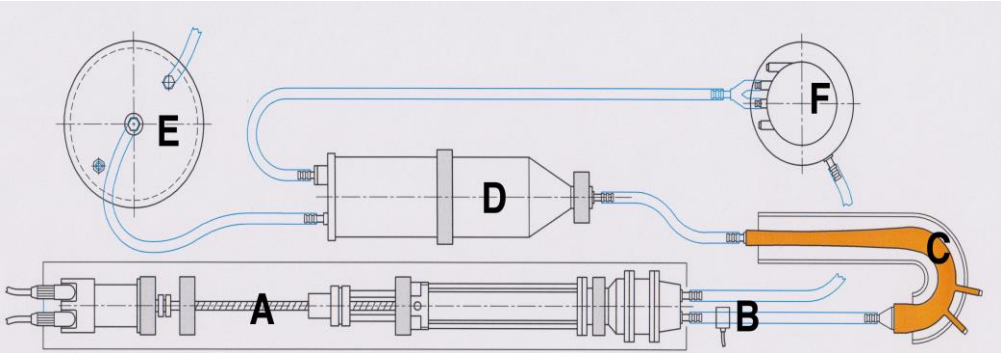


4D MRI*: posso misurare flussi aortici in 3D in modo non invasivo

*Markl et al. Journal of Cardiovascular Magnetic Resonance 2011, 13:7

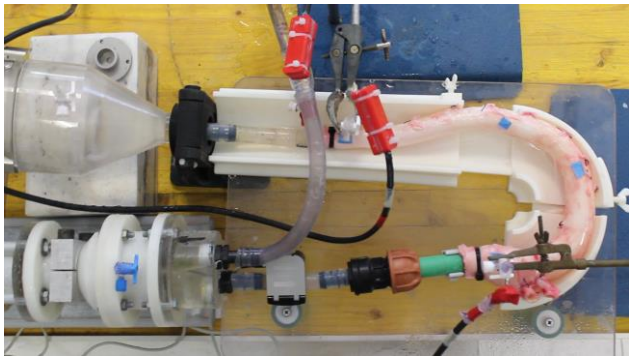


…and its biomechanical changes have a systemic impact

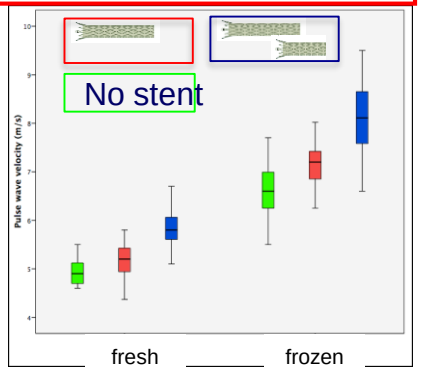


Pulsatile system based on Windkessel principle

Measuring PWV in vitro

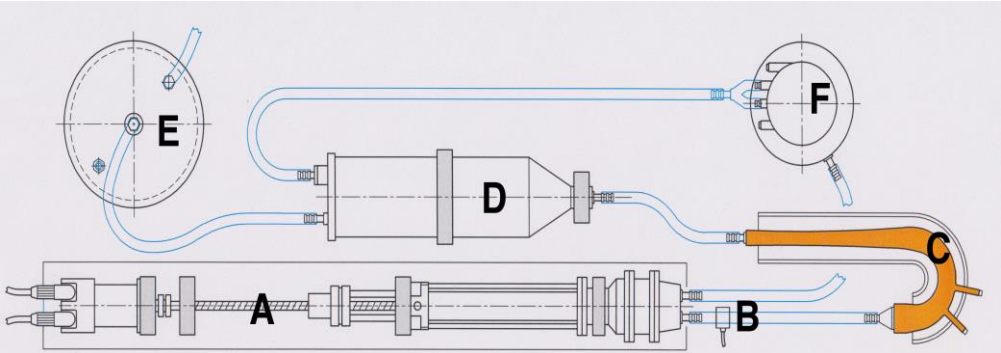


TEVAR stiffens the artery



de Beaufort H., **MC**, Kamman A., Nauta, F., Lanzarone E., Moll F., van Herwaarden J., Auricchio F., Trimarchi S. Stent Graft Deployment Increases Aortic Stiffness in an Ex-vivo Porcine Model. Annals fo Vascular Surgery. Available on line.

…and its biomechanical changes have a systemic impact

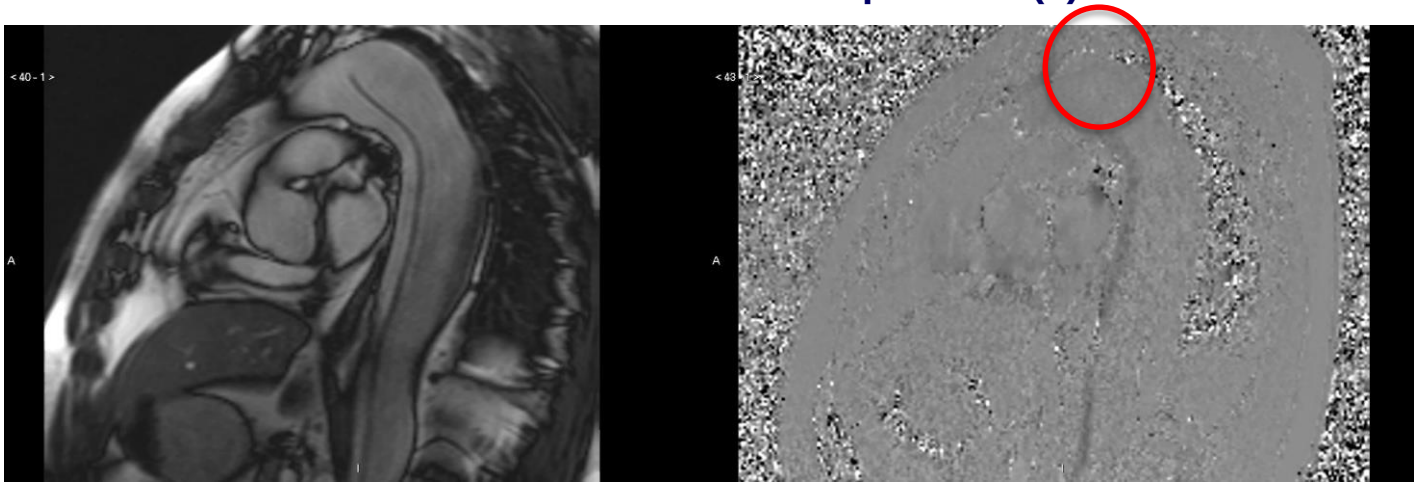


Pulsatile system based on Windkessel principle

+

In-vitro analysis of aortic dissection: background

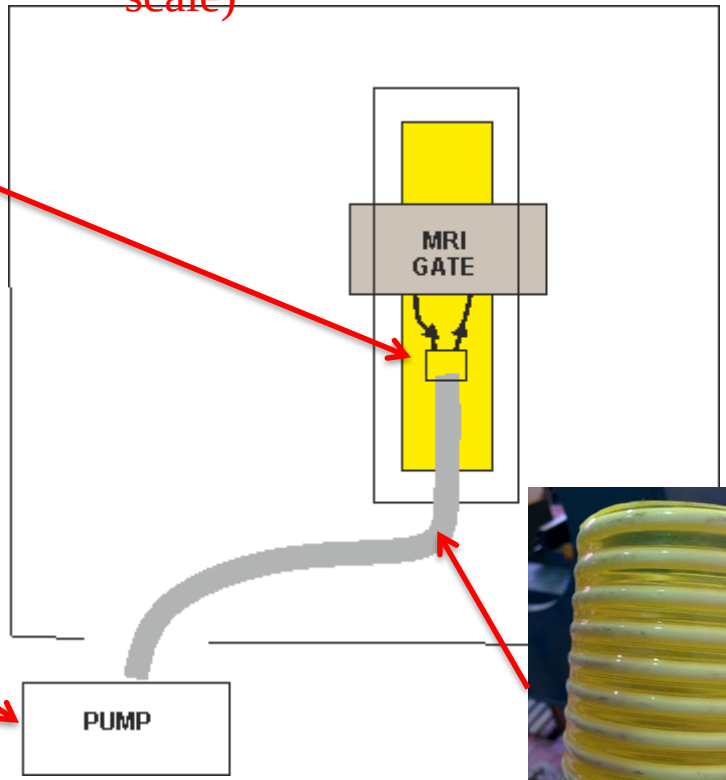
What we would to observe/reproduce (1)?



The complex flow pattern/yet due to the entry tears

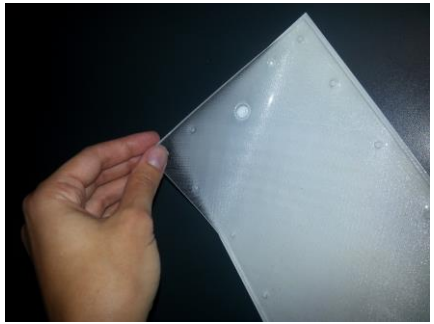
In-vitro analysis of aortic dissection: the experiment

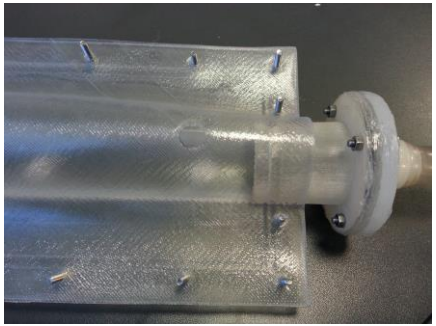
MRI room (sketch not in scale)

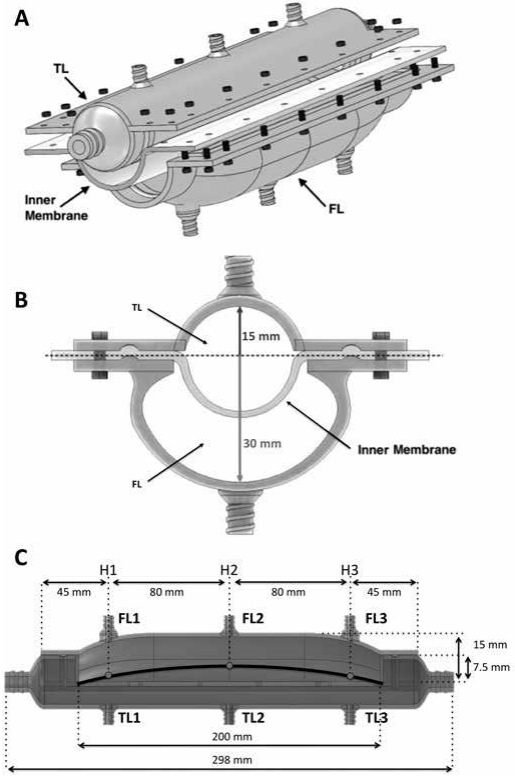


In-vitro analysis of aortic dissection: the model

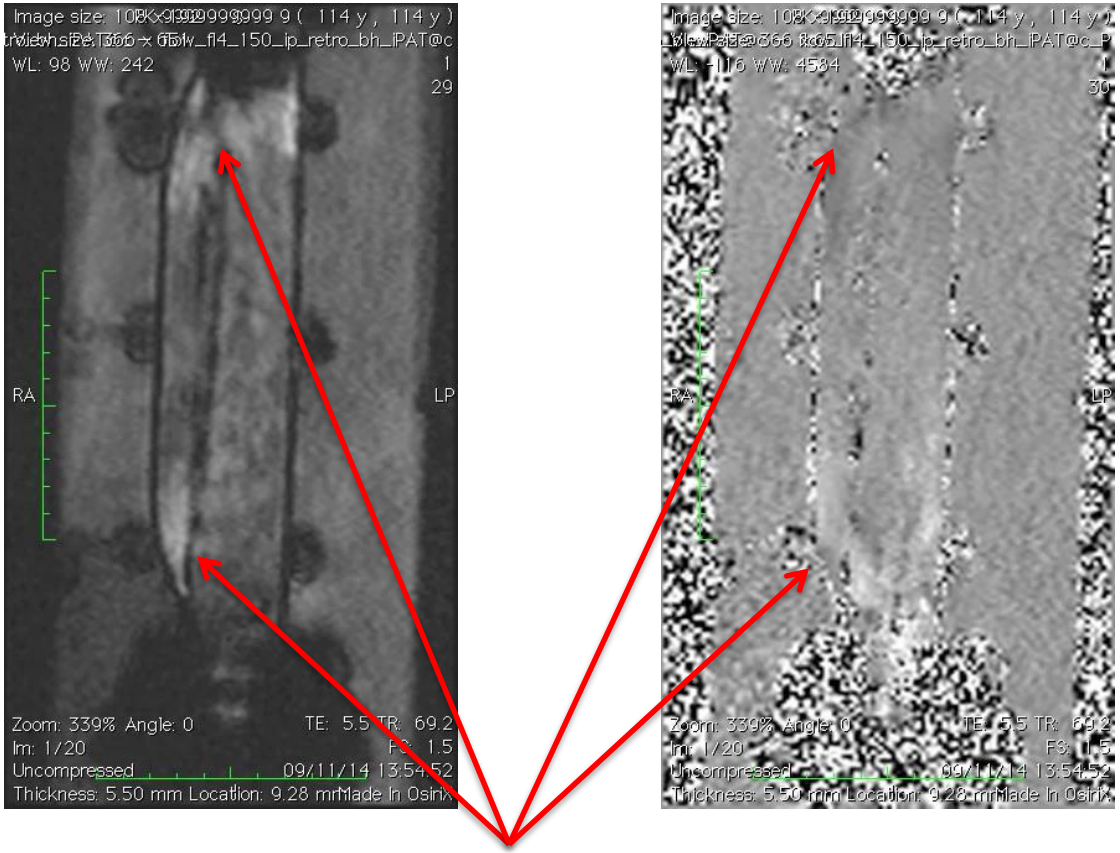
- **Model:**
  - Two rigid plates separated by a silicone membrane
    - TRUE lumen
    - FALSE lumen
  - Three points to read the pressure in each side







In-vitro analysis of aortic dissection: preliminary results



we are able to see the jets in the entry tears

MRI for in-vitro experiments

ViVitro Labs Inc.
First in Cardiovascular Device Testing

SUPERPUMP

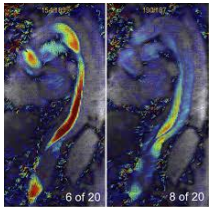
Pulsatile pump for physiological cardiac flows

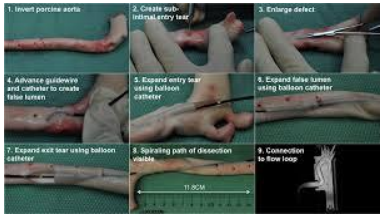
ELSEVIER
The Journal of Thoracic and Cardiovascular Surgery
Volume 157, Issue 2, February 2019, Pages 467-476.e1

Adult: Aorta: Evolving Technology

Four-dimensional flow cardiovascular magnetic resonance in aortic dissection: Assessment in an ex vivo model and preliminary clinical experience

Hector W. de Beaufort MD [a, b], Dipan J. Shah MD [a], Avni P. Patel MSc [a], Matthew S. Jackson MSc [a], Domenico Spinelli MD [b], Eric Y. Yang MD [a], Mohamad G. Ghosn PhD [a], Kyle Autry RT(R) [a], Stephen R. Igo BSc [a], Alan B. Lumsden MD [a], Stephen H. Little MD [a], Santi Trimarchi MD, PhD [b, c], Jean Bismuth MD [a]





In the current era of precision medicine, 4D flow MRI holds the potential to characterize novel sequelae of aortic pathologies and thus inform physiologically tailored surgical decision making. The current study of de Beaufort and colleagues,[1] provides key validation of this powerful technique, justifying the need for further studies to test the incremental utility of 4D flow with respect to guidance of interventional strategies and prediction of surgical outcomes.

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3D4MED: the Lab

3D4MED is equipped with all the **hardware** and **software** necessary to perform the **entire process**, from medical images elaboration to the production of the 3D printed r
are equipped with:

- **Image elaboration** and **segmentation software;**
- **Software** for **virtual models' manipulation;**
- **3D printers management software;**
- **Professional 3D printers;**
- **Post-processing instrumentation.**

Conclusions

- 4D-MRI is technologically ready but some limitations as low spatial resolution limits its use (e.g. carotid)
  Dual VENC
- PC-MRI is accepted as gold standard to set-up reliable fluid-dynamic computer based simulations
- Combination of MRI, mock circulatory loop, 3D printing provides a powerful tool but…
  requires dedicated MRI scan
  requires dedicated TIME

Modeling blood flow for clinical applications: technical side

THANKS FOR YOUR ATTENTION

Michele Conti

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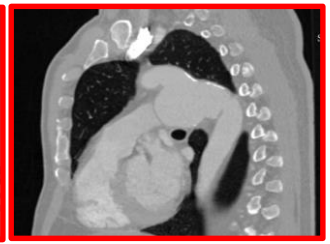
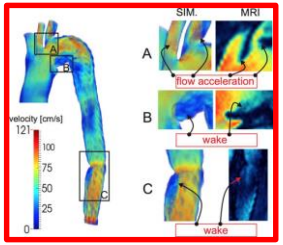
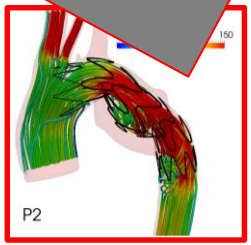
β-lab

Credits: Ferdinando Auricchio, Santi Trimarchi, Rodrigo Romarowski, ti, Massimiliano Marrocco-Trischitta, UMCUtrecht (Prof. Moll), Francesco Secchi, F elli