Functional Cardiovascular MRI

Assessment, Visualization & Quantification of 3D Blood Flow Characteristics

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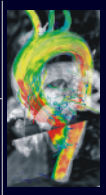
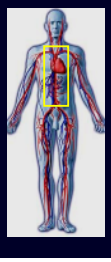


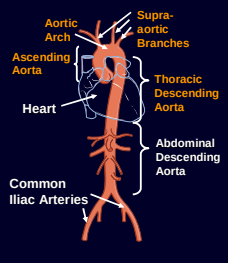
Los Angeles, AAPM, July 2009

Functional CV-MRI — *Outline*



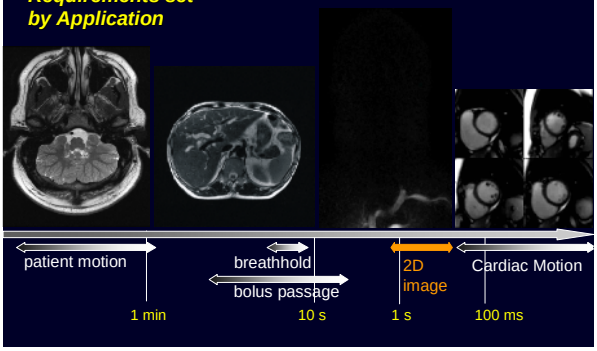
Cardiovascular MRI

- Morphology: heart and vessels
- Cardiac & valve function
- Blood Flow → flow sensitive 4D MRI

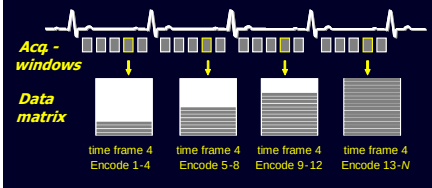


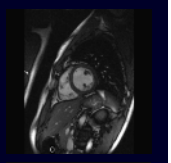
Functional CV-MRI — *Background*

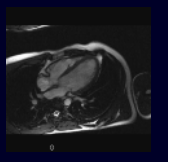
Requirements set by Application



Functional CV-MRI — *Dynamic 2D Imaging*







2D Dynamic (CINE) MRI

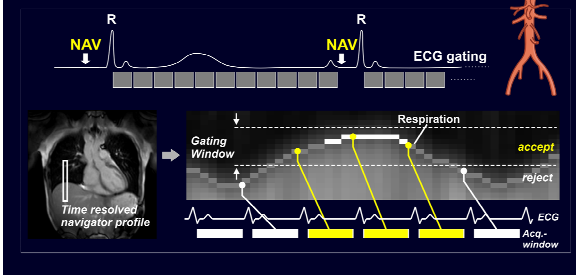
- ECG gating & synchronization of data acquisition with periodic motion

→ Breath-hold (5-15) sec

Functional CV-MRI — *Dynamic 3D Imaging*

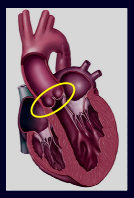
Dynamic 3D (CINE) MRI

- Thoracic & Abdominal Applications
  - ➔ Respiration control - navigator gating



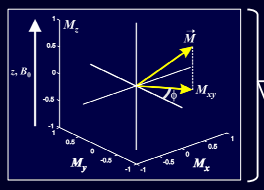
Functional CV-MRI — *Dynamic 3D Imaging*

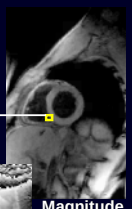
- Full coverage
- Retrospective evaluation of valve function



Functional CV-MRI — *MR Signal Phase*

MR Signal = Vector





Magnitude (M_{xy})

Phase (ϕ)

Signal Phase ~ Flow

➔ Measurement of blood flow velocities

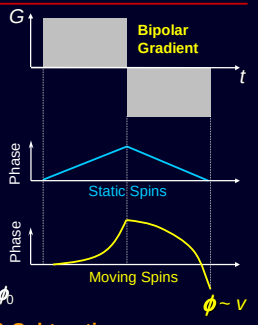
Functional CV-MRI — *Velocity Mapping*

Concept: Velocity Encodin

- Exploit sensitivity of MR-signal phase to flow

Bipolar Gradients

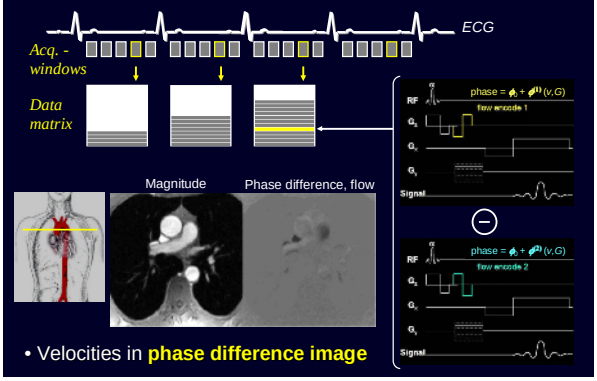
- Phase $\phi \sim v$ for moving spins
- Controlled by gradient design
  - ➔ Encoding of blood flow



But: unknown background phase ϕ_0

➔ **Reference-Measurement & Subtraction**
- Flow in 1 direction - 2 measurements

Functional CV-MRI — *Velocity Mapping*

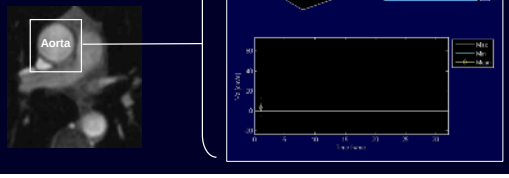


• Velocities in **phase difference image**

Functional CV-MRI — *Velocity Mapping*

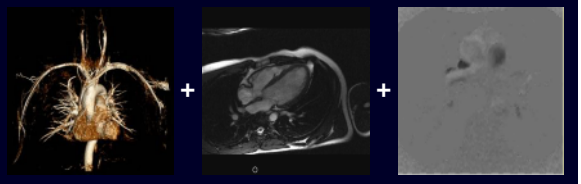
2D Slices & Through-Plane Flow

• Heart & great vessels: cardiac output, regurgitation volumes, valve function, etc.



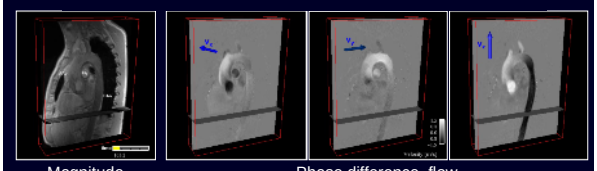
Functional CV-MRI — *3D Velocity Mapping*

Dynamic 3D MRI & Flow Encoding



➔ 3D blood blow & anatomy
➔ **Flow Sensitive 4D MRI**

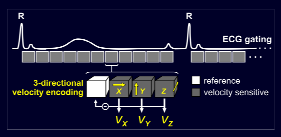
Functional CV-MRI — *3D Velocity Mapping*



Magnitude — Phase difference, flow

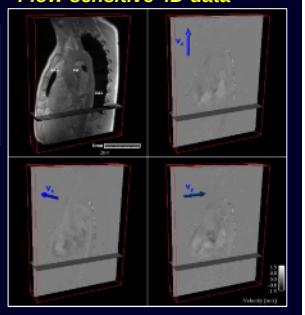
Functional CV-MRI — 3D Velocity Mapping

MR Imaging



- 3T MR-System
- Respiration control
- Res. ~ 2mm³
- T_{Res} ~ 40ms
- T_{Acq} ~ 15 - 25min

Flow-sensitive 4D data

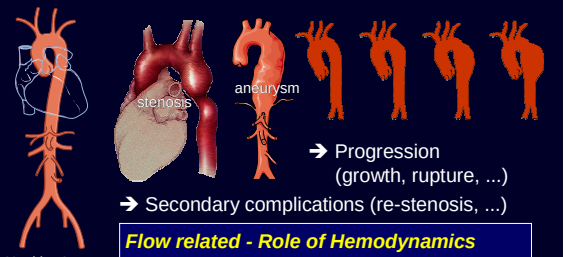


Markl M, et al *J Magn Reson Imaging* 2007;25:824–831

Functional CV-MRI — 3D Velocity Mapping

Motivation

- Atherosclerosis: Focal, predisposed sites, risk factors, ...
- Aortic pathologies: aneurysms, dissection, stenosis, ...



Healthy Aorta

➔ Progression (growth, rupture, ...)

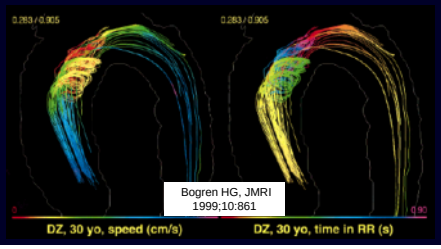
➔ Secondary complications (re-stenosis, ...)

Flow related - Role of Hemodynamics
Link between disturbed 3D flow & disease

Functional CV-MRI — 3D Velocity Mapping

Flow sensitive 4D MRI is an evolving technology

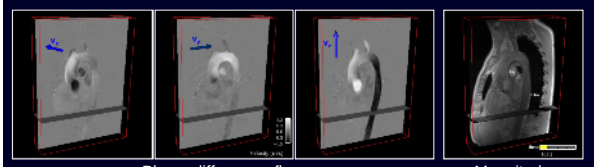
- Moran, PR MRI 1982 - A flow velocity zeugmatographic interlace
- Kilner, PJ Circulation 1993 - Secondary flow patterns in the aortic arch
- Wigstrom L, MRM 1996 - Temporally resolved 3D phase-contrast imaging.
- Bogren, HG JMRI 1999 - 4D MR velocity mapping of blood flow patterns
- Hope T, JMRI 2007 - Flow Patterns in Aortic Aneurysms and Volunteers



Functional CV-MRI — Visualization

Phase Contrast MR-Angiography

MRI Data



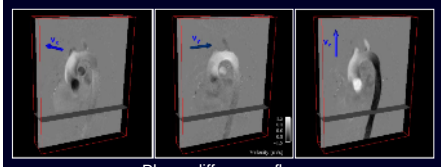
Phase difference, flow

Magnitude

Functional CV-MRI — *Visualization*

Phase Contrast MR-Angiography

MRI Data → **Anatomy** Magnitude Image



Phase difference, flow

Functional CV-MRI — *Visualization*

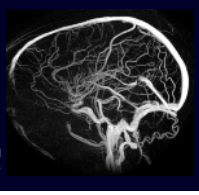
Phase Contrast MR-Angiography

Velocity |v| $V = \sqrt{V_x^2 + V_y^2 + V_z^2}$ ← **MRI Data** → **Anatomy** Magnitude Image

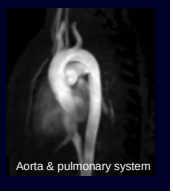
Combination: background suppression

PC-MRA

Use |v| to separate blood & tissue



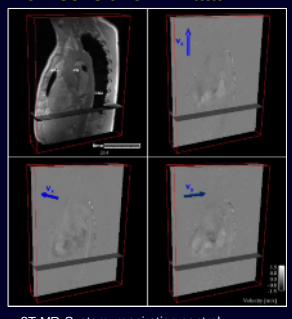
Cranial vessels

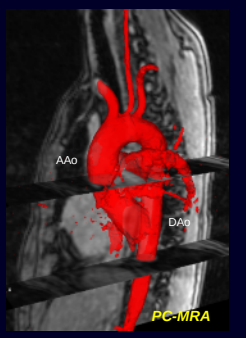


Aorta & pulmonary system

Functional CV-MRI — *Visualization*

Flow sensitive 4D Data

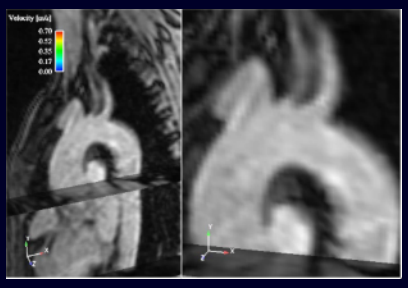




- 3T MR-System, respiration control
- Res. ~ 2mm^3, T_{Res} ~ 40ms, T_{Acq} ~ 15 - 25min

Functional CV-MRI — *Visualization*

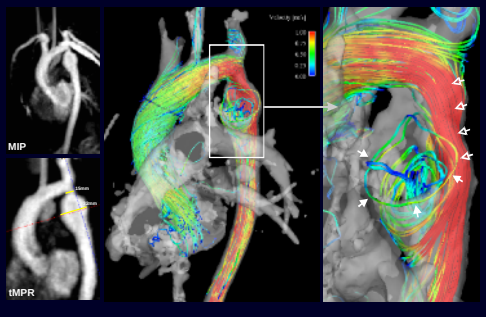
3D Particle Traces: Path of virtual particles over all time frames
→ Includes all available information, virtual 3D blood flow



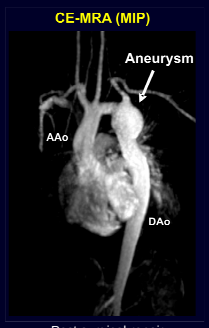
Healthy Volunteer
Normal 3D blood flow

Functional CV-MRI — *Visualization*

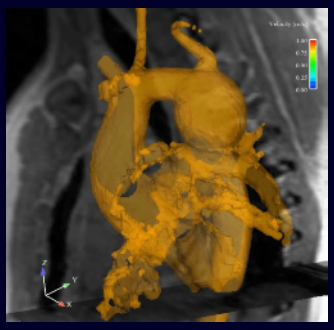
Stream-Lines: Traces along velocity field for given time-frame
→ Depiction of complex 3D velocity patterns in 3D



Functional CV-MRI — *Flow sensitive 4D MRI*



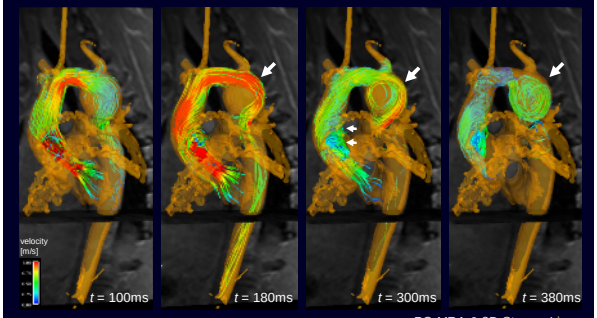
Post surgical repair
of aortic coarctation



Frydrychowicz A, Markl M et al. J Cardiovasc Magn Reson 2008;10(1):30

Functional CV-MRI — *Visualization*

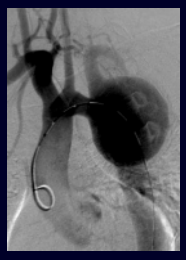
Aortic Aneurysm: Effect on blood flow in entire aorta



PC-MRA & 3D Stream-Lines

Functional CV-MRI — *Visualization*

Large Aneurysm in Proximal DAo



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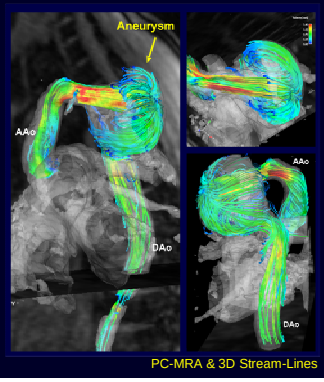


PC-MRA & 3D Stream-Lines

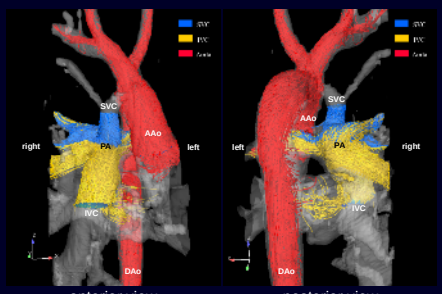
Functional CV-MRI — *Visualization*

Flow Connectivity Mapping: Color coded by vascular origin
→ Complex flow pathways, mixing of blood

http://www.cincinnatichildrens.org/health/heart-encyclopedia/anomalies/sv.htm

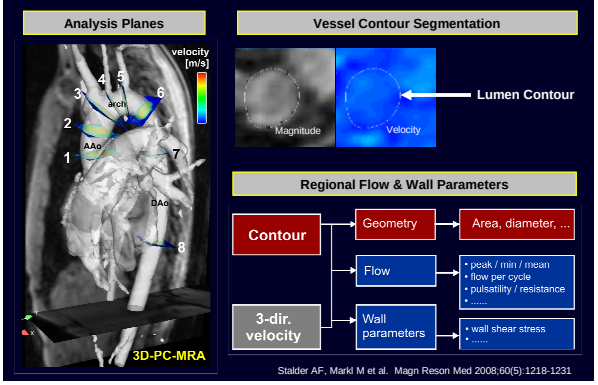
Functional CV-MRI — *Visualization*

Congenital Disease: Single ventricle & Fontan Procedure
→ direction connection of venous & pulmonary system



anterior view posterior view

Functional CV-MRI — *Quantification*



Stalder AF, Markl M et al. Magn Reson Med 2008;60(5):1218-1231

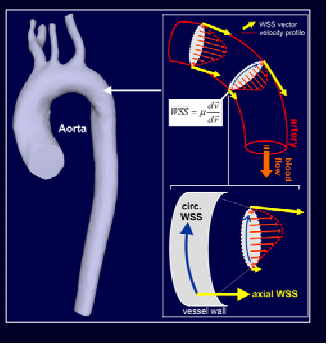
Functional CV-MRI — *Quantification*

Wall Shear Stress (WSS)

- Drag force of blood on the arterial wall
- Vector quantity
- Time resolved
  - oscillatory
  - shear index (OSI)

$$\overrightarrow{WSS} = \mu \frac{d\vec{v}}{d\vec{r}} \quad \mu : \text{viscosity}$$

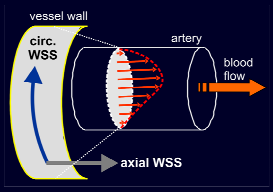
= velocity gradient normal to direction of shear

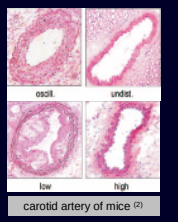


Functional CV-MRI — *Quantification*

WSS & Atherosclerosis

- Spatial variations: amplitude & direction
- Responsible for arterial remodeling
- Predictor for high risk plaques (1-4)

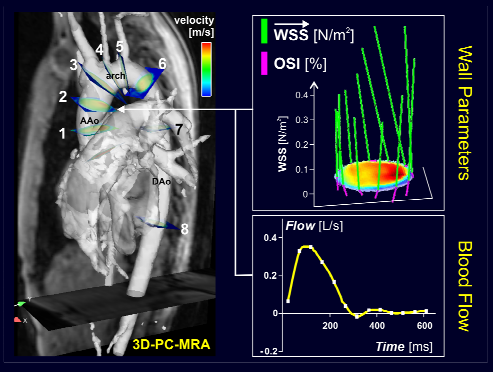




(1) Chatzizisis YS et al. Circulation. 2008;117:993-1002
(2) Cheng C et al. Circulation. 2006;113:2744-2753
(3) Ku DN, et al. Arteriosclerosis 1985;5:293-302
(4) Friedman MH, et a. Atherosclerosis 1986;60:161-171

Atherogenic { **low WSS** → vulnerable plaques
high OSI → stable lesions

Functional CV-MRI — *Flow & Wall Parameters*



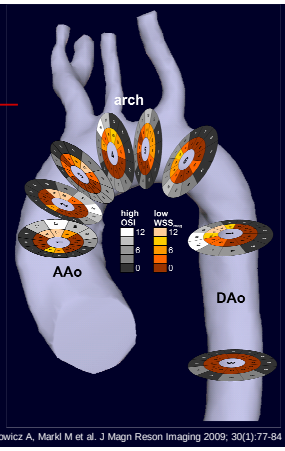
Functional CV-MRI
Flow & Wall Parameters

Normal WSS Distribution

- 31 normal volunteers
- age = 23.7 +/- 3.3 years

Data Analysis

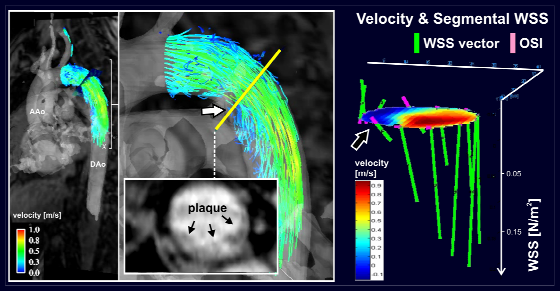
- Risk for plaque formation
  → low WSS_{mag} & high *OSI*
- Segments with individual
  - upper 15% of *OSI*
  - lower 15% of WSS_{mag}



Frydrychowicz A, Markl M et al. J Magn Reson Imaging 2009; 30(1):77-84

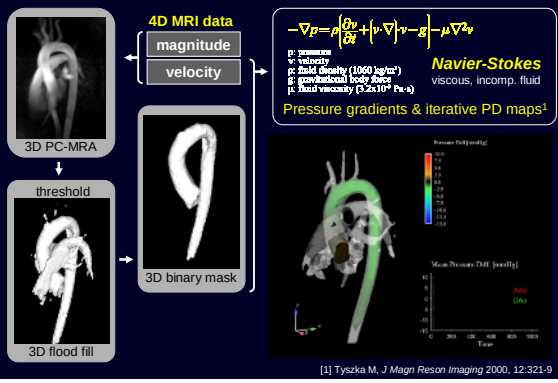
Functional CV-MRI — *Flow & Wall Parameters*

Aortic Plaque: WSS changes



Studies: Link between altered WSS & atherosclerosis

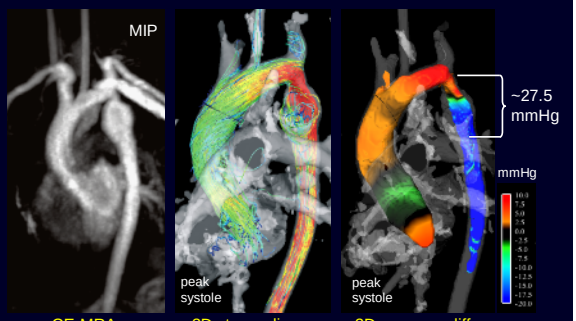
Functional CV-MRI — *Pressure*



[1] Tyszka M, *J Magn Reson Imaging* 2000, 12:321-9

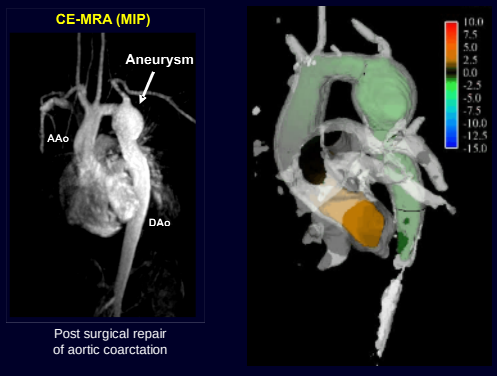
Functional CV-MRI — *Pressure*

Patient - re-stenosis in coarctation & post-stenotic dilatation



CE-MRA | 3D stream-lines | 3D pressure difference

Functional CV-MRI — *Pressure*

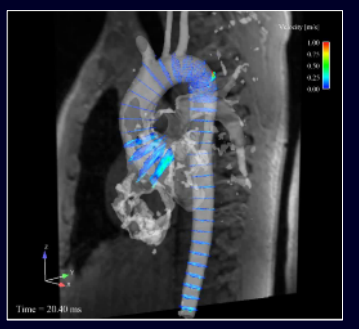


Post surgical repair of aortic coarctation

Functional CV-MRI — *Compliance*

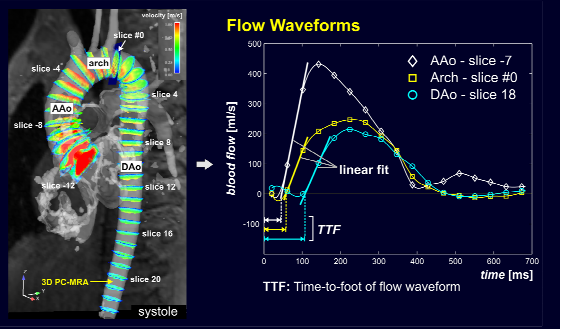
Pulse Wave Velocity
- Stiffness measure
- Propagation of flow waveform
- PC-MRI transit-time methods [1]

4D Flow MRI
- Full 3D coverage
- Complex shapes



[1] Vulliemoz S, et al. Magn Reson Med 2002;47:649–654

Functional CV-MRI — *Compliance*

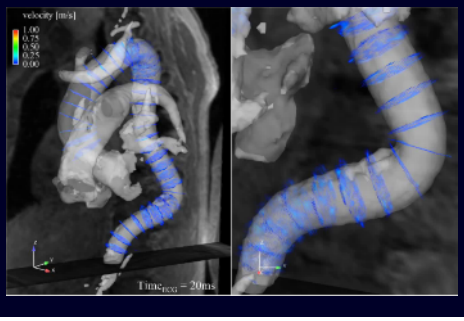


TTF: Temporal differences in flow waveforms → PWV & stiffness

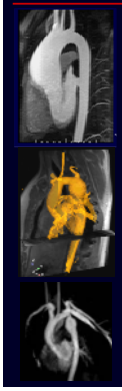
Functional CV-MRI — *Compliance*

4D Flow MRI & Pulse Wave Velocity

Analysis of complex aortic shapes & regional PWV changes

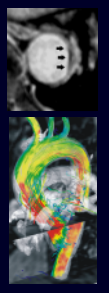


Functional CV-MRI — *Flow & Wall Parameters*



Comprehensive Analysis

Multiple hemodynamic parameters



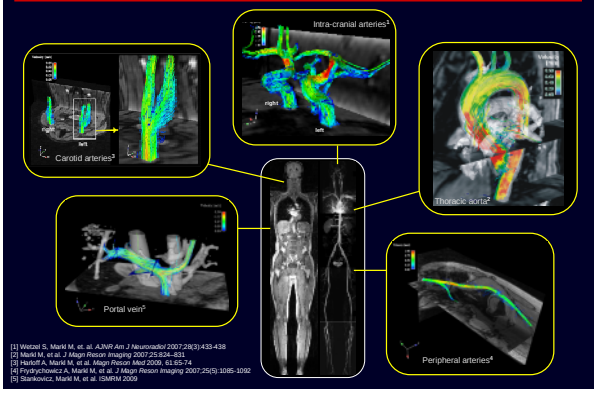
Flow

Wall Shear Stress

PWV compliance

Pressure Difference

Functional CV-MRI — *Outlook*



[1] Wetzel S, Markl M, et. al. *AJNR Am J Neuroradiol* 2007;28(3):433-438
[2] Markl M, et al. *J Magn Reson Imaging* 2007;25:824–831
[3] Harloff A, Markl M, et al. *Magn Reson Med* 2009, 61:65-74
[4] Frydrychowicz A, Markl M, et al. *J Magn Reson Imaging* 2007;25(5):1085-1092
[5] Stankovicz, Markl M, et al. ISMRM 2009

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Functional Cardiovascular MRI

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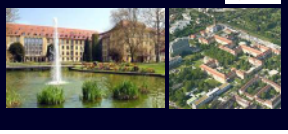
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