Functional Cardiovascular MRI
Assessment, Visualization & Quantification of 3D Blood Flow Characteristics

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

Functional CV-MRI
Background

Dynamic 2D Imaging
2D Dynamic (CINE) MRI
- ECG gating & synchronization of data acquisition with periodic motion
  ➔ Breath-hold (5-15) sec
**Dynamic 3D Imaging**

**Functional CV-MRI**

**Dynamic 3D (CINE) MRI**
- Thoracic & Abdominal Applications
  - Respiration control - navigator gating

**MR Signal Phase**

- MR Signal = Vector
- Signal Phase ~ Flow
  - Measurement of blood flow velocities

**Concept: Velocity Encoding**
- Exploit sensitivity of MR-signal phase to flow

**Bipolar Gradients**
- Phase $\phi$ for moving spins
- Controlled by gradient design
  - Encoding of blood flow

**But:** unknown background phase

**Reference-Measurement & Subtraction**
- Flow in 1 direction - 2 measurements
**Functional CV-MRI**

**Velocity Mapping**

- **Echo Planar Imaging (EPI)**
- **Data matrix**
- **Magnitude**
- **Phase difference, flow**

*Velocities in phase difference image*

**2D Slices & Through-Plane Flow**

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

**Functional CV-MRI**

**Velocity Mapping**

**2D Slices & Through-Plane Flow**

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

**3D Velocity Mapping**

**Dynamic 3D MRI & Flow Encoding**

- 3D MRI
- Dynamic MRI
- 3-dir. Blood Flow

3D blood flow & anatomy

*Flow Sensitive 4D MRI*
Functional CV-MRI  3D Velocity Mapping

**MR Imaging**

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

**Flow-sensitive 4D data**

Motivation

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

- Progression (growth, rupture, ...)
- Secondary complications (re-stenosis, ...)

Flow related - Role of Hemodynamics

Link between disturbed 3D flow & disease

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**Flow sensitive 4D MRI is an evolving technology**

- Moran, PR MRI 1982 - A flow velocity zeugmatographic interface
- Kilner, PJ Circulation 1993 - Secondary flow patterns in the aortic arch
- Wigstrom L, MRA 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

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**Phase Contrast MR-Angiography**

MRI Data

Phase difference, flow

Magnitude

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**Functional CV-MRI  3D Velocity Mapping**

**Visualization**

Healthy Aorta

Secondary complications (re-stenosis, ...)

Flow related - Role of Hemodynamics

Link between disturbed 3D flow & disease
**Functional CV-MRI Visualization**

**Phase Contrast MR-Angiography**

MRI Data → Anatomy Magnitude Image

Phase difference, flow

**Use |v| to separate blood & tissue**

**Combination: Background suppression**

**PC-MRA**

Cranial vessels

Aorta & pulmonary system

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**Flow sensitive 4D Data**

• 3T MRI System, respiration control
• Res = 3mm³, TR = 40ms, TE = 16 - 25ms

**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
**Stream-Lines**: Traces along velocity field for given time-frame

- Depiction of complex 3D velocity patterns in 3D

**Functional CV-MRI**

**Visualization**

**Aortic Aneurysm**: Effect on blood flow in entire aorta

- Post surgical repair of aortic coarctation

**Functional CV-MRI**

**Flow sensitive 4D MRI**

**Visualization**

- Post surgical repair of aortic coarctation

**Post surgical repair of aortic coarctation**

Functional CV-MRI Visualization

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

Functional CV-MRI Visualization

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

Functional CV-MRI Quantification

Analysis Planes

Vessel Contour Segmentation

Lumen Contour

Flow

3-dim. velocity

Wall shear stress

Regional Flow & Wall Parameters

Contour

Geometry

Area, diameter

Flow parameters

Wall shear stress

Wall Shear Stress (WSS)

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

\[ WSS = \mu \frac{dV}{dt} \]

\( \mu \) : viscosity

= velocity gradient normal to direction of shear
WSS & Atherosclerosis

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

Atherogenic
- low WSS → vulnerable plaques
- high OSI → stable lesions

Functional CV-MRI
Quantification

Normal WSS Distribution
- 31 normal volunteers
- age = 23.7 +/- 3.3 years

Data Analysis
- Risk for plaque formation
  - low WSS_{mean} & high OSI
- Segments with individual
  - upper 15% of OSI
  - lower 15% of WSS_{mean}

Functional CV-MRI
Flow & Wall Parameters

Aortic Plaque: WSS changes
- Link between altered WSS & atherosclerosis

References:
(2) Cheng C et al. Circulation. 2006;113:2744-2753

Functional CV-MRI
Flow & Wall Parameters

**Functional CV-MRI**

- **Pressure**
  - 4D MRI data
  - Magnitude
  - Velocity
  - Pressure gradients & iterative PD maps
  - **Navier-Stokes**
  - Incompressible fluid

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

- **Pressure**
  - ~27.5 mmHg

**Functional CV-MRI**

- **Pressure**
  - CE-MRA
  - 3D streamlines
  - 3D pressure difference

**Compliance**

- **Pulse Wave Velocity**
  - Stiffness measure
  - Propagation of flow waveform
  - PC-MRI transit-time methods

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

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**Note:**

- MIP: Maximum Intensity Projection
- PC-MRI: Phase Contrast Magnetic Resonance Imaging
Functional CV-MRI

**Compliance**

**Flow Waveforms**

TTF: Temporal differences in flow waveforms → PWV & stiffness

**Functional CV-MRI**

**Flow & Wall Parameters**

Comprehensive Analysis
Multiple hemodynamic parameters

Flow
Wall Shear Stress
PWV compliance
Pressure Difference

**Functional CV-MRI**

**Outlook**

4D Flow MRI & Pulse Wave Velocity
Analysis of complex aortic shapes & regional PWV changes

[References]

Acknowledgements

Functional Cardiovascular MRI

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