Coronary Magnetic Resonance Imaging

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• The Need for MRI
Background

- **X-ray coronary angiography (gold standard)**
  - Invasive
  - Radiation exposure for operator and patient
  - Small, but significant risk of complications
  - Substantial minority of patients are found to have no significant coronary stenosis (~30-50%)\(^1\)
  - High procedural costs ($3000-$6000)\(^2\)
  - Inability to identify early atherosclerotic disease

- Both in the USA and in Germany ~1 million x-ray coronary angiograms are performed each year\(^2\)

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\(^1\) Budoff et al. *Circulation* 1996; 93: 898
\(^2\) 2002 AHA Heart and Stroke Statistical Update
Motivation

• Need for an alternative, non-invasive, more cost efficient & patient friendlier technique, which....

  – Accurately detects significant ($\geq 50\%$) CAD
  – Rules out non-significant CAD

• $\Rightarrow$ Coronary Magnetic Resonance Angiography (MRA)
• Challenges
Technical Challenges

• Small caliber & geometry of the coronary arteries
  – Necessitates a *high spatial resolution* & sufficient *volumetric coverage*.

• Contrast
  – Contrast enhancement between coronary blood-pool, and surrounding tissue (epicardial fat, myocardium).

• Myocardial motion
  – Effective suppression of intrinsic (RR-interval) and extrinsic (respiration) myocardial motion.
Technical Challenges

Intrinsic: Cardiac cycle: ~60/min; ~2cm
Extrinsic: Respiratory cycle: ~12/min; ~2cm

Expiration

Inspiration

32cm
• Solutions
Technical Challenges & Solutions

- No motion suppression
- No contrast enhancement
Technical Challenges & Solutions

• Suppression of *intrinsic* myocardial motion
  – *ECG triggering, segmentation* of data acquisition\(^1\),
    *late diastolic* image acquisition\(^2\)

Technical Challenges & Solutions

- No motion suppression
- No contrast enhancement

- ECG triggering
- No resp. mot. suppression
- No contrast enhancement
Technical Challenges & Solutions

- Suppression of *extrinsic* myocardial motion
  - Breath-holding\(^1\)
  - Serial averaging\(^2\)
  - Bellows gating\(^2\)
  - Navigators\(^2,3\)
  - ‘Self’ Navigation\(^4\)
  - Hybrid (Navigators & Breath-hold)\(^5\)

2) Oshinski JN, Hofland L, Mukundan S. et al.: *Radiology* 201(3); (1996).
3) Li D, Kaushikkar S, Haacke, EM. Et al.: *Radiology* 201(3); (1996).
Technical Challenges & Solutions

• Suppression of extrinsic myocardial motion
  – Breath-holding
    • Diaphragmatic drift/registration errors in serial breath-holds (~1cm)
    • Major operator and patient involvement
    • Patient compliance
      → Applicability to patients with coronary disease is limited
      → Removed flexibility for enhanced spatial resolution

⇒ Free-breathing approaches

Technical Challenges & Solutions

- Suppression of *extrinsic* myocardial motion
  - MR navigator technology: *Navigator gating & tracking*¹

Technical Challenges & Solutions

- No motion suppression
- No contrast enhancement

- ECG triggering
- No resp. mot. suppression
- No contrast enhancement

- ECG triggering
- Navigator & free breathing
- No contrast enhancement
Contrast Generation

- Contrast enhancement (lumen *blood-pool* and surrounding *epicardial fat, myocardium*).

<table>
<thead>
<tr>
<th></th>
<th>T1 [ms]</th>
<th>T2 [ms]</th>
<th>$\Delta \omega_0$ [Hz]</th>
<th>flow</th>
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</thead>
<tbody>
<tr>
<td>Blood</td>
<td>1200</td>
<td>250</td>
<td>0</td>
<td>yes</td>
</tr>
<tr>
<td>Muscle</td>
<td>850</td>
<td>50</td>
<td>0</td>
<td>no</td>
</tr>
<tr>
<td>Fat</td>
<td>250</td>
<td>100</td>
<td>220</td>
<td>no</td>
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</table>
Technical Challenges & Solutions

- Contrast enhancement
  - Endogenous contrast enhancement (T2Prep)

Technical Challenges & Solutions

- No motion suppression
- No contrast enhancement

- ECG triggering
- Navigator & free breathing
- No contrast enhancement

- ECG triggering
- No resp. mot. suppression
- No contrast enhancement

- ECG triggering
- Navigator
- T2Prep
• State-of-the-Art & Comparison to Gold Standard
## Single Center Coronary MRA Results*

*Navigators & free breathing

<table>
<thead>
<tr>
<th>Study (n)</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstede’99 (23)</td>
<td>81</td>
<td>89</td>
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<tr>
<td>Huber’99 (?)</td>
<td>73</td>
<td>50</td>
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<tr>
<td>Sardinelli’00 (39)</td>
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<td>90</td>
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<tr>
<td>Lethimonnier’99 (20)</td>
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<tr>
<td>Ikonen’00 (14)</td>
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<tr>
<td>Sommer’02 (77)</td>
<td>81</td>
<td>97</td>
</tr>
</tbody>
</table>

Adapted from: Sommer et al.: Rofo Fortschr Geb Rontgenstr N 2002; 459-466
Multicenter Coronary MRA Study

- **Purpose & Methods**
  - Using uniform hardware, software & methodology\(^1,2\), to examine the sensitivity, specificity, PPV, NPV of coronary MRA for the diagnosis of significant disease of the proximal coronary arteries.
  - Prospective comparison with gold standard (MR prior to X-Ray coronary angiography, independent core lab)
  - 109 patients from 8 international centers in Philips Cardiac MR Users network.

### Multicenter Coronary MRA Results*

* Navigators & free breathing

- **Results (Detection of >50% stenosis, n=109)**

<table>
<thead>
<tr>
<th></th>
<th>Any CAD [%]</th>
<th>LM/3VD [%]</th>
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<tr>
<td><strong>Sensitivity</strong></td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td>42</td>
<td>85</td>
</tr>
<tr>
<td><strong>PPV</strong></td>
<td>70</td>
<td>54</td>
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<tr>
<td><strong>NPV</strong></td>
<td>81</td>
<td>100</td>
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Multicenter Coronary MRA Study

Multicenter Coronary MRA Study

Patient with LM/LAD & LCX disease

Patient with 2 lesions in proximal RCA

Multicenter Coronary MRA Study

- Conclusions
  - Among patients referred for elective coronary angiography, coronary MRA with real-time navigator technology and T2Prep
    - Accurately detects significant ($\geq 50\%$ lumen $\varnothing$) coronary artery disease$^1$.
    - Reliably rules out non-significant coronary artery disease$^1$

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Multicenter Coronary MRA Study

• Conclusions

⇒ There is a need for alternative methods which

• ultimately improve specificity of coronary MRA in general

• provide additional/different information

• support access to more distal/branching vessels

• Enables visualization of atherosclerotic disease that precedes lumen-narrowing

• Outlook and Promise
Works in Progress and Outlook

- **Alternative methods** include
  - Contrast agents for coronary MRA
  - SSFP coronary MRA
  - ‘Whole heart’ imaging
  - Arterial spin labeling
  - Interventional coronary MRI
  - Coronary vessel wall imaging, atherosclerosis & molecular imaging
  - High field (3T) coronary MRI
• CONTRAST AGENTS
## Contrast Generation

- Contrast agents *(Blood-Pool Agents)*

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Contrast Generation

- Inversion Pre-Pulse
- LV Navigator
- Fat Sat (SPIR)

Magnetization $M_z$ [%M0]

Time [ms]

- Blood
- Muscle
- Fat

Imaging
Contrast Generation

TRIGGER DELAY

Ti

Motion Tracking

ECG

INVERSION

NAVIGATOR

FAT SAT

3D TFE-EPI

3D TFE

30ms

15ms

70ms

Intravascular Contrast Agent

Courtesy: Paetsch I, Nagel E, Fleck E; Deutsches Herzzentrum Berlin
• Coronary Vessel Wall Imaging
Background

angiographically invisible!!

0.5..1mm

lumen

wall

foam cells

lipid core

macrophages, LDL....

Wall inflammation

macrophages

25%

50%

plaque disruption with thrombosis

Introduction

- MRI has demonstrated ability to visualize the vessel wall and its components (carotids, aorta)\(^1-3\)

- Coronary vessel wall imaging is technically very challenging
  - Small dimensions
  - Constant motion
  - Contrast ?

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Methods: Contrast Generation

- **Contrast enhancement concept:** ‘Dual inversion’

Methods: Motion Suppression

ECG

Trigger Delay

Inversion Delay (TI)

Gx

Gy

Gz

RF

Non-Selective Inversion

2D Selective Re-Inversion

Navigator

Spiral Imaging (<60ms)

45°

90°
Coronary Vessel Wall Imaging

3D SSFP

4th Order Local Inversion & 3D Spiral

RCA wall
79y old patient with “luminal irregularities” in RCA

RCA Vessel Wall Thickness

P < 0.01

1.0 ± 0.2 mm

1.7 ± 0.3 mm

Healthy subjects

Patients with non-significant CAD

RCA Lumen Diameter

Healthy subjects

Patients with non-significant CAD

3.4 ± 0.5 mm

3.6 ± 0.7 mm

P = 0.53

• High-Field Coronary MRA
Coronary MRA at 3 Tesla
(0.34x0.35x1.5mm voxel size)

→ MR System
  → Philips 3T Achieva
  → Dual Quasar Gradient System
  → 6-Element Cardiac SENSE Coil

→ Imaging Sequence
  → 3D TFE
  → TE/TR: 2.3/7.6ms
  → Matrix/FOV: 800/270mm
  → Acquired Voxel Size: 0.34x0.35x1.5mm
  → Reconstructed Voxel Size: 0.26x0.26x0.75mm
  → Fat Saturation

→ Motion Suppression
  → FREEZE (automated prescription of diastolic rest period)
  → VECG
  → Free-Breathing & Real-Time Navigator

M. Stuber, A. Ustun, R.G. Weiss, JHU