Non-Contrast-Enhanced (NCE) MR Angiography – Methods for Assessment of Morphology and Flow

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Declaration of Relevant Financial Interests or Relationships
Speaker Name: Oliver Wieben

I have the following relevant financial interest or relationship to disclose with regard to the subject matter of this presentation:

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Outline
Motivation for Noncontrast-Enhanced (NCE)-MRA
NCE MRA Acquisition Methods
- Time-of-Flight (TOF)
- balanced SSFP
  - MRA
  - Arterial spin-labeling (ASL)
- Phase Contrast (PC)
  - MRA
  - 4D PC MR - Hemodynamics
- Fast Spin Echo (FSE)
  - Fresh Blood Imaging (FBI)

Summary & Outlook
Contrast-Enhanced (CE)-MRA

Advantages of CE-MRA
- Very high SNR
- Robust, insensitive to artifacts
- Slow flow, susceptibility, etc.
- Well established — clinically proven
- Quantitative perfusion

Disadvantages of CE-MRA
- Bolus Imaging
  - Arterial-venous window
  - Limited scan time for first pass
  - Limited spatial resolution coverage
  - Susceptibility to motion
  - Venous injection: bolus dispersion
  - Use of Gd based contrast agents
  - Cost
- Patients with compromised kidney function
  - Nephrogenic Systemic Fibrosis

Time-resolved CE-MRA

Why NCE-MRA

Advantages of NCE-MRA
- No Gd
  - Cost reduction
  - Reduced subtraction for superb acr (e.g. perfusion)
  - No background enhancement from Gd
  - Provide alternative for patients at risk for NSF
- Extended scan times
  - Navigator/bellows instead of breathholds
  - Aim for higher spatial resolution
  - Additional parameters can be added
- Functional information
  - Arterial Spin Labeling
  - Quantitative Perfusion Imaging
  - PC VIPR
  - Velocity Vector Fields
  - Diffeomorphic Brain Atlas
  - T2* mapping
  - Wall shear stress

Extended scan times
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NCE MRA - Progress

Hardware Advances
- Higher field strength (3T+)
  -更高场强
- Faster gradients
- Fast imaging
- Reduced artifacts
  -Reducing flow (e.g. T2*)
- Balanced-SSFP
- Multiple receiver coils

Methodology Advances
- Novel reconstruction approaches
  - Parallel Imaging
  - SENSE, GRAPPA, SMASH, ARC...
  - Reconstrained Reconstruction
  - Compressed Sensing
  - k-t BLAST, RIGR
- Novel contrast mechanisms
  - Balancing contrast
  - Arterial spin labeling
  - Proximal blood (proximal FT)
  - Novel sampling strategies
  - Radial undersampling, spiral trajectories...
**TOF – Gradient Echo**

**2D SPGR – Pulse sequence**
- RF
- $G_{phoe}$
- $G_{read}$
- $S(t)$

**TOF – Contrast Mechanism**
- Spoiled Gradient Echo
- Gradient Spoiling
- RF spoiling
- 2D multislice or 3D acquisition
- Signal in steady state
- $S \sim f(\text{TR})$
- Short TR ($\text{TR} < 25\text{ ms}$)
- Signal for moving spins

**Signal strength in TOF**

- Vessel
- Slice/slab thickness
- Unsaturated spins
- Saturated spins
- $v \times \text{TR}$

**TOF with Spatial Saturation**
- Superior
- Inferior
Peripheral MRA with 2D TOF

**2D TOF at 1.5T**
- Multistation exam
- up to 4 slabs
- Magnetization transfer, fat saturation
- ECG gated, 32 views per segment
- TR/TE: 12.7/1.5 ms
- Flip angle: 70 deg
- FOV: 360 (380) x 150 (180) mm²
- Matrix: 256 x 192
- Slice thickness: 3.0 mm
- Slices per slab: ~140-170
- Scan time: 5.7 min
- Acquired resolution: 1.2 x 1.6 x 3 mm²
- Reconstructed resolution: 0.6 x 0.6 x 3 mm²

Cranial MRA with 3D TOF

**Intracranial 3D TOF – 38 y female volunteer**
- Incidental finding of 2mm posterior-inferior cerebellar artery (PICA) aneurysm

**Typical Imaging Protocol**
- 3 Tesla, magnetization transfer, flow compensation, fat sat, parallel imaging
- FOV = 22x16.5 cm;
- TR/TE = 24/2.4 ms; flip angle = 20 deg (ramped),
- Scan time = 4:30 min
- Acquired:
  - imaging matrix = 512x224,
  - 3 slabs, 42 slices per slab, 1mm slice thickness
- Reconstructed:
  - spatial resolution: 0.5 x 0.5 x 0.5 mm
  - 192 slices – 9.6 cm coverage

*J. Frahm et al., MRM, 1986*
from SPGR to bSSFP

\[ \int G_x = 0 \]
\[ \int G_y = 0 \]
\[ \int G_z = 0 \]

A. Oppelt et al., Electromedica, 1986

SPGR vs. bSSFP: cardiac cine

Spoiled Gradient Echo
T<sub>1</sub> weighted

SPGR, FLASH, FFE, ...

balanced SSFP
T<sub>2</sub>/T<sub>1</sub> weighted

FIESTA, TrueFISP, bFFE, ...

K. Schelcher et al., Eur Radiol, 2003

bSSFP MRA

- Rapid imaging
- T2-like image contrast
- Bright fluid signal
- Bright blood signal
- High image SNR
- Higher spatial resolution than CE MRA
- Bright vein signal
- Bright lipid signal
- Short TR requirement
- Susceptibility-induced signal drop-out

Thoracic MRA

Coronary MRA

Images courtesy J Carr, Northwestern University, Chicago, IL
bSSFP with inflow spin labeling

Inhance Inflow IR

Typical parameters at 1.5T
- TR/TE: 4.2/2.1 ms
- TI: 1300 ms
- Flip angle: 70°
- Prep Time: 200 ms
- FOV: 360 x 288 mm
- Matrix: 256 x 256
- Resolution: 1.40 x 1.13 mm²
- ST: 2 mm
- Acquisition time: 4:17

Typical parameters at 3.0T
- TR/TE: 5.1/2.5 ms
- TI: 1300 ms
- Flip angle: 70°
- Prep Time: 240 ms
- FOV: 340 x 272 mm²
- Matrix: 256 x 256
- Resolution: 1.32 x 1.06 mm²
- ST: 2 mm
- Acquisition time: 3:18

Inhance Inflow IR at 1.5T

45 year-old male with suspected renovascular hypertension

Trans-stenotic pressure gradient (TSPG) in DSA
- Right common iliac artery > 10 mmHg → angioplasty
- Transplant renal artery < 10 mmHg → no treatment
**PCASL Angiography**

- **PCASL Tagging**
  - A new endogenous tagging scheme
  - Commonly utilized for MR perfusion
  - Blood that passes through a plane is "tagged"

- **Imaging paradigm**
  - 1-3 s
  - 0.5-1 s

  - **BG1**: Tagging
  - **FAIR**: Acquisition
  - **BG2**: Control
  - **FAIR**: Acquisition
  - **Tag On**
  - **Tag Off**

  - Subtract

**Static Imaging**

- **Static MRA**
- **Vessel Selective MRA**

  - Courtesy of K. Johnson, University of Wisconsin
Time Resolved PC VIPR

• Adjusting tag duration allows time resolved imaging
• 250 ms frames
• Useful for AVM’s/ bilateral flow

Phase Contrast MR

Clinical Standard
- Single slice, 1-directional velocity encoding, ECG gated
- Velocities encoded in phase difference image ∆φ

Magnitude

Phase Diff. ∆φ

Flow, z

‘4D MR Flow’

Acquisition
- Volumetric coverage
- 3-directional flow encoding: 4 acquisitions
- ECG gating
- Breathing motion

Reduce acquisition times
- View sharing & advanced ref-gating
- Radial undersampling (PC VIPR)
- Hi-BLAST

Kozerke S et al. JMRI 2001
C Baltes et al., MRM 2005
M Markl et al., JMRI 2003
TL Gu et al., AJNR 2005
‘4D MR Flow’

Also referred to as:
- 4D MR Flow (3D Flow)
- Time-resolved 3D PC MR
- Dynamic, volumetric PC MR with three directional velocity encoding

- Magnitude and velocity field inherently coregistered
- 10-25 min scan time
- 15-20 cardiac phases
- Spatial resolution: (1-3 mm)
- Many major advances over the last decade

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‘4D MR Flow’

Vascular Anatomy
- Velocity vector field
- Cardiac gating
- Volumetric Imaging
- Comprehensive information
- Vascular anatomy
- 3D velocity field
- Hemodynamic parameters
- Combination

Post-processing and Visualization
- Flow measurements
- Visualization
- Pressure gradients
- Wall shear stress

MR Angiogram from PC Data

Phase Contrast MR-Angiography
- 3-dir. velocity encoding / non-gated → average flow

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
Normal Volunteer
PC VIPR – Cranial

PC VIPR Parameters
- 3T (GE Healthcare)
- Dual Echo
- FOV: 20 x 20 x 20 cm
- Res: 0.6 x 0.6 x 0.6 mm
- 9000 Projections (36x)
- TR=15.9
- Bandwidth = 31.25
- VENC = 50 cm/s
- 5:07 min Scan Time

Same Cartesian PC
- 48+ min Exam (Partial)

Same TOF
- 24+ min Exam (Partial)

KM Johnson et al.
ISMRM 2006 # 2384, 2958
ISMRM 2007 # 3116

PC VIPR – Sequence Design

A Barger et. al, MRM 2002
TL Gu, AJNR 2005
KM Johnson, MRM 2008

PC VIPR – Renal Artery Stenosis

Intravoxel dephasing - signal void

3D PC – product seq. 2008

CE-MRA
3D PC – product seq. 2008

Much smaller vessels - No dephasing

PC VIPR
DSA
Renal MRA: PC VIPR vs CE-MRA

Study
- 27 subjects
  - 4 healthy volunteers
  - 23 patients
  - 3 patients with native renal arteries
  - 3 patients with kidney transplants

Image quality reviewed by 2 board certified radiologists
- 5 point scale, 221 paired vessel segments

Measure vessel diameter at various locations

Results
- Vessel diameter
- Correlation = 0.960 (Bland-Altman)

Diagnostic Quality (2 readers)
- Proximal Renal Arteries
  - 94% of PC VIPR Vessels
  - 99% of CE MRA Vessels

- Segmental Renal Arteries
  - 96% of PC VIPR Vessels
  - 87% of CE MRA Vessels

Vessel Diameter (mm)

C. Francois et al, Radiology 2011

Abdominal Inhance 3D Velocity

73 year-old male with possible renal transplant artery stenosis

CE MRA

TR/TE: 3.9/1.3 ms
FOV: 350 x 350 mm2
Matrix: 256 x 192
Resolution: 1.37x1.82 mm2
ST: 2 mm
Acquisition time: 0:23

CE MRA

TR/TE: 8.3/3.1 ms
FOV: 380 x 304 mm2
Matrix: 256 x 192
Resolution: 1.48x1.58 mm2
ST: 2 mm
Acquisition time: 6:48
Venc: 50 cm/s

Enhance 3D Velocity
Flow patterns – RV, RVOT, PA

Normal volunteers
- Small vortices beneath TV leaflets
- Flow primarily directed toward RVOT

TOF patients
- Large vortices beneath TV leaflets
- Flow directed toward RV apex in patients with PR

Quantification based on velocity fields
- Wall shear stress
- Pressure difference mapping
- Turbulence & turbulent kinetic energy
- Pulse wave velocity & vessel elasticity
- ....

Pressure Gradient


Pearson Correlation
\[ r = 0.977; \ p < 0.001 \]
95% CI: 0.939-0.991

Swine model – carotid artery stenosis, n=19
Navier-Stokes equation
\[ \nabla P = \rho \left( \nabla \times \mathbf{v} \right) + \rho \ddot{\mathbf{v}} + \mu \nabla^2 \mathbf{v} \]

Summary

Established NCE MRA
- TOF
- 3D PC
NCE MRA – up and coming
- balanced SSFP
- 4D MR Flow

Advantages
- No Gd (cost, NSF)
- Information beyond luminography
- Scan times beyond AV window
- Free breathing, ECG gated, patient comfort

Areas to improve
- Large clinical studies
- Demonstrate robustness
- Solid Validation
- Post-processing Workflow
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Arterial Spin Labeling

Time of Flight (TOF) MRA
PC VIPR – Aortic Coarctation

2 month old boy
Aortic Coarctation
PC VIPR Anatomy and Velocities

CHD: PC VIPR Anatomy and Velocities

Velocities
Pressure gradient

2 month old boy
aortic coarctation

Interactive Visualization and Analysis of Complex Flow Patterns in Congenital Heart Disease

Abstract #2968

Double Inlet Left Ventricle

2 year old female
Status post Bidirectional Glenn procedure
Anterior View
RA and RV Flow with 4D PC-MRI in Normal Volunteers and Tetralogy of Fallot

**Abstract**

#4067

**Flow patterns – SVC, IVC, and RA**

**Normal volunteers**
- Primary RA filling in systole
- Single clockwise vortex during systole

**TOF patients**
- Primary RA filling in diastole
- One large vortex where SVC and IVC come together with part of IVC flow directed toward RA appendage (*)

*Patient with TOF*

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**Scimitar Syndrome**

**A. Frydrychowicz et al., Circulation 2010 121(23)**

18 month old male with Scimitar Syndrome

- Qs/Qa = 1.33
- Atrial Septal Defect
  - Flow = 1.34 L/min
- Anomalous Pulmonary Venous Return
  - “Scimitar Vein” Flow = 0.42 L/min
- Abnormal Systemic Artery
  - Flows to right lung

**PC VIPR - CHD**

A. Francois, ISMRM 2009

- Anomalous PV draining into IVC
- Right PA going to RLL
- Abnormal systemic artery to RLL

18 month old boy
Pulmonary venolobar (Scimitar) syndrome
18 month old male with Scimitar Syndrome

**Atrial Septal Defect**
- Flow = 1.34 L/min

**Anomalous Pulmonary Venous Return**
- "Scimitar Vein" Flow = 0.42 L/min

**Abnormal Systemic Artery**
- Flows to right lung

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**bSSFP with inflow spin labeling**

**Balanced SSFP (FIESTA)**
- Provides high blood signal with T2/T1 contrast
- Inflow effect is utilized to visualize vessels

**Inversion pulse**
- Suppresses veins and background tissues
- Select any vessels you want to depict

**Advantages**
- High blood signal
- Artery and venous separation
- Depiction of blood flow in any direction
- Free breathing (respiratory triggered with bellows)

**Works well in abdomen and pelvis**