Valvular Flow Quantification with Phase Contrast Imaging (2D, 4D)

Christopher J François, MD
Associate Professor, Chief of Cardiovascular Imaging
Department of Radiology, Cardiovascular and Thoracic Sections
University of Wisconsin-Madison

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Learning Objectives

- Physics of imaging blood flow with MRI
- How phase contrast MRI is used in valve disease
- Role for 4D flow MRI in valve disease
Velocity encoding

- Spins protons in constant magnetic field have same phase
- Magnetic field gradient induces phase shifts in spins relative to their location in gradient

\[ \Phi = 0^\circ \]

\[ \Phi = 20^\circ \]

\[ \Phi = 40^\circ \]

\[ \Phi = 60^\circ \]
Velocity encoding

- Spins protons in constant magnetic field have same phase
- Magnetic field gradient induces phase shifts in spins relative to their location in gradient

Constant Magnetic Field

- Phase \( \Phi = 0^\circ \)
- Stationary tissue

Moving tissue

Magnetic Field Gradient

- Phase \( \Phi = 0^\circ \)
- \( \Phi = 20^\circ \)
- \( \Phi = 40^\circ \)
- \( \Phi = 60^\circ \)

Stationary tissue

Moving tissue

\[ \Phi = (0^\circ + 20^\circ + 40^\circ)/3 = 20^\circ \]
1-directional flow MRI

Magnitude

Phase ($\Delta \Phi$)

Flow ($V$) = \frac{\Delta \Phi}{\gamma \Delta m} = \frac{\Delta \Phi}{\rho V_{enc}}

Flow [mL/s]

Time [ms]
1-directional flow MRI

Through-plane

In-plane

Flow, z

Flow, x
3-directional flow MRI

2D, 1-directional flow MRI

2D, 3-directional flow MRI
Valvular Flow Quantification with MRI

4D flow MRI

2D, 3-directional flow MRI

3D, 3-directional flow MRI

Magnitude
Phase (L/R)
Phase (S/I)
Phase (A/P)

CD
Phase (A/P)
Phase (S/I)
Phase (R/L)
# 2D vs 4D flow MRI

<table>
<thead>
<tr>
<th></th>
<th>2D PC</th>
<th>4D PC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coverage</strong></td>
<td>2D slice</td>
<td>3D volume</td>
</tr>
<tr>
<td><strong>Flow sensitivity</strong></td>
<td>1-directional</td>
<td>3-directional</td>
</tr>
<tr>
<td></td>
<td>3-directional</td>
<td></td>
</tr>
<tr>
<td><strong>Scan time</strong></td>
<td>Short (seconds)</td>
<td>Long (minutes)</td>
</tr>
<tr>
<td></td>
<td>Breath-hold</td>
<td>Free-breathing</td>
</tr>
<tr>
<td></td>
<td>Free-breathing</td>
<td></td>
</tr>
<tr>
<td><strong>Temporal resolution</strong></td>
<td>≥2×TR</td>
<td>≥4×TR</td>
</tr>
<tr>
<td><strong>Image reconstruction</strong></td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td><strong>Post-processing</strong></td>
<td>Short</td>
<td>Long</td>
</tr>
</tbody>
</table>
Errors in flow MRI

System errors

• Imperfections in scanner
  – Concomitant gradients
  – Eddy currents
  – Gradient non-linearity

Spin assumption errors

• Incomplete spin characterization
  – Turbulence signal loss
  – Intravoxel dephasing
  – Acceleration based distortion
  – Velocity aliasing
Aliasing

Venc 250 cm/s

Venc 550 cm/s
**Oblique vs. Orthogonal**

- **Flow: 101 mL/beat**
  - Peak velocity: 156 cm/s

- **Flow: 98 mL/beat**
  - Peak velocity: 144 cm/s

**Graph**

- Time (ms)
- Flow (mL/s)

Small ($\neq 0$)
Flow compensation

Flow compensation “OFF”  Flow compensation “ON”

120 mL/beat  101 mL/beat

Flow compensation on  Flow compensation off

Small (≠0)

Flow (mL/s)

Time (ms)
Background correction

Flow without background correction

Flow with background correction

Small (≠0)

Flow [mL/s]

Time [ms]

0 200 400 600 800

-10 -8 -6 -4 -2 0 200 400 600 800

Flow [mL/s]

Time [ms]

0 200 400 600 800

-50 0 50 100 150 200 250 300 350 400

Small (≠0)

Flow without background correction

Background

Flow with background correction
Background correction

Chernobelsky, et al. JCMR 2007

Patient
Stationary phantom

Aorta flow
Phantom
Small ($\neq 0$)

Flow [mL/s]

Time [ms]

-20
-15
-10
-5
0
5
10
15
20

400
800

0
100
200
300
400
500
600
700

640
650
660
670
680

40
60
80
100
120

0
400
800

Small ($\neq 0$)

Aorta flow - phantom

Aorta flow
Phantom

400
800

Time [ms]
Flow MRI for valve disease

- Setting up planes for 2D flow MRI
- Flow quantification with 2D flow MRI
- Clinical examples using 2D flow MRI
- 4D flow MRI in valve disease
Flow MRI for valve disease

- Setting up planes for 2D flow MRI
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- 4D flow MRI in valve disease
Valvular Flow Quantification with MRI

Tricuspid valve

RV 2ch

4ch
Mitral valve

Valvular Flow Quantification with MRI

4ch

3ch

A

P
Pulmonary valve

Sagittal oblique

Axial oblique

Valvular Flow Quantification with MRI
Aortic valve
Flow MRI for valve disease

- Setting up planes for 2D flow MRI
- Flow quantification with 2D flow MRI
- Clinical examples using 2D flow MRI
- 4D flow MRI in valve disease
Atrioventricular valves

**Tricuspid valve**

**Mitral valve**

**Flow [mL/s]**

**Time [ms]**

- E
- A

---

**Flow [mL/s]**

**Time [ms]**

- E
- A
Ventriculoarterial valves

Flow [mL/s] vs. Time [ms]

Pulmonary

Aorta
Effect of breathing

Breath-hold (expiration)
Flow: 97 mL/beat
Peak velocity: 89 cm/s

Free breathing
Flow: 105 mL/beat
Peak velocity: 89 cm/s

Flow (mL/s)

Time (ms)

Free breathing
Breath-hold
Small (≠0)
## Velocity measurements

<table>
<thead>
<tr>
<th>Authors</th>
<th>Reference</th>
<th>Subjects</th>
<th>Comparison</th>
<th>Results</th>
</tr>
</thead>
</table>
| C Kondo, et al.       | AJR 1991;157:9     | 12 adults         | Doppler       | • Peak MPA velocity with MRI slightly lower than Doppler (p > 0.05)  
• Peak aorta velocity with MRI lower than Doppler (p < 0.05)  
• Intra-observer variability 2.9% for aorta and 4.6% for MPA  
• Inter-observer variability 4.4% for aorta and 7.0% for MPA |
| VS Lee, et al.        | AJR 1997;169:1125  | 8 adults          | Doppler       | • Peak MPA and aorta velocities lower than echocardiography (SEE: 10-12cm/s)                                                          |
| P Kilner, et al.      | Circulation 1993;87:1239 | 15 adults         | Doppler       | • Peak velocity lower with MRI than Doppler  
• Bias: -0.1±0.5m/s  
• Inter-observer variability 0.1±0.3m/s |
| AC Eichenberger, et al. | AJR 1993;160:971  | 13 adults         | Doppler       | • Peak pressure higher with MRI than Doppler  
• Bias: 2.6±13.3mmHg |
| L Sondergaard, et al. | Am Heart J 1993;126:1156 | 12 adults         | Doppler       | • Peak velocity lower with MRI than Doppler  
• Bias: -0.9±0.9m/s |

In general, peak velocities lower with MRI than Doppler
## Flow measurements

<table>
<thead>
<tr>
<th>Authors</th>
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<th>Subjects</th>
<th>Comparison</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>WG Hundley, et al.</td>
<td>Circulation 1995;91:2955.</td>
<td>12 adults</td>
<td>Oximetry Indicator dilution</td>
<td>• $Q_p/Q_s$ 10% higher with MRI&lt;br&gt;• Inter-observer variability 3-5%</td>
</tr>
<tr>
<td>P Beerbaum, et al.</td>
<td>Circulation 2001;103:2476</td>
<td>50 children</td>
<td>Oximetry</td>
<td>• $Q_p/Q_s$ 2% lower with MRI&lt;br&gt;• Inter-observer variability 0.2±1.5mL&lt;br&gt;• Repeatability 5.3±4.0%</td>
</tr>
<tr>
<td>K Debl, et al.</td>
<td>Br J Radiol 2009;82:386</td>
<td>21 adults</td>
<td>Oximetry</td>
<td>• Slightly higher $Q_p/Q_s$ with MRI&lt;br&gt;• 2/6 with $Q_p/Q_s&lt;1.5$ by oximetry were &gt;1.5 by MRI</td>
</tr>
<tr>
<td>H Arheden, et al.</td>
<td>Radiology 1999;211:453</td>
<td>24 adults</td>
<td>Radionuclide angiography</td>
<td>• $Q_p/Q_s$ 14% lower with MRI&lt;br&gt;• Inter-observer variability 0±4%&lt;br&gt;• Repeatability 1±5%</td>
</tr>
<tr>
<td>S Petersen, et al.</td>
<td>Int J Cardiovasc Im 2002;18:53</td>
<td>17 adults</td>
<td>Oximetry</td>
<td>• $Q_p/Q_s$ 2.5% lower with MRI&lt;br&gt;• $Q_p/Q_s$ during free breathing and during breath-hold</td>
</tr>
</tbody>
</table>

**Mixed results**

Volumes lower and higher than standards of reference
Flow MRI for valve disease

- Setting up planes for 2D flow MRI
- Flow quantification with 2D flow MRI
- Clinical examples using 2D flow MRI
- 4D flow MRI in valve disease
Aortic stenosis

<table>
<thead>
<tr>
<th>Severity</th>
<th>$V_{\text{max}}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>$\leq 3.0$</td>
</tr>
<tr>
<td>Moderate</td>
<td>3.0-4.0</td>
</tr>
<tr>
<td>Severe</td>
<td>$\geq 4.0$</td>
</tr>
</tbody>
</table>

Aortic stenosis

\[ V_{\text{max}} = 3.8 \text{ m/s} \]

\[ \Delta P = 4V_{\text{max}}^2 = 4(3.8)^2 = 57.8 \text{ mmHg} \]
### Aortic regurgitation

<table>
<thead>
<tr>
<th>Severity</th>
<th>Volume (mL/heartbeat)</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>≤30</td>
<td>≤30</td>
</tr>
<tr>
<td>Moderate</td>
<td>30-56</td>
<td>30-59</td>
</tr>
<tr>
<td>Severe</td>
<td>≥60</td>
<td>≥60</td>
</tr>
</tbody>
</table>

Aortic regurgitation

Forward flow = 69.76 mL/beat
Backward flow = 15.05 mL/beat
Regurgitant fraction = $\frac{15.05}{69.76} = 22\%$
Pulmonary regurgitation

- Pulmonary regurgitation (PR) fraction
- PR severe if RF ≥40%

- PR volume indexed to BSA
- PR volume better indicator of RV preload
Pulmonary regurgitation

Forward flow = 9.65L/min

Backward flow = 4.60L/min (2.09L/min/m²)

Regurgitant fraction = 4.60/9.65 = 47%
Tricuspid & mitral valve motion
Atrioventricular valve regurgitation

- Mitral valve regurgitation volume ($RV_{MV}$)
  \[ RV_{MV} = SV_{LV} - Q_{Aorta} \]

- Tricuspid valve regurgitation volume ($RV_{TV}$)
  \[ RV_{TV} = SV_{RV} - Q_{MPA} \]

Mitral regurgitation

Aorta flow = 53.9mL/beat
LV SV = 65.3mL/beat
Mitral RF = (65.3 - 53.9)/65.3 = 17%

Forward flow: 59.4 mL
Backward flow: 5.5 mL
Net flow: 53.9 mL
RF: 9%
Flow MRI for valve disease

- Setting up planes for 2D flow MRI
- Flow quantification with 2D flow MRI
- Clinical examples using 2D flow MRI
- 4D flow MRI in valve disease
4D flow MRI in valve disease

- Retrospective valve tracking
- Effects on flow patterns
- Energy losses
Valve motion

Tricuspid

Mitral

Pulmonary

Aortic
Valve motion

Valvular Flow Quantification with MRI

- Tricuspid
- Mitral
- Pulmonary
- Aortic
Retrospective valve tracking


Greater internal consistency with valve tracking than 2D PC
Retrospective valve tracking

No valve tracking

Valve tracking

Images courtesy S Vasanawal, MD PhD (Stanford)

**Measurement**

<table>
<thead>
<tr>
<th>No valve tracking</th>
<th>Valve tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (L/min)</td>
<td>1.70</td>
</tr>
<tr>
<td>Forward Flow (L/min)</td>
<td>1.86</td>
</tr>
<tr>
<td>Reverse Flow (L/min)</td>
<td>-0.16</td>
</tr>
<tr>
<td>Regurgitant Fraction (%)</td>
<td>9</td>
</tr>
<tr>
<td>Flow (L/min)</td>
<td>1.96</td>
</tr>
<tr>
<td>Forward Flow (L/min)</td>
<td>2.10</td>
</tr>
<tr>
<td>Reverse Flow (L/min)</td>
<td>-0.14</td>
</tr>
<tr>
<td>Regurgitant Fraction (%)</td>
<td>7</td>
</tr>
</tbody>
</table>
4D flow MRI in BCAV

Multiple studies:
- Altered flow patterns in BCAV, AS
- Vary with type of BCAV

- Areas with high WSS had fewer elastin fibers that are thinner and further apart

- Systolic flow displacement predicted growth of ascending aorta in BCAV patients
Energy loss in aortic stenosis


- Turbulence calculated from distribution of velocities in voxel
- TKE reflects irreversible energy loss as a result of disturbed flow

\[ TKE = \frac{1}{2} \rho \sum_{i=1}^{3} \sigma_i^2 \]

\[ S(k_v) = C \int s(u)e^{-ik_vu}du \]

- \( u \) = velocity (of an individual water proton)
- \( k_v \) = gyromagnetic ratio
- \( M_1 \) = first gradient moment
- \( \gamma \) = gyromagnetic ratio
- \( C \) = complex-valued scaling factor

Images courtesy: P Dyverfeldt, Linkoping University

Pt. 1

Pt. 2
Summary

- Flow MRI can accurately assess severity of valvular disease
- Be aware of sources of artifact & error
  - Aliasing
  - Perpendicular to flow direction
  - Background correction
- 4D flow MRI has potential to
  - Improve accuracy with valve tracking
  - Provide prognostic information for BCAV
Thank you

cfrancois@uwhealth.org

http://go.wisc.edu/rsna2016