Respiratory Motion Prediction for Renal Perfusion MRI

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Agenda

- Overview of Renal Hemodynamics
- Perfusion MRI Techniques
- Free-breathing Perfusion MRI of the Abdomen
Renal Hemodynamics

• Arterial velocities
  - Descending aorta: 14 (0-75) cm/s
  - Renal arteries: 30-100 cm/s
  - Doppler ultrasound or phase contrast Cine MRI

• Renal blood flow (RBF): 1.1 L/min (22% of total blood flow).
  - ~10% of blood flow is filtered by glomeruli (GFR: 125 mL/min)
  - Gold standard p-aminohippurate (C_{PAH}) - invasive.
    - Ultrasound vascular resistance

• Renal perfusion: 250-500 ml/100g-min for cortex, 50-100 ml/100g-min for medulla
  - Radiotracer techniques (H_2^{15}O, ^{133}Xe)
  - Contrast ultrasound
  - Contrast MRI methods

P Martirosian et al., MRM 5: 353-361 (2004). http://web.squ.edu.om/med-Lib/MED_CD/E_CDs/anesthesia/site/content/v03/030422r00.htm
Why Perfusion?

- Blood supply to the kidney indicates renal health and function.
- Transient/functional AKI results from decreased perfusion and may be rapidly reversible.
- Ischemic hypoxia initially impacts cortical metabolism.
- In renal transplant, cortical perfusion is significantly lower in acute rejection than acute tubular necrosis or normal allografts.
- Whole organ perfusion can be quantitatively measured noninvasively without risk to the kidney.

MRI Perfusion Techniques

- **Intravascular Contrast (T₁-wtd DCE or T₂*-wtd DSC)**
  - Uses injected Gadolinium chelates as exogenous tracer.
  - High signal changes (~50%) but high error (~50%)
  - Complicated tracer kinetics and deconvolution.
  - Difficult to obtain quantitative measurements.
  - Contraindicated for AKI, renal failure and impairment.

- **Arterial Spin Labeling (ASL)**
  - Uses blood water as endogenous tracer.
  - Small signal changes (~3%) but small error (~15%)
  - Tracer kinetics are simpler.
  - Absolute quantification may be possible.
  - Limitations with multi-slice acquisitions.
  - Subtraction technique (Control – Label) is highly sensitive to motion.
  - Safe.
MRI ASL Perfusion Milestones

1992: Perfusion MRI with single-slice continuous arterial spin labeling (ssCASL) first reported in animal (CMU).
1994: ssCASL used in human brain to measure CBF (Penn).
1994: ssCASL used to measure perfusion in rat kidneys (CMU).
1995: ssCASL used in human kidneys (Penn).
1998: ssCASL used in transplanted rat kidney (CMU).

2000: Multislice Pulsed arterial spin labeling (mmPASL) used in the human kidney.
2005: PASL used in human RCC.
2005: pCASL is created, allowing high-field CASL.

PubMed Citations for ASL
CASL: Arterial spins are continuously inverted as they travel through descending aorta, label decays on route to imaging volume. Label is created at fixed labeling plane.

PASL: Fresh spins outside of the imaging volume flow into the imaging volume. The labeled imaging volume decays as spins move into it. Source of label is dispersed outside of the imaging volume.
Continuous Arterial Spin Labeling (CASL)

CASL uses RF-based adiabatic fast passage to invert flowing blood water spins. Inverted spins flow into the tissue resulting in a small signal drop.
The adiabatic inversion efficiency can be modeled using:

\[ \alpha = 1 - e^{-\pi \gamma B_l^2 / 2G_l \cdot \vec{v}} \]

- \( G_l \): Labeling gradient
- \( B_l \): Labeling RF
- \( \vec{v} \): Spin velocity
- \( \gamma \): Gyromagnetic ratio

**Takeaway:** The inversion efficiency decreases with higher arterial flow velocities.

CASL Signal Kinetics

- Labeling RF
- Transit Delay
- Image
- Control RF
- Transit Delay
- Image

Transit Times (s)
- ~2 s
- ~1 s
- ~1 s
- ~2 s
- ~1 s
- ~1 s

Perfusion Rate
- 250 ml/100g-min
- \( \alpha = 0.8 \)

Arterial Input Function \( a(t) \)

Relaxation Function \( m(t) \)

Image Acquisition

\[ \frac{M_C(t) - M_L(t)}{M_0(t)} \]
Respiratory Motion

Coronal 3D Fast Gradient Recalled Echo
\((T_1 \text{ weighted})\)

Free-Breathing  Breathhold  Navigator-Echo Gating
Renal Perfusion Images using SPDI CASL (w/ Breathholds) at 1.5 T

Six Axial Slices (Control-Label) of Healthy Female

Coronal Localizer
Real-Time Tracking Free-Breathing Navigator Motivation

- Physiologic motion of internal organs introduces unacceptable error in quantitative MRI/MRS studies (e.g., in abdomen and chest).
- Multiple or long (e.g., DSC) breathholds during long exams are too difficult for sick and most healthy subjects.
- Accurate and reproducible breathhold positioning (better than +/- 1 mm) is very difficult.
- Wasted scan time (i.e., deadtime) using gated navigators can exceed 50% of the scan time or worse for breathholds.

*Ideally, we want real-time data acquisition corrections without breathholds, deadtimes, or discarded acquisitions.*
Respiratory Motion

Subject 1

Subject 2

Superior

Inferior

1.5 T MRI, Coronal EPI: 256x128, TR: 137 ms, FOV: 39 cm
## Respiratory Motion

### Human Motion Displacement Ratios

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Normal Respiration</th>
<th>Deep Respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diaphragm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/I : R/L</td>
<td>6.0 +/- 1.9</td>
<td>8.8 +/- 3.8</td>
</tr>
<tr>
<td>S/I : A/P</td>
<td>5.1 +/- 1.9</td>
<td>5.0 +/- 2.7</td>
</tr>
<tr>
<td><strong>Lung</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/I : R/L</td>
<td>6.0 +/- 1.9</td>
<td>N/A</td>
</tr>
<tr>
<td>S/I : A/P</td>
<td>5.1 +/- 1.9</td>
<td>N/A</td>
</tr>
</tbody>
</table>

S/I: Superior/Inferior  
R/L: Right/Left  
A/P: Anterior/Posterior

## Respiratory Motion

### S/I Displacement

<table>
<thead>
<tr>
<th>Organ</th>
<th>Normal Respiration Mean (Range)</th>
<th>Deep Respiration Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>2.5 (1-4) cm</td>
<td>5.5 (3-8) cm</td>
</tr>
<tr>
<td>Pancreas</td>
<td>2.0 (1-3) cm</td>
<td>4.3 (2-8) cm</td>
</tr>
<tr>
<td>Right Kidney</td>
<td>1.9 (1-4) cm</td>
<td>4.0 (2-7) cm</td>
</tr>
<tr>
<td>Left Kidney</td>
<td>1.9 (1-4) cm</td>
<td>4.1 (2-7) cm</td>
</tr>
<tr>
<td>Diaphragm</td>
<td>1.3 cm</td>
<td>3.9 cm</td>
</tr>
<tr>
<td>Lung</td>
<td>1.0 (0.3-2.5) cm</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Navigator Echo

2D Excitation (x-y)

1D Readout Direction (z)

1D Readout Direction

Acceptance Window

VS Deshpande and D Li. Current Protocols, June 2008
### Navigator Options

<table>
<thead>
<tr>
<th>Excitation</th>
<th>Readout</th>
<th>Description</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D</td>
<td>1D</td>
<td>B0 correction (e.g., in Siemens EPI readout)</td>
<td>~1 ms</td>
</tr>
<tr>
<td>2D or 2-1D's (SE)</td>
<td>1D</td>
<td>1D Translation (1D PACE) used for cardiac and respiratory gating</td>
<td>~30 ms</td>
</tr>
<tr>
<td>1D</td>
<td>2D</td>
<td>1D Translation (2D PACE) used for respiratory gating</td>
<td>&gt;100 ms</td>
</tr>
<tr>
<td>1D or 2D</td>
<td>2D</td>
<td>2D In-plane: rotation and translations</td>
<td>~30 ms</td>
</tr>
<tr>
<td>Non-Selective?</td>
<td>3D</td>
<td>3D: Rotations and translations (typically integrated into 3D pulse sequence readout).</td>
<td>~30 ms</td>
</tr>
<tr>
<td>1D</td>
<td>2D Multislice</td>
<td>3D: Rotations &amp; translations (3D PACE). Reconstructed images used to prospectively correct subsequent acquisitions (e.g., fMRI)</td>
<td>Depends on Image Acq. Time</td>
</tr>
</tbody>
</table>
Prospective Motion Correction (PMC) & Respiratory Motion Prediction (RMP)

* w/o Respiratory Motion Motion Prediction (RMP)
  - Navigator Acquired Image plane is shifted per ROI displacement
  - Image plane is acquired as ROI moves out of imaging plane.

* w/ RMP
  - Navigator Acquired
  - Image plane position is predicted and shifted
  - Image plane and ROI are aligned.
## Motion Compensation

<table>
<thead>
<tr>
<th>Technique</th>
<th>Patient Effort</th>
<th>Scan Time</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Compensation</td>
<td>Minimal</td>
<td>Minimal</td>
<td>~ 5 cm</td>
</tr>
<tr>
<td>Breathhold</td>
<td>Very Difficult</td>
<td>Medium</td>
<td>~ 1 cm</td>
</tr>
<tr>
<td>Breathhold with respiratory feedback display</td>
<td>Very Difficult</td>
<td>Medium</td>
<td>~ 2-4 mm</td>
</tr>
<tr>
<td>Navigator gating (narrow window)</td>
<td>Minimal</td>
<td>Long</td>
<td>~ 1-2 mm</td>
</tr>
<tr>
<td>Navigator gating (wide window)</td>
<td>Minimal</td>
<td>Medium</td>
<td>~ 2-4 mm</td>
</tr>
<tr>
<td>Navigator gating with respiratory feedback display</td>
<td>Medium</td>
<td>Medium</td>
<td>~ 1-2 mm</td>
</tr>
<tr>
<td>Real-time tracking &amp; prospective motion correction (PMC)</td>
<td>Minimal</td>
<td>Medium</td>
<td>~ 1 mm</td>
</tr>
</tbody>
</table>
Real-Time Tracking Navigator (1.5 T)

No Motion

Transverse Image Slice
S/I Harmonic Motion (10 mm/s, 10 mm amplitude)

Imaging Volume (Fixed)

Imaging Volume (Dynamic)

50 ms 500 ms

Time after Navigator

Superior

Inferior

Phantom

Phantom

CASL Perfusion Map

Renal Cortex

CASL at 1.5 T with single-shot spiral (64x64, FA:90°, TE: 8 ms, TR: 8 s, 3.7 s label, 100 ms postlabel delay).

Prediction Theories

Goal: Predict the future location $X_{t>0}$ from samples acquired in the past $X_{t<0}$

Approaches:
- Deterministic: Seek a “true” prediction.
- Stochastic: Location is a random variable. Seek to minimize variance.
## Comparison of RMP Models

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Pre-Training</th>
<th>Training/Warm-Up</th>
<th>Pros</th>
<th>Cons</th>
<th>Computational Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Not Required</td>
<td>Yes</td>
<td>Simplicity</td>
<td>Operates on single linear mode</td>
<td>Low</td>
</tr>
<tr>
<td>Multiple Linear Linear</td>
<td>Not Required</td>
<td>Yes</td>
<td>Adaptive switching among multiple models</td>
<td>Inferior for long prediction in which active model switches</td>
<td>Low</td>
</tr>
<tr>
<td>Kernal Density Estimator</td>
<td>Yes</td>
<td>Not Required</td>
<td>Flexible, almost constant with respect to prediction length</td>
<td>Computation, single point prediction</td>
<td>High</td>
</tr>
<tr>
<td>Local Circular Motion</td>
<td>Not Required</td>
<td>Yes</td>
<td>Consistent performance with respect to sampling rate</td>
<td>Intrinsically local, degraded performance for long prediction</td>
<td>Low</td>
</tr>
</tbody>
</table>
Respiratory Motion Predictor (RMP)

Model Training: Real-time Sampling & Analysis
Operation: Periodic Sampling, Model Updating, & Prospective Compensation (if applicable)

Navigator Excitations & Readouts, Navigator History Data Processing
Motion Corrections & Prediction, Real-time Updates

RMP Training (Scout) → Label or Control → RTT → PMC → Image Acquisition
Motion Compensation Objectives

- Accurately measure organ motion in real-time for both MRI and PET motion correction using:
  - Sufficient motion degrees of freedom.
  - Adequate sampling rates.
  - Accurate and efficient algorithms.

- Minimize image acquisition deadtimes associated with navigators.
  - Efficient MRI navigator design.
  - Motion prediction/extrapolation during image acquisitions from motion history and models.
  - Efficient PET/MR data integration for image reconstructions.
NIH Funded Research: Respiratory Motion Prediction (RMP) in pCASL Perfusion MRI of Clear Cell Renal Cell Carcinoma (ccRCC)

124I-cG250 PET/CT of ccRCC

pCASL MRI sequence with RMP.

Navigator Scouts/Model Training
Label or Control
Navigators/Model Update & Prediction
2D or 3D Image Acquisition
Navigators/Model Update
Label or Control

TR (~5 s)
Hybrid or Pure Image-Based RMP

- Two folds of image-base processing for improved accuracy:
  - Image volume in training: Build a motion manifold model: improves on the 1D or 3D point trajectory modeling.
  - During acquisition, combine navigator info (during transit delay) and acquired volumetric image information to update the manifold model and perform online prediction.
Improving the Prediction: Inference Training (Pre-Training)

1D Navigators | 2D or 3D Image Acquisition | 2D or 3D Image Acquisition | 2D or 3D Image Acquisition | 2D or 3D Image Acquisition

1D Motion

Inference Model

Prediction Model

3D Motion
Non-Parametrically Reconstructed Motion Manifold (Voxel Based)

Spatiotemporal behavior of the volume of interest (kidney in this example)

<table>
<thead>
<tr>
<th></th>
<th>Motion Manifold</th>
<th>Optical Flow</th>
<th>Mutual Information</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAE</td>
<td>Std.</td>
<td>MAE</td>
</tr>
<tr>
<td>Whole Domain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/o I.C.</td>
<td>4.87</td>
<td>2.16</td>
<td>2.61</td>
</tr>
<tr>
<td>With I.C.</td>
<td>4.92</td>
<td>2.13</td>
<td>7.61</td>
</tr>
<tr>
<td>Within Kidneys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/o I.C.</td>
<td>4.34</td>
<td>1.81</td>
<td>5.68</td>
</tr>
<tr>
<td>With I.C.</td>
<td>4.33</td>
<td>1.81</td>
<td>8.89</td>
</tr>
</tbody>
</table>

Error (mm) in motion manifold characterization
Estimated Motion using Shape Contouring (Boundary-Based)
Respiratory Motion Prediction Algorithm Development

Weighted Fourier Linear Combiner

Kernal Density vs. Adaptive Linear Model
10 Hz Sampling Rate

Comparison of Predictors

Prediction Window: 0.2 s

Prediction Window: 0.4 s

Prediction Window: 0.6 s

Benchmarking
Dell T1500 workstation with 64-bit quad-core, 2.93 GHz running Linux

Average computational time/prediction (μs)

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>IMM</th>
<th>WFLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATLAB</td>
<td>106.2</td>
<td>342.5</td>
<td>4551.8</td>
</tr>
<tr>
<td>C++</td>
<td>1.1</td>
<td>7.2</td>
<td>211.3</td>
</tr>
</tbody>
</table>
Status: Respiratory Motion Prediction

- Acquired human respiratory motion data and testing basic protocol.
- Began evaluating prediction algorithms using *in vivo* data in collaboration with Dan Ruan (UCLA).
- Integrated 1D navigator excitations into 2D EPI pCASL and 3D GRASE pCASL.
- Developing real-time feedback interface for receiving and processing navigator data, and predicting organ position.
Collaborators

Respiratory Motion Predictor
Hao Song (Pitt Radiology)
Dan Ruan (UCLA, Radiation Oncology)
Sungkyu Jung (Pitt Statistics)
Xiang He (Pitt Radiology)
Tejas Nair (GE)

Original Sequences:
Maria Fernandez Seara (FIMA, Univ. Navarra)
Rolf Pohmann (Max Planck Institute)
Siemens