Non-Invasive MR-based Evaluation of Kidney Function without Exogenous Contrast Agent

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• MR-based non-invasive estimation of single kidney GFR without Exogenous Contrast: baseline & protein-loading challenge

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Estimation of Single-Kidney Glomerular Filtration Rate from MR Renography without Use of Exogenous Contrast Agent: A Preliminary Study
SK-GFR: Motivation

• SK-GFR as the best measure for early detection of unilateral kidney dysfunction; obstructive nephropathy; kidney transplant; live donor

• Existing imaging-based SK-GFR requires the injection of exogenous contrast agents; renal scintigraphy; electron-bean CT

• Low dose Gd-DTPA MR Renograph
  sensitive to signal model & data acquisition

Accurate, non-invasive MR imaging method for single kidney GFR measurement that does not require an exogenous contrast agent is an urgent clinical need.
Probing Glomerular Filtration by ASL

Filtration Fraction: $\text{FF}$
Renal Plasma Flow: $\text{RPF}$

$\text{GFR} = \text{FF} \times \text{RPF} \times V$

- Void of macromolecules and large protein; similar to CSF
- Equilibrium with parenchyma water due to fast exchange

He, et al., to be published
MRI Methods: FAIR-T1ρ with FFSP

Spin Tagging → Relaxation → Fast Imaging

SAT3

SAT1,2

SAT3

[Diagram with pulse sequences and imaging parameters]
Renal ASL Perfusion Images

Siemens 3T; FOV 300×225×6 mm³; Matrix 192×144
TR: 9000 ms; TI: 1800 ms; TD: 900 ms; Label/control: 200/25 mm
Multiple timed breath-holding at the end of expiration stage
T1ρ-Weighted Renal ASL Signal

TSL=20 ms

TSL=40 ms

TSL=60 ms

TSL=80 ms

TSL=100 ms

Cortex Mask
Quantification of FF & GFR

\[ S \propto FF \cdot \exp\left(-\frac{TSL}{T1_\rho_{\text{filtr}}}\right) + \left(1 - FF\right)\exp\left(-\frac{TSL}{T1_\rho_{\text{tissue}}}\right) \]

- \( T1_\rho_{\text{filtr}} \): fixed, 500 ms
- \( T1_\rho_{\text{tissue}} \): pre-determined

\[ GFR = FF \times RPF \times V \]
<table>
<thead>
<tr>
<th>Study</th>
<th>T1ρ of ASL (ms)</th>
<th>FF (%)</th>
<th>Cortex RPF (ml/100g/min)</th>
<th>SK-GFR (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>right</td>
<td>148</td>
<td>35%</td>
<td>275</td>
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<tr>
<td></td>
<td>left</td>
<td>147</td>
<td>34%</td>
<td></td>
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<td></td>
<td>left(1)</td>
<td>120</td>
<td>20%</td>
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<td>119</td>
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<td></td>
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<tr>
<td></td>
<td>right(3)</td>
<td>132</td>
<td>30%</td>
<td>267</td>
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<tr>
<td></td>
<td>left(3)</td>
<td>124</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>129 ± 11</td>
<td>25 ± 6%</td>
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</table>
Kidney Hemodynamic after Protein-Intake

- Overnight fasting; normal hydration;
- 60 minutes after 2g/Kg BW protein challenge

<table>
<thead>
<tr>
<th>Study</th>
<th>MR-FF</th>
<th>Cortex RPF (ml/100g/min)</th>
<th>GFR (ml/min)</th>
<th>GFR increase</th>
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<tbody>
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<td>1</td>
<td>baseline</td>
<td>22%</td>
<td>323</td>
<td>95</td>
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<tr>
<td></td>
<td>meal</td>
<td>30%</td>
<td>307</td>
<td>123</td>
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<tr>
<td>2</td>
<td>baseline</td>
<td>28%</td>
<td>267</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>meal</td>
<td>35%</td>
<td>273</td>
<td>129</td>
</tr>
</tbody>
</table>

- Significant increase of transient GFR (60 mins)
- Change of GFR is mainly from filtration fraction
- Insignificant changes of transient RBF
SK-GFR: Conclusion

- Using MR arterial spin label water as endogenous tracer, it is feasible to probe the renal glomerular filtration process; leading to a MR based non-invasive approach to estimate single-kidney filtration fraction and glomerular filtration rate;

- This method creates a convenient tool to advance early diagnosis and evaluation of kidney function; The method is capable of monitoring the dynamics of kidney response under acute physiological, mental stress, or pharmaceutical challenges.
Mapping of Absolute Intra-Renal Oxygenation by Quantitative BOLD (qBOLD)
Renal qBOLD: Motivation

- Renal medullary hypoxia is a hallmark of the pathogenesis for renal diseases;
  diabetic nephropathy; renal artery stenosis; ATN
- Micro-electric or optical oxygen probe for invasive measurement of renal pO2 or µPO2
  not applicable to human
- Non-invasive MR BOLD (T2*/R2*)
  semi-quantitative; relative

MR qBOLD-based approach allows for regional, in-vivo, absolute quantification of oxygen saturation level in renal venous vasculature.
BOLD: Blood Oxygen Level Dependent

\[ \text{deoxyHb} + O_2 \rightleftharpoons Hb \]

- \( Hb \) – diamagnetic
- \( \text{deoxyHb} \) – less diamagnetic

**BOLD Signal and Blood Oxygenation**

\[ S_{meso}(t) = \text{Exp}[-DBV \cdot f(t/t_c)] \]

\[ R2' = \frac{4\pi}{3} \cdot DBV \cdot \gamma \cdot \Delta \chi_0 \cdot \text{Hct} \cdot (1-Y) \cdot B_0 \]

\[ DBV = \ln \frac{S_{extrapolated}(0)}{S_{measured}(0)} \]

- **DBV**: deoxyhemoglobin-containing blood volume
- **Y**: blood oxygenation level

Yablonskiy & Haccke, MRM, 1994
Quantitative BOLD (qBOLD)

He and Yablonskiy, MRM, 2007, 2008

$y = 0.9968x$

$R^2 = 0.92$
Renal qBOLD: Baseline

T1 Weighted

T2* Weighted

R2* (1/sec)

He, et al., to be published
Renal qBOLD: Acute Water Intake

Anti-Diuresis

Water-Diuresis

Y*100

R2* (1/sec)

He, et al., to be published
Renal qBOLD: Conclusion

- MR-qBOLD based approach is capable of non-invasively measuring regional, in vivo, absolute renal microvascular blood oxygenation level and oxygen metabolism in baseline and during kidney functional challenge;

- Renal qBOLD technique provides new tool to non-invasively quantify kidney hypoxia; offers new opportunities to investigate the mechanisms that regulate intra-renal oxygenation, i.e., glomerular filtration rate, renal blood flow and renal oxygen metabolism.
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