Motion Management in Kidney Diffusion-Weighted MRI

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Declaration of Financial Interests or Relationships

Speaker Name: Simon K. Warfield, Ph.D.

I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Motivation for Kidney DWI

- The kidney is a highly perfused organ with complex anatomy.
  - MRI can reveal morphology, vasculature and function.
- DWI is sensitive to kidney microstructure that changes with maturation, disease and injury:
  - CKD: tubular atrophy, tubular interstation fibrosis
  - Renal ischemia
  - Acute pyelonephritis

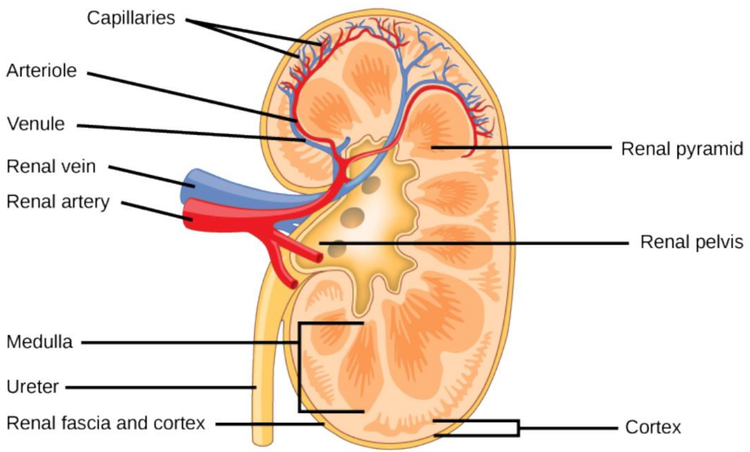
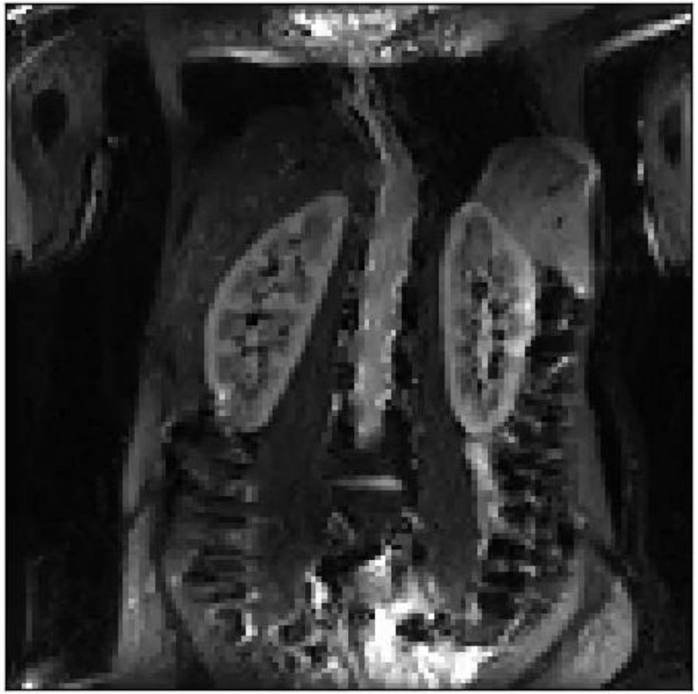


Figure from Chapter 28 of ``Principles of Biology'' 2016 by Robert Bear and David Rintoul http://cnx.org/content/m47445/1.4/

- Goal: Improved imaging markers that better characterize microstructure
  - Caroli et al. Nephrol Dial Transplant (2018) doi:10.1093/ndt/gfy163

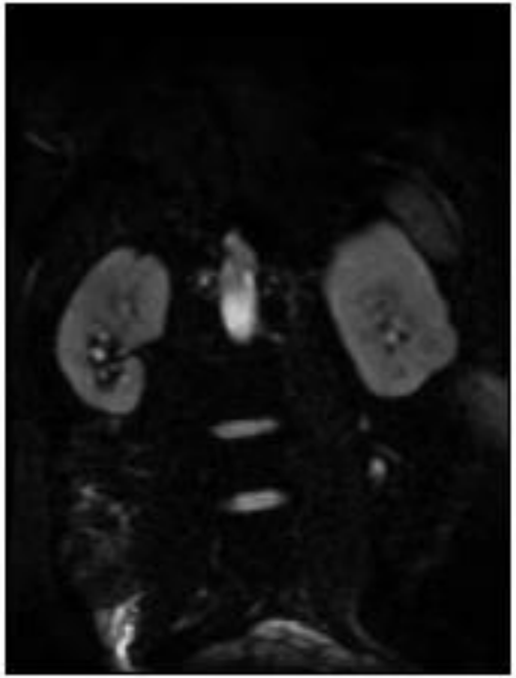
DWI for Kidney Imaging

- DWI contrast is manipulated by changing the diffusion encoding
  - Diffusion length scale, b-value
  - Orientation of diffusion gradient
- Microstructure from DWI
  - Comparison of signal changes reveals microstructural properties
- Motion can arise from
  - Respiration
  - Cardiac pulsation
  - Bulk motion
    - the subject rolls in the scanner.



DWI for Kidney Imaging: Motion

- Motion causes the signal from any one voxel in the images to arise from different places in the subject.
  - This reduces the fidelity of parameter estimates of models of the tissue microstructure.
- The DWI signal is measured at different times with varying gradient strengths and orientations.
  - We want to compare the DWI signals arising from the same anatomical location.
- Geometric distortion can also cause misalignment.

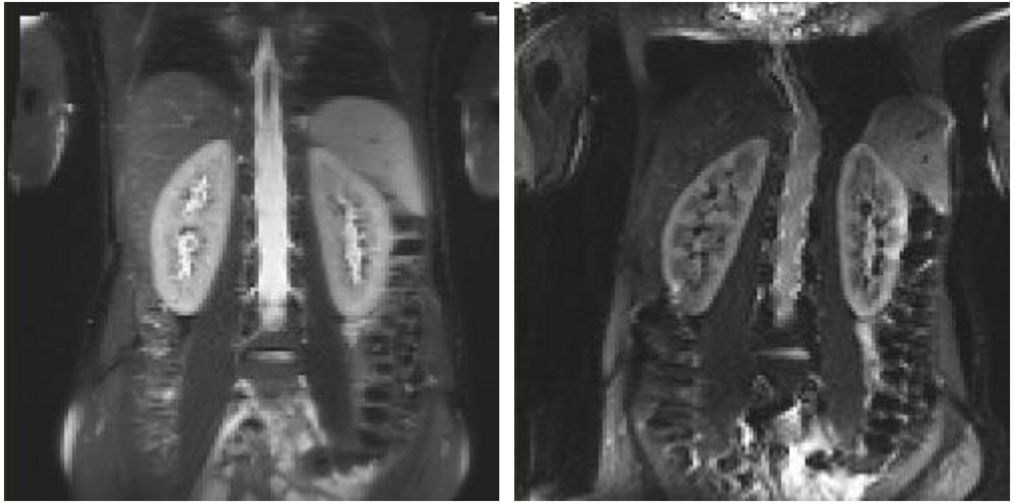


DWI for Kidney Imaging: Motion

- **Approaches for motion compensation in renal DW-MRI:**
- Navigator triggering, respiratory gating:
  - Acquire data at one instant of the respiratory cycle
  - Don’t acquire data at other times in the respiratory cycle
  - Increases scan time (not very practical for routine clinical use)
- Breath holding:
  - Eliminate respiratory motion by not breathing during the scan.
  - Children and subjects who are ill may not be able to breath hold for long.
- We would prefer to continuously acquire DWI during free breathing:
  - Seek to minimize the total scan time
  - Increase patient comfort

DWI for Kidney Imaging

- Geometric distortion
  - Due to additional phase change during EPI readout due to magnetic susceptibility differences.



DWI for Kidney Imaging

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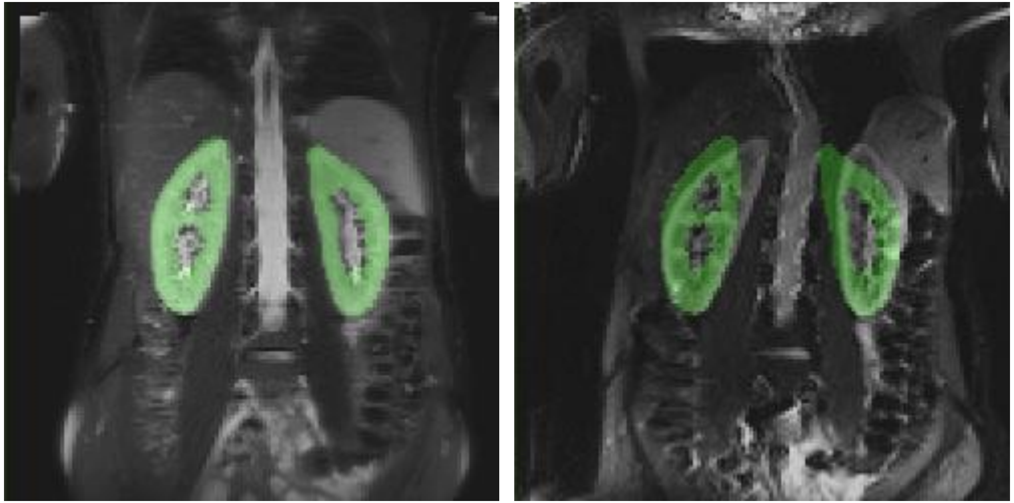


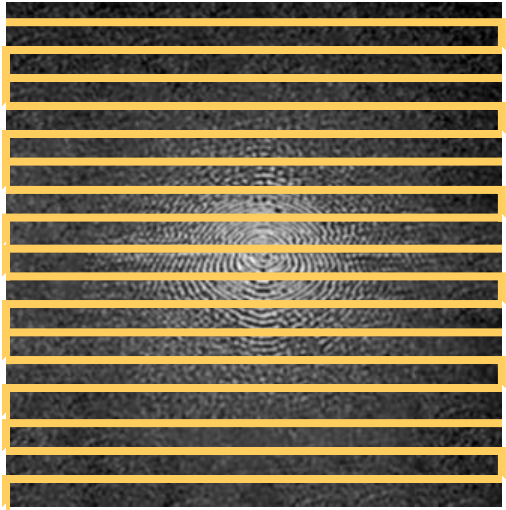
- Image acquired with opposite phase encoding direction do not align.
  - Any change in orientation between the static magnetic field and the phase encoding direction alters the geometric distortion.
  - Magnitude of change in distortion depends on the local magnetic susceptibility differences.

Conventional Distortion Correction

- Measure the distortion field
- Apply correction for the distortion field
- Sequences:
  - PSF mapping
  - Gradient echo sequence to measure phase change
  - Spin echo with phase reversal.

Conventional Distortion Correction

- Measure the distortion field
- Apply correction for the distortion field
- Sequences:
  - PSF mapping
  - Gradient echo sequence to measure phase change
  - Spin echo with phase reversal
    - Acquire two EPI images
      - Opposite phase encoding directions
    - Align the distorted images to measure the magnitude of the change in distortion.
    - Estimate distortion field.



k-space

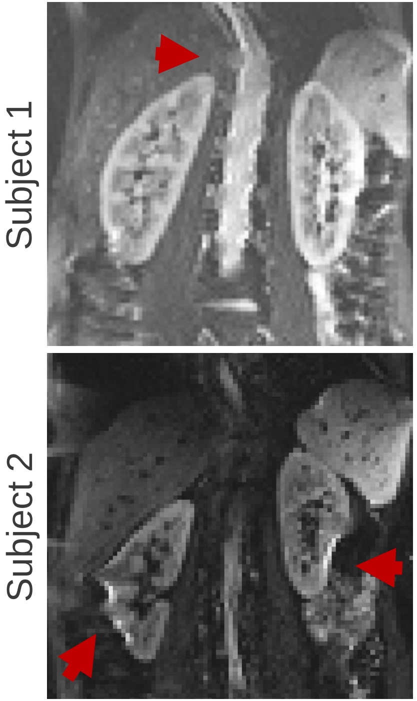
Coll-Font, J., Afacan, O., Hoge, S., Garg, H., Shashi, K., Marami, B., Gholipour, A., Chow, J., Warfield, S. and Kurugol, S., 2021. Retrospective Distortion and Motion Correction for Free-Breathing DW-MRI of the Kidneys Using Dual-Echo EPI and Slice-to Volume Registration. Journal of Magnetic Resonance Imaging, 53(5), pp.1432-1443.

Problem for Distortion Correction

- Distortion fields are not static!
  - Breathing moves the tissues and changes the distortion field
  - Pockets of air in the bowel move over time
  - Time to acquire two DWI volumes with opposite phase encoding direction is too long.
    - By the time the second phase encode is acquired, the anatomy has moved to a new position.

<u>Proposed solution:</u>
Acquire two readouts at the same position with opposite phase encoding direction.

EPI readout L->R



Coll-Font, J., et. al. Journal of Magnetic Resonance Imaging, 53(5), pp.1432-1443.

Proposed Distortion Correction

- Modify sequence to obtain images with a dual-echo EPI readout[1]
  - Reverse phase encoding (L->R and R->L) on second readout
  - Very short delay (~40ms) between readouts
  - **Assume no motion in between two echos => distortion field is static**
- Correct for distortion using L->R and R->L readouts
  - T2 decay between readouts may be non-negligible!
  - Adjust for contrast differences
    - Apply median filter to improve SNR
    - Compensate for amplitude difference
  - Run registration-based distortion compensation[2]

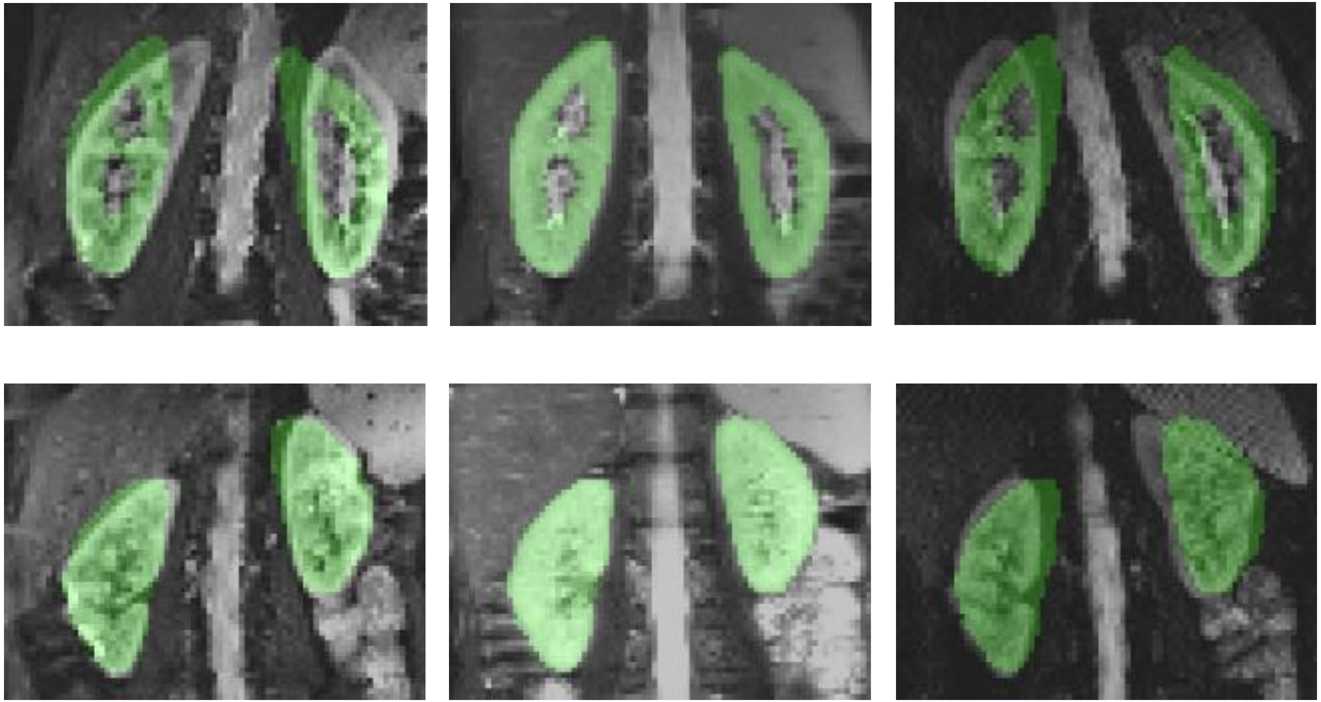
[1] Afacan et al. *J. NeuroIm* 2020. DOI: 10.1111/jon.12708
[2] Hedouin et al. ``Block-Matching Distortion Correction of Echo-Planar Images With Opposite Phase Encoding Directions'' IEEE TMI 2017. DOI: 10.1109/TMI.2016.2646920

Proposed Distortion Correction

L->R readout | T2 HASTE | R->L readout

Subject 1

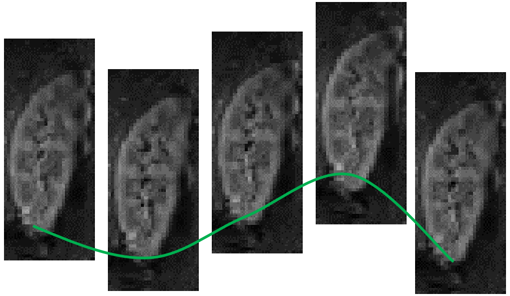
Subject 2



Distorted | Aligned | Distorted

Motion Compensation

- Respiration creates inter-slice motion.
- Slice-to-Volume Registration:
  - Segment each kidney to target organ moving with six degrees of freedom.
  - Motion estimate with registration of each slice to 3D volume.
  - Rigid body motion of kidney with Kalman filter through time.



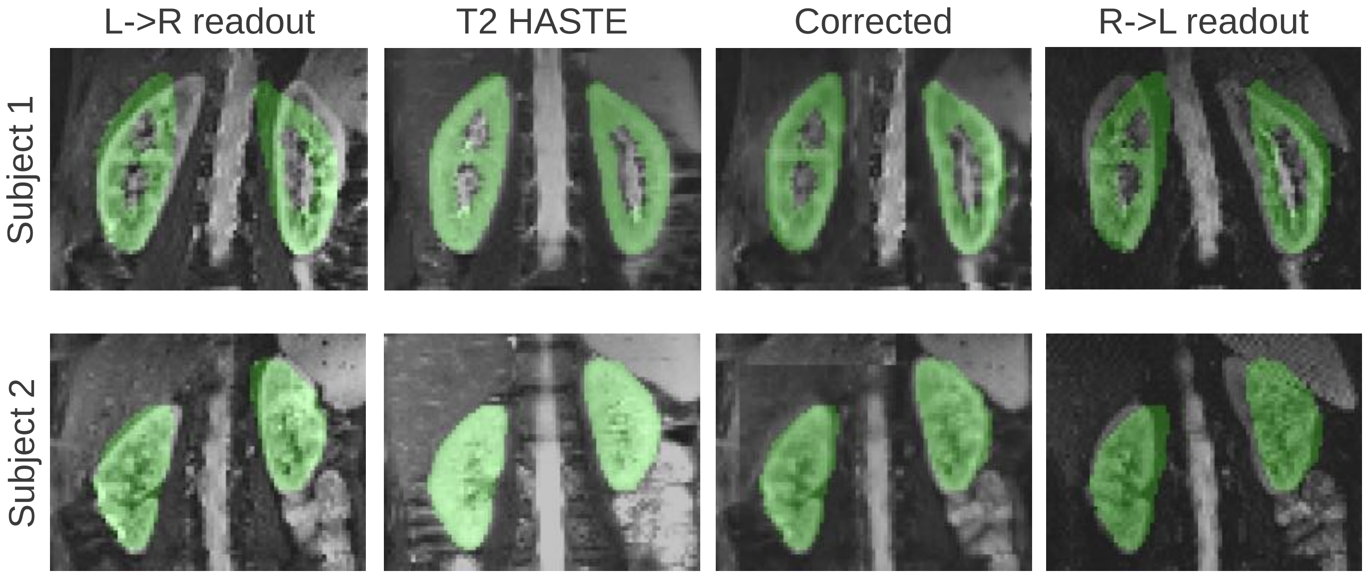
Kurugol, S. et al., 2017. Motion-robust spatially constrained parameter estimation in renal diffusion-weighted MRI by 3D motion tracking and correction of sequential slices. In Molecular Imaging, Reconstruction and Analysis of Moving Body Organs, and Stroke Imaging and Treatment (pp. 75-85). Springer, Cham.

Experiments

- 10 Subjects (ages 29-38, 3 females).
    - Healthy volunteers
- Acquisition: Imaged with dual-echo DWI sequence
    - 17 directions each with 10 b-values each
- Analysis pipeline
    - Geometric Distortion Correction of dual echo slices.
    - Slice to volume alignment for motion compensation.
- For IVIM and DTI models
    - Estimate parameters
    - Leave-one-direction-out cross-validation

IMAGING PARAMETERS:
- Dual-echo DWI sequence
- EPI acquisition
    - L->R and R->L phase encoding
- 10 b-values and 17 directions
- 3T Siemens Prisma
- TE1/TE2/TR 72ms/108ms/7000ms
- 18 coronal slices
- Res. 2.81x2.81x4 mm

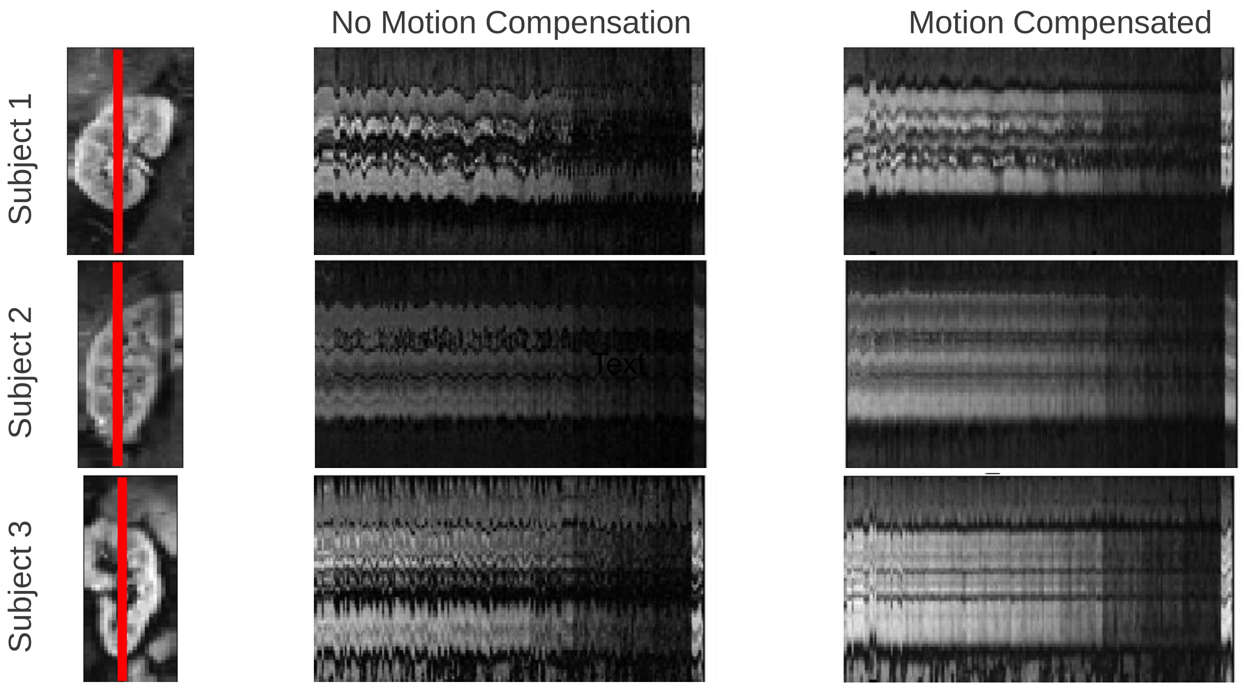
Result: Distortion and Motion Correction



Correction for both the geometric distortion of each image and for the respiration induced motion of each image.

Coll-Font, J., et. al. Journal of Magnetic Resonance Imaging, 53(5), pp.1432-1443.

Result: Slice-to-Volume Registration



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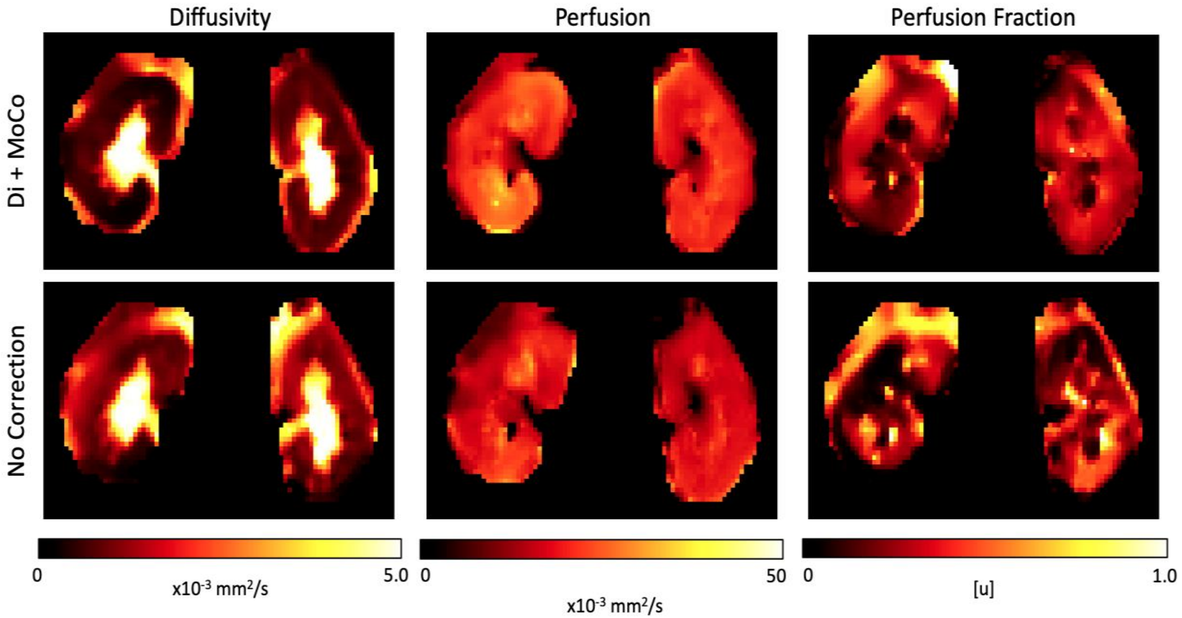
Results: Parameter Estimates

Model param CV (%) / method		No correction	DiMoCo
IVIM	Slow diff. (D) [%]	25.7+/-18.3	28.6+/-18.4
	Fast diff. (D*) [%]	63.3+/-21.6	49.6+/-20.5
	Perf. Frac, (f) [%]	38.5+/-14.5	31.4+/-13.7
	nRMSE	0.290+/-0.052	0.154+/-0.056
DTI	MD [%]	8.1+/-1.8	4.3+/-2.6
	FA [%]	14.4+/-1.1	12.4+/-2.4
	nRMSE	0.28+/-0.04	0.12+/-0.01

Correction for distortion and motion leads to:

- Reduction in coefficient of variation
- Improved normalized root mean square error.

Results: IVIM parameter maps



The corrected data leads to improved IVIM parameter estimates.

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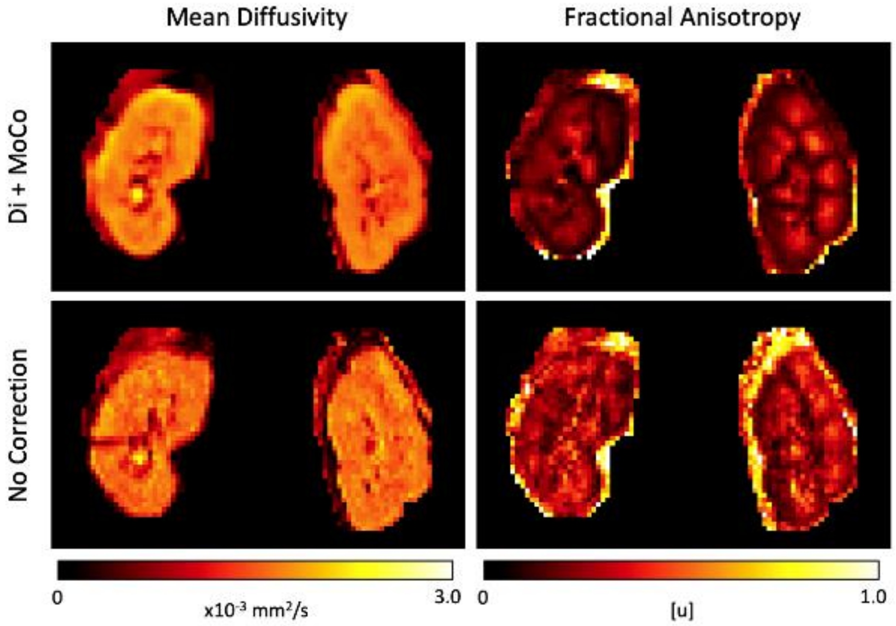
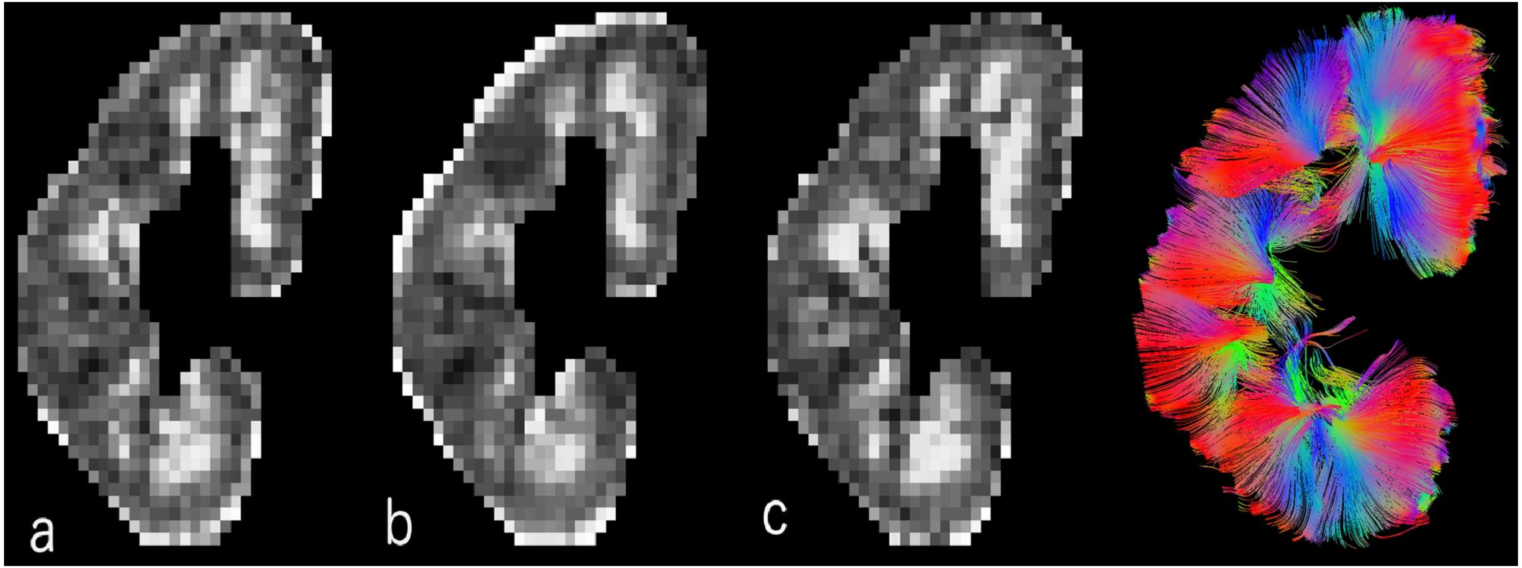
Results: DTI parameters



The corrected data leads to improved DTI parameter estimates.

Results: DTI parameters

FA FA FA Orientation



No correction Volume alignment. Slice alignment improved orientation visualization.

Conclusions and Future Work

- Conclusions
  - We can correct for distortion despite the presence of motion
    - Enabled by dual echo DWI with polarity reversal for each slice.
  - We can correct for respiration induced changes in position.
    - The distortion correction makes it easier to compensate for the respiratory motion.
  - These corrections enable DWI to be aligned, increasing the fidelity of parameter estimates for models of tissue microstructure.

- Future work
  - We plan to evaluate the utility of models of kidney microstructure.
    - Reduced influence of the confounds due to motion and distortion.

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