Motion-Robust Functional Imaging of Kidneys with DCE-MRI

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Declaration of Conflict of Interest

- No conflict of interest, financial or otherwise.

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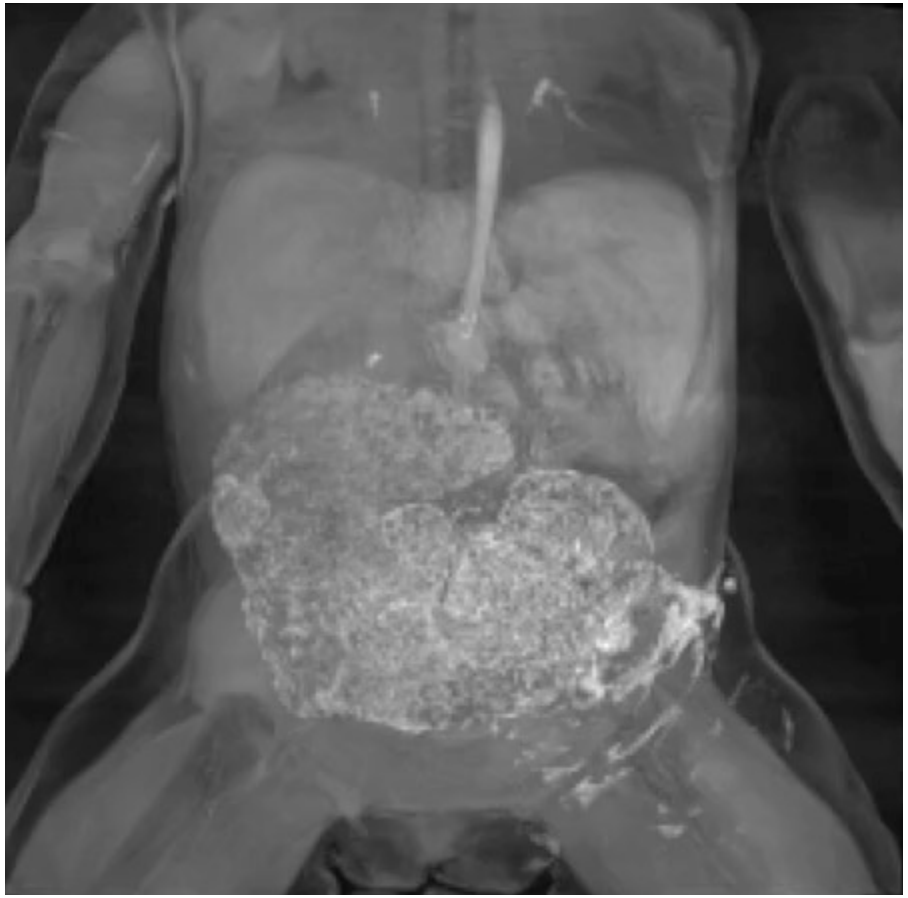
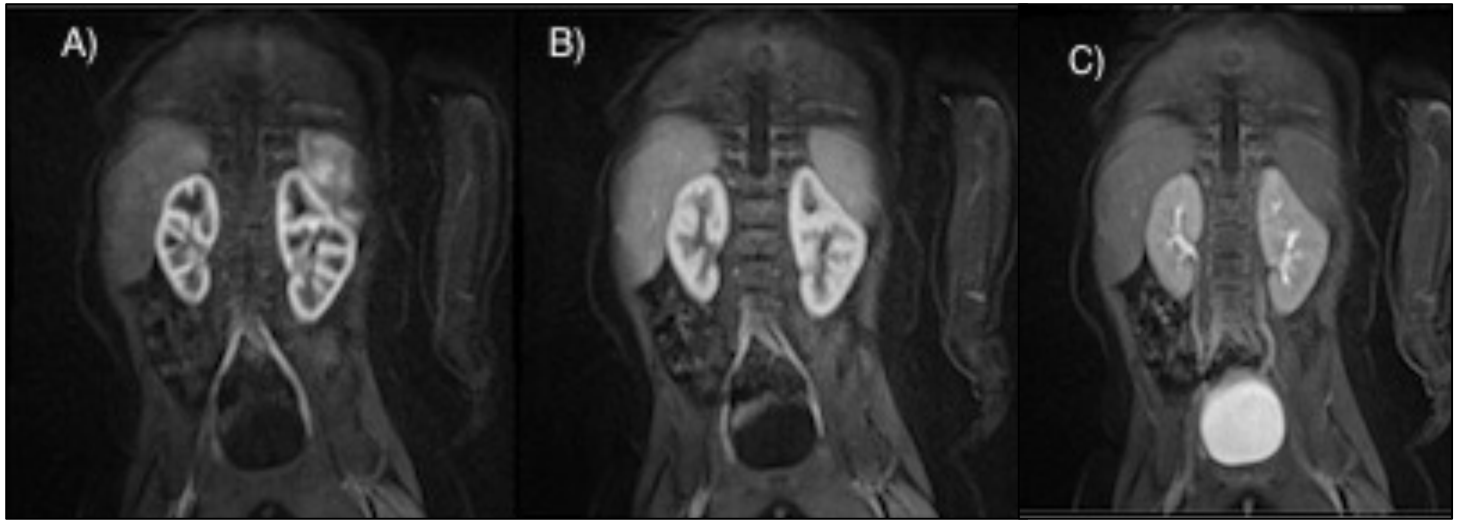
Dynamic Contrast Enhanced MRI (DCE-MRI)

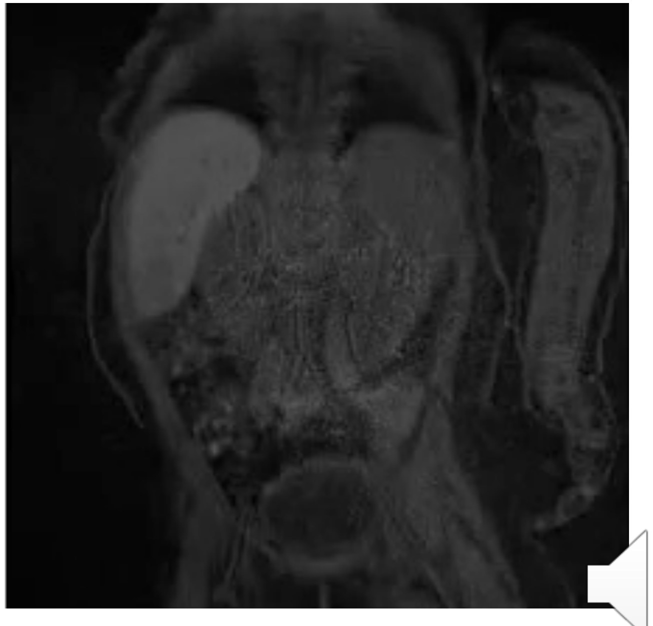
- DCE-MRI is an important tool to evaluate the anatomy and function of the kidneys
- DCE-MRI offers
    - detailed anatomical evaluation by assessing the contrast uptake visually
    - quantified kidney function by fitting a tracer kinetic model and estimating its parameters.



DCE-MRI in clinical MR urography exams for children

- Identify changes in renal pathophysiology that occur in association with impaired drainage and obstruction.
- high temporal resolution (~3sec/volume) to capture the passage of contrast agent in vascular system and through the organs
- high spatial resolution to evaluate the degree of hydronephrosis, crossing vessels etc.

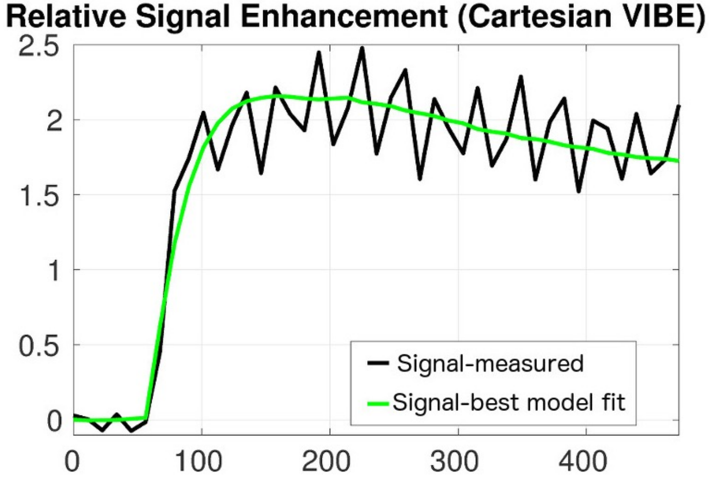


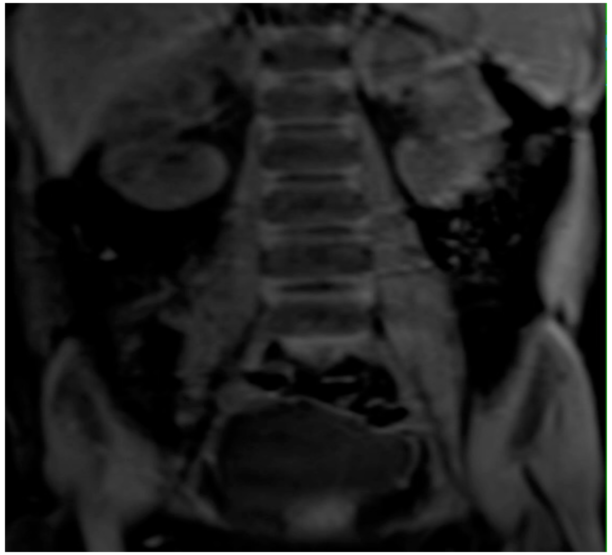


Conventional DCE-MRI with Cartesian Imaging

Limitations

- Sensitive to **respiratory motion**
- Fails to achieve **high temporal resolution** required for accurate tracer kinetic model fitting





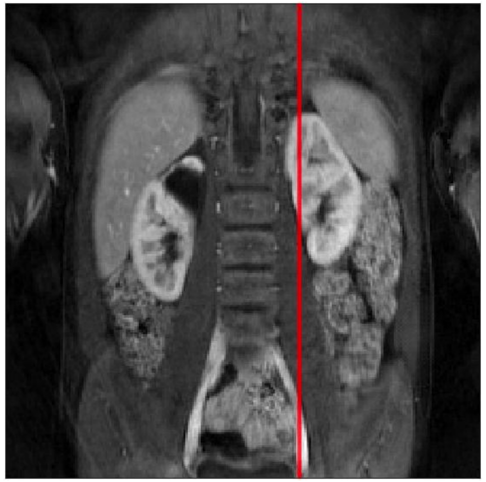
- Sensitive to motion
- Low temporal resolution (12s)

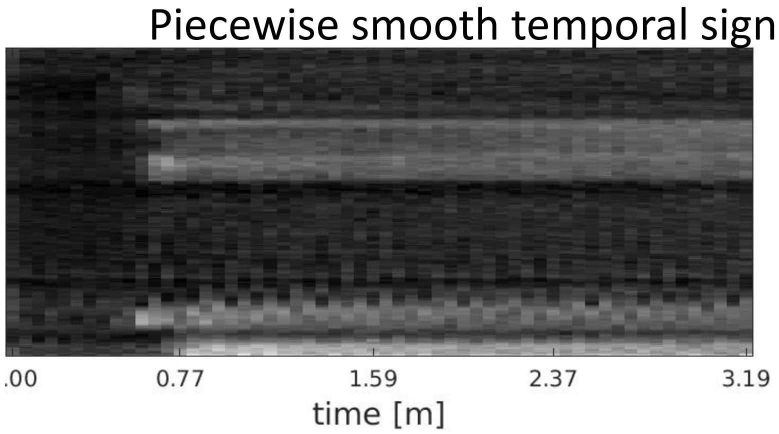
How to achieve higher temporal resolution?

Accelerated imaging: Undersampling kspace + parallel imaging: taking advantage of coil sensitivity information to remove aliasing due to undersampling

Compressed sensing increases imaging speed by exploiting image redundancy, i.e. **sparsity** in some appropriate transform basis

- Sparsity in temporal dimension (t)





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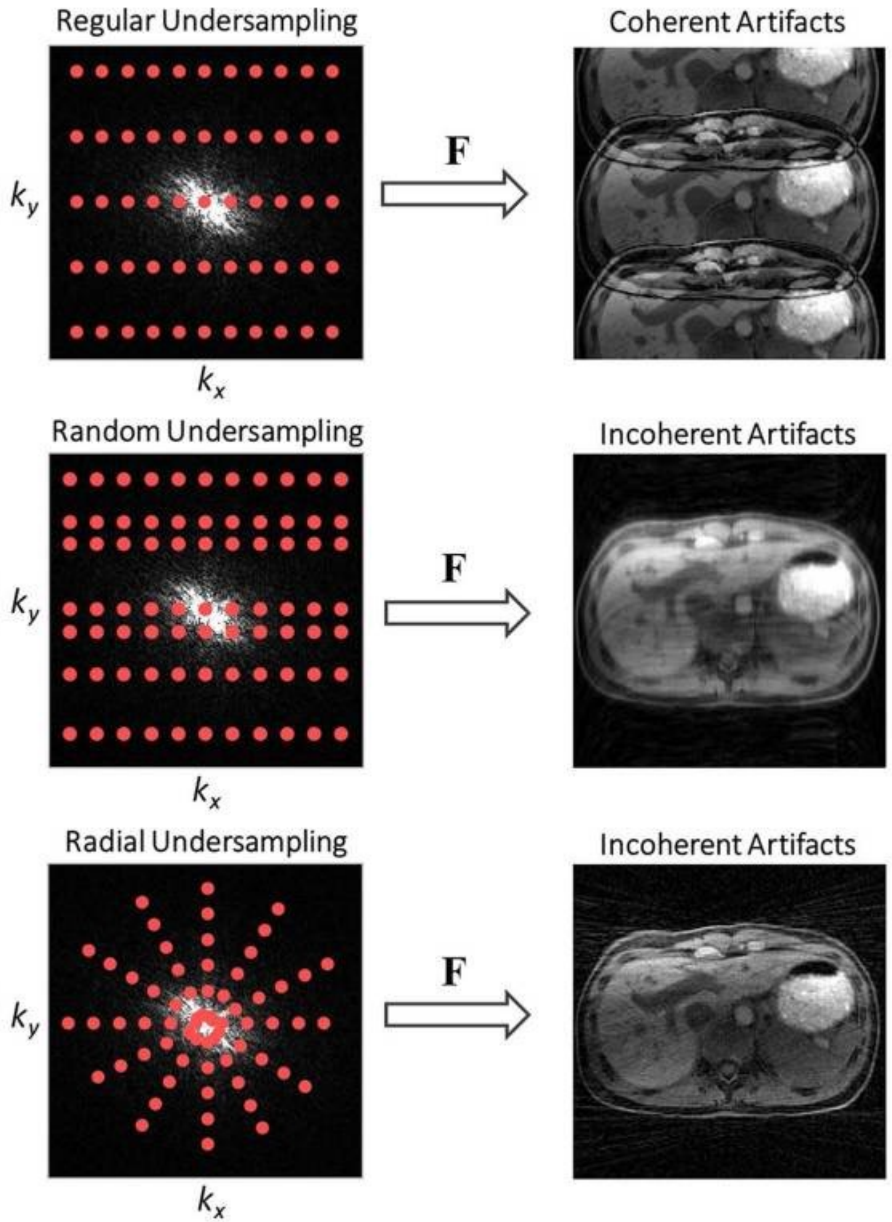
How to achieve higher temporal resolution?

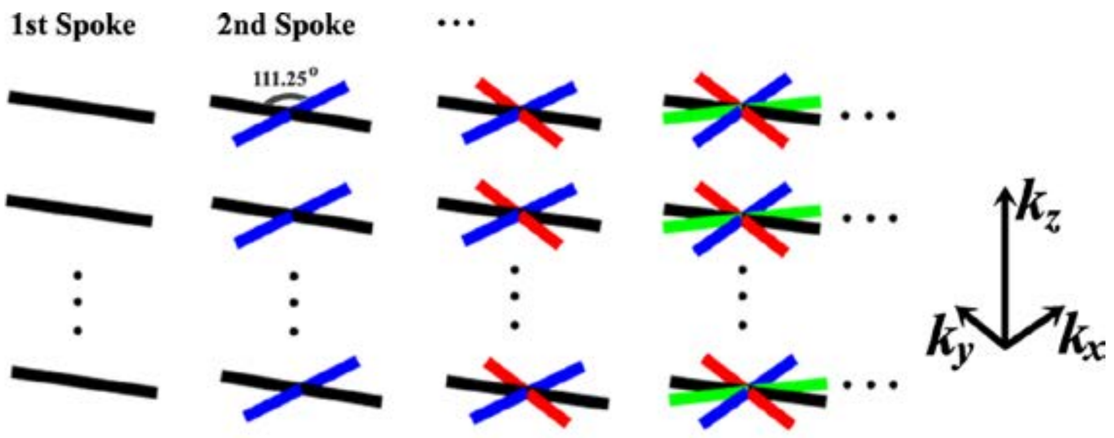
Compressed sensing enables reconstruction from a reduced number of k-space samples acquired in an **incoherent** fashion=> accelerated imaging

- Translated to MRI by Lustig et. al



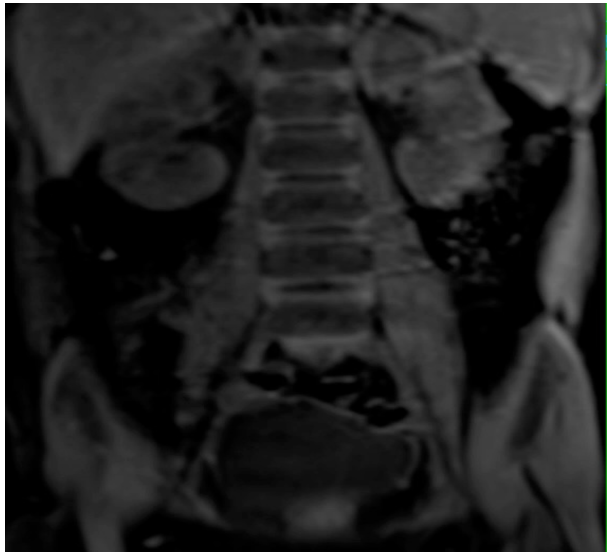
Golden angle stack of stars radial k-space sampling

- **Radial k-space sampling**
  - Incoherent sampling, pseudo noise like artifacts
  - Radial lines are continuously acquired including the center of k-space
  - Each sampled line contains equally important information, especially the contrast information.
  - Balanced sampling of k-space makes the acquisition motion-robust.
  - Can achieve desired temporal resolution by selecting number of spokes per volume
- **Radial imaging + Compressed Sensing Reconstruction of Dynamic Volumes*:** improves image quality by reducing streaking artifacts due to undersampling.

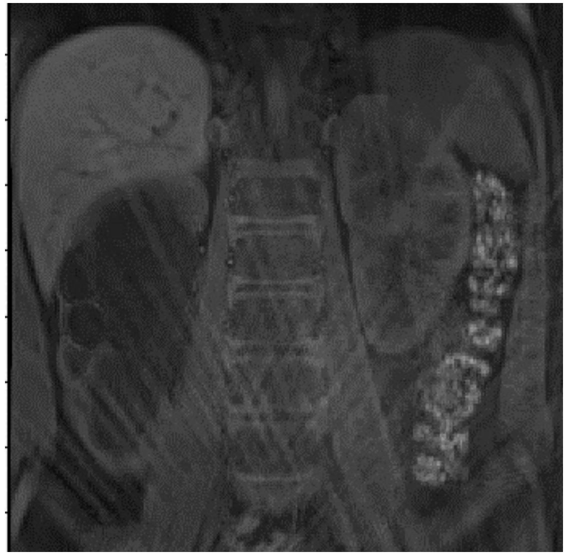


*Feng L, et al. GRASP. Magn Reson Med. 2014;72: 707–717.

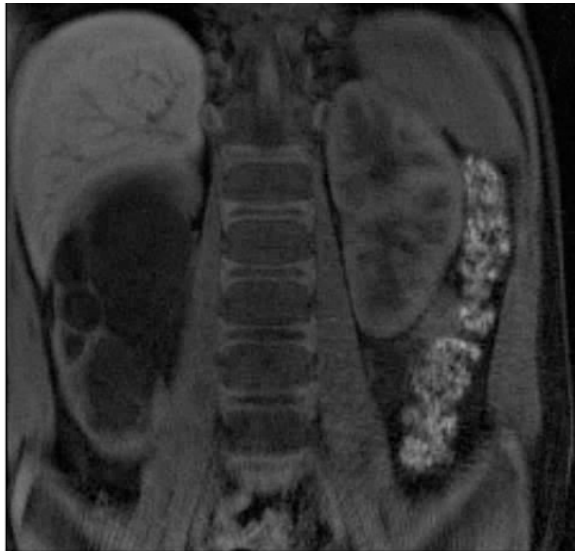
DCE-MRI for kidney imaging



Cartesian VIBE
Time resolution=11s
- Sensitive to motion
- Low temporal resolution



Dynamic Radial VIBE
Time resolution=3.3s
+ Robust to respiratory motion
+ Hight temporal resolution
- Streaking artifacts



Dynamic Radial VIBE+ CS reconstruction (GRASP)
Time resolution=3.3s
+ Streaking artifacts are eliminated with CS reconstruction

Kurugol et. al, Ped. Radiol. 2020

Kurugol et. al, J. Ped Urology 2020

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Challenge: DCE-MRI in the presence of motion

Challenge: Bulk motion

- Babies with congenital kidney disease
  - Assess kidney function[1,2]
- Non-sedated, feed and wrap method[2]

Challenge: Heavy breathing motion

- Nervous, sick children with kidney disease

[1]Kurugol, Ped. Radiol. 2020
[2]Kurugol et. al, J. Ped Urology 2020

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Factors effecting motion compensation in DCE-MRI

- Rate of motion events
- Duration of motion free periods.
- Scale of motion

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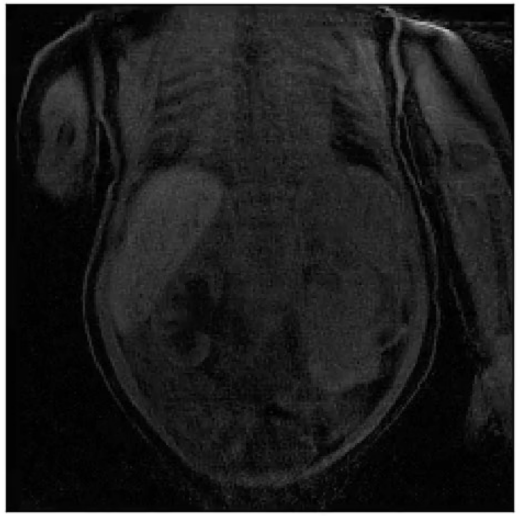
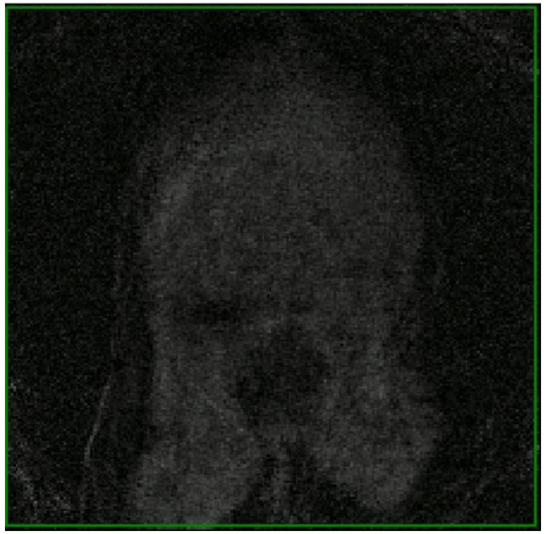
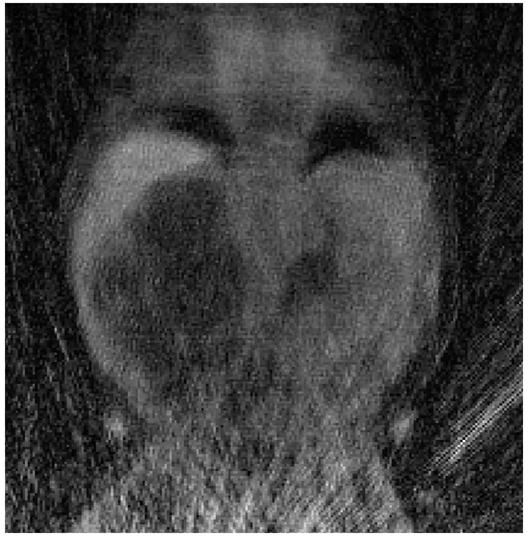
Challenge: Bulk Motion causes signal dropout



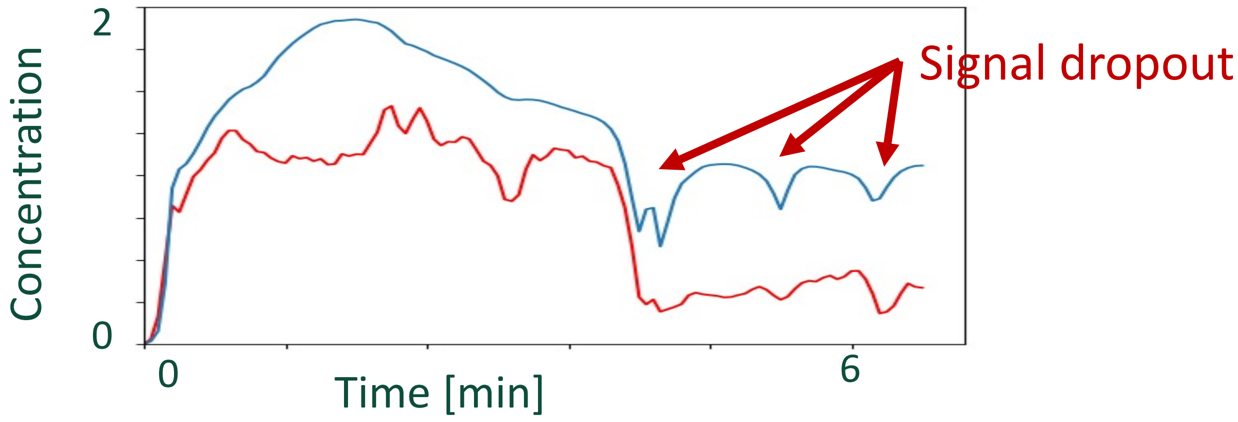
No Motion



Intermittent Motion



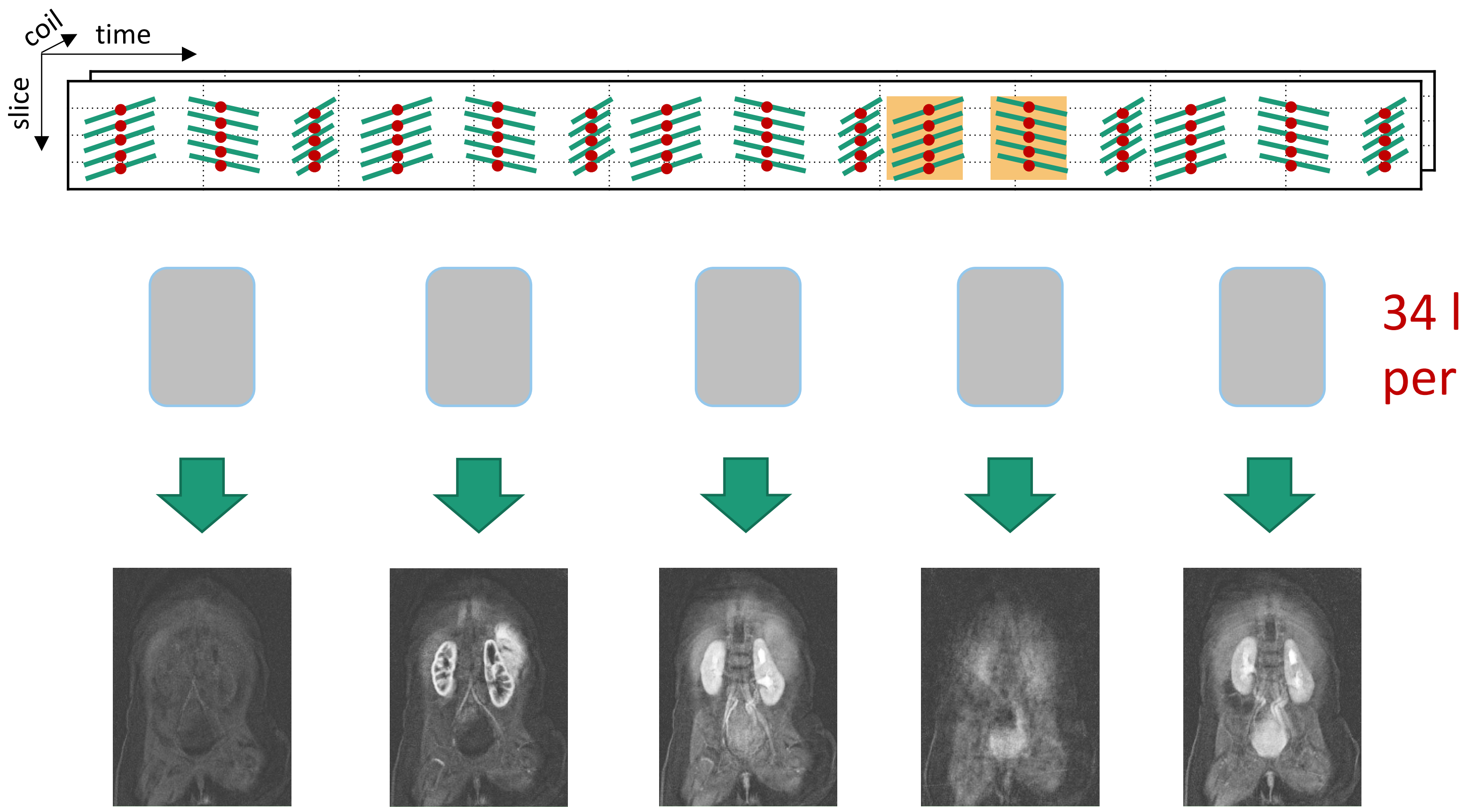
Continuous Motion



Coll-Font J, Afacan O, Chow JS, Lee RS, Stemmer A, Warfield SK, Kurugol S. Bulk motion-compensated DCE-MRI for functional imaging of kidneys in newborns. JMRI 2020 Jul;52(1):207-16.

Standard GRASP Reconstruction

Feng L. et al, *MRM* 2014.

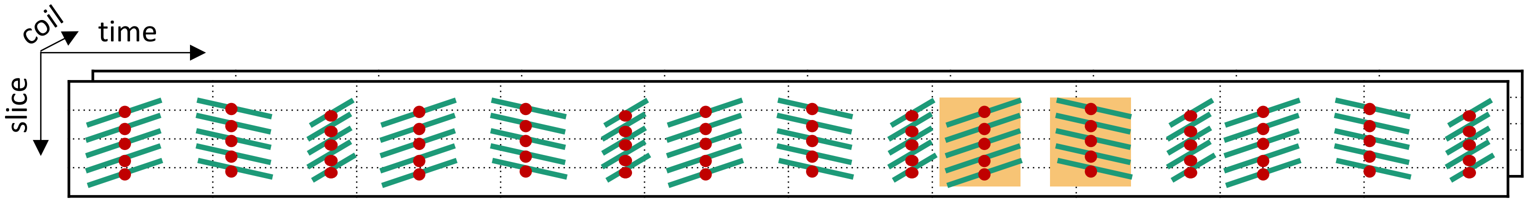


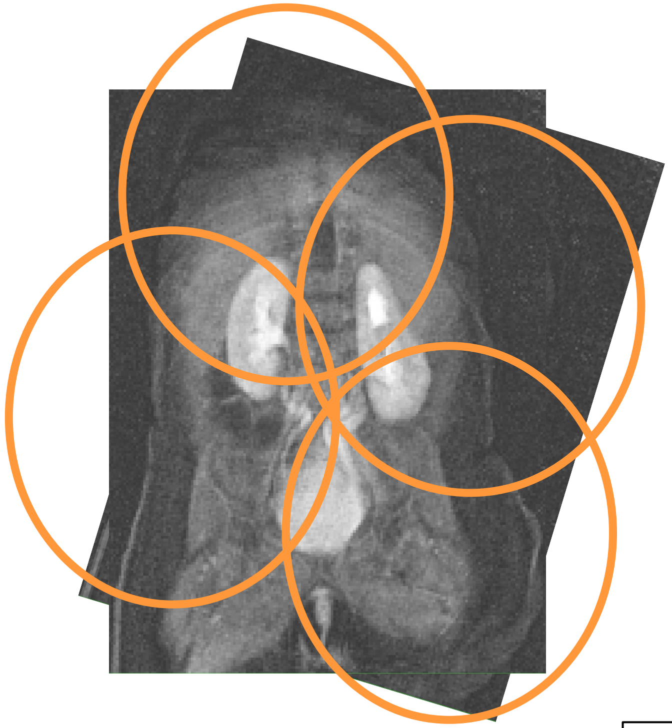
34 lines
per image

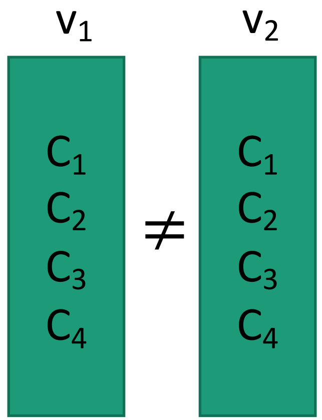
$$\min_{x_t} \sum_{s} \sum_{t} \| FSx_{t,s} - y \|_2^2 + \lambda \| x_{t,s} - x_{t-1,s} \|_1$$

Motion
Center of line
K-space line

Bulk Motion Detection







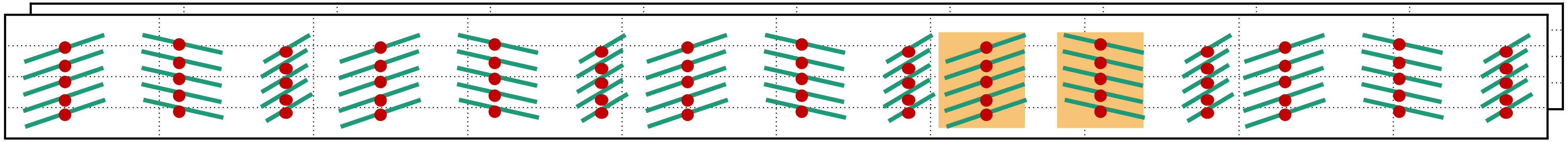
Small inner product!

$$v(sl,t)^T v(sl,\tau)$$

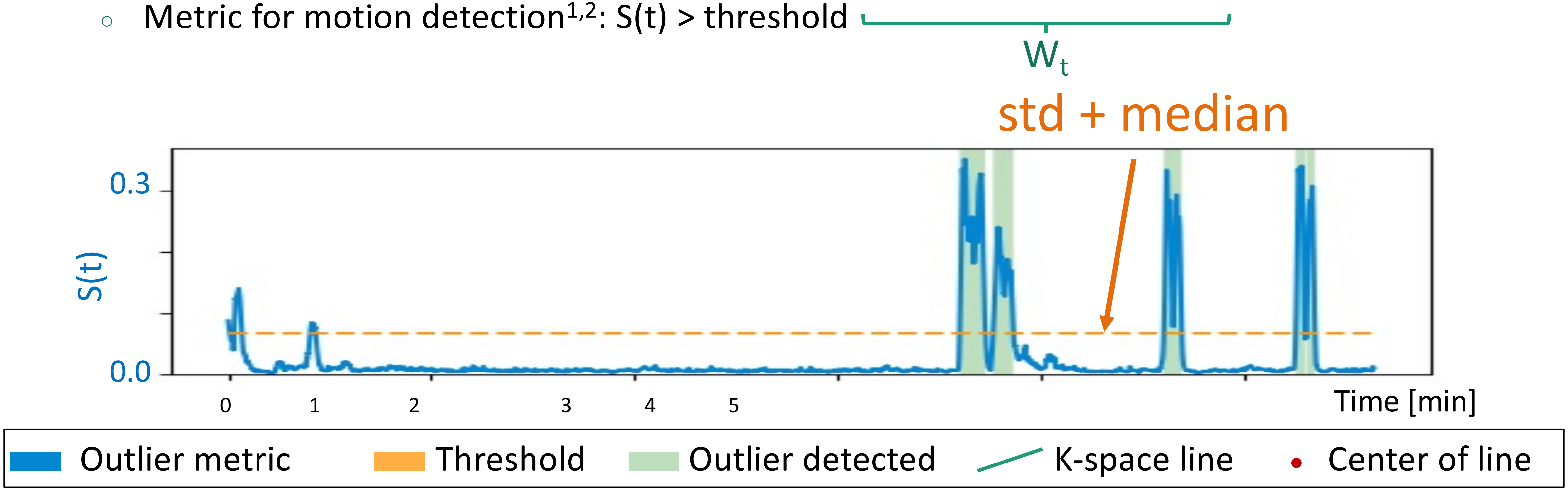
Coil profile — K-space line — Center of line

Coll-Font J, Afacan O, Chow JS, Lee RS, Stemmer A, Warfield SK, Kurugol S.. JMRI 2020 Jul;52(1):207-16.

Motion detection using self navigation



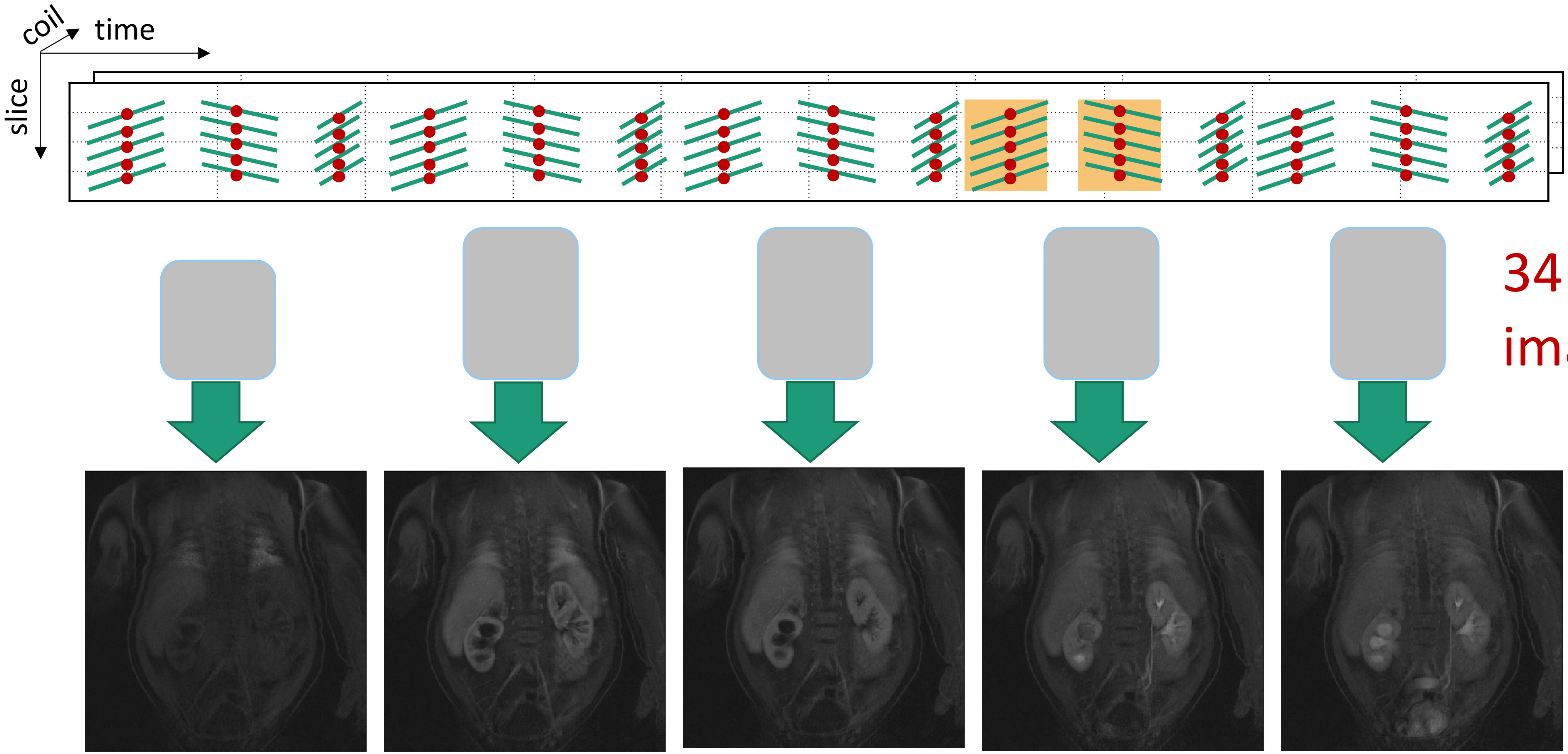
- Metric for motion detection[1,2]: S(t) > threshold



$$S(t) = \max_{sl} \; 1 - \frac{1}{|W_t|} \sum_{\tau \in W_t} v(sl,t)^T v(sl,\tau)$$

Coll-Font J, Afacan O, Chow JS, Lee RS, Stemmer A, Warfield SK, Kurugol S.. JMRI 2020 Jul;52(1):207-16.

Motion-compensated (MoCo) GRASP

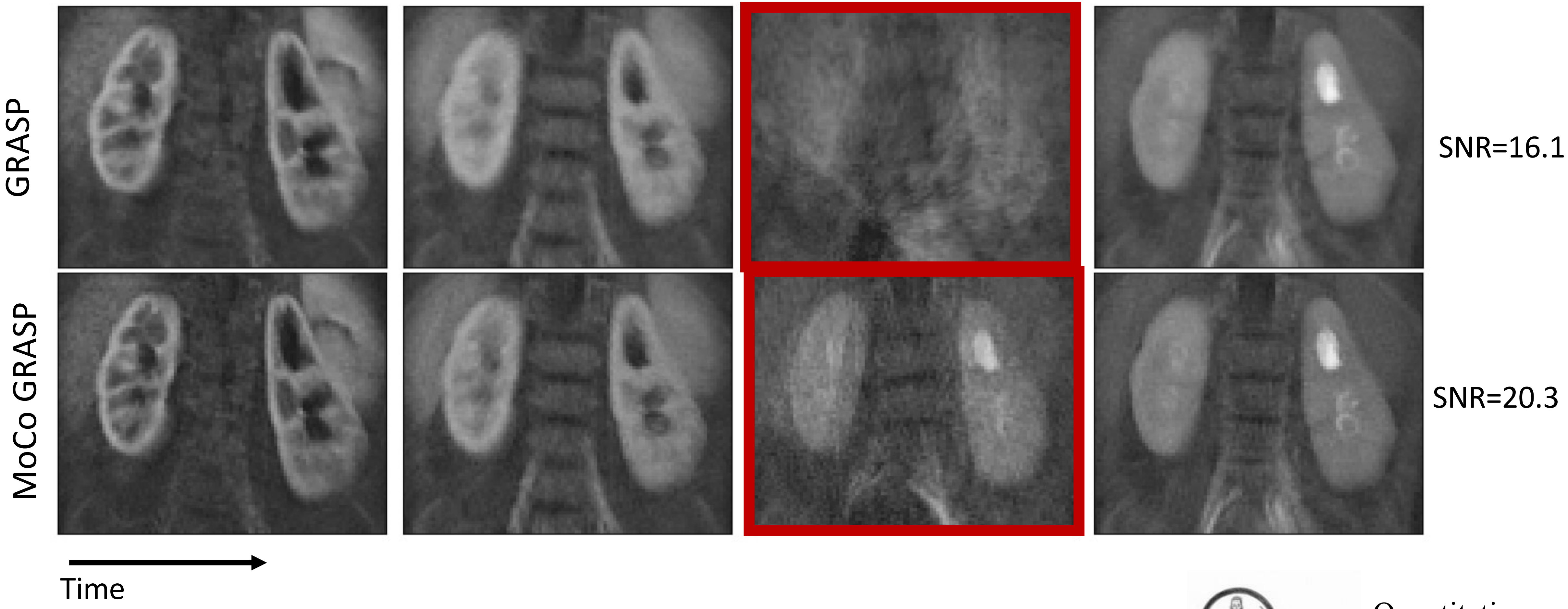


34 lines per image

$$\min_{x_t} \sum_{s} \sum_{t} \| FSx_{t,s} - y \|_2^2 + \lambda \| x_{t,s} - x_{t-1,s} \|_1$$

Motion
Center of line
K-space li[illegible]e

MoCo GRASP improves image quality



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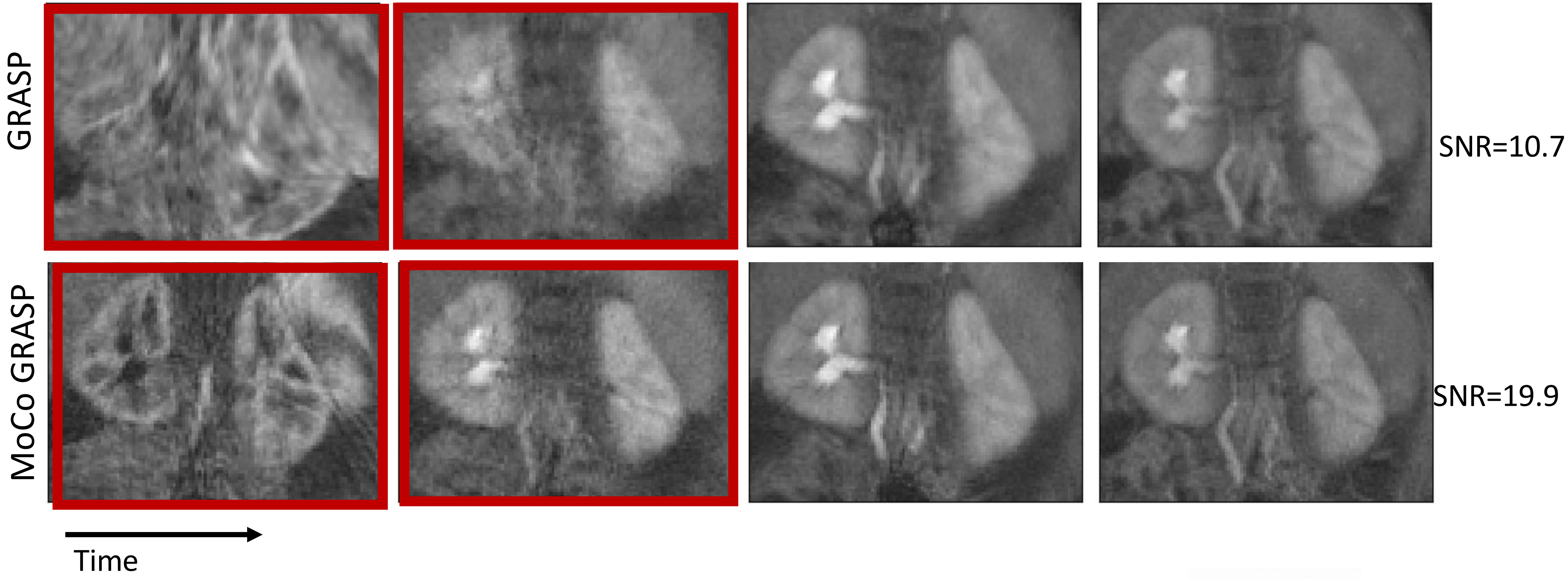
MoCo GRASP improves image quality



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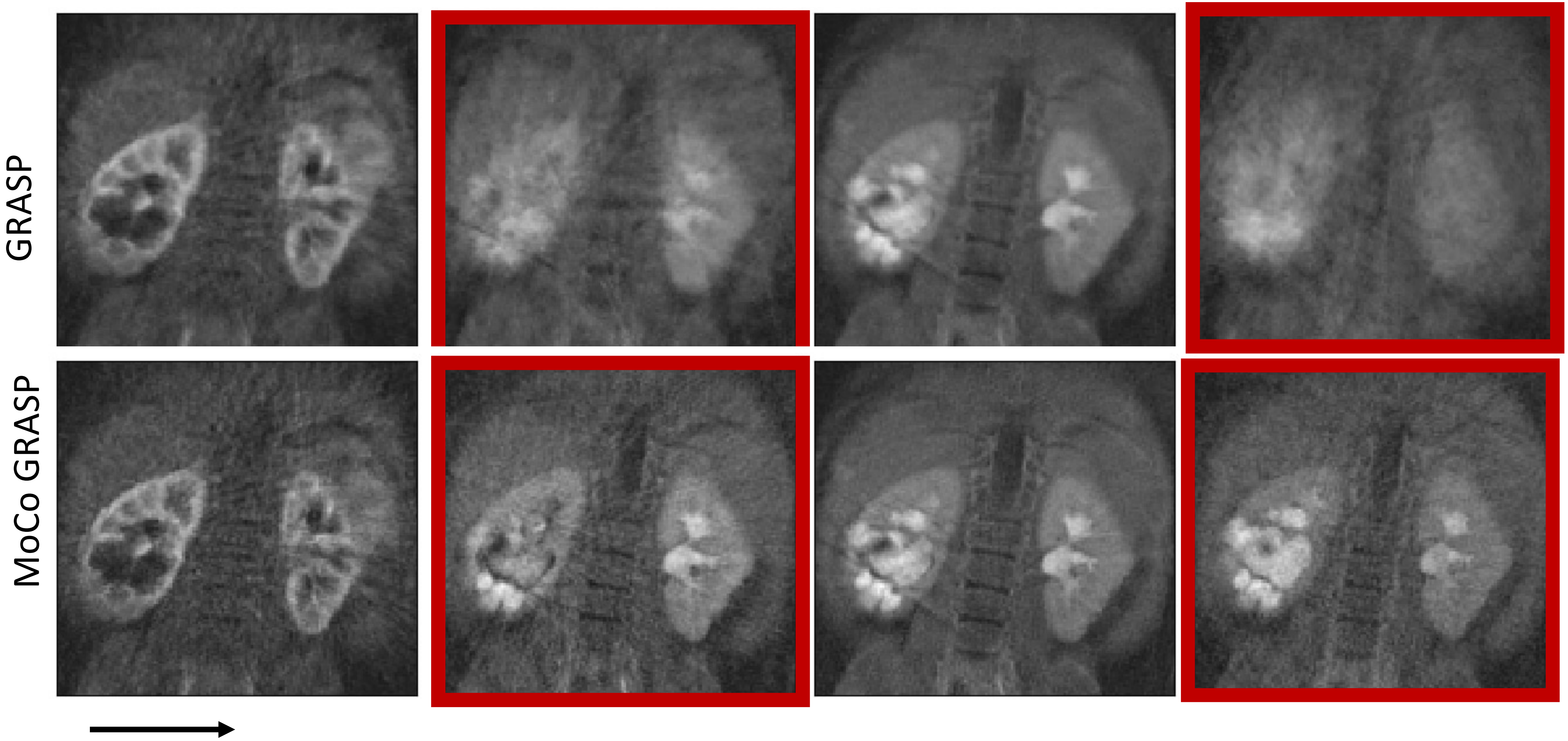
MoCo GRASP improves image quality



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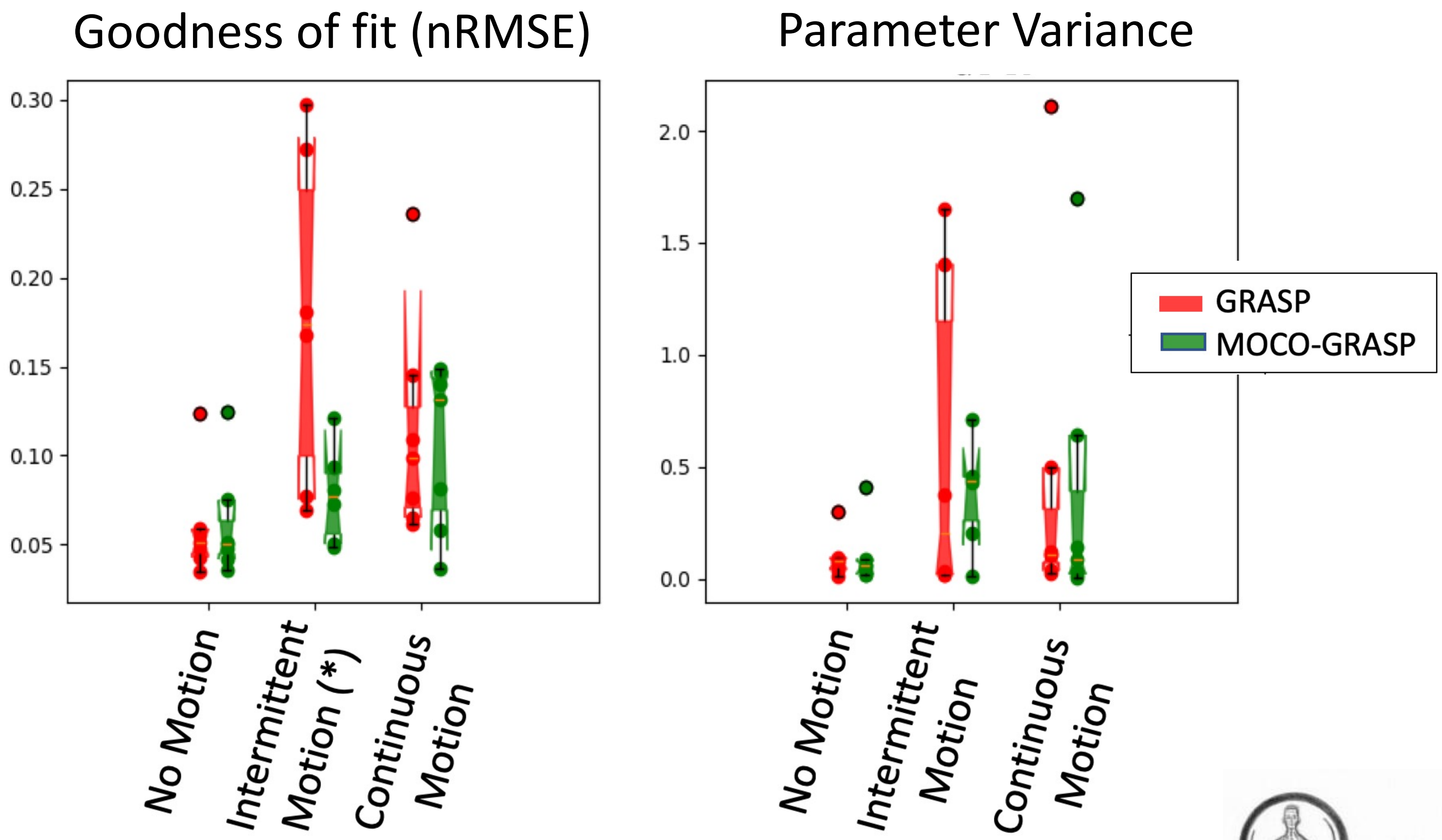
Results: Tracer-Kinetic Model Fit



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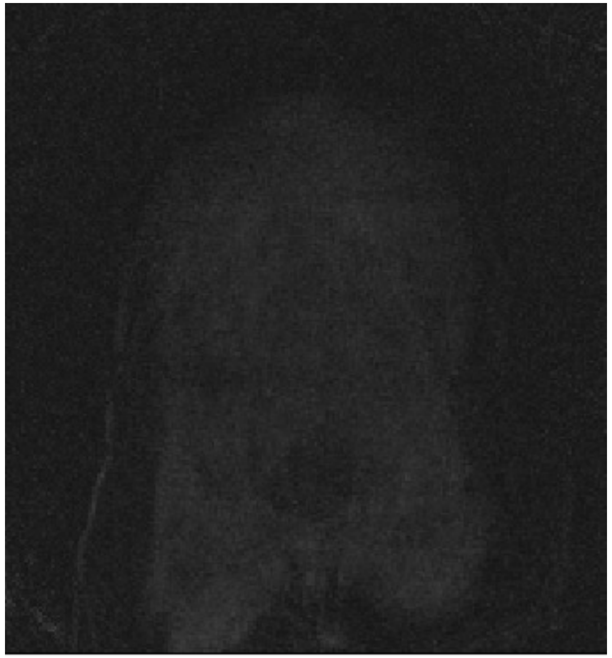
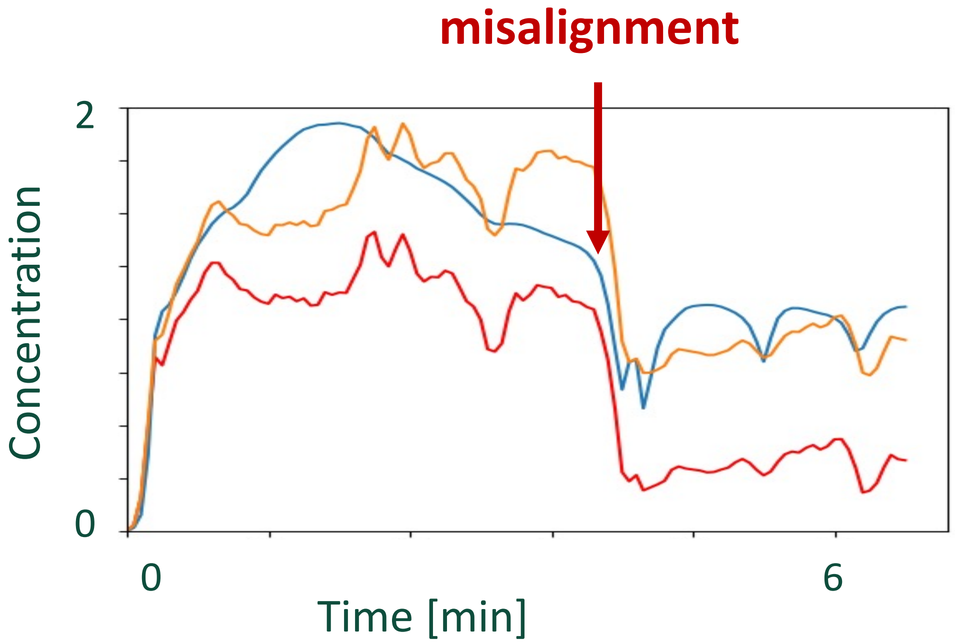
Challenge: Motion in DCE-MRI causes misalignment





Coll-Font J, Afacan O, Chow JS, Lee RS, Warfield SK, Kurugol S. Modeling dynamic radial contrast enhanced MRI with linear time invariant systems for motion correction in quantitative assessment of kidney function. MEDIA. 2021 Jan 1;67:101880.

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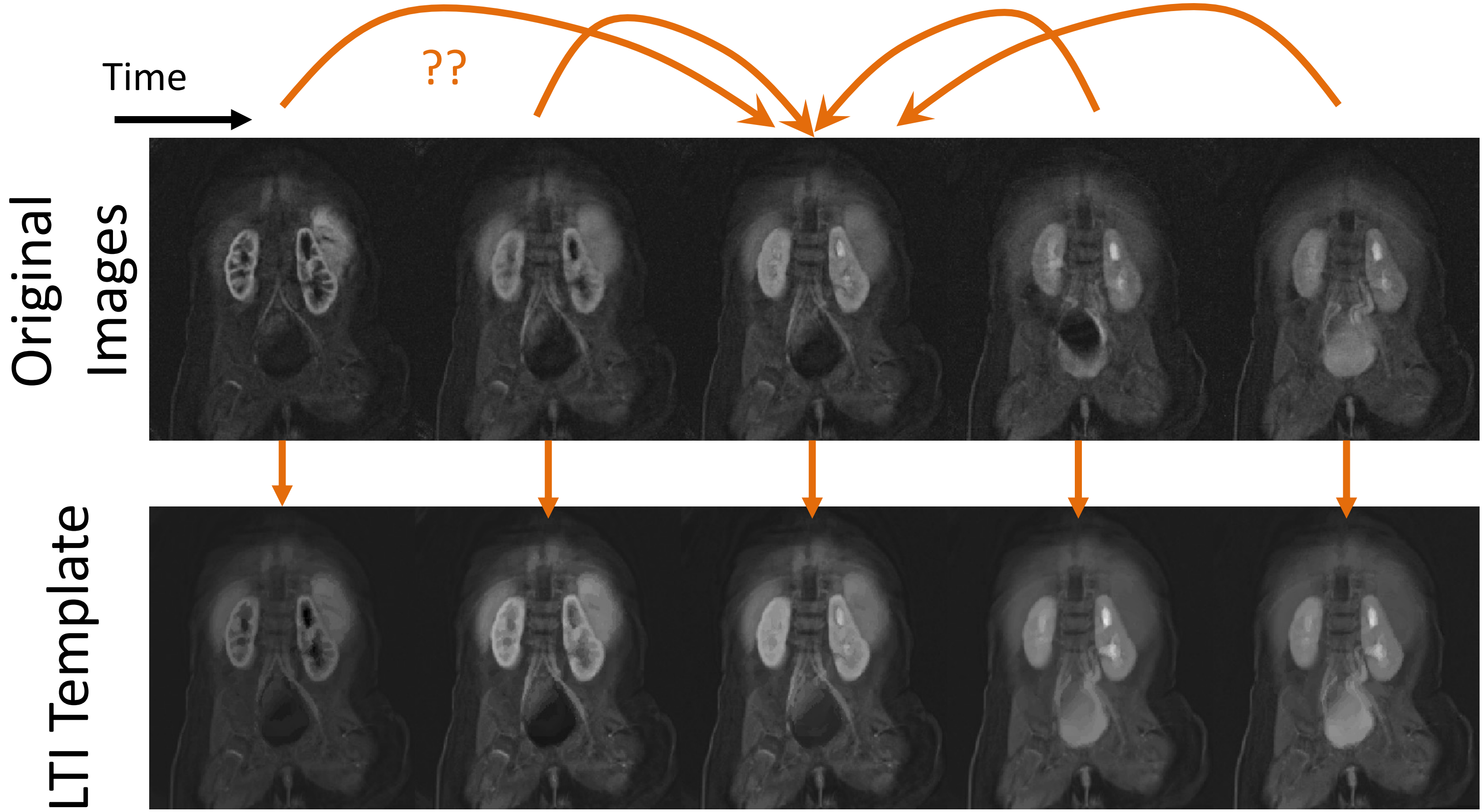
Registration

- Challenge: Contrast changes over time



LTI model

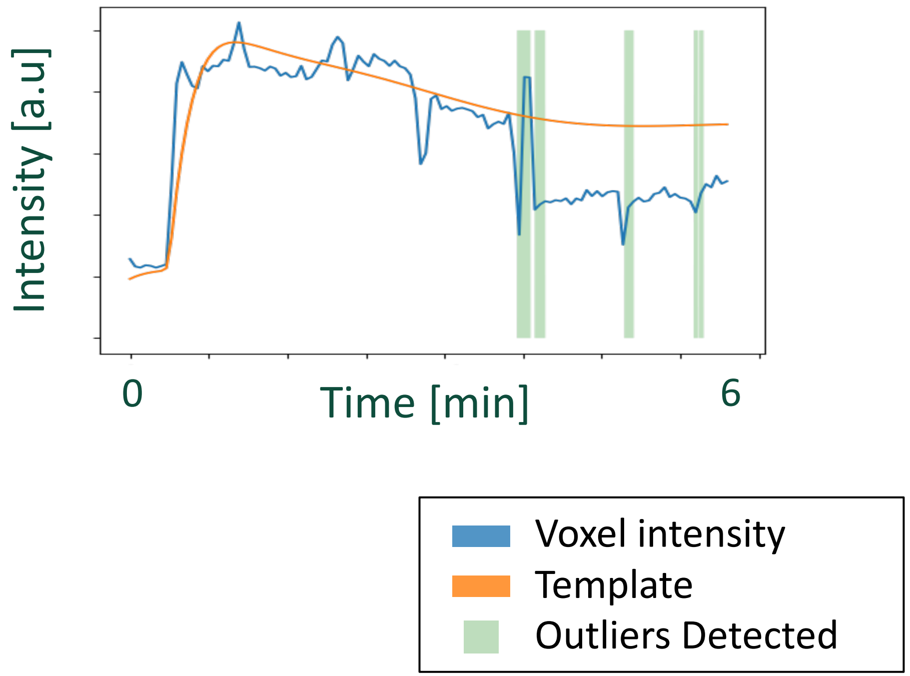
Harvard Medical School

Measured signal

$$s(t) \approx h(t) * a(t)$$

Tissue filtration

Input function



h(t) -> LTI model

$$a(t) = \delta(t - t_0)$$

https://github.com/quin-med-harvard-edu/LiMO_MoCo

Coll-Font J, Afacan O, Chow JS, Lee RS, Warfield SK, Kurugol S. MEDIA. 2021 Jan 1;67:101880.

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Experiments

- 10 infants (0-4 months)
- Imaging protocol:
  - 3T Siemens Skyra/Trio
  - Stack-of-stars 3D FLASH
  - GRASP reconstruction 1.25x1.25x3.0 mm x 3.3 sec
- Sequence of images aligned:
  - Registration to LiMo-MoCo reference[1]
  - Registration to single volume (for comparison)
- Fitted tracer-kinetic model
  - 100 wild bootstrap repetitions

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MEDIA. 2021 Jan 1;67:101880.

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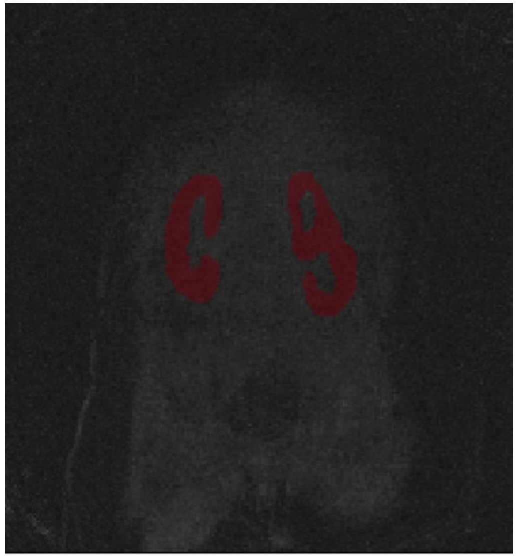
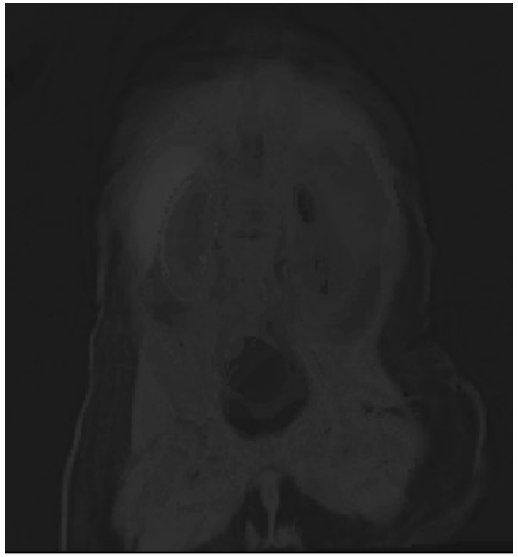
Results: Registration

Original Images



Motionless Template



Registered Images

Coll-Font J, Afacan O, Chow JS, Lee RS, Warfield SK, Kurugol S. MEDIA. 2021 Jan 1;67:101880.

Results: Registration

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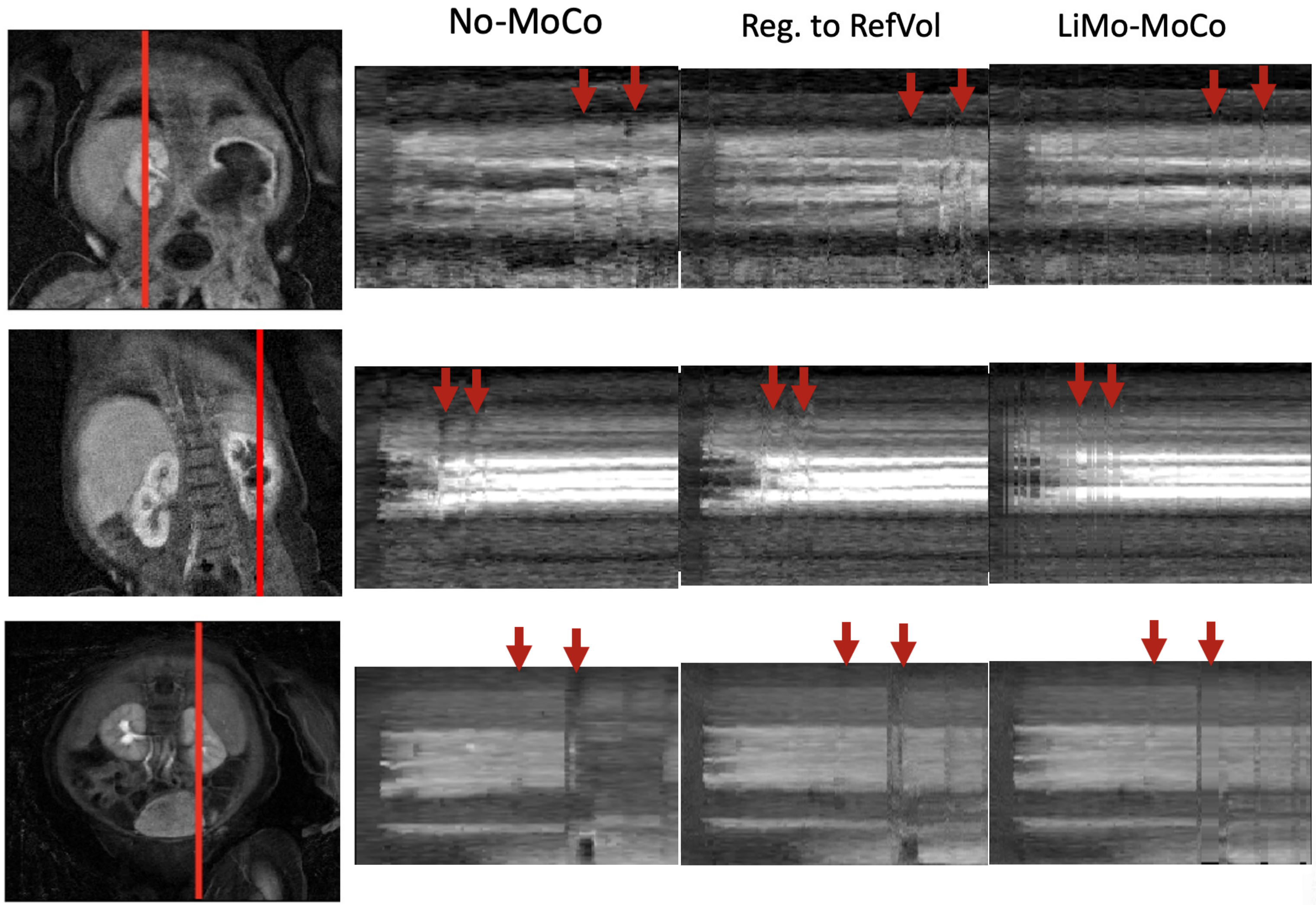

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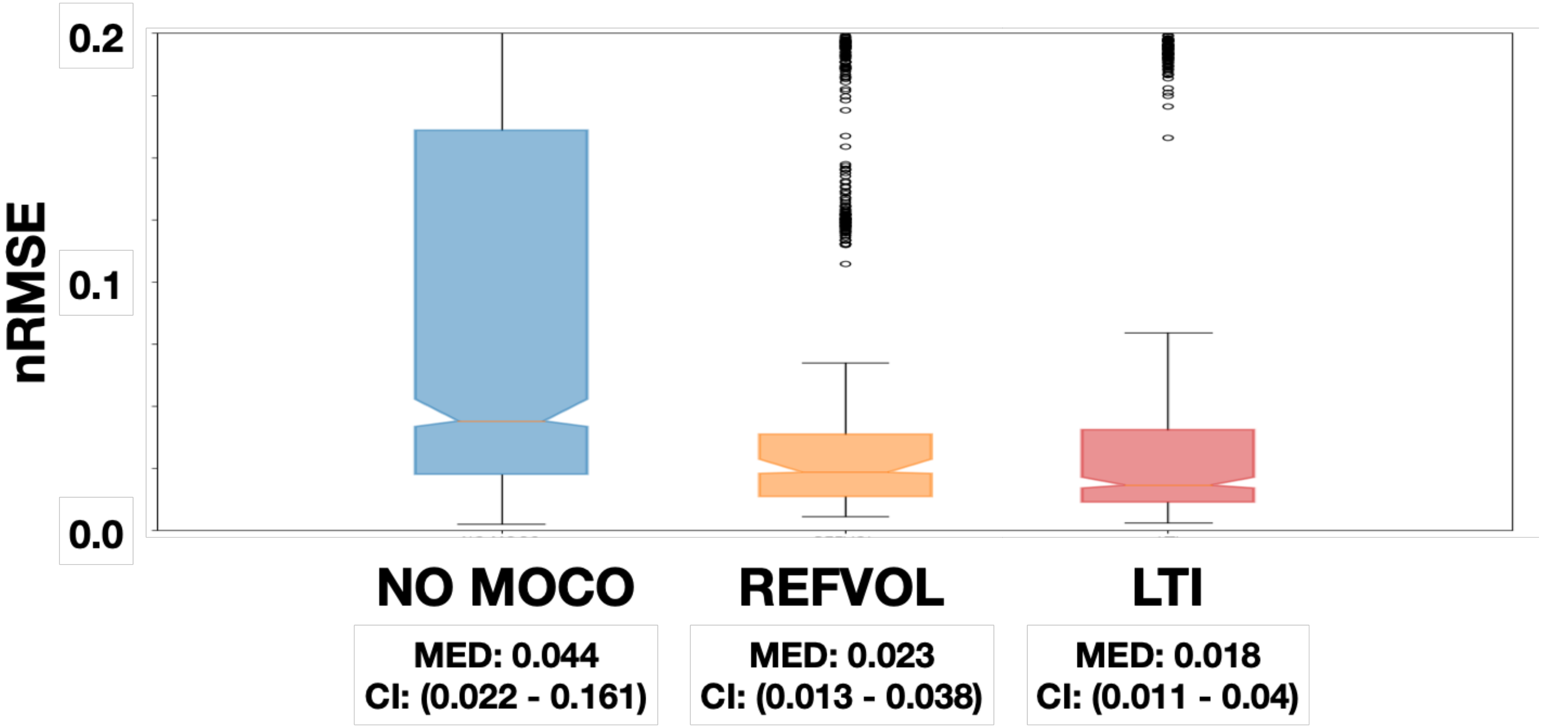
Results: Tracer-kinetic fit



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Conclusions

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- DCE-MRI can be used to both to evaluate renal anatomy and quantify renal function
- DCE-MRI requires high temporal resolution to capture the passage of CA in vascular system and through the organs
- Accelerated imaging can be achieved with compressed sensing (CS) using incoherent undersampling (golden angle stack of stars sequence), and sparsity in time domain during non-linear, iterative CS reconstruction.
- Bulk motion in babies when imaging without sedation and in children reduce the image quality
- Intermittent motion can be detected and removed during reconstruction.
- Motion may also cause misalignment between the series of volumes
- Model based registration realigns the volumes and improves the accuracy in estimating the tracer kinetic model parameters.

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An arterial input function (AIF) model using a combination of a population model and a reference region for improved estimation of the kidney function

Cemre Ariyurek, Onur Afacan, Jeanne Chow, Sila Kurugol

Session 2 Friday 17.20 EDT, Proffered Papers, oral session

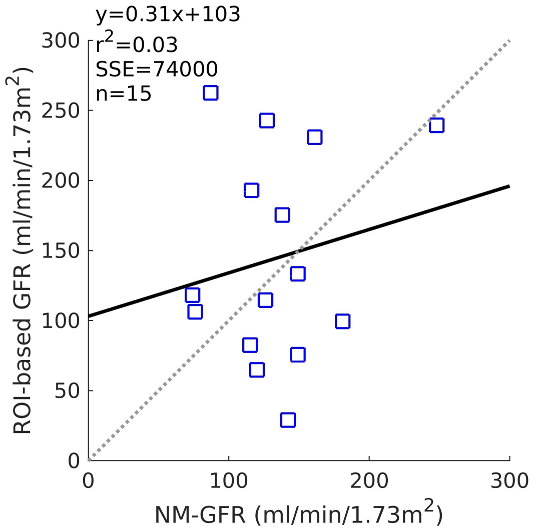
Purpose: To generate an AIF, when the measured AIF may be inaccurate, using a population AIF combined with a reference region model.

Cost function: $$\hat{\bar{\theta}} = \arg\min_{\bar{\theta}} \sum_k \left\| K_{trans_{REF_k}}(\bar{\theta}) - K_{trans_{ETM_k}}(\bar{\theta}) \right\|_2^2 + \lambda \left\| C_{pop}(t) - C_{fit}(t, \bar{\theta}) \right\|_2^2$$

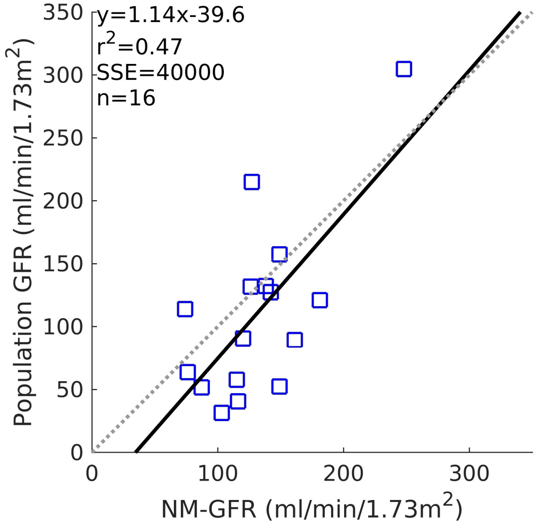
Minimizes the error between transfer constants obtained from reference region model and optimized AIF

Minimizes the error between population AIF and optimized AIF

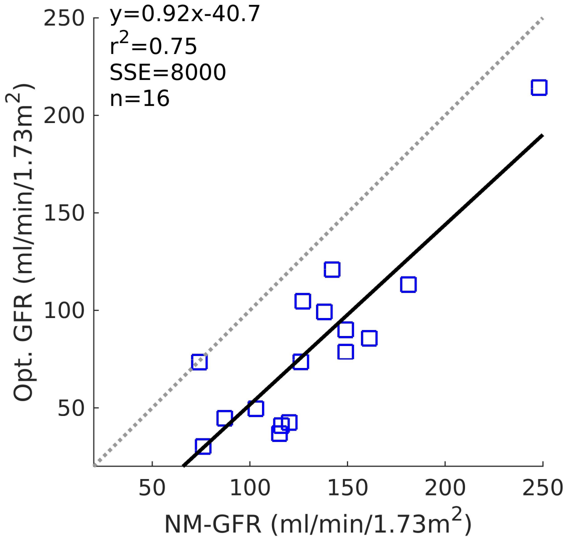
ROI-based AIF



Population AIF



Optimized AIF



GFR estimation was improved (R^2=0.75) by using an optimized AIF which combines a population and a reference region model

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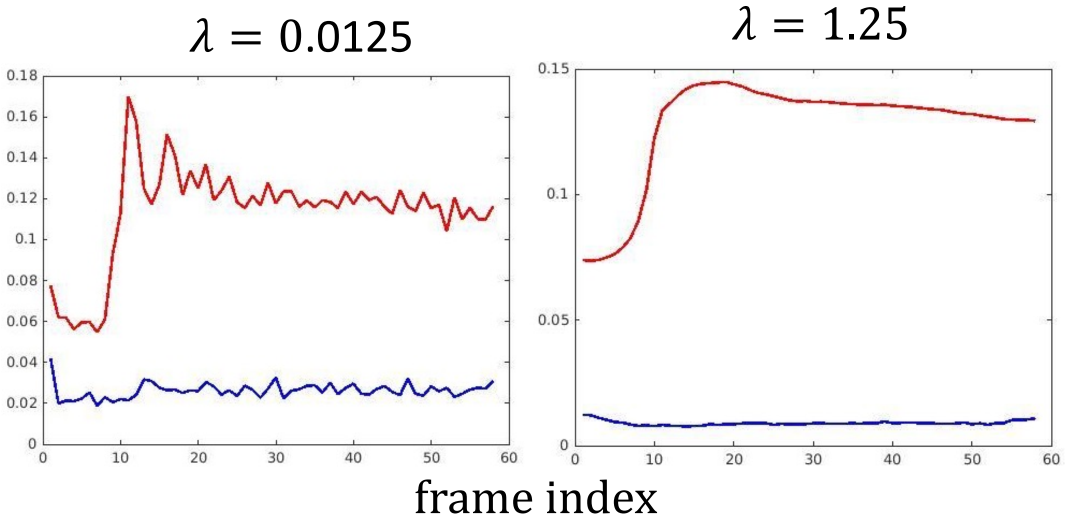
Deep image prior based DCE-MRI Reconstruction for Functional Imaging of Kidneys

Aziz Kocanaogullari, Cemre Ariyurek, Onur Afacan, Sila Kurugol

Session 5 Saturday 18.10 EDT,
Poster Number: 4

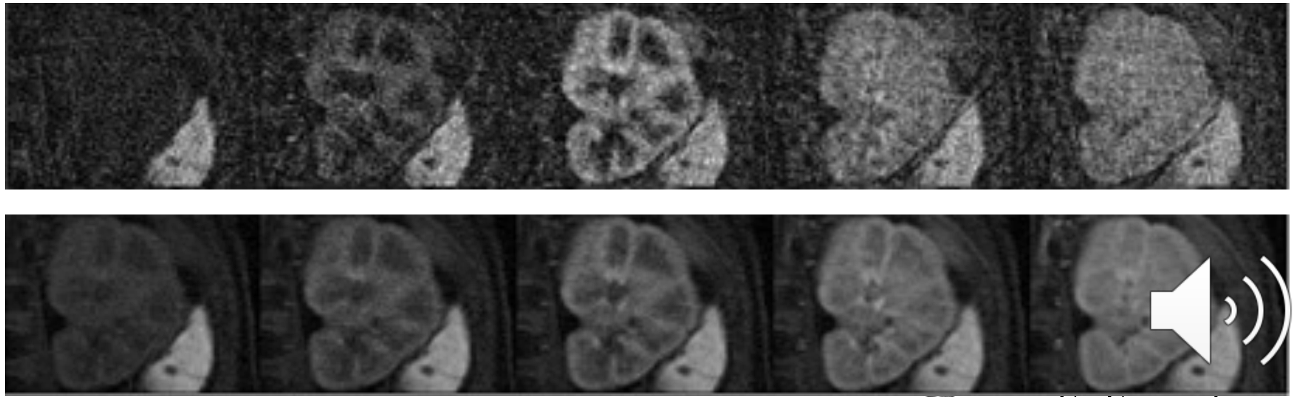
Purpose: To introduce a deep image prior based DCE-MR image reconstruction. It will achieve both improved image quality as in compressed sensing reconstruction, but also will keep temporal features of the signal for accurate estimation of quantitative parameters.

$$\hat{X} = \arg\min_{X} \sum_{i,t} \|FC_i x_t - k_{i,t}\|_2^2 + \lambda \left\|TV(X)\right\|_{1,1}$$



λ = 0.0125

λ = 1.25



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Acknowledgements

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NIDDK R21DK123569

NIBIB R21EB029627.

NIH National Institutes of Health

Society of Pediatric Radiology

Crohn’s and Colitis Foundation

National Multiple Sclerosis Society

Translational Research Program at Boston Children’s Hospital

Open positions in CRL and QUIN

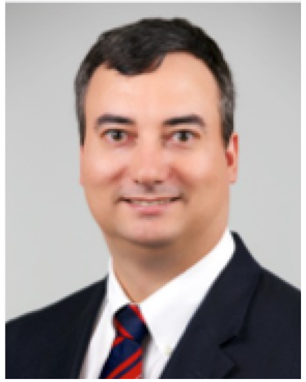
contact sila.kurugol@childrens.harvard.edu to join us!

https://projects.iq.harvard.edu/quin/positions

Onur Afacan, PhD

Jaume Coll-Font, PhD

Jeanne Chow, MD



Simon Warfield, PhD

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