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Compressed Sensing in Cardiac MR

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Motivation

long acquisition time impact :

- spatial and temporal resolution
- spatial coverage
- SNR, CNR
- artifact level (motion, contrast media change)

long CMR exams:

- cardiac MR exams are generally long
- comprehensive exams are becoming more common
- emphasis on patient throughput to reduce cost

Outline

- Brief overview of acceleration methods

- A new CS reconstruction algorithm for high-resolution CMR

- CS-accelerated image acquisition for
  - coronary
  - late gadolinium enhancement
  - cine
  - perfusion
  - other CMR applications

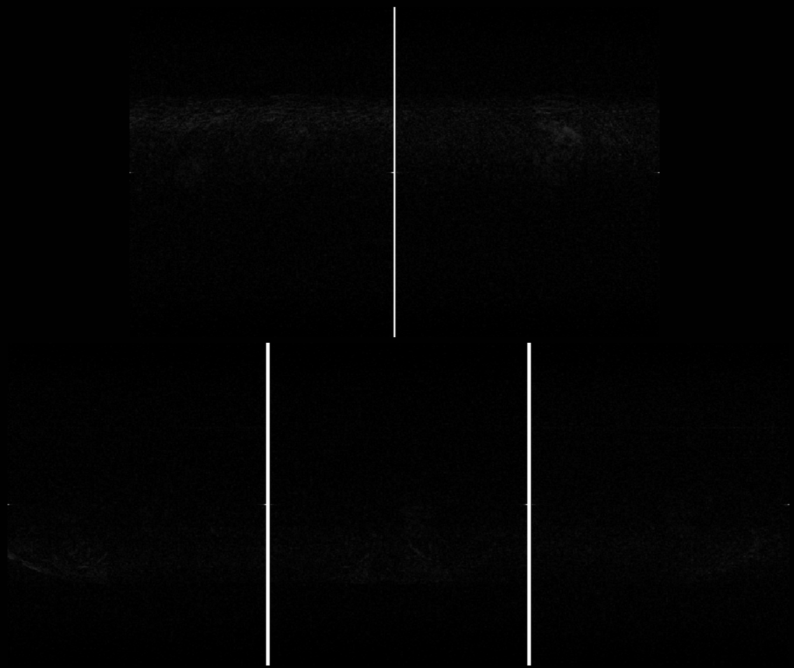
Methods for Acceleration

- Partial Fourier
- Parallel Imaging
- Non-Cartesian Trajectories
- Compressed Sensing
- Spatio-temporal methods
  (for dynamic imaging)

Multiple Receiver Coils

- In clinical MRI, receiver coil arrays are used.

- They modulate the intensity of the signal based on their spatial locations.



$$\begin{pmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \\ \vdots \\ \mathbf{S}_{N_C} \end{pmatrix} = \begin{pmatrix} \mathbf{F}_\Omega \mathbf{C}_1 \mathbf{m} \\ \mathbf{F}_\Omega \mathbf{C}_2 \mathbf{m} \\ \vdots \\ \mathbf{F}_\Omega \mathbf{C}_{N_C} \mathbf{m} \end{pmatrix}$$

C_k : Coil sensitivity profiles

Parallel Imaging

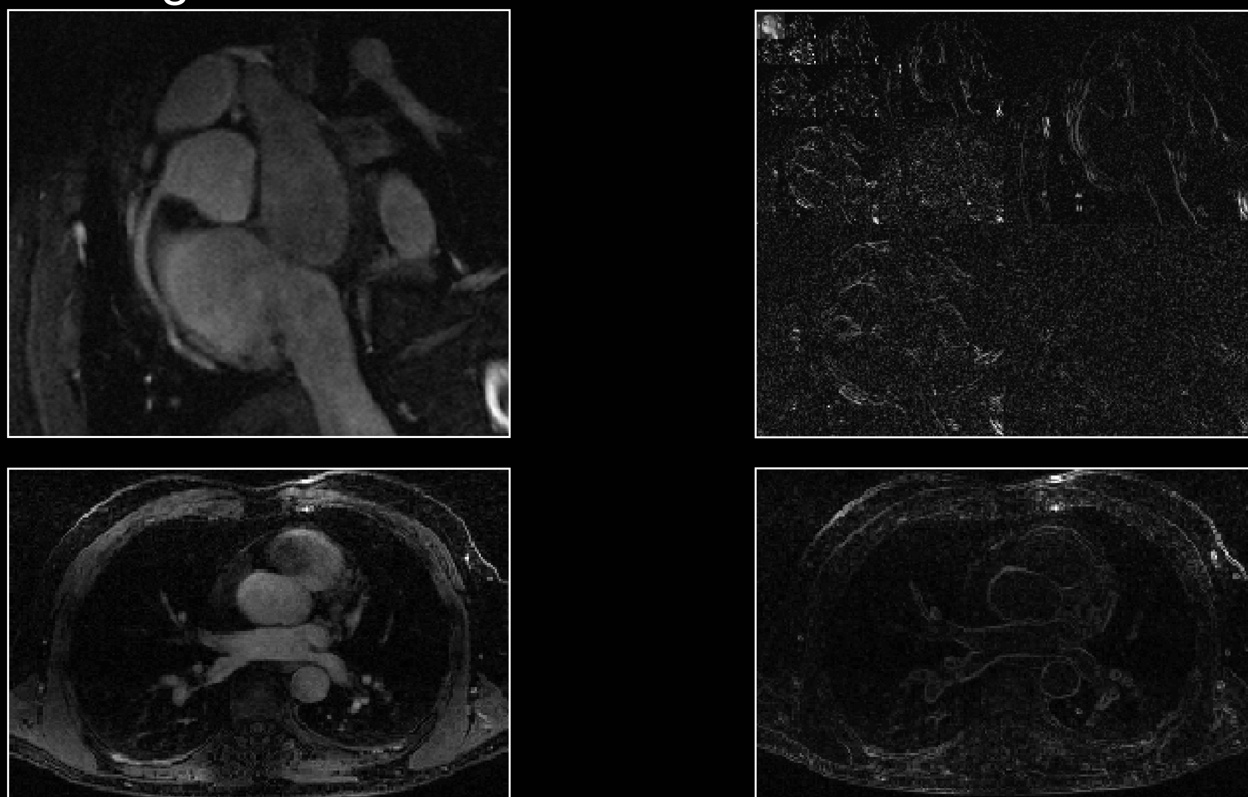
- Utilizes redundancy in acquisition due to phased-array coils.
- SENSE
  - Image-domain least squares solution
  - Uses estimates of coil sensitivity maps
- GRAPPA
  - k-space interpolation
  - Interpolation kernels estimated from center of k-space

- SENSE and GRAPPA are <u>linear</u> reconstruction methods.

Compressed Sensing (CS)

Recently proposed MRI acceleration technique[1]

Images are compressible in transform domains

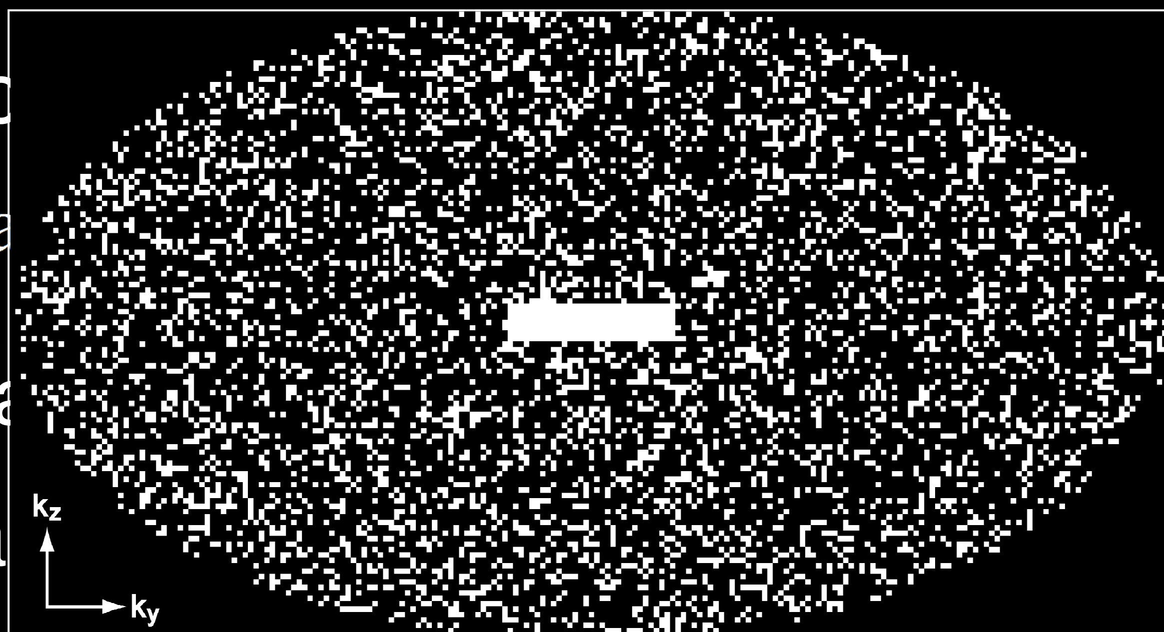


[1] Block et al, MRM, 2007; Lustig et al, MRM, 2007.

CS Reconstruction

F_Ω : incoherent k-space undersampling operator

S : measured k-space data (undersampled)



- CS rec

a

Φ : spa ≤ 1)

$\boldsymbol{\Psi}$: tra te

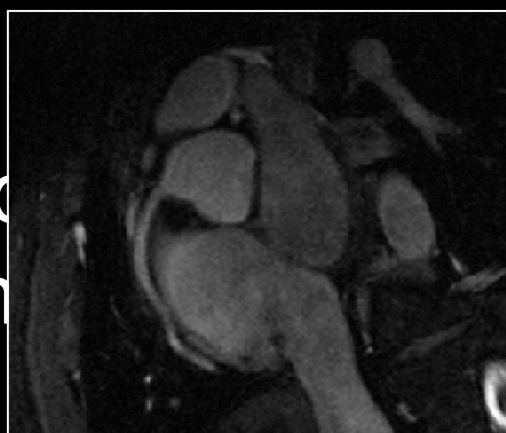
τ : weight of sparsity term

CS in Cardiac MR

- Potential for higher acceleration rates
- Limited use in high spatial-resolution cardiac MR applications
  - Blurring and residual artifacts

Aim

- To use patient-specific and anatomic-specific information for improved reconstruction

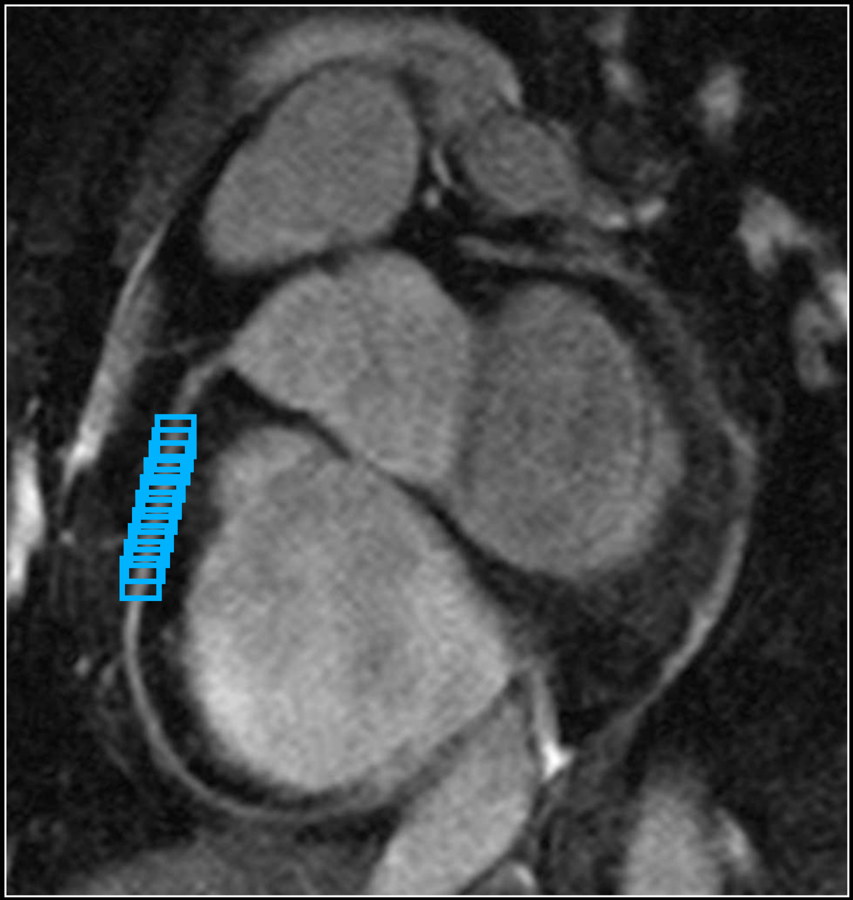


- We pro … imens … re self-learnin … olding

LOST

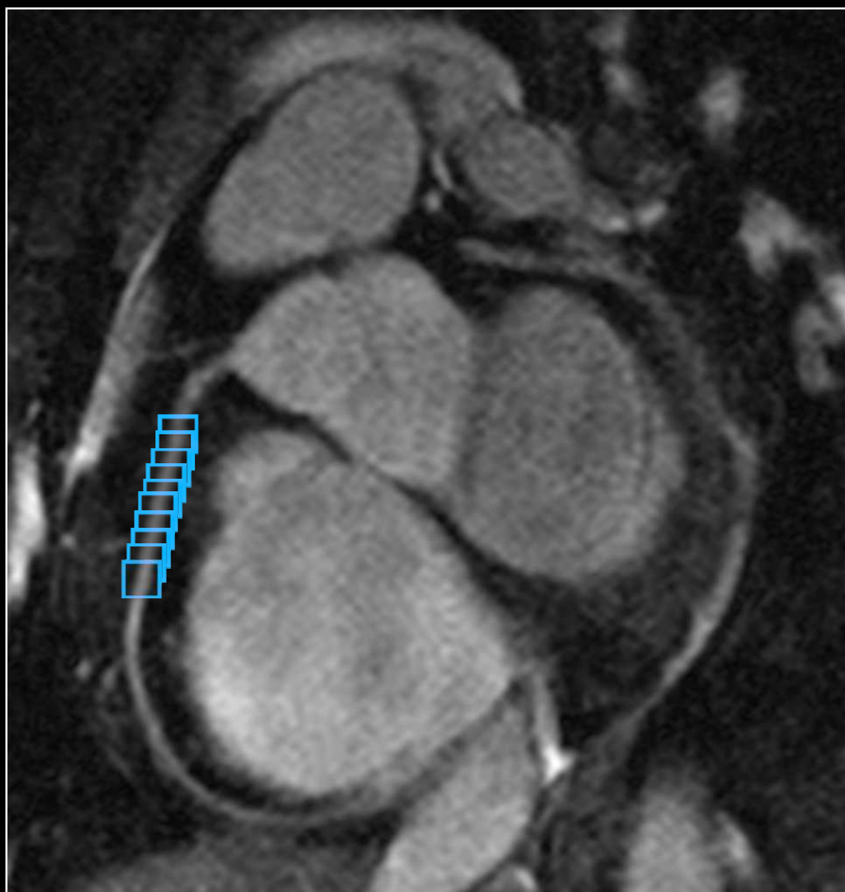
- Coronary images contain 2D patches of similar signal content at various spatial locations

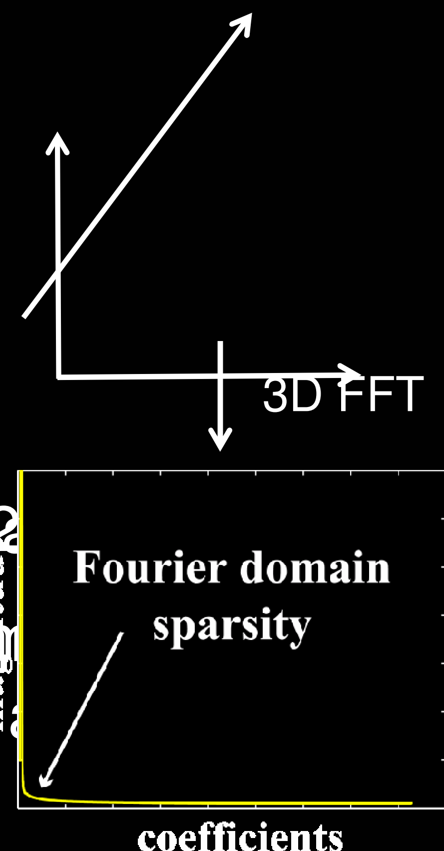
LOST



- Coronary images contain 2D patches of similar signal content at various spatial locations

LOST





Apply FFT 2 block:

Prior emb vially

since a milar

Block Matching

- Construct similarity clusters by block matching[1]

matched similar blocks (similarity cluster for the reference block / voxel)

reference block

check similarity with other blocks

- Clusters are produced for every voxel of the image.

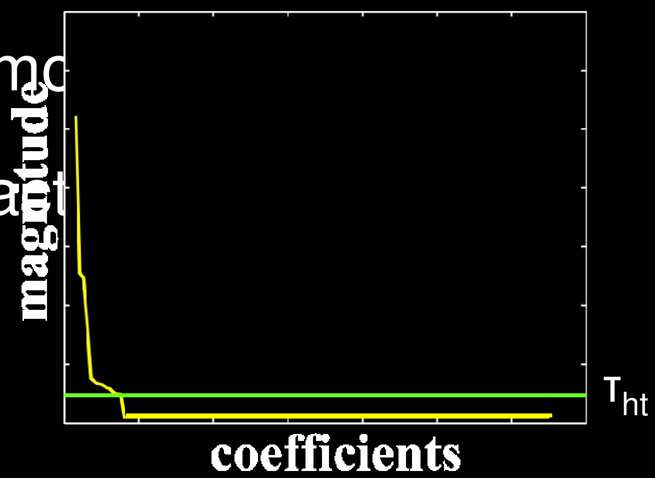
[1] Dabov et al, IEEE TIP, 2007.

Thresholding

- Remove aliasing by using the FFT-sparsity of similarity clusters

1) Hard thresholding in FFT domain

  - Captures l_0 norm of similarity clusters
  - If FFT coefficient < τ_{ht}, set to zero. Otherwise unchanged
  - Efficiently remo
  - Blurring artifa



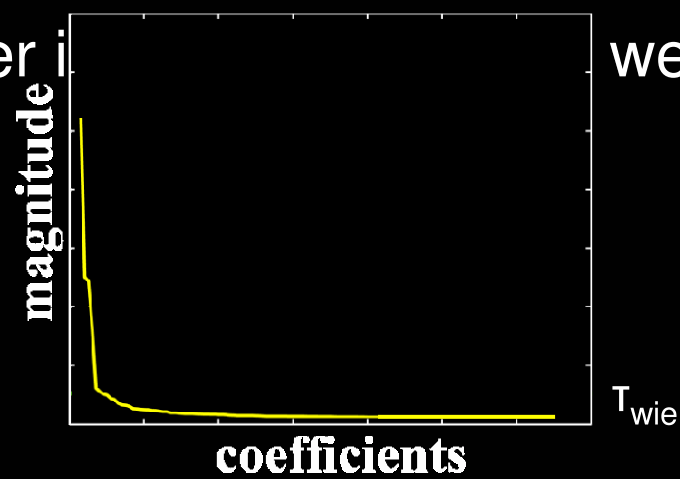
Thresholding

2) Wiener Filtering in FFT domain

- Captures weighted l_2 norm of similarity clusters
- Weight each FFT coefficient, f_k by

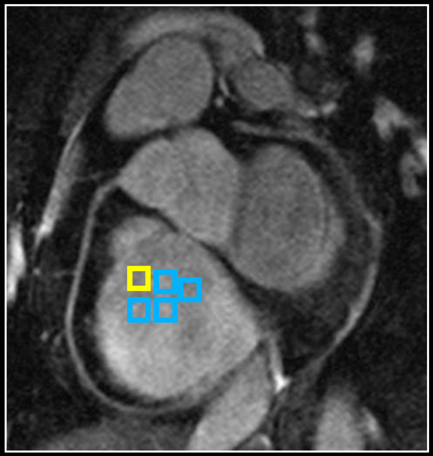
$$|f_k|^2 / (|f_k|^2 + \tau^2_{wie})$$

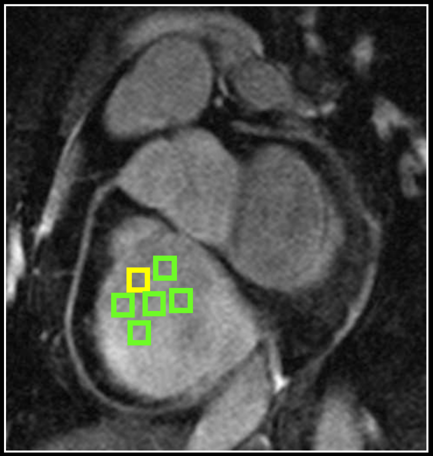
- Reduces blurring artifacts
- Useful in later i weights are reliable



Combining Blocks

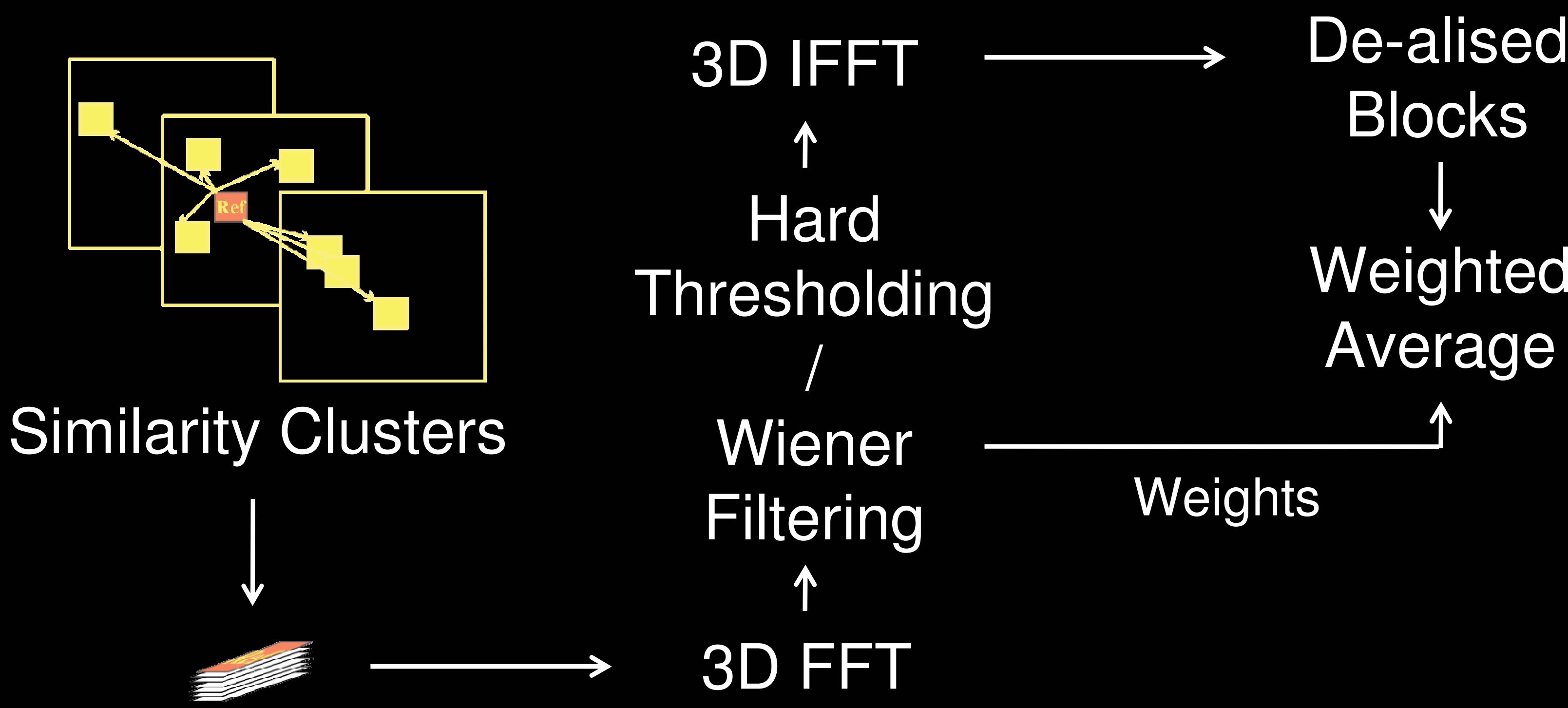
- Each block may be in multiple clusters





- Combine these by weighted averaging
  - Intuition: Smaller weight to more aliased blocks

LOST



Ref
Similarity Clusters
3D FFT
Wiener Filtering
/
Hard Thresholding
3D IFFT
De-alised Blocks
Weighted Average
Weights

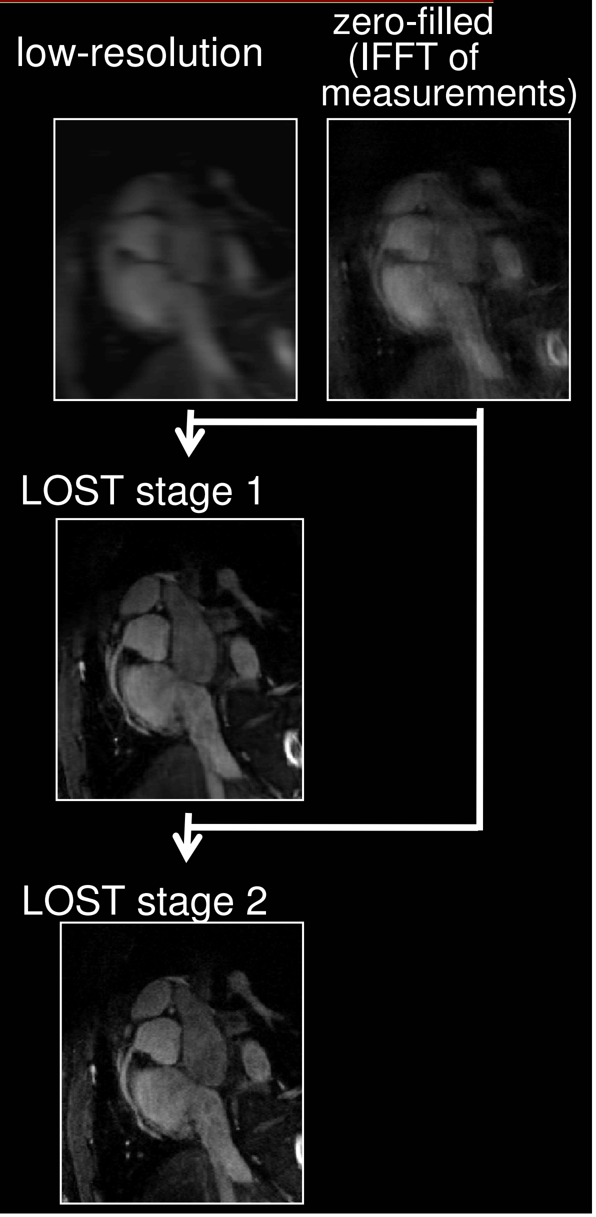
Implementation

Stage 1: Generate low-resolution estimate from center of k-space

1) Adaptively identify similarity clusters ($N_b = 8$)
2) Threshold via hard-thresholding

Stage 2: From estimate of stage 1

1) Adaptively identify similarity clusters ($N_b = 4$)
2) Alternate between hard-thresholding and Wiener filtering

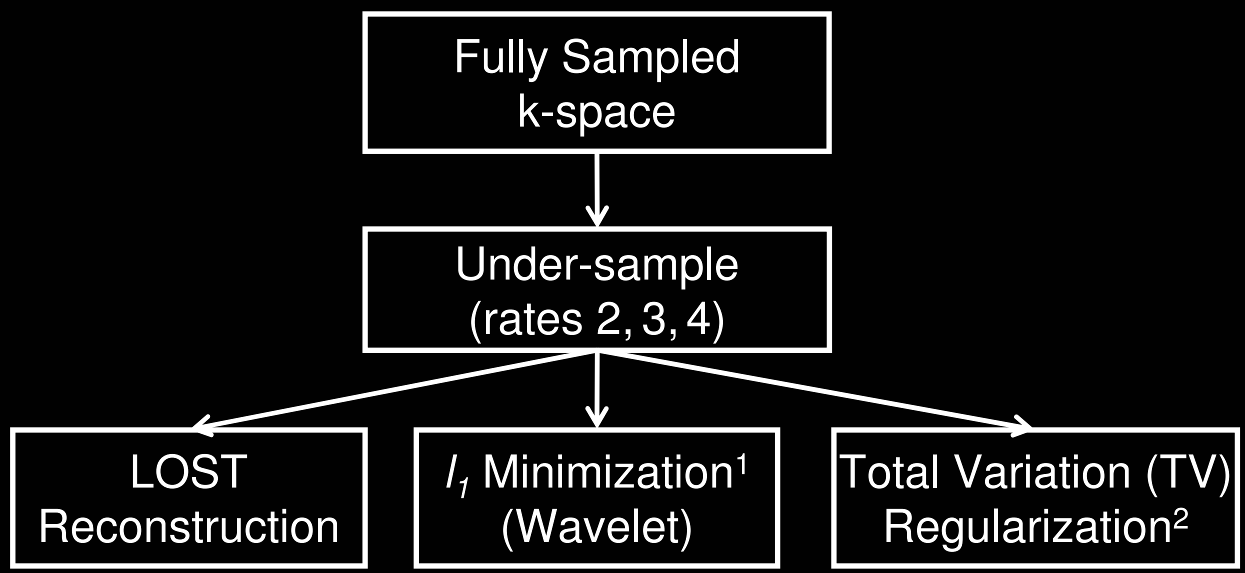


Methods

- Performance evaluation of LOST
  - Targeted coronary MRI
    - Retrospective undersampling
    - Prospective undersampling
- Clinical application of LOST
  - Contrast-enhanced coronary MRI
  - Late Gadolinium enhancement

Retrospective Undersampling

- 1.5T Philips Achieva magnet with 5-channel cardiac coil.
- Right and left coronaries (N_H = 10)

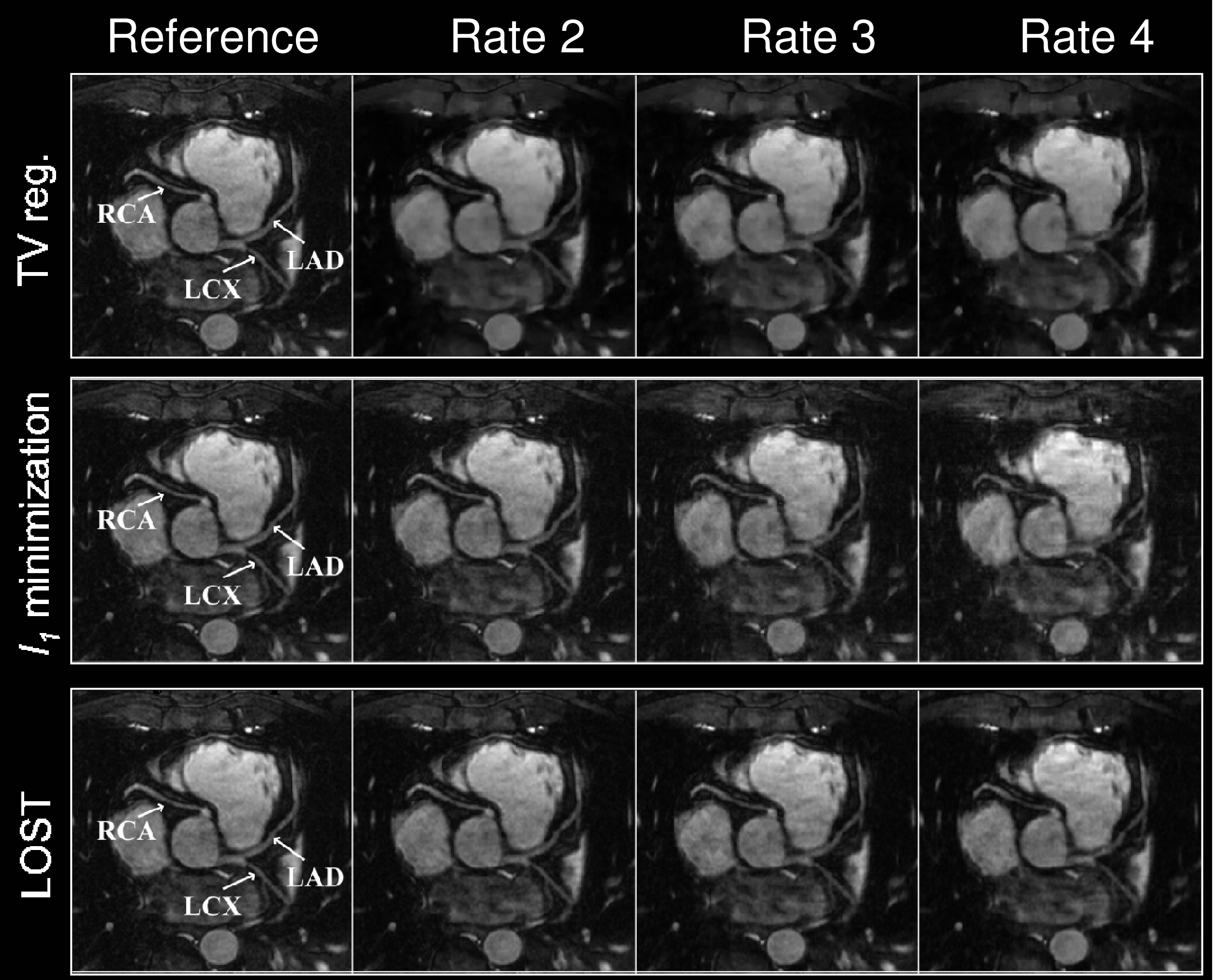


- Retrospective undersampling:
  - 50x5 lines in the center
  - randomly discarding the edges

[1] van den Berg et al, SIAM JSC, 2008; [2] Yang et al, IEEE JSTSP, 2010.

LAD/LCX Results

- NAV-gated
- ECG-triggered
- T_2-Prep SSFP
- $1 \times 1 \times 3$ mm^3 resolution
- Retrospective random under-sampling
- 5-channel cardiac coil



RCA: Right Coronary Artery, **LAD**: Left Anterior Descending Artery, **LCX**: Left Circumflex Artery

Performance Evaluation

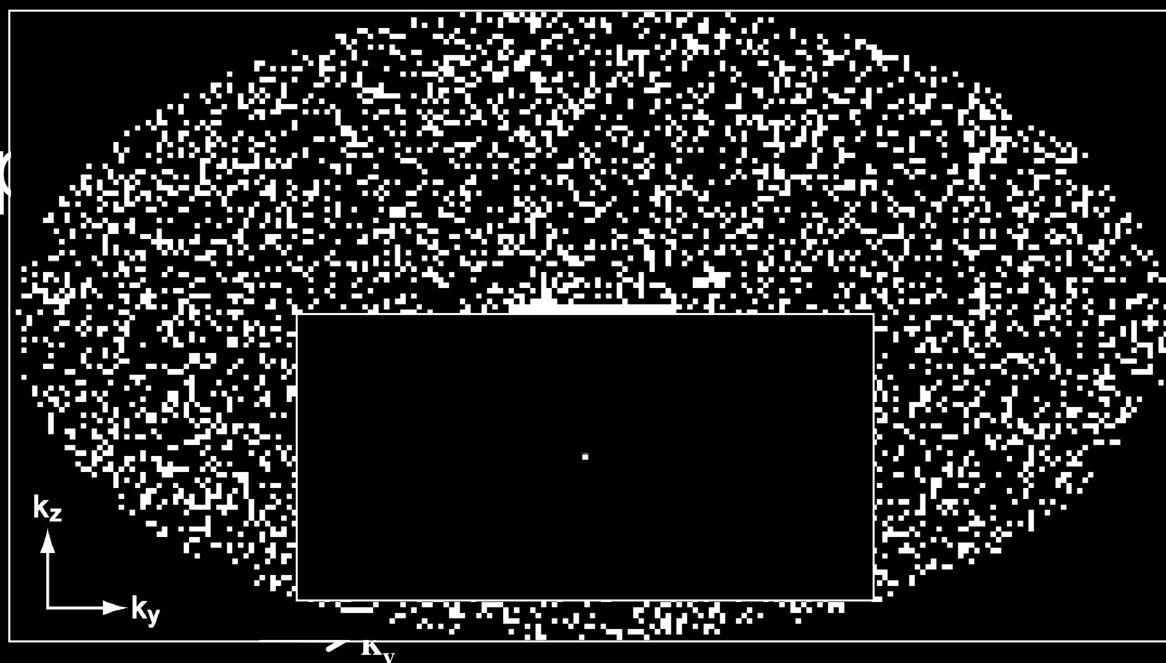
- Our evaluation shows improved
  - subjective image scores
  - sharpness of the RCA
  - mean square error

  with respect to l_1 minimization and TV regularization

- Next step: implement and evaluate LOST in prospective acquisition

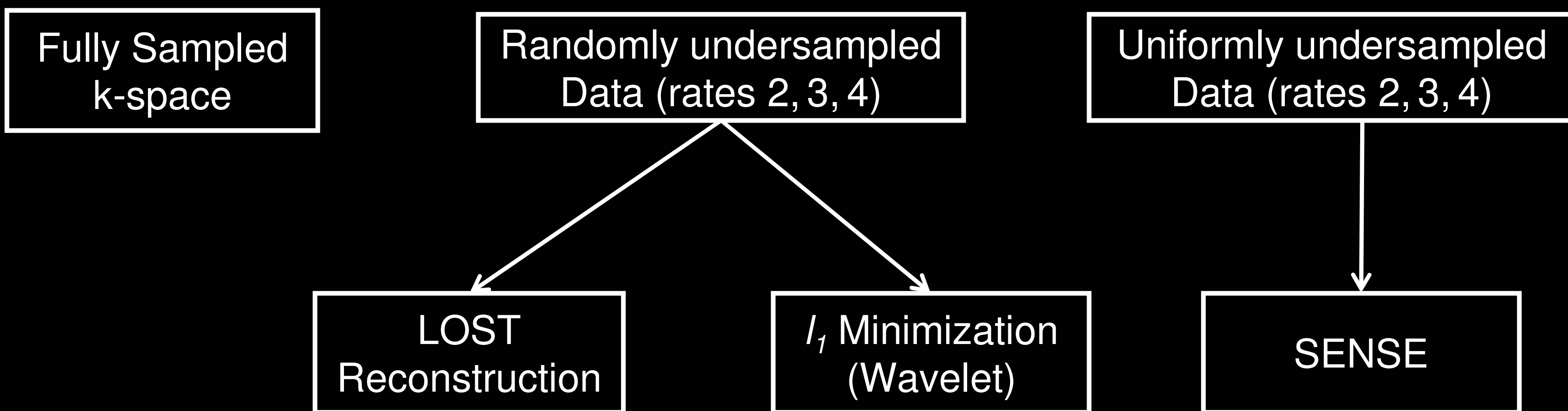
Prospective Undersampling

- Random k-space undersampling in SSFP sequences artifacts
- Radial p s[1]



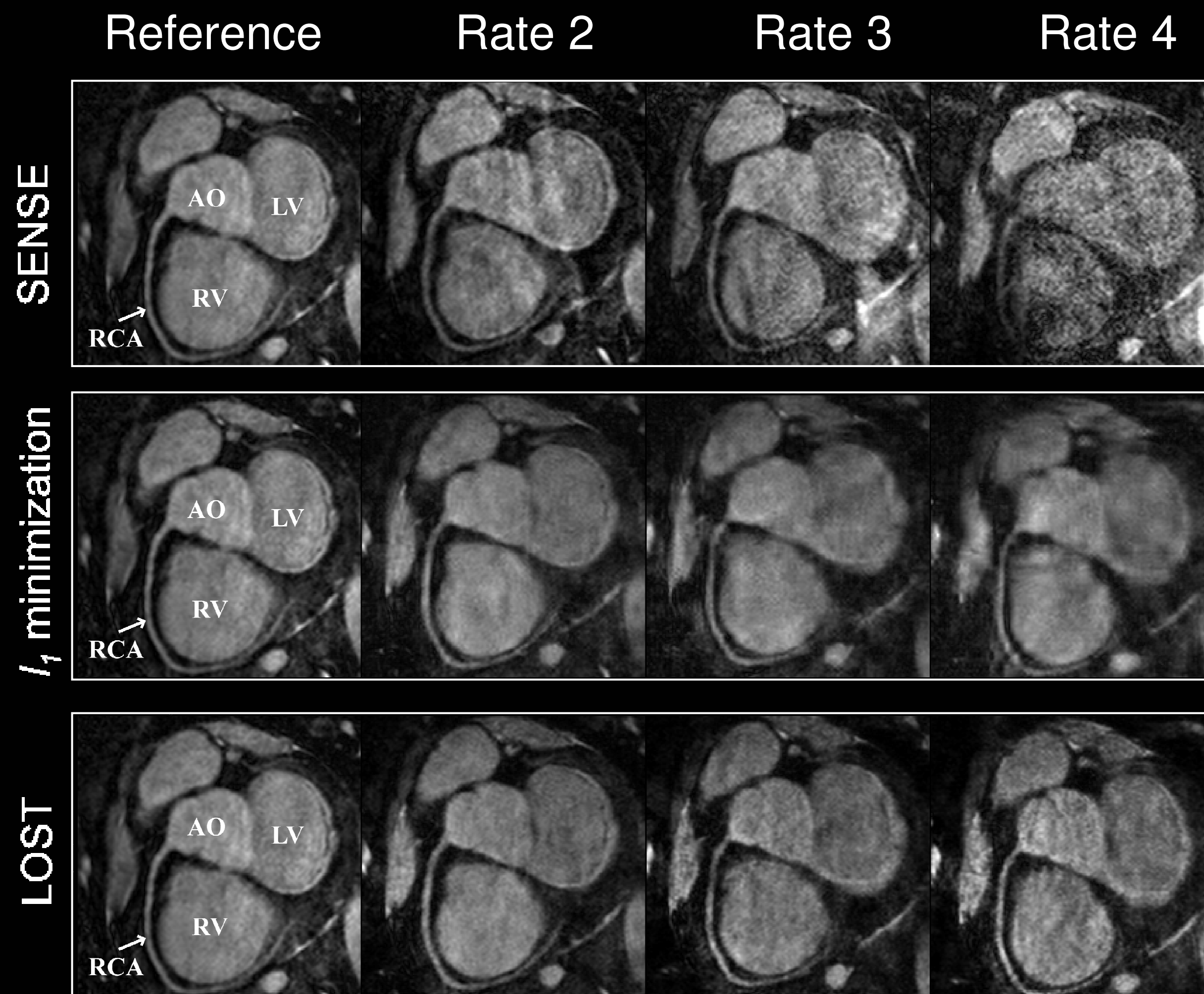
[1]Basha et al, ISMRM, 2011

Prospective Undersampling



RCA Results

- NAV-gated
- ECG-triggered
- T_2-Prep SSFP
- $1 \times 1 \times 3$ mm^3 resolution
- Prospective random under-sampling with radial profile order
- 5-channel cardiac coil

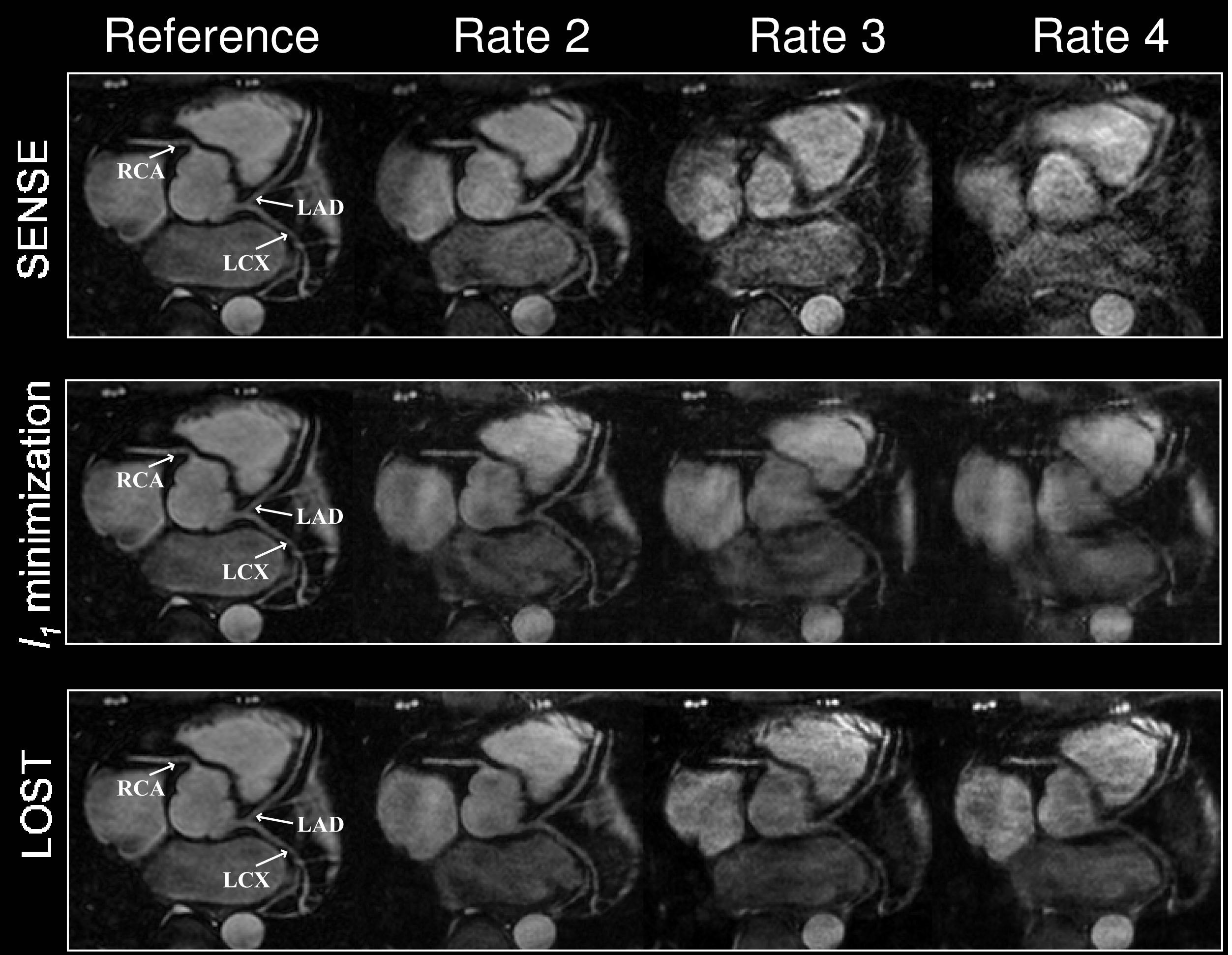


LOST allows images to be acquired with 4× acceleration even with 5-channel coil

RCA: Right Coronary Artery, **AO**: Aortic Root, **LV**: Left Ventricle, **RV**: Right Ventricle

LAD/LCX Results

- NAV-gated
- ECG-triggered
- T_2-Prep SSFP
- $1 \times 1 \times 3$ mm^3 resolution
- Prospective random under-sampling with radial profile order
- 5-channel cardiac coil



RCA: Right Coronary Artery, **LAD**: Left Anterior Descending Artery, **LCX**: Left Circumflex Artery

Contrast Enhanced (CE) Coronary MRI

- Advantages[1]:
  - higher SNR
  - higher CNR
- Disadvantages:
  - long acquisition time (~10-12 minutes)
  - artifacts due to varying inversion time / contrast washout

Rapid acquisition is needed

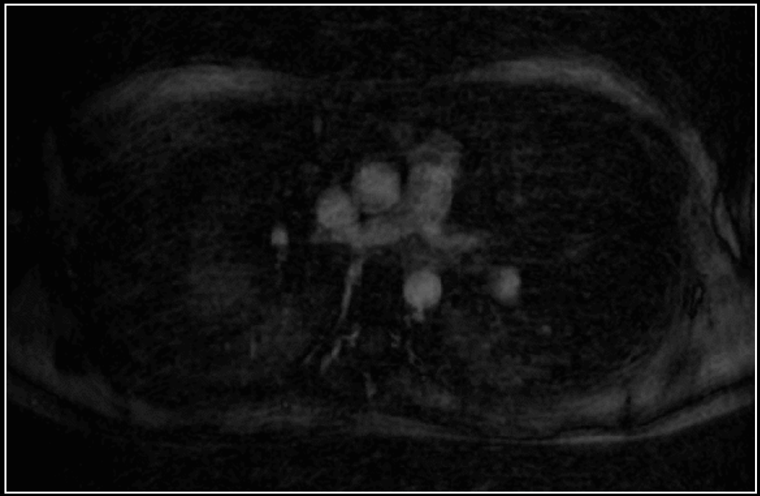
- 10 healthy subjects
  - 4-fold acceleration

[1] Bi et al, MRM, 2007; Hu et al, MRM, 2010.

CE WH Coronary MRI Results

- IR-SSFP
- NAV-gated, ECG-Triggered
- bolus 0.2 mmol/kg Gd-BOPTA
- imaging after 2 min of contrast
- resolution =1.3×1.3×1.3 mm^3
- 4-fold k_y-k_z acceleration
- 5-channel phased-array coil
- 2:50 minutes at 70 bpm,
  100% gating efficiency

zero-filled



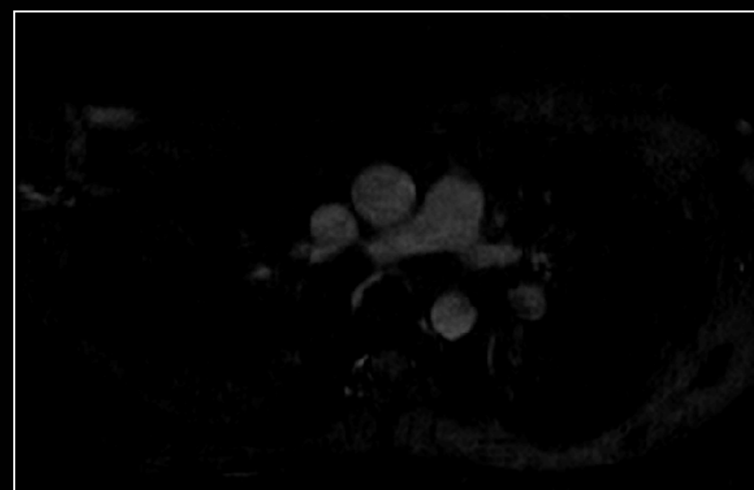
LOST

CE WH Coronary MRI Results

- IR-SSFP
- bolus 0.2 mmol/kg Gd-BOPTA
- resolution =1.3×1.3×1.3 mm^3
- 4-fold k_y-k_z acceleration
- 5-channel phased-array coil

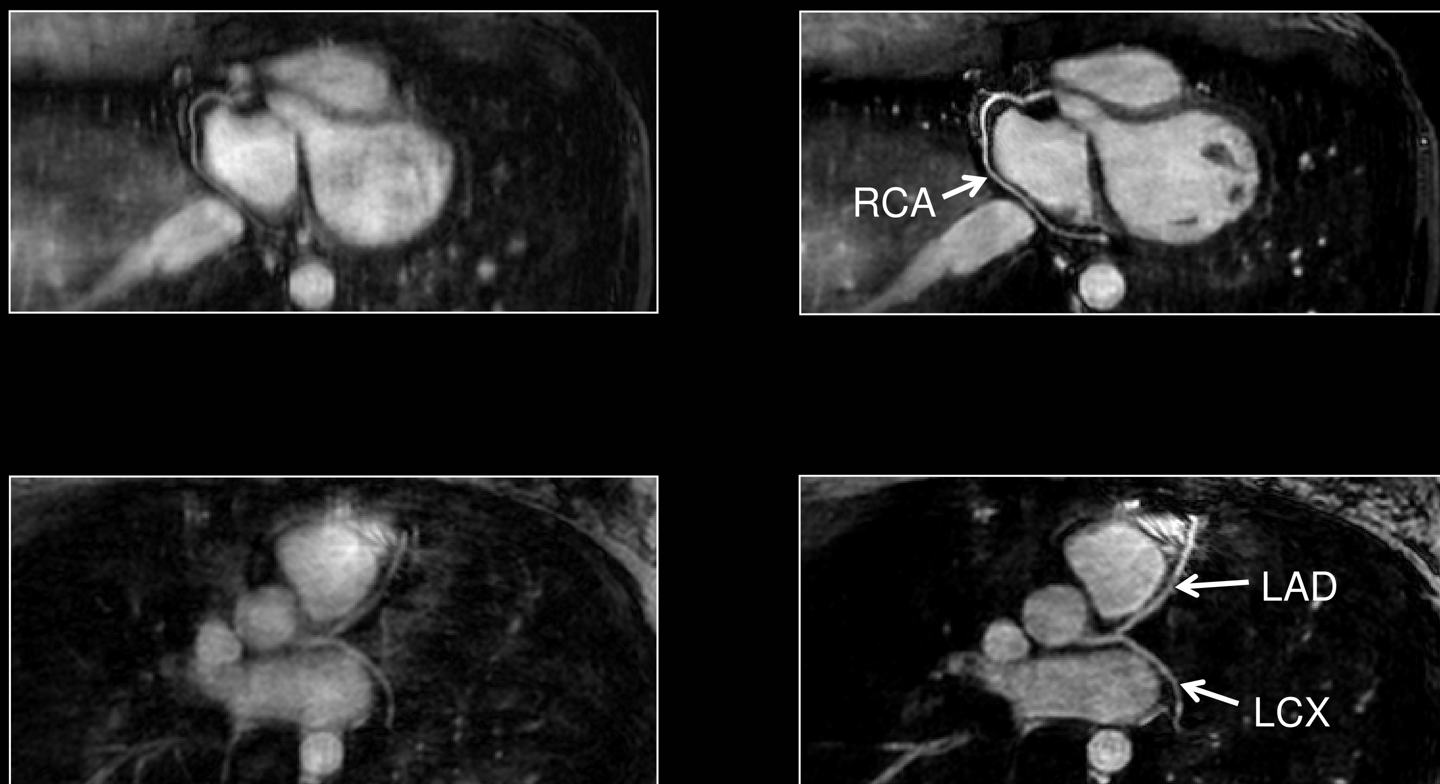
zero-filled

LOST



CE WH Coronary MRI Results

zero-filled LOST



RCA: Right Coronary Artery, **LAD**: Left Anterior Descending Artery, **LCX**: Left Circumflex Artery

CE WH Coronary MRI Results

- Subjective quality assessment by two blinded readers in consensus
  - 1 = poor, 4 = excellent [1]
  - Overall score: 3.6 ± 0.5

[1] Kim et al, NEJM, 2001

Late Gadolinium Enhancement

- Late Gadolinium Enhancement (LGE) is used for viability studies
  - Quantification of scar volume and border zone morphology[1]
- Higher resolution allows[2]
  - Identification of small areas of scar
  - Improved gray zone characterization

2D with BH
2×2 mm^2,10 mm gap

Higher resolution and shorter acquisition are desirable

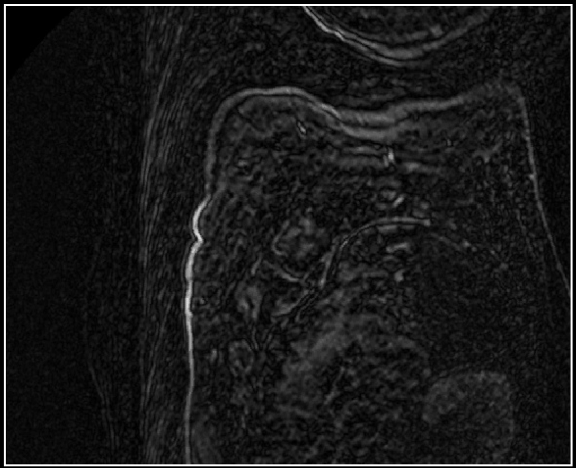
[1] Kim et al, Circulation, 1999; [2] Peters et al, JMRI, 2007

3D WH LGE Results

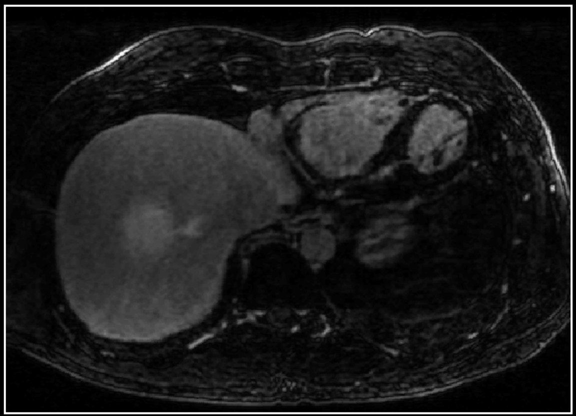
- 46 year old male
- hypertrophic cardiomyopathy
- LGE in myocardium

- IR-GRE
- axial acquisition with WH coverage
- resolution =$1.0\times1.0\times1.5$ mm^3
- 3-fold k_y-k_z acceleration
- 5-channel phased-array coil
- 7 minutes total acquisition time

Low Resolution
$1.5\times1.5\times4.0$ mm^3

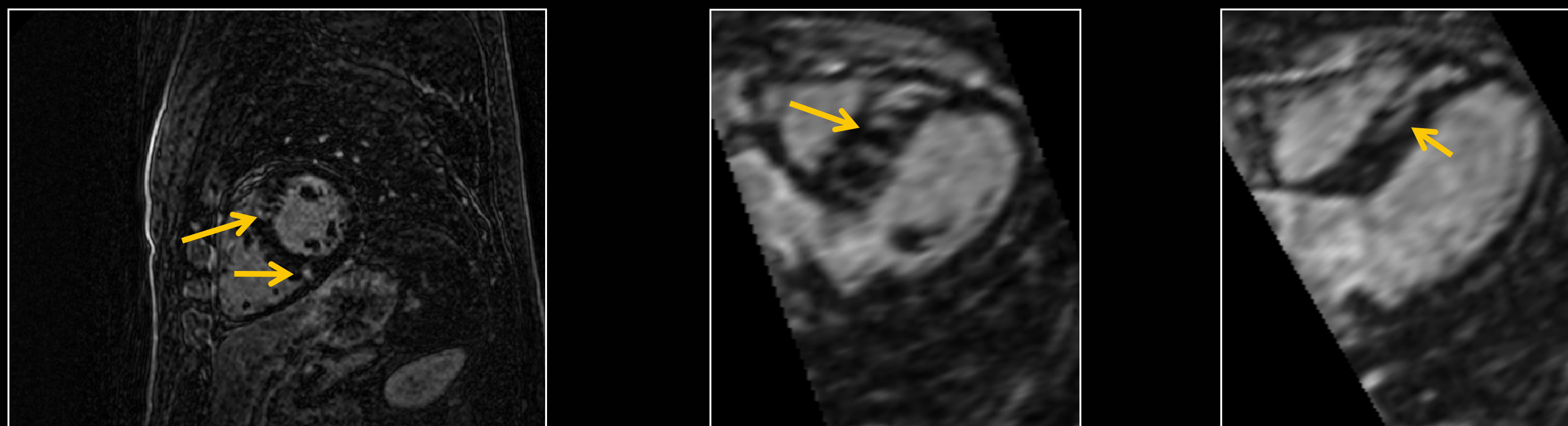


LOST

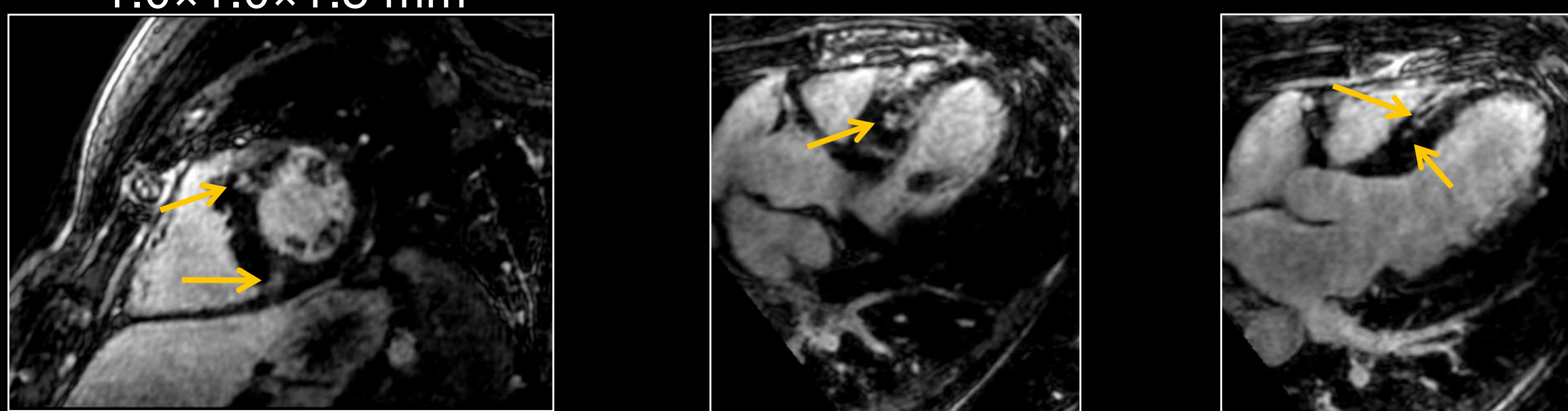


3D WH LGE Results

Low Resolution
1.5×1.5×4.0 mm^3



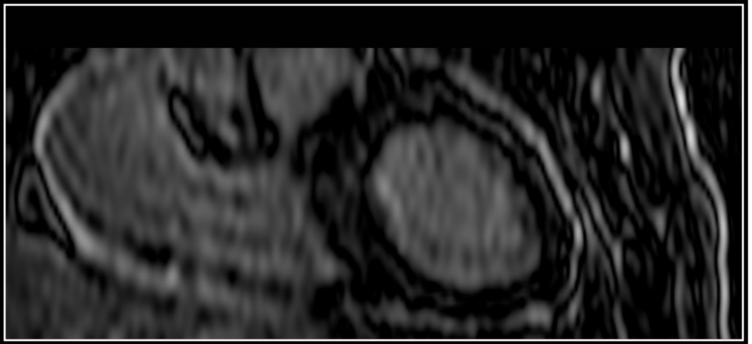
LOST, Rate = 3
1.0×1.0×1.5 mm^3



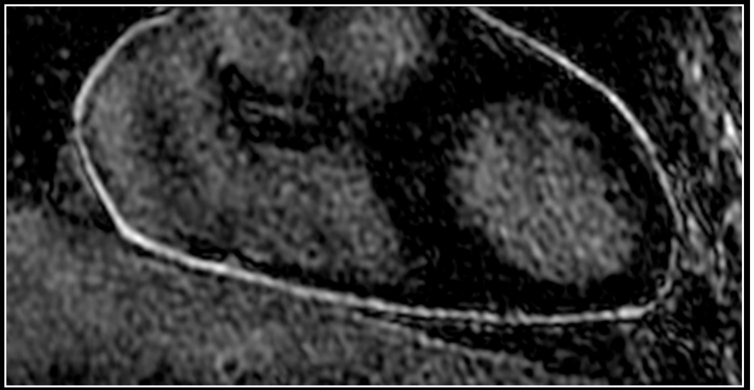
Motion Correction in LGE[1]

- 51 year old female
- pericarditis
- LGE in pericardium

Low-Resolution
1.7×1.7×5.0 mm^3



with LOST



- IR-GRE
- resolution =1.3×1.7×1.7 mm^3
- 5-channel phased-array coil

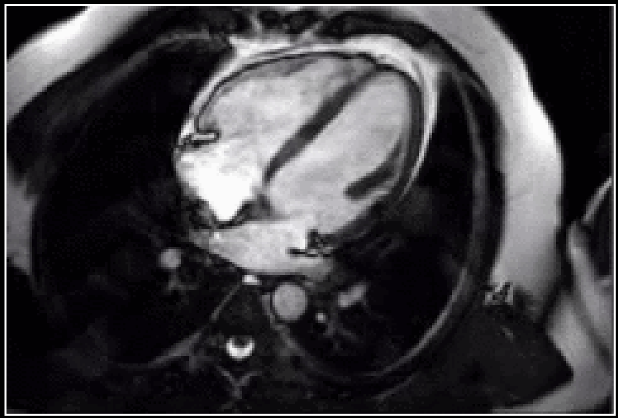
[1] Moghari et al, MRM, in press

Images courtesy of S. Hong and M. H. Moghari

Cine CMR

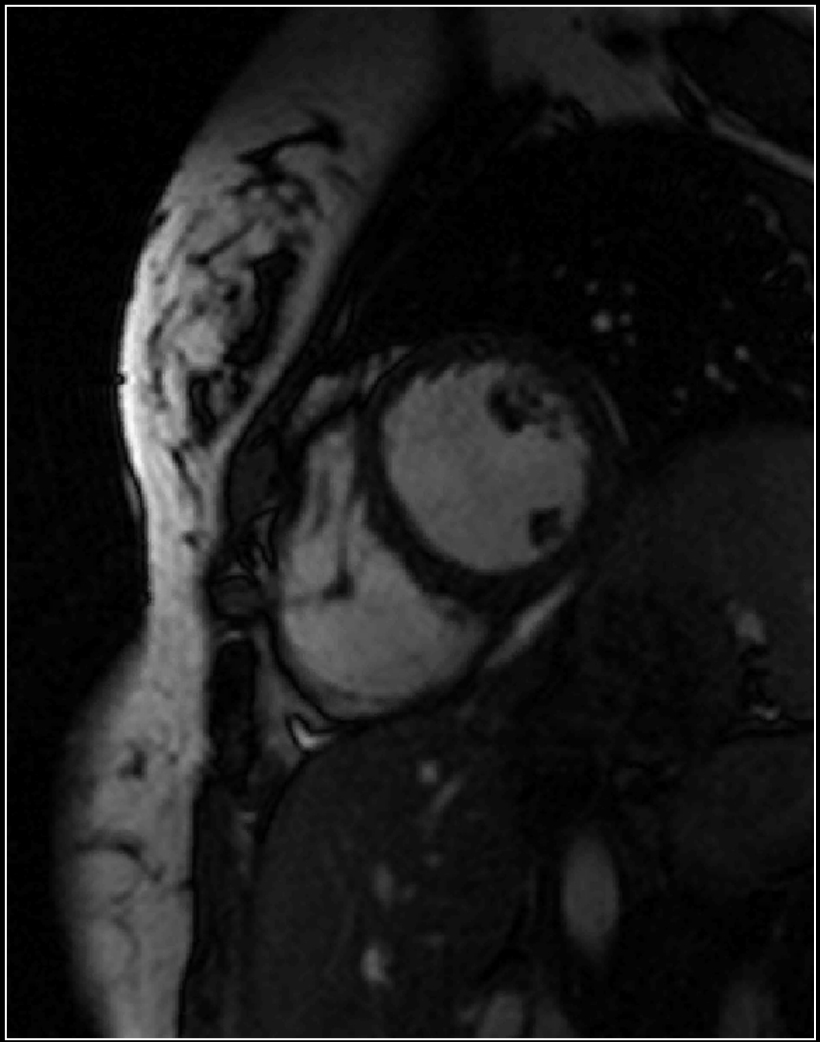
- Image the cardiac morphology throughout different phases of the cardiac cycle.
- Used for functional assessment.
  - Quantification of ejection fraction, end-diastolic volume, end-systolic volume, stroke volume, etc
- Accelerated imaging allows
  - Higher spatial or temporal resolution
  - Less breath-holds

2D with BH
2×2 mm^2, 30 ms temp. res.

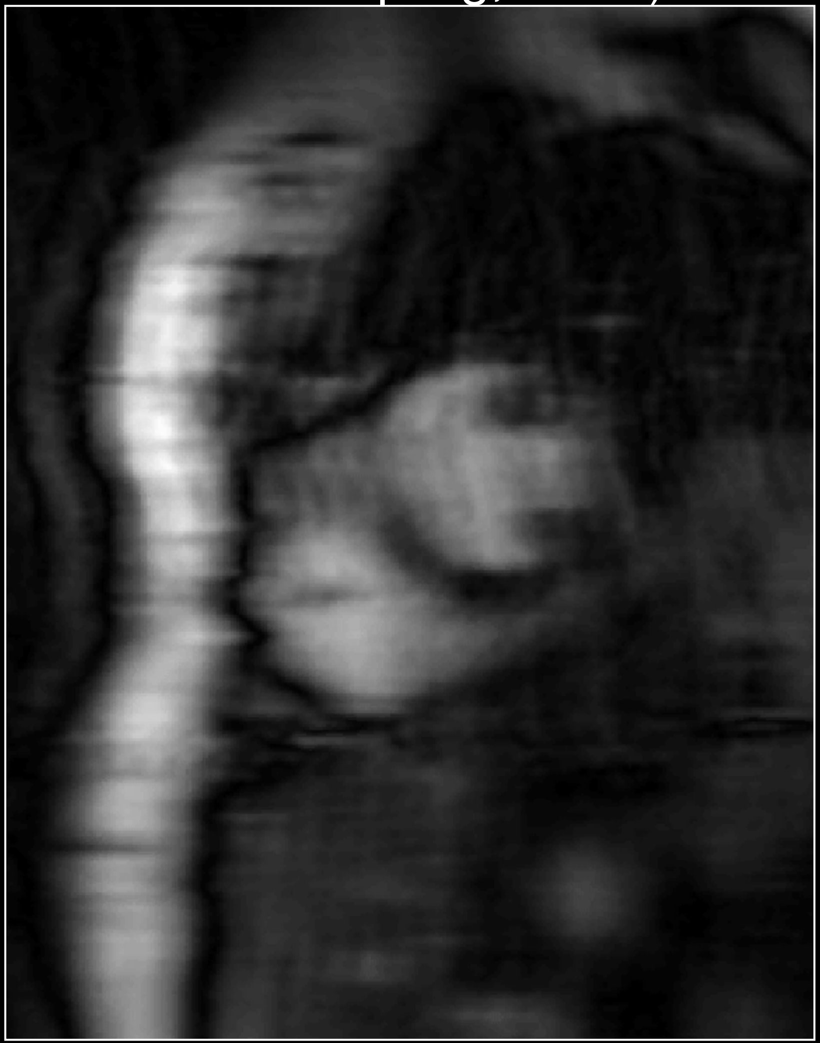


Retrospective Cine

Fully-Sampled

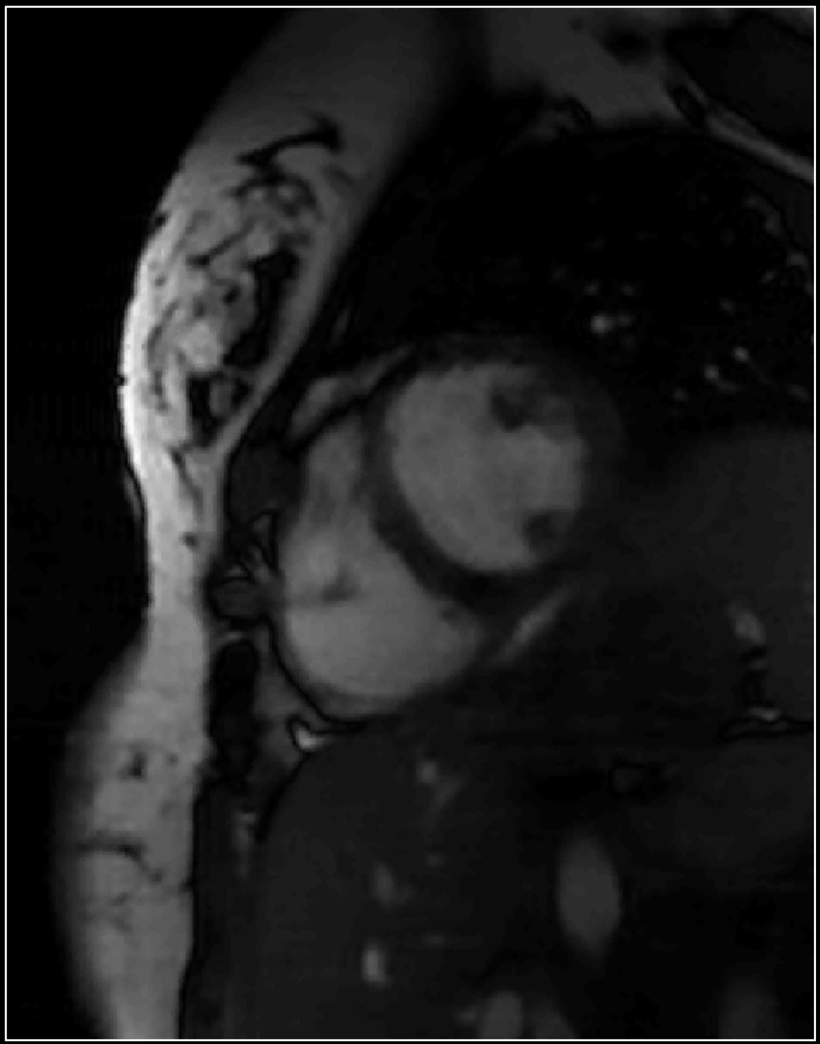


Zerofilled (retrospective undersampling, R = 6)

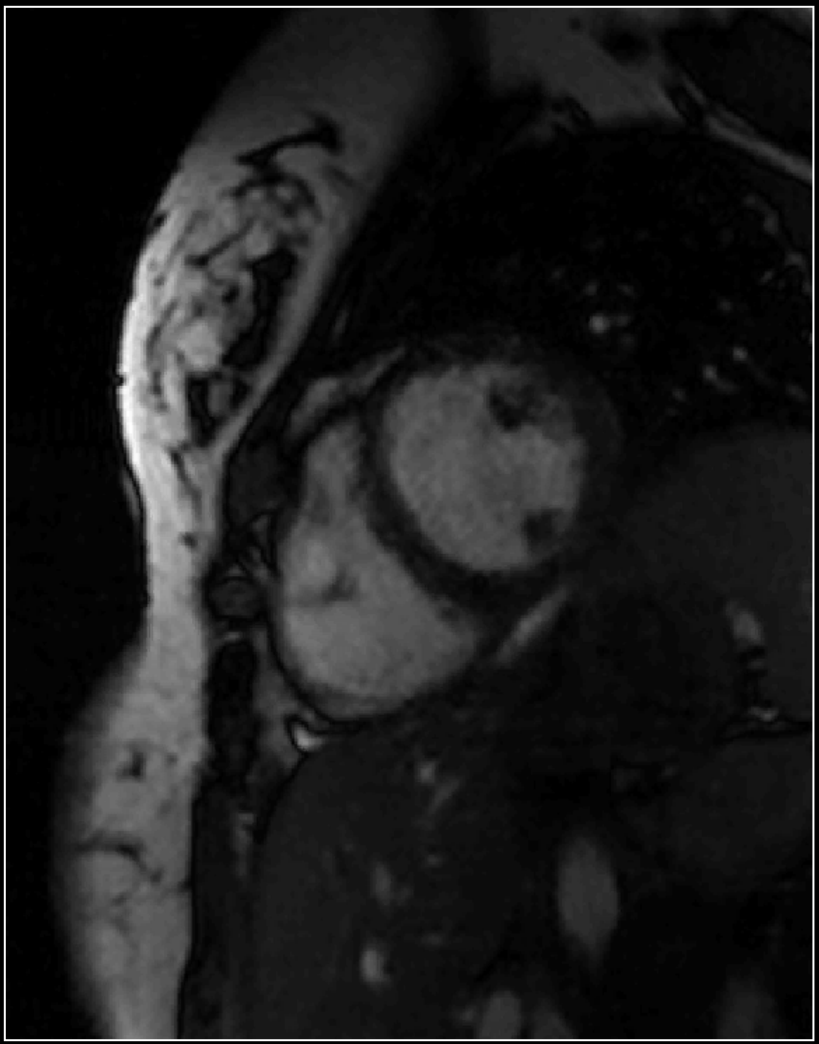


Transform Domain LOST

l_1 minimization in x-f space , R = 6

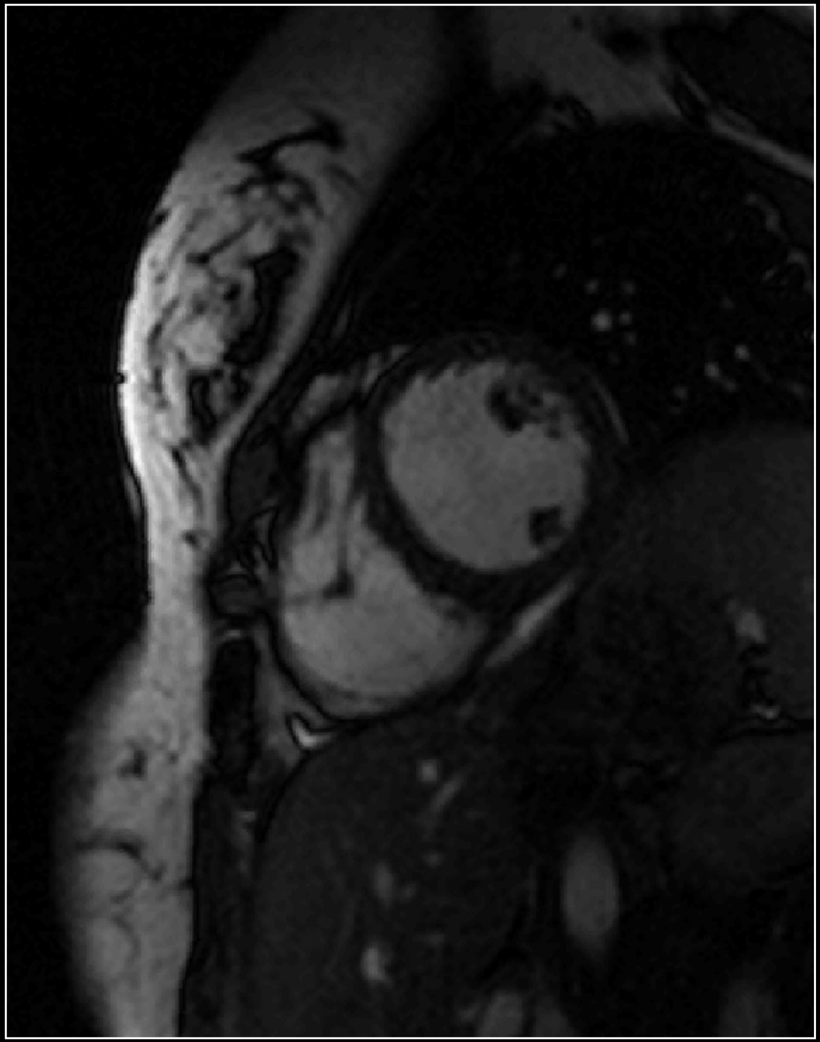


reconstruction in x-f space, with transform-domain LOST , R = 6

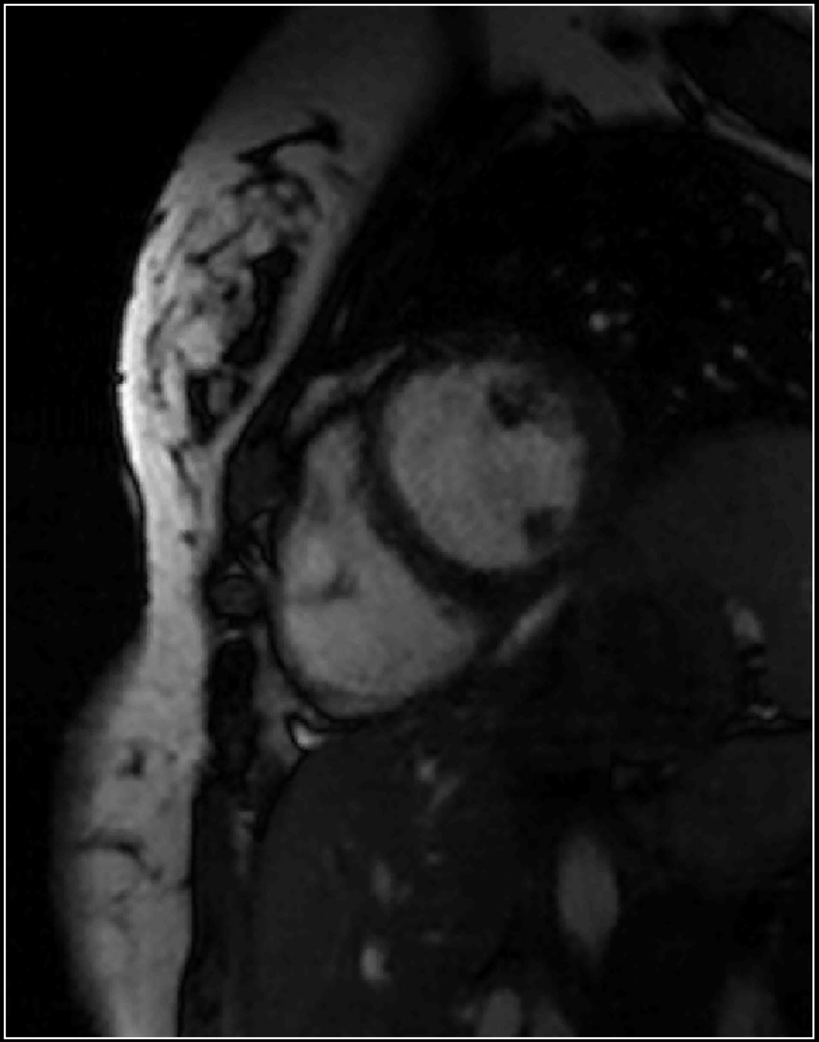


Transform Domain LOST

Fully-Sampled



reconstruction in x-f space, with transform-domain LOST , R = 6



kt-SPIRiT for Retrospective Cine

fully-sampled

kt-GRAPPA (R=7)

kt-SPIRiT (R=7)

Lai, ISMRM 2010

Courtesy of Drs. P. Lai (GE), M. Lustig (UC Berkeley)

kt-SPIRiT for Prospective Gating

fully-sampled

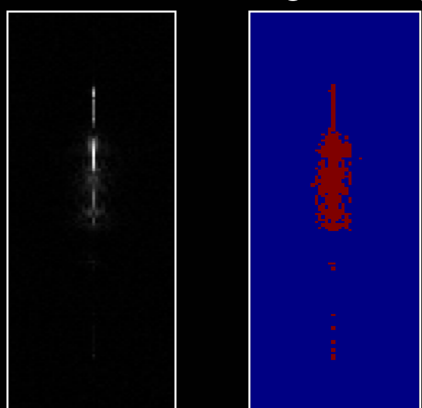
kt-GRAPPA (R=6)

kt-SPIRiT(R=6)

Lai, ISMRM 2010

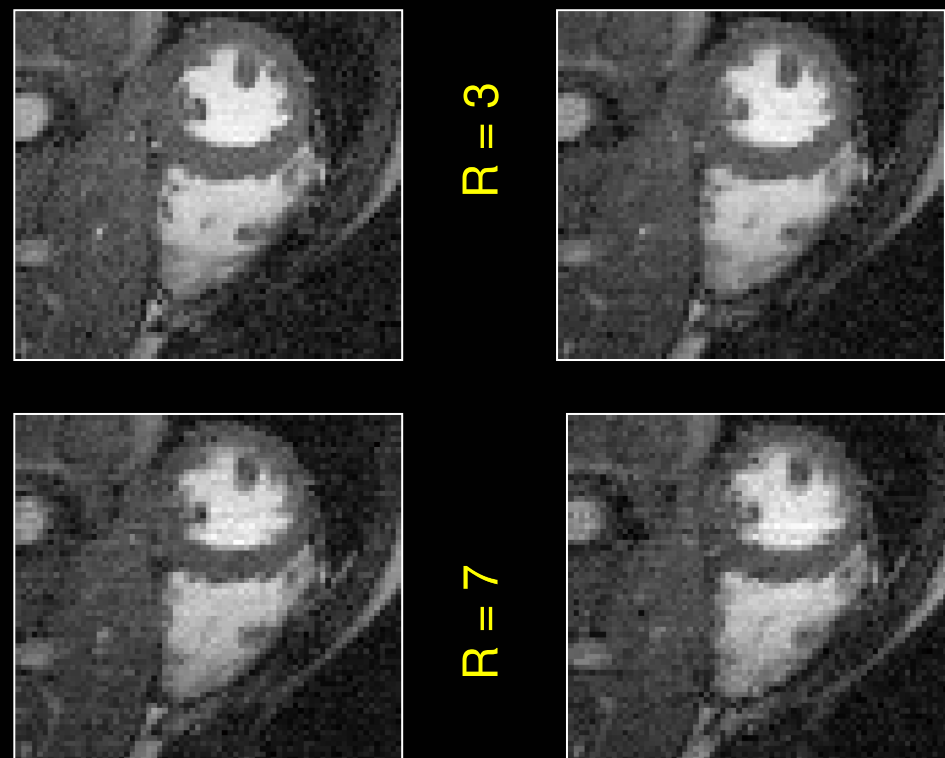
Courtesy of Drs. P. Lai (GE), M. Lustig (UC Berkeley)

kt-Group Sparse for Cine



Training data: 12.5%

kt group sparse

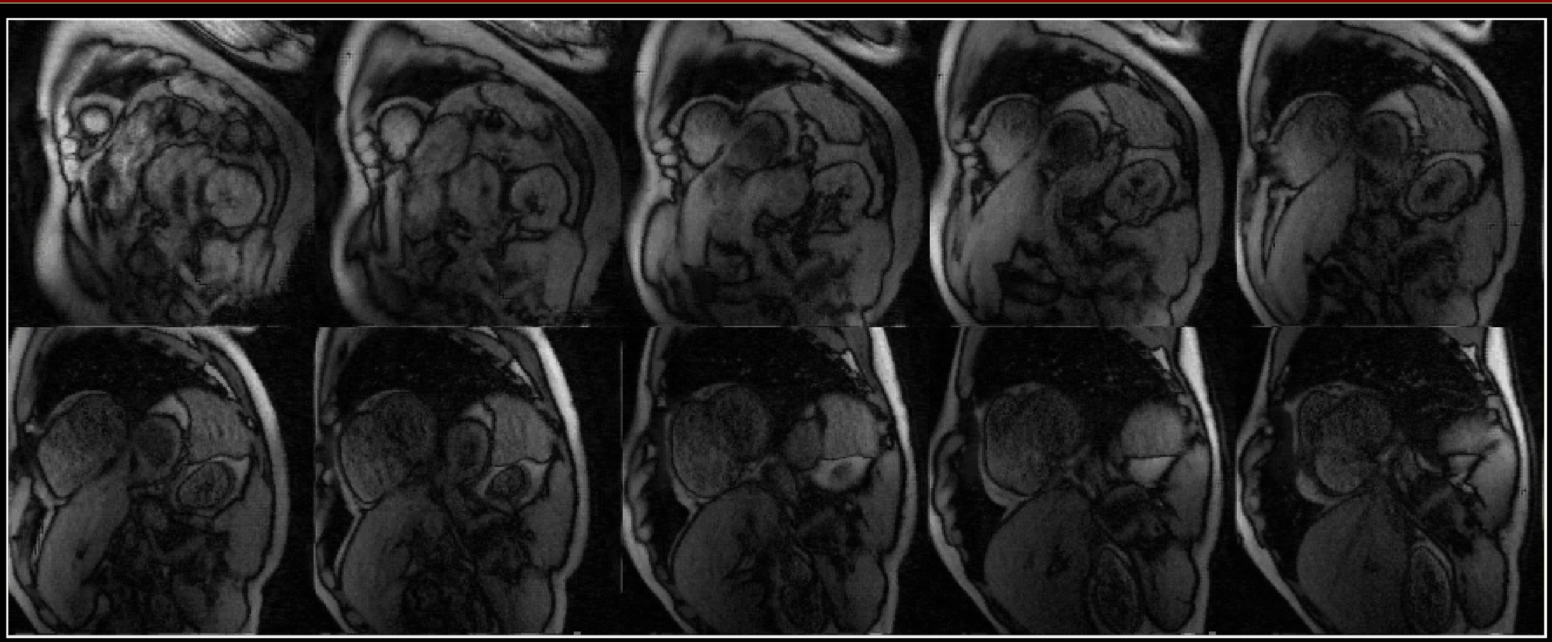


Courtesy of U. Muhammad, T. Schaeffter, KCL

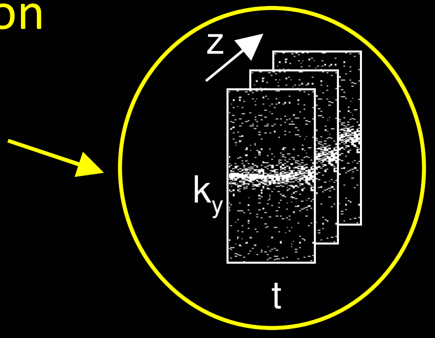
Perfusion CMR

- Images wash-in of contrast media with the blood during the initial pass through myocardium
- Used for assessment of perfusion defects
  - Diagnosis of coronary artery disease
- Accelerated imaging allows
  - Higher spatial or temporal resolution
  - Better coverage

Multislice-2D CMR Perfusion



- Multislice TurboFLASH sequence with 8-fold k_y-t acceleration
- Spatial resolution = 1.6×1.6×8 mm^3
- Temporal resolution = 60 ms



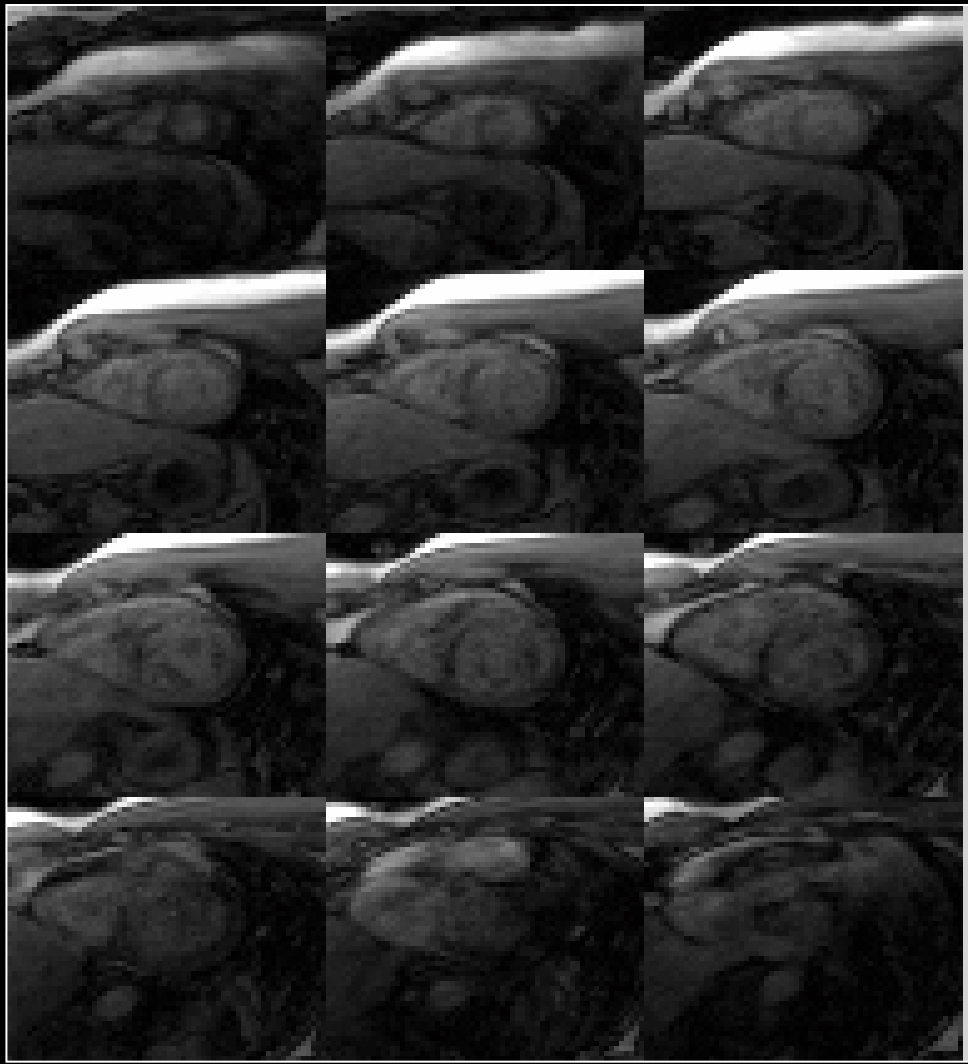
- 3T Siemens Tim Trio, 12-element coil

Courtesy of R. Otazo, D. Sodickson, NYU

3D First-Pass CMR Perfusion

- TurboFLASH sequence
- FOV = $340\times340\times100$ mm^3
- 40 dynamics
- temporal resolution = 220.8 ms
- spatial resolution = $2.7\times2.7\times8$ mm^3
- 16-fold k_y-k_z-t acceleration

- 3 Tesla Siemens Verio
- 32-channel body array

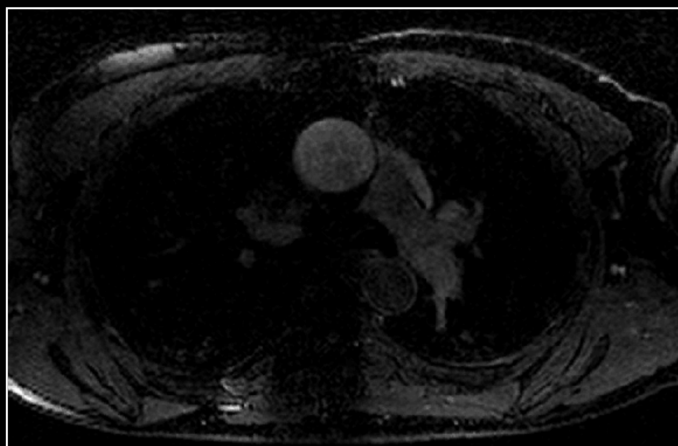


Courtesy of Drs. R. Otazo, D. Sodickson, NYU

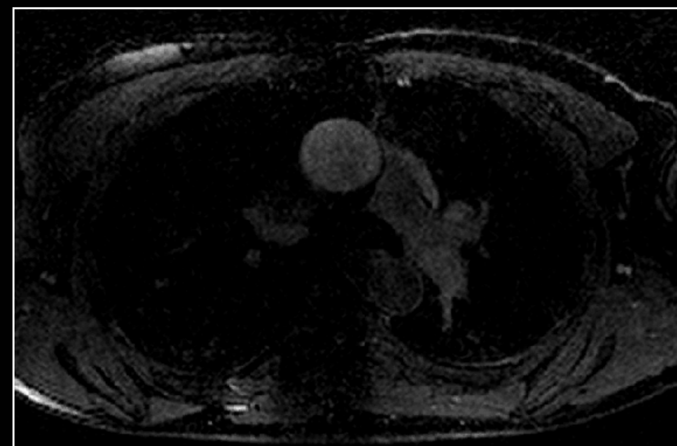
Other CMR Applications

Non-Contrast PV-MRA

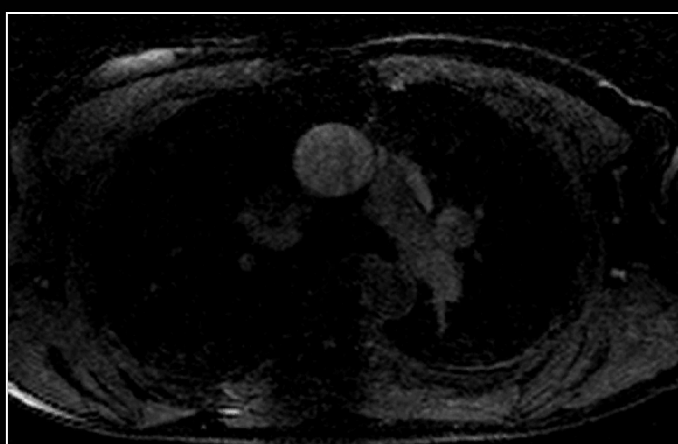
Fully Sampled



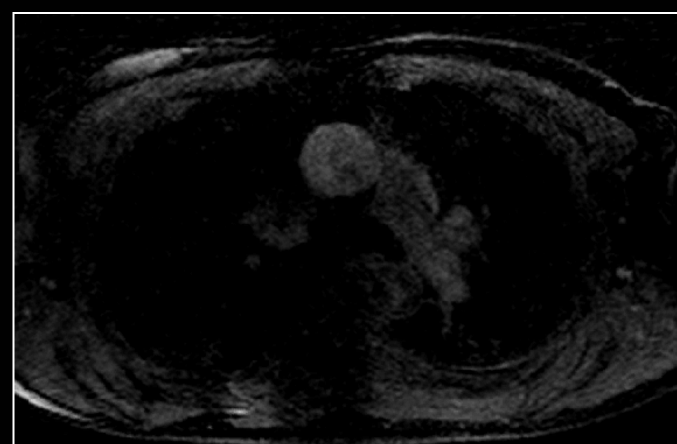
R = 2



R = 4

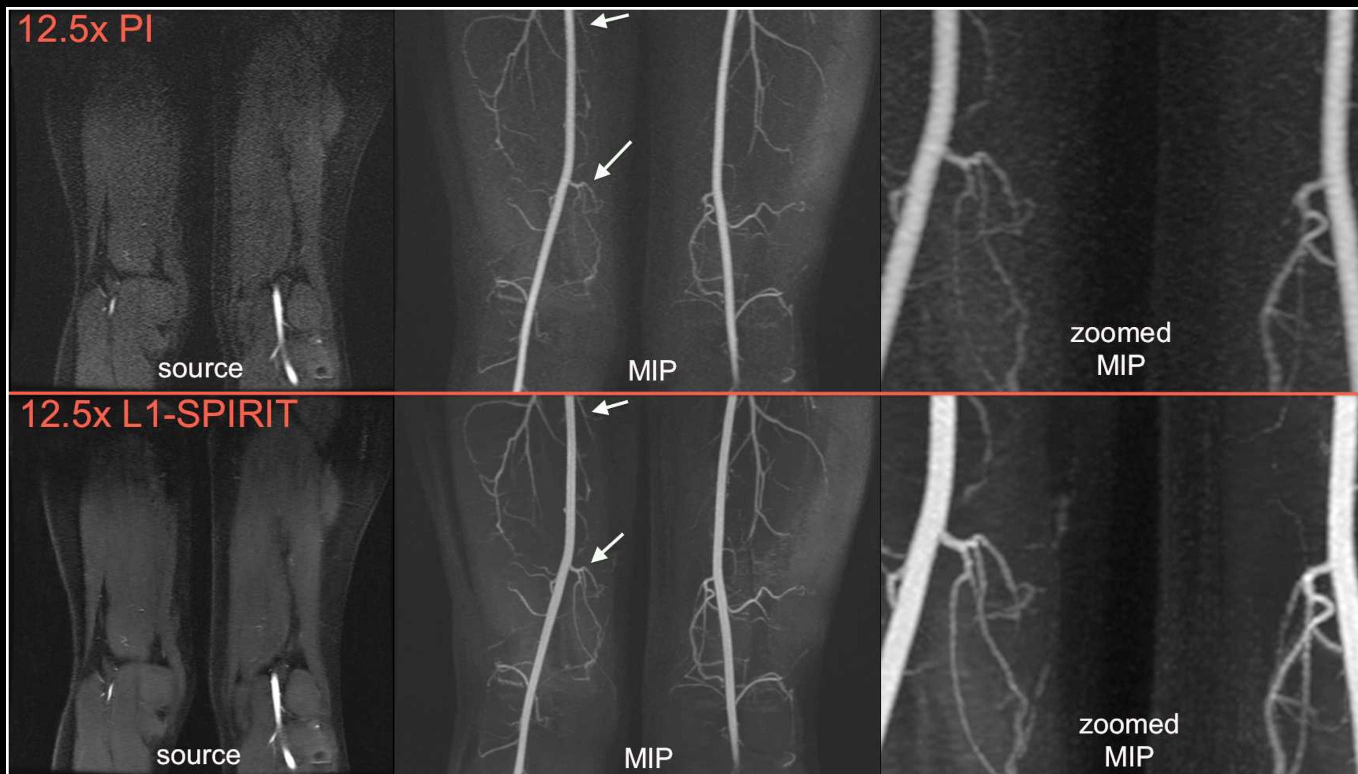


R = 6



Akcakaya, JMRI, 2011

MR Angiography with L_1-SPIRiT



Top: 12.5 fold accelerated blood-pool contrast-enhanced extremity MR angiogram in a 4 year old with a parallel imaging alone (ARC) using a dedicated 32 channel pediatric coil. 750 x 750 x 800 μm resolution. Bottom: L1-SPIRiT reconstruction recovers substantial detail, with quality rivaling a catheter angiogram. The fast scan avoids venous contamination.

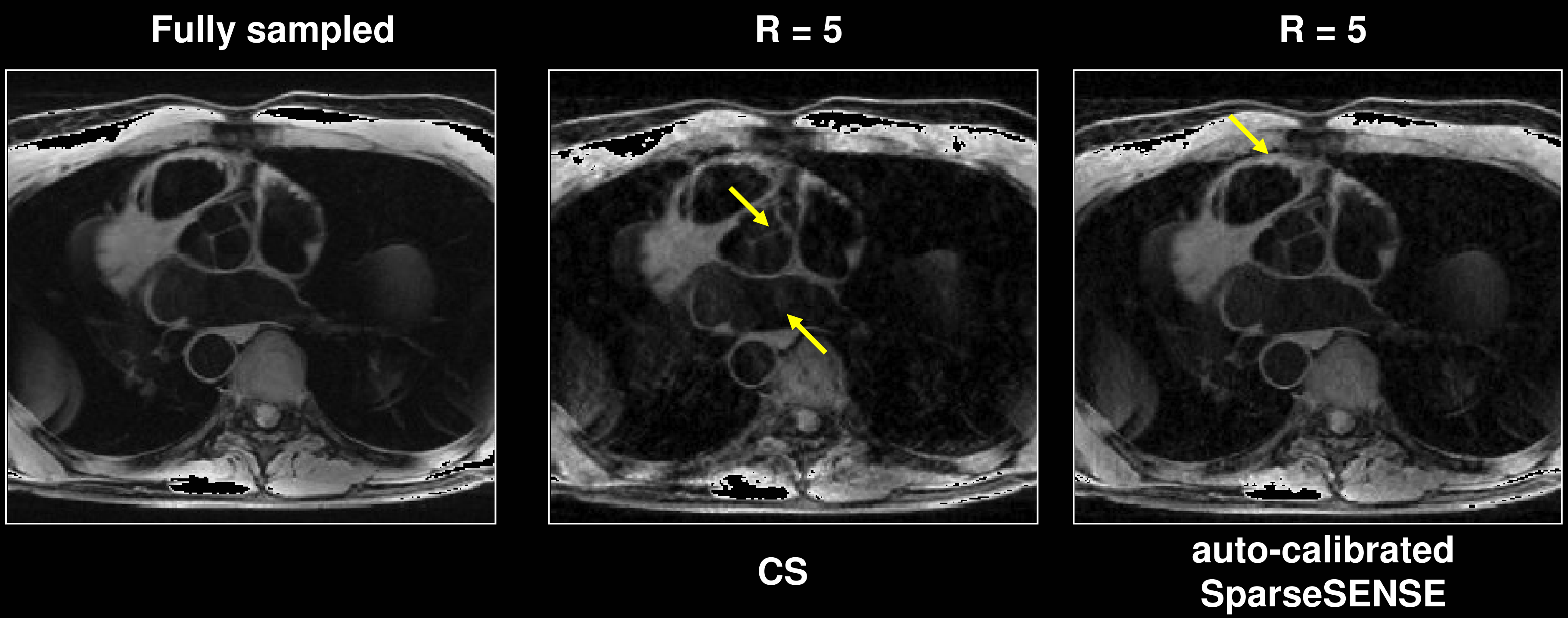
Courtesy of Drs. M. Lustig and S. Vasanawalla, Stanford

Real-Time Cine MRI

- True-FISP
- 8-fold acceleration
- Temporal resolution = 42.5 ms
- Spatial resolution = 2.3 mm

Feng et al. ISMRM 2010; 3602

CS in Black Blood CMR



Prieto, ISMRM 2010

Courtesy of Drs. C. Prieto, T. Schaeffter, R. Botnar KCL

Conclusions

- Introduced the LOST algorithm, which uses patient-specific and anatomy-specific information for improved reconstruction
- Provided an overview of applications of CS in CMR

The Future

- More clinical validation needed
- Not available by vendors
- Faster and robust reconstruction needed

§ Potential to significantly accelerate and/or improve CMR image acquisition

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