Joint Reconstruction for Phase-Cycled Balanced SSFP

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10/13/2016

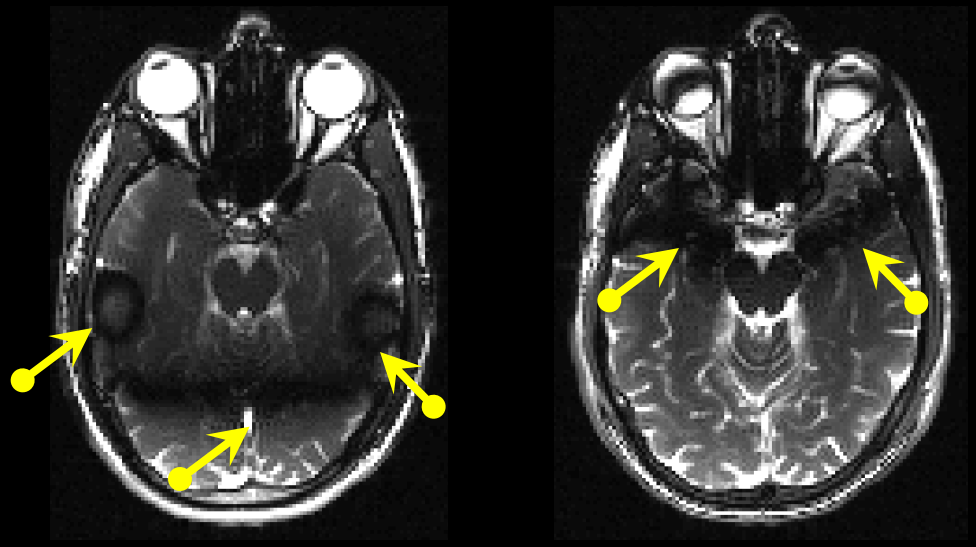
Balanced SSFP

- bSSFP has unique T2 / T1 contrast
  inherent high SNR efficiency
  fast imaging time: short TE & TR

- Provides strong contrast between tissues with different T2 / T1 ratios
  - Cardiac [1] (blood – myocardium contrast)
  - Angio [2] (blood – surrounding tissue)
  - MSK [3] (fat – muscle)
  - Neuro [4] nerves at skull base (CSF – cranial nerve)

[1] DC Peters et al MRM 2002
[2] NK Bangerter et al MRM 2011
[3] GE Gold et al JMRI 2007
[4] JW Casselman et al Am Soc Neuroradiology 1993

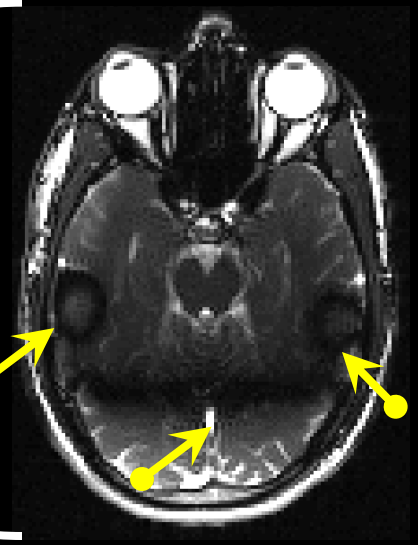
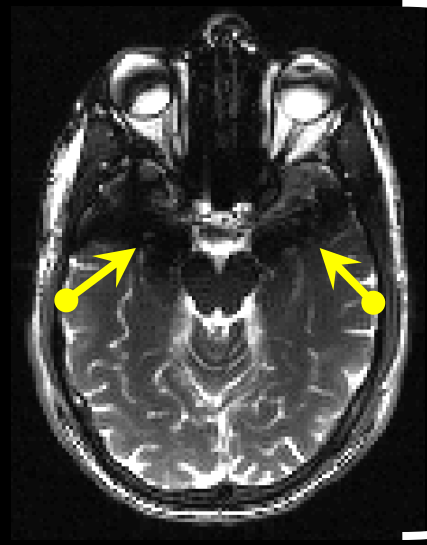
Phase-cycled bSSFP



- But suffers from banding artifacts due to sensitivity to B0 inhomogeneity
- Can be mitigated by phase-cycling:
  - multiple acquisitions with different phase increment btw successive RFs
  - this shifts location of banding artifacts

Phase-cycled bSSFP

banding-free MIP

max {  ,  } = 

- But suffers from banding artifacts due to sensitivity to B0 inhomogeneity
- Can be mitigated by phase-cycling:
  - multiple acquisitions with different phase increment btw successive RFs
  - this shifts location of banding artifacts
  - combine cycles with Max Intensity Projection (MIP)

Phase-cycled bSSFP

- Phase-cycling mitigates banding artifacts
- But increases scan time, counteracting inherent efficiency of bSSFP
- Parallel Imaging [1,2] and Simultaneous MultiSlice (SMS) [3,4] employ receiver sensitivity encoding to reduce scan time
- And have been deployed in phase-cycled bSSFP for up to 4-fold acceleration [5,6]

[1] KP Pruessmann et al MRM 1999
[2] MA Griswold et al MRM 2002
[3] DJ Larkman et al JMRI 2001
[4] FA Breuer et al MRM 2005
[5] D Stab et al MRM 2011
[6] Y Wang et al MRM 2015

Joint Recon for Phase-cycled bSSFP

- In this work, we propose to **jointly recon phase-cycled images**

- We introduce **Joint GRAPPA**:
  - recons all phase-cycles simultaneously to exploit their mutual info
  - fit GRAPPA kernels **jointly across coils and phase-cycles**
  - analogous to *k-t* in dynamic imaging [1] and *virtual coil* in diffusion imaging [2]

martinos.org/~berkin/JointGRAPPA.zip

[1] F Huang et al MRM 2005
[2] E Dai et al MRM 2016

Joint Recon for Phase-cycled bSSFP

- In this work, we propose to **jointly recon phase-cycled images**

- We introduce **Joint GRAPPA**:

  - by creating virtual coils out of the phase-cycles,

    converts banding artifacts into useful, additional spatial encoding

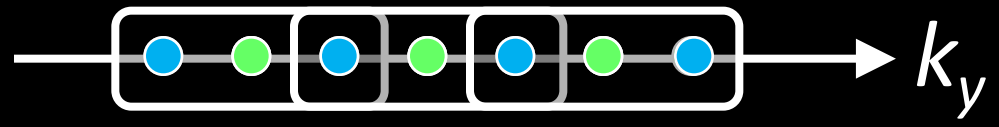
  - reduction in g-factor noise amplification is > 1.5-fold relative to GRAPPA

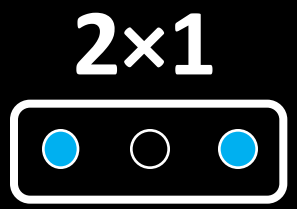
    i.e. SNR improvement is similar to 2 averages of GRAPPA recon

martinos.org/~berkin/JointGRAPPA.zip

GRAPPA Recon

- R=2 acceleration, ignoring coil and readout axes

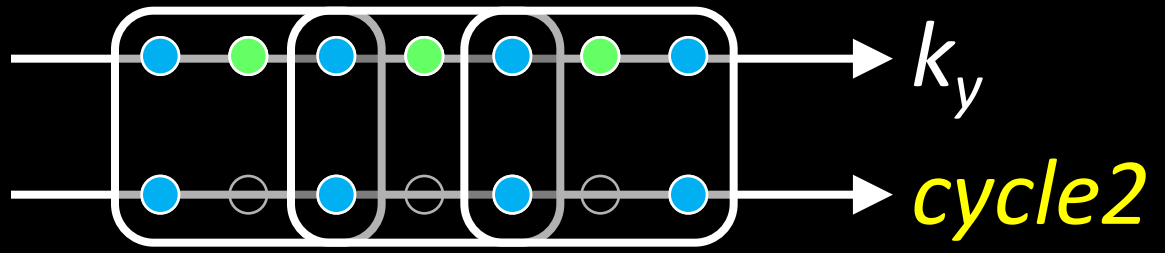


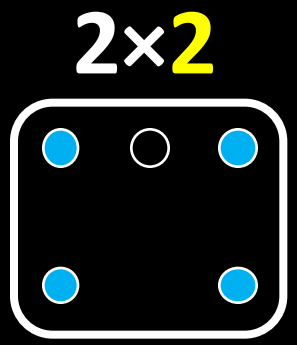


martinos.org/~berkin/JointGRAPPA.zip

Proposed: Joint GRAPPA

- R=2 acceleration, ignoring coil and readout axes

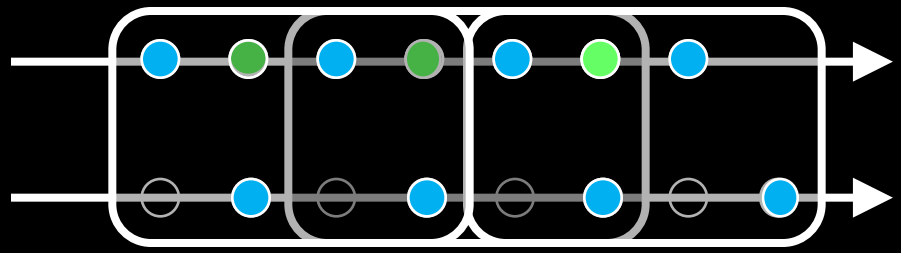




martinos.org/~berkin/JointGRAPPA.zip

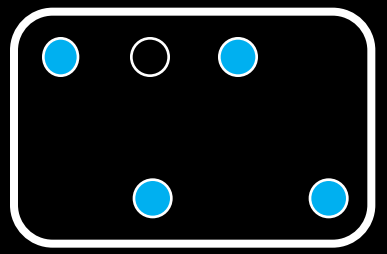
Proposed: Joint GRAPPA

- R=2 acceleration, ignoring coil and readout axes
- Staggered sampling for complementary k-space info:



cycle2

staggered



martinos.org/~berkin/JointGRAPPA.zip

Data Acquisition @ 3T

1. **Breath-hold abdominal imaging:**
   - 5 mm thick slice, four cycles {0, π/2, π, 3π/2}
   - FOV = 380×380 mm^2, mtx = 160×160
   - TR/TE = 3.3/1.54 ms, 34-chan

2. **Neuroimaging: 2D**
   - 4.5 mm thick slice, four cycles
   - FOV = 240×240 mm^2, mtx = 160×160
   - TR/TE = 3.37/1.57 ms, 32-chan

3. **Neuroimaging: SMS**
   - 8 slices acquired separately, then collapsed
   - FOV/4 slice shift

martinos.org/~berkin/JointGRAPPA.zip

Data Reconstruction @ 3T

- GCC coil compression to 12 channels [1]
- Kernels estimated with Tikhonov regularization from 32 ACS lines
- Regularization and kernel sizes optimized for best RMSE
- G-factor from 300 Monte-Carlo iterations [2]

martinos.org/~berkin/JointGRAPPA.zip

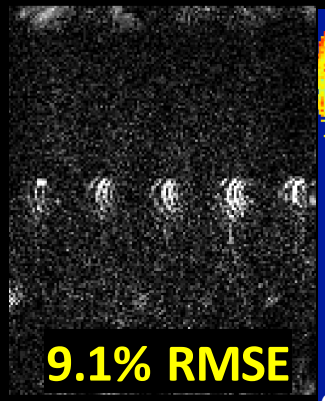
[1] T Zhang et al MRM 2013
[2] FA Breuer et al MRM 2009

Abdominal 2D acquisition

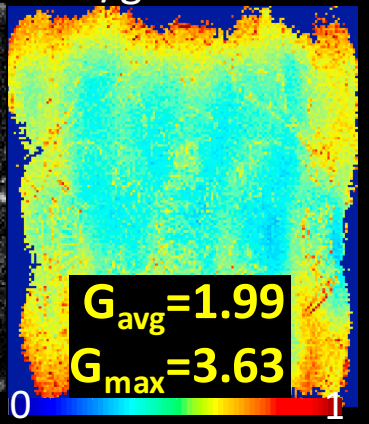
four cycles, Acceleration R=6

GRAPPA

Error scaled 5×



1/g-factor

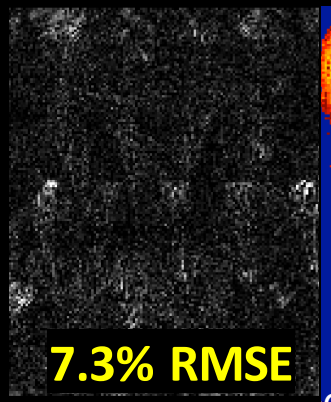


Abdominal 2D acquisition

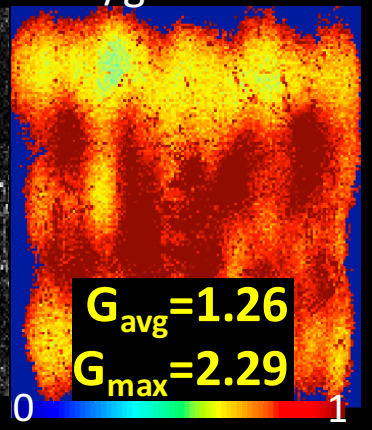
four cycles, Acceleration R=6

Proposed: Joint GRAPPA

Error scaled 5×



1/g-factor

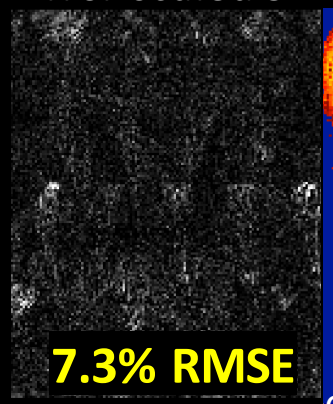


Abdominal 2D acquisition

four cycles, Acceleration R=6

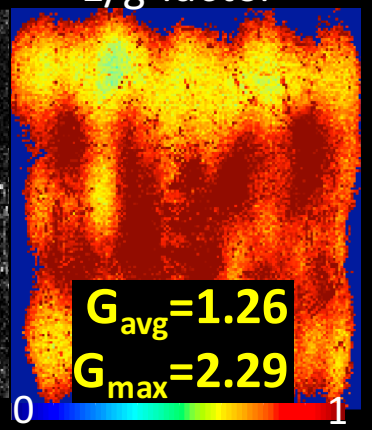
Proposed: Joint GRAPPA

Error scaled 5×



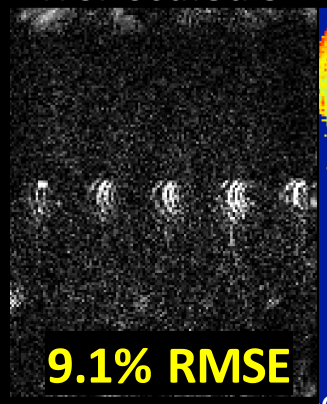
7.3% RMSE

1/g-factor



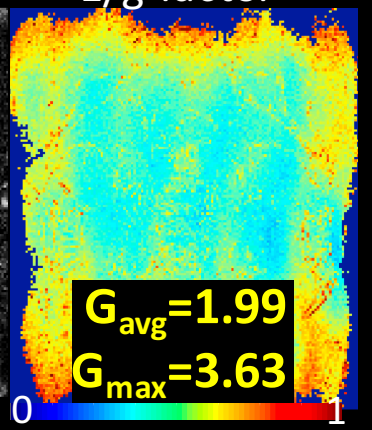
GRAPPA

Error scaled 5×



9.1% RMSE

1/g-factor



RMSE reduced 25%

G_{max} reduced 1.6-fold

G_{avg} reduced 1.6-fold

SNR improvement is >2 averages of GRAPPA

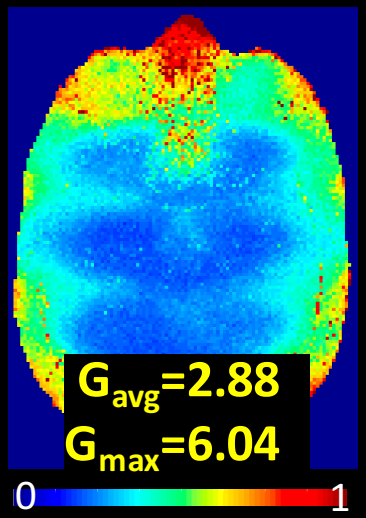
Neuro 2D acquisition

four cycles, Acceleration R=6

GRAPPA

10.0% RMSE

1/g-factor



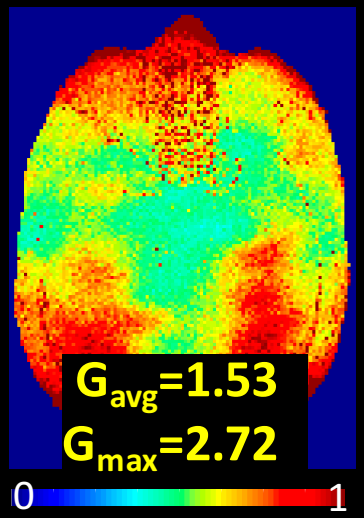
Neuro 2D acquisition

four cycles, Acceleration R=6

Joint GRAPPA

6.8% RMSE

1/g-factor



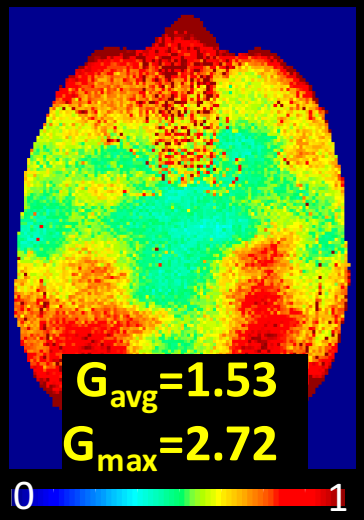
Neuro 2D acquisition

four cycles, Acceleration R=6

Joint GRAPPA

6.8% RMSE

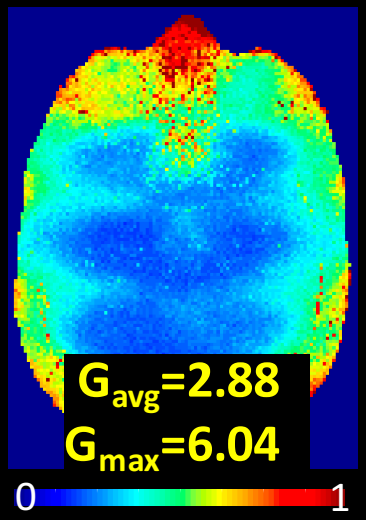
1/g-factor



GRAPPA

10.0% RMSE

1/g-factor



RMSE reduced 47%

G_{max} reduced 2.2-fold

G_{avg} reduced 1.9-fold

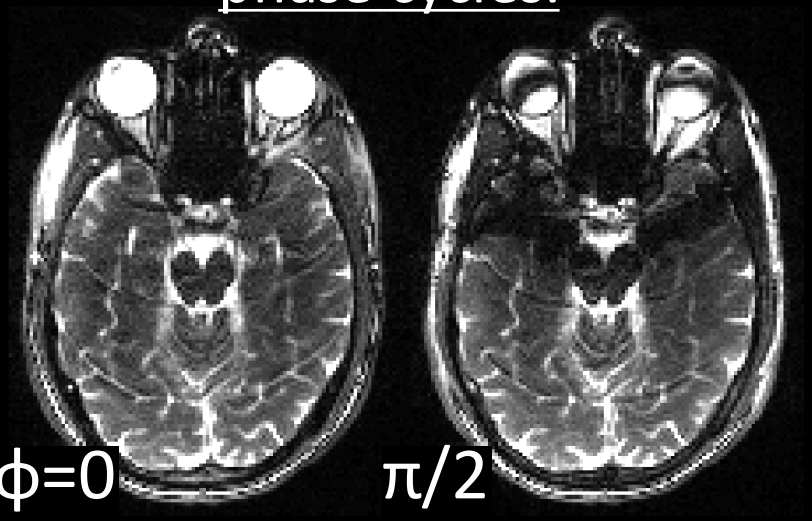
SNR improvement is >2 averages of GRAPPA

Neuro 2D acquisition

four cycles, Acceleration R=6

Joint GRAPPA

phase cycles:

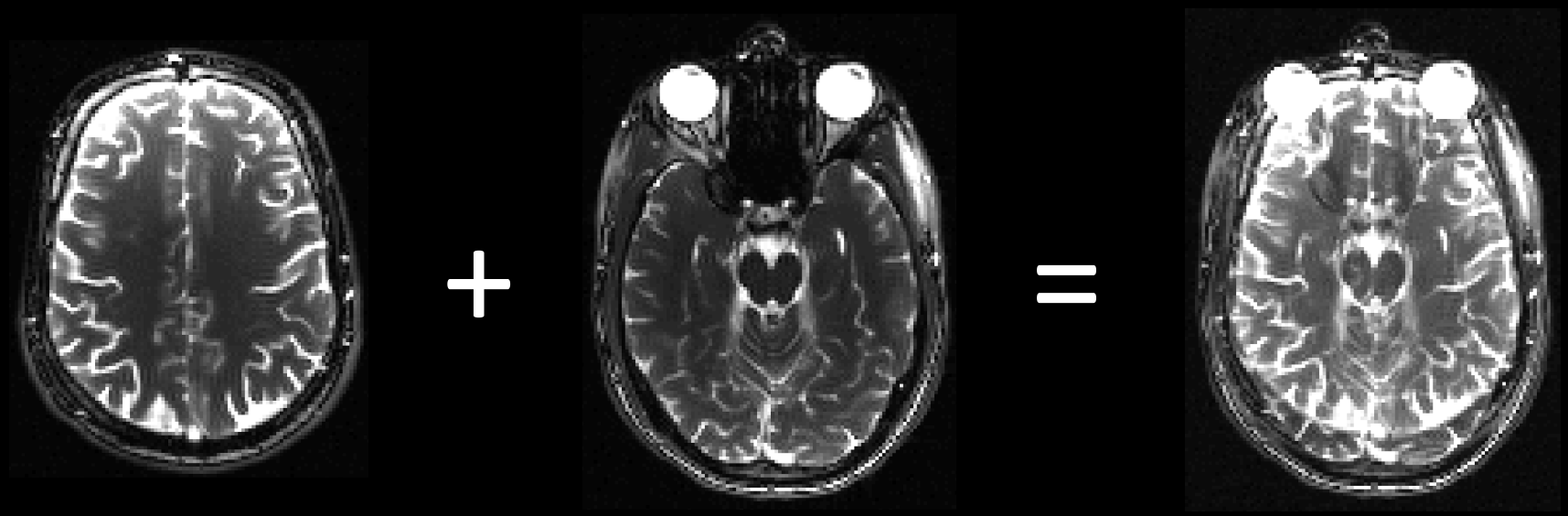


GRAPPA

phase cycles:

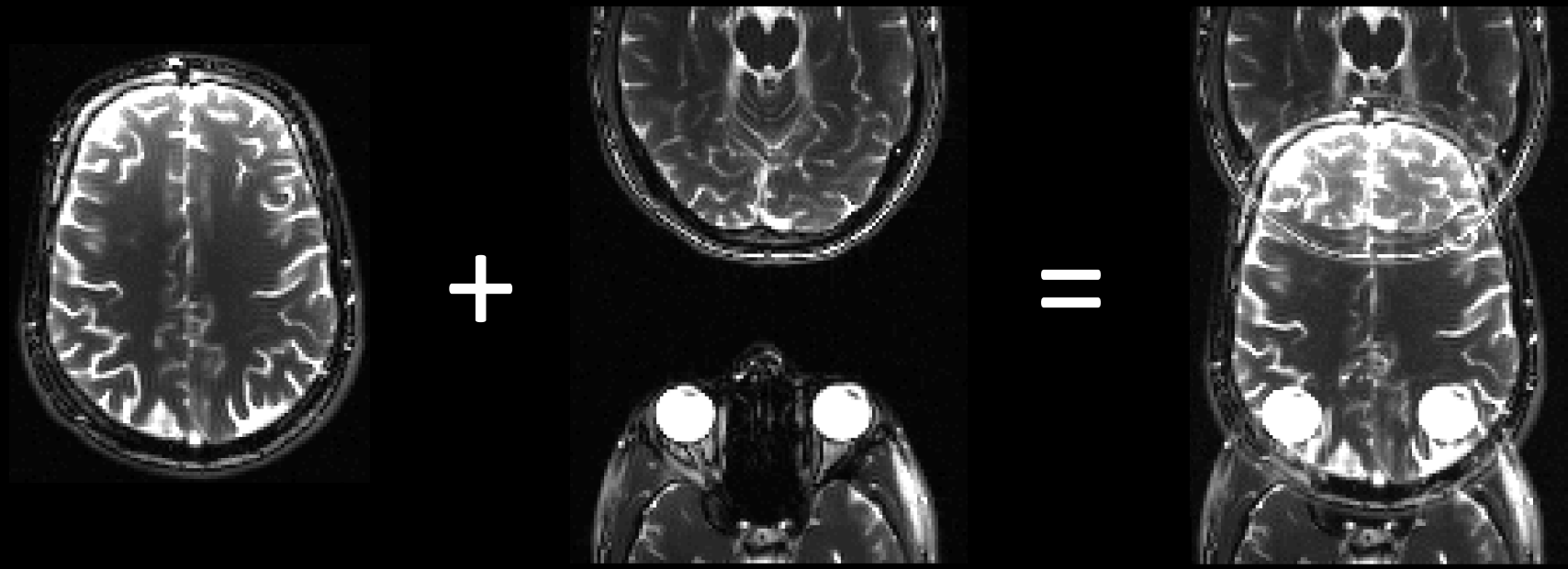
Simultaneous MultiSlice bSSFP

- SMS: simultaneously excite and encode multiple slices



Simultaneous MultiSlice bSSFP

- SMS: simultaneously excite and encode multiple slices
- Incur FOV shift across slices to improve parallel imaging



$\phi_{rf}=3\pi$

$\phi_{rf}=2\pi$

$\phi_{rf}=\pi$

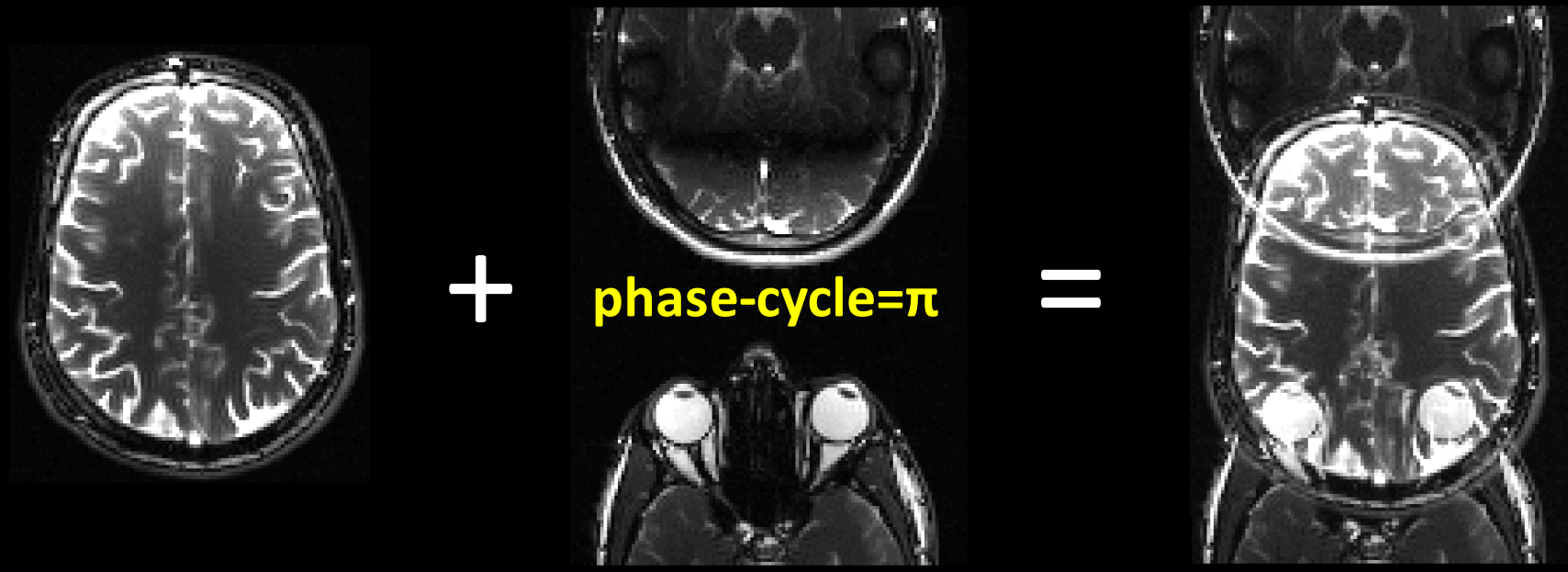
$\phi_{rf}=0$

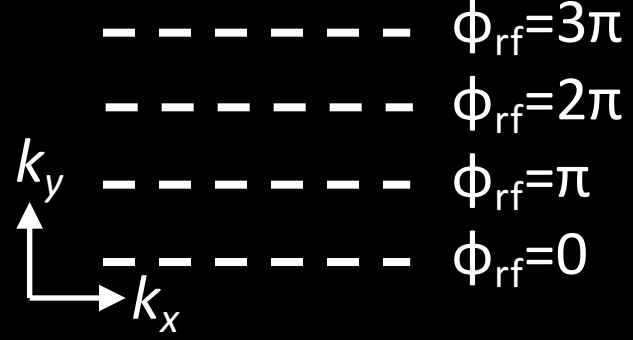
k_y

k_x

Simultaneous MultiSlice bSSFP

- SMS: simultaneously excite and encode multiple slices
- Incur FOV shift across slices to improve parallel imaging

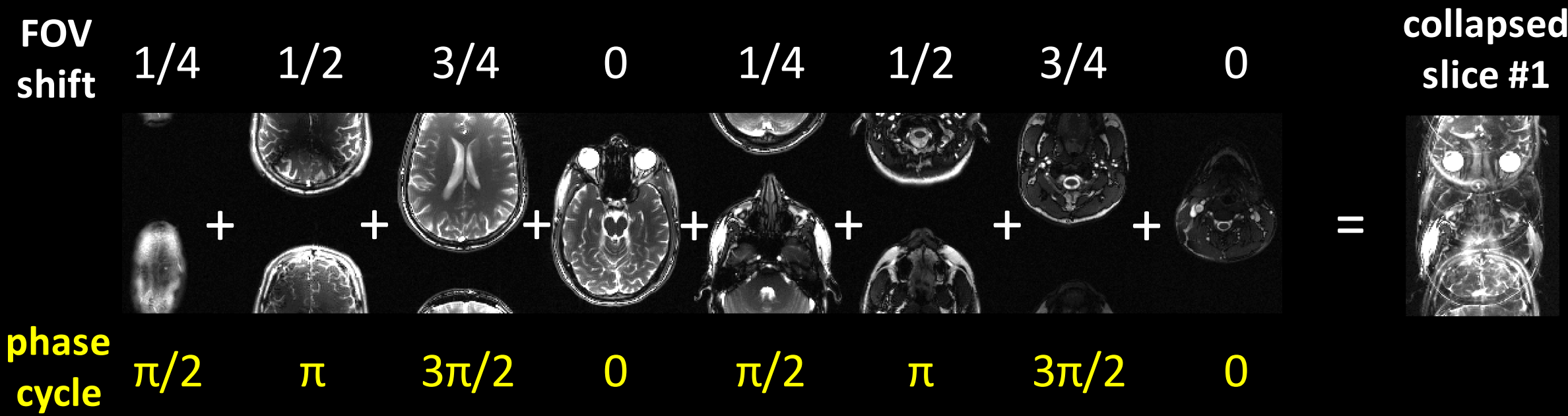




FOV/2 slice shift also causes off-resonance shift by π

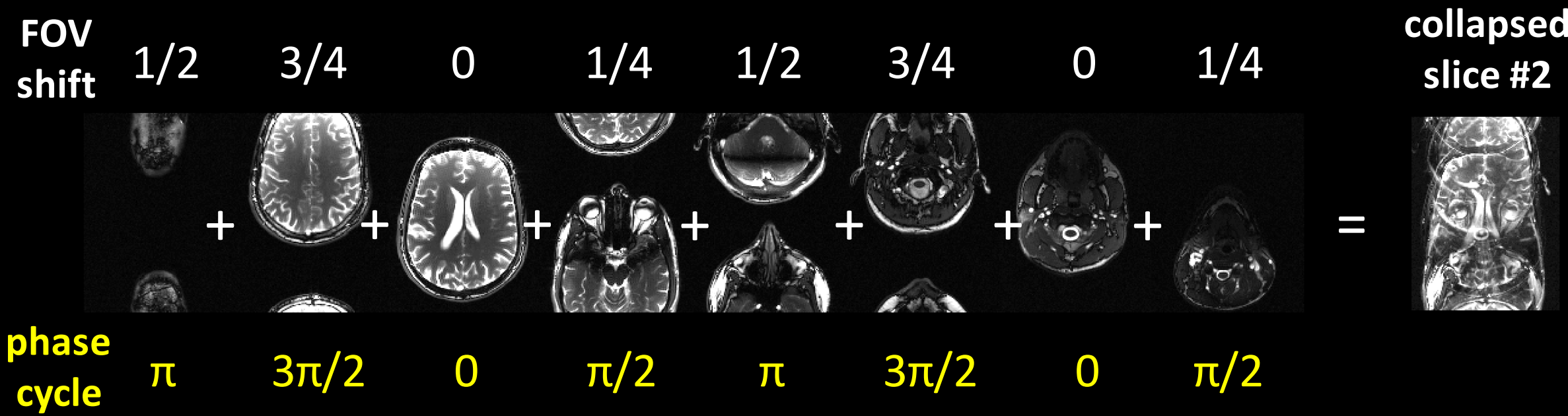
Simultaneous MultiSlice bSSFP @ MultiBand=8

- At MultiBand=8, each collapsed slice has contribution from four phase-cycles:



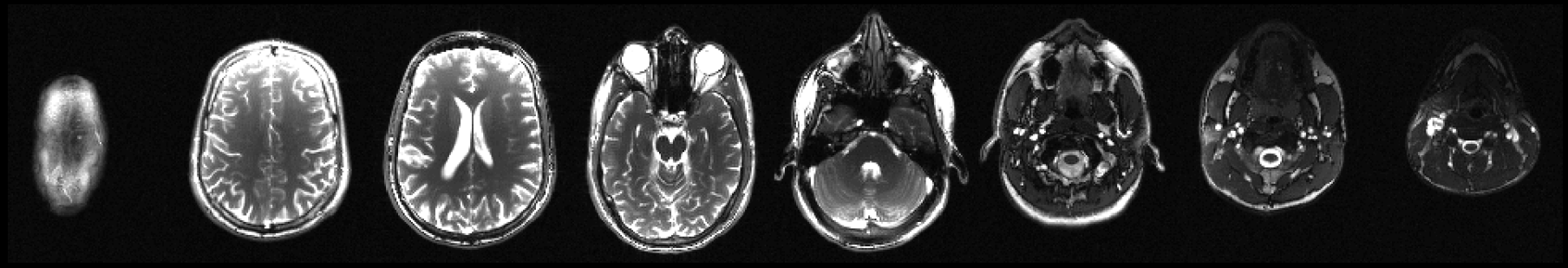
Simultaneous MultiSlice bSSFP @ MultiBand=8

- At MultiBand=8, each collapsed slice has contribution from four phase-cycles:



Simultaneous MultiSlice bSSFP @ MultiBand=8

- At MultiBand=8, each collapsed slice has contribution from four phase-cycles
- After unaliasing collapsed slices and shifting slices back, apply MIP combination:

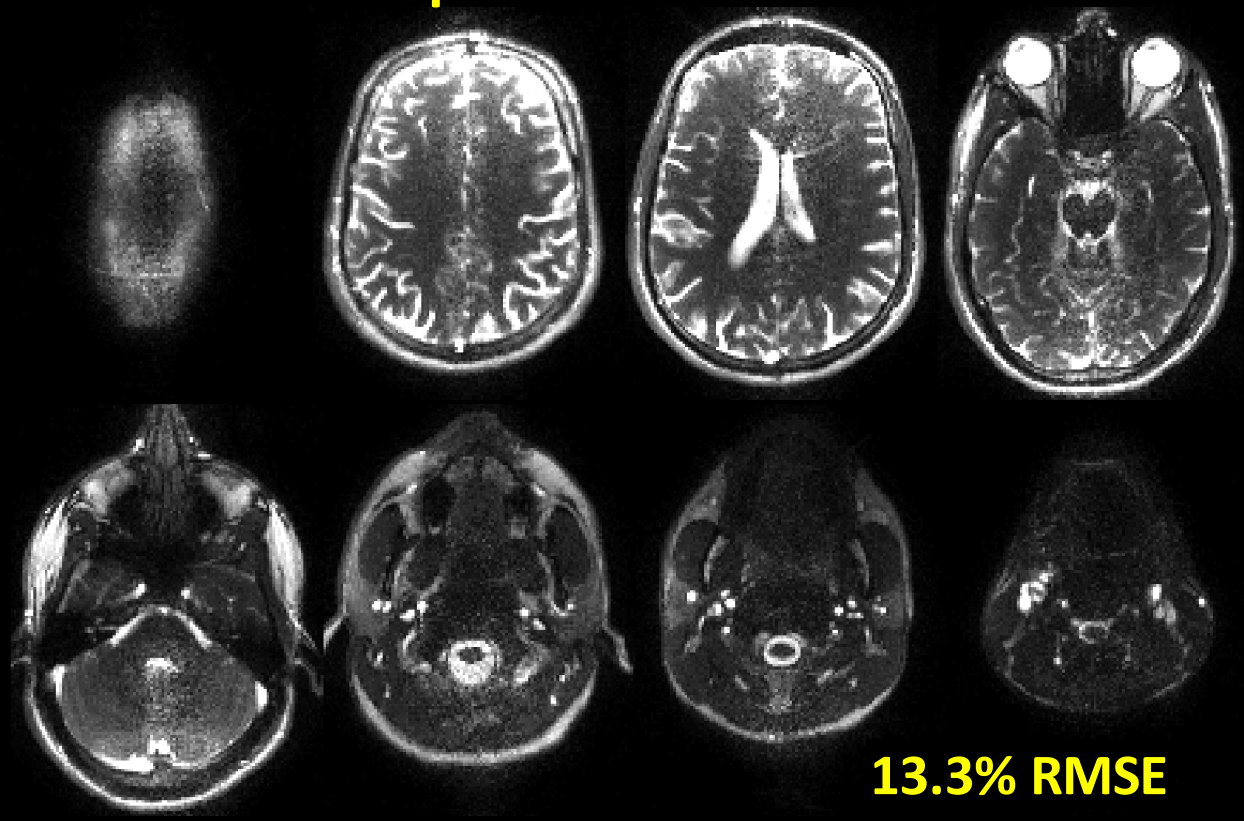


MIP combination

Neuro SMS acquisition

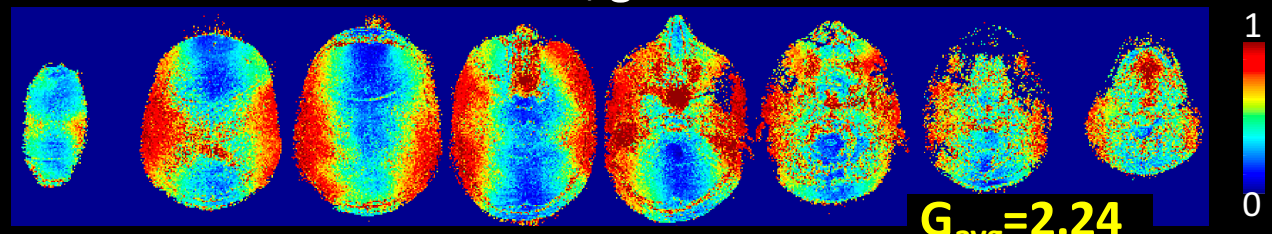
four cycles, MultiBand = 8

Split Slice GRAPPA



13.3% RMSE

1/g-factor



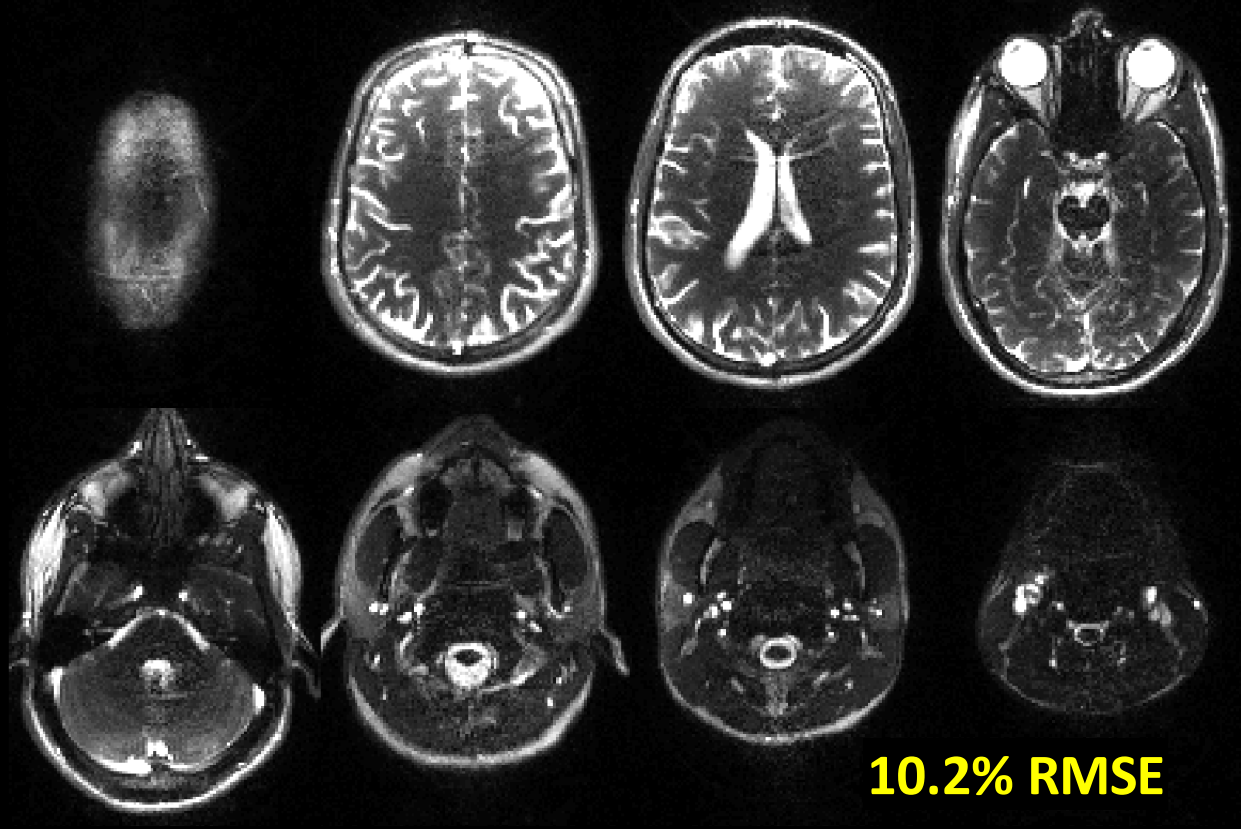
G_{avg}=2.24

G_{max}=36.17

Neuro SMS acquisition

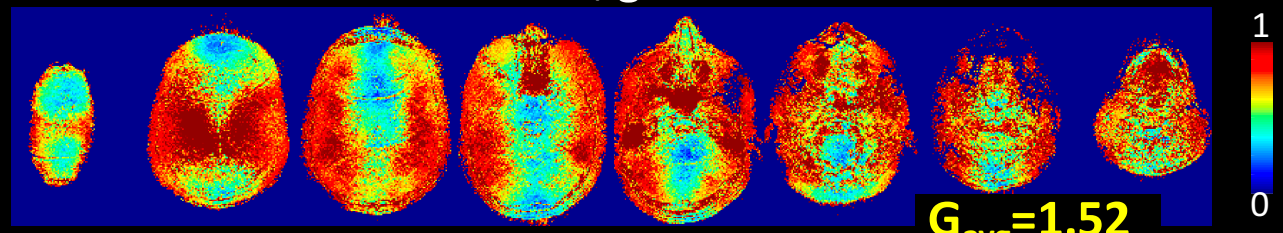
four cycles, MultiBand = 8

Joint Slice GRAPPA



10.2% RMSE

1/g-factor



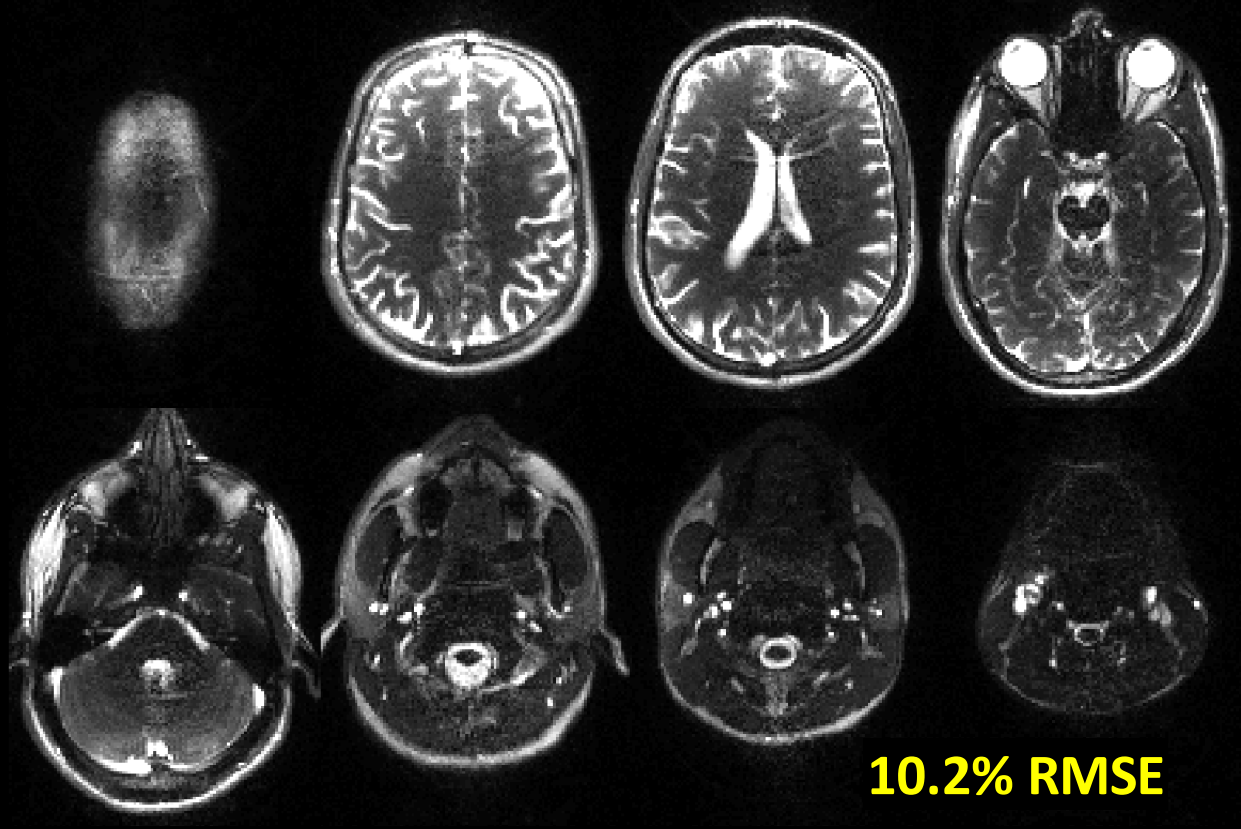
G_{avg}=1.52

G_{max}=10.23

Neuro SMS acquisition

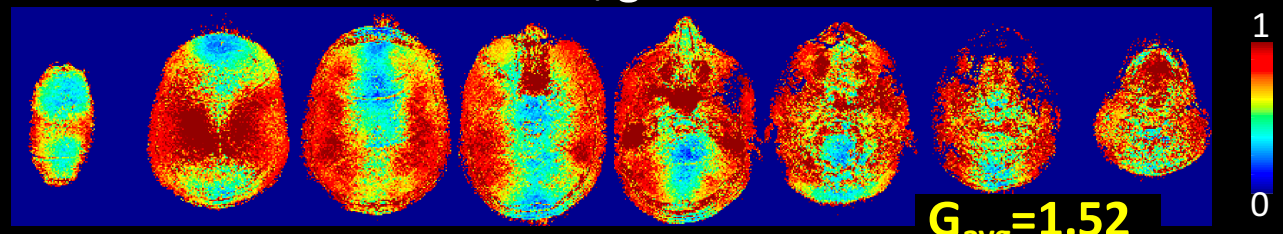
four cycles, MultiBand = 8

Joint Slice GRAPPA



10.2% RMSE

1/g-factor



G_{avg}=1.52

G_{max}=10.23

RMSE reduced 30%

G_{max} reduced 3.5-fold

G_{avg} reduced 1.5-fold

SNR improvement is ~2 averages of GRAPPA

Conclusion

- Joint GRAPPA improves parallel imaging for phase-cycled bSSFP, with substantial reduction in noise amplification and recon error
- This allows high acceleration to mitigate scan time burden of phase-cycling
- **Limitations include:**
  - Cycles need to be registered for joint recon → gating, breath-hold
  - No of kernels scale with (no of cycles)^2 → smaller no of GCC channels
- **Extension:**
  - Compressed Sensing with joint regularization over phase-cycles

Thanks!

Questions / Comments:

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Support: NIH R24 MH106096
R01 EB020613
R01 EB017337
U01 HD087211