Accelerated Imaging Strategies for Combined Spin and Gradient Echo (SAGE) Acquisitions

July 26, 2021

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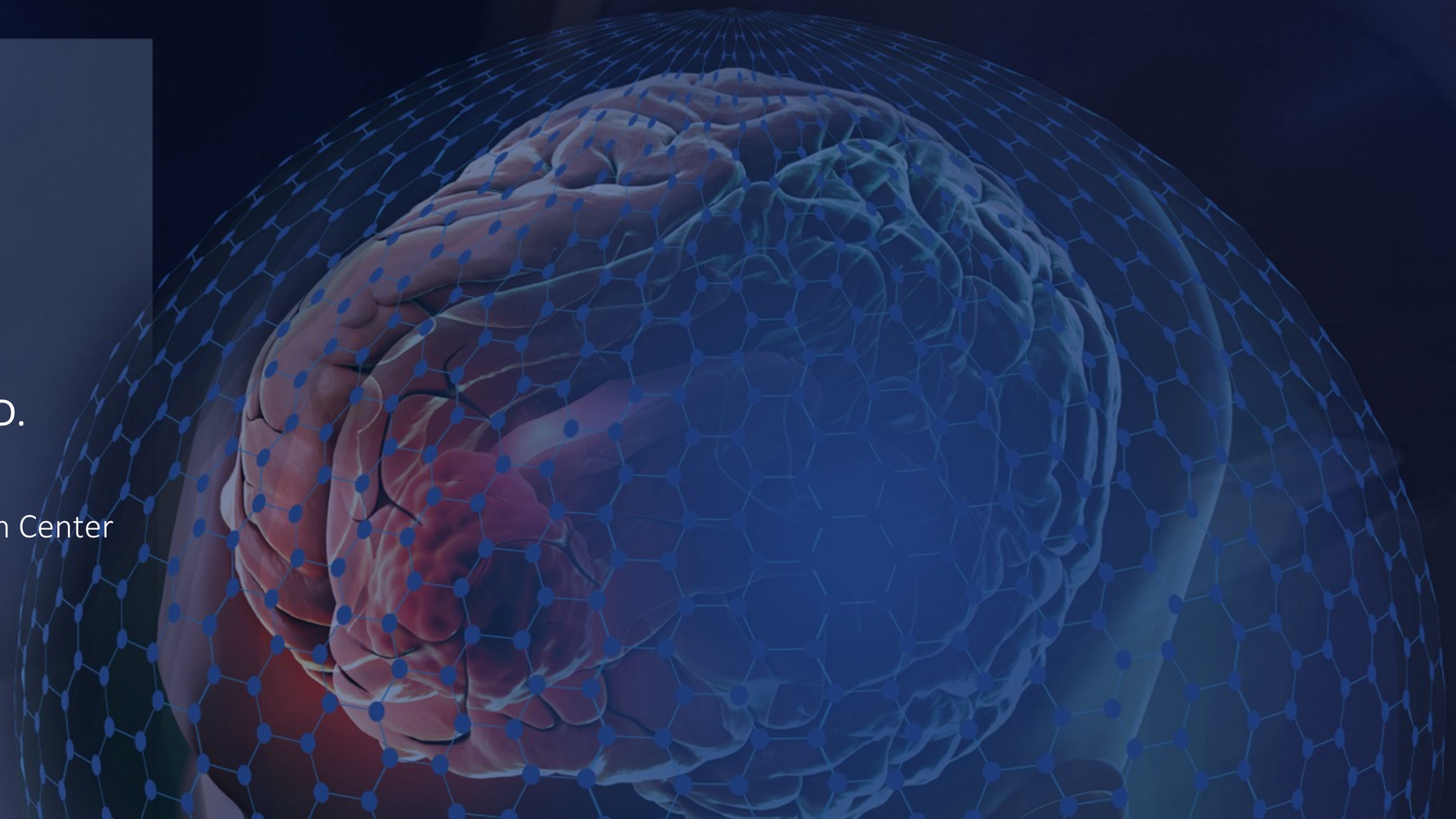
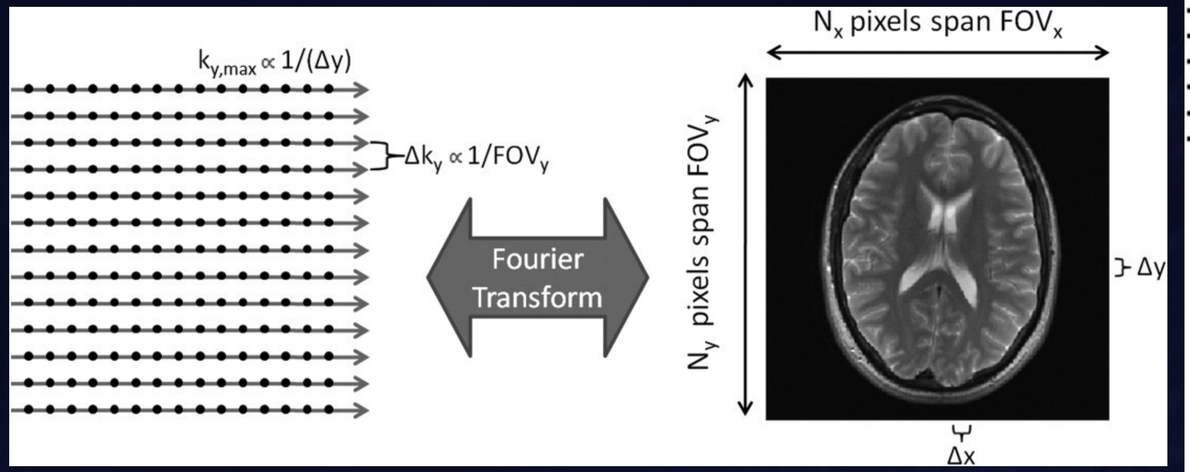
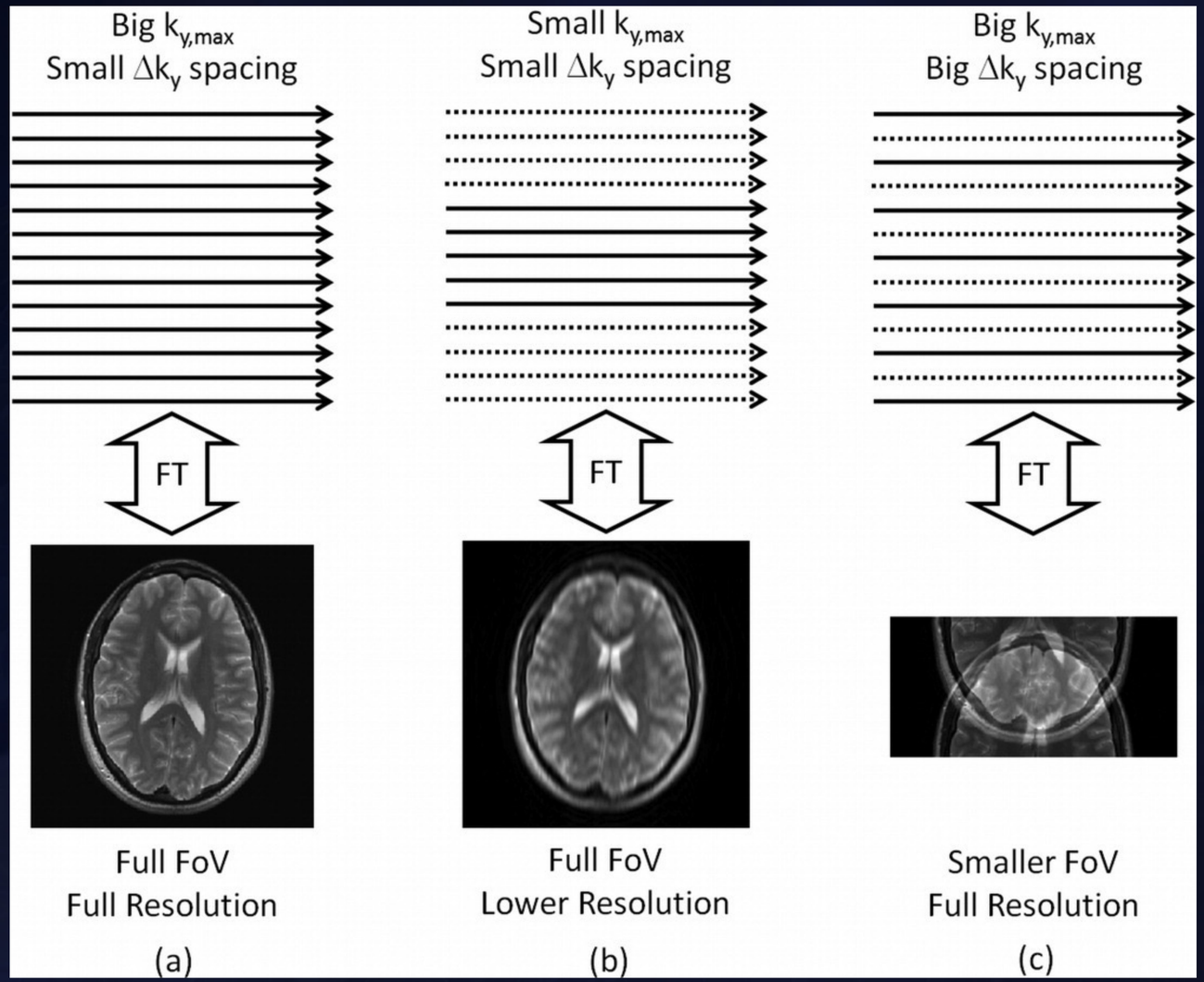


Outline

- Parallel imaging review
- Clinical DSC MRI
- SAGE as an alternative to single echo DSC MRI
  - SMS/MB + SENSE/GRAPPA
- Other SAGE implementations
- Summary

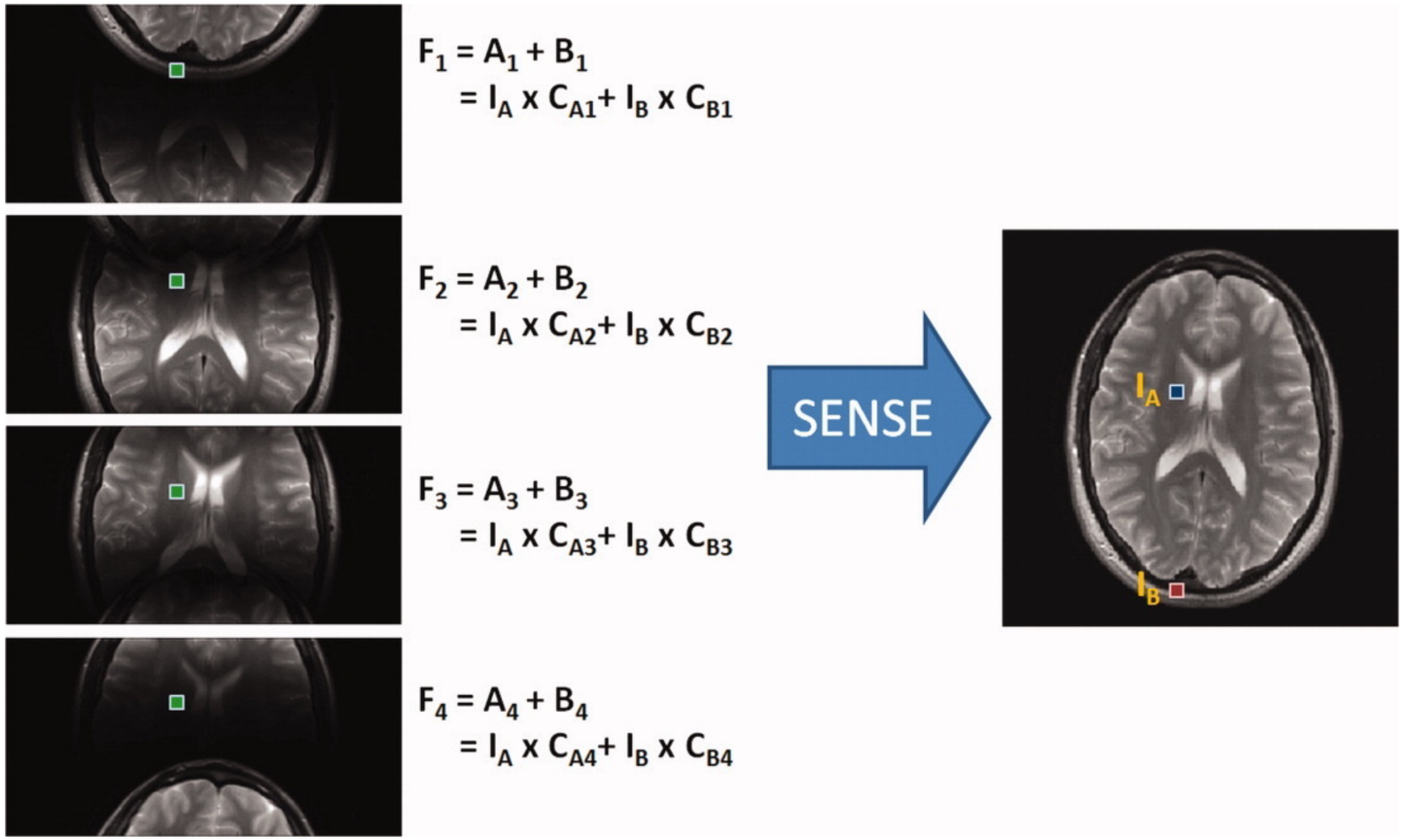
Parallel Imaging Review





Journal of Magnetic Resonance Imaging, Volume: 36, Issue: 1, Pages: 55-72, First published: 13 June 2012, DOI: (10.1002/jmri.23639)

SENSE



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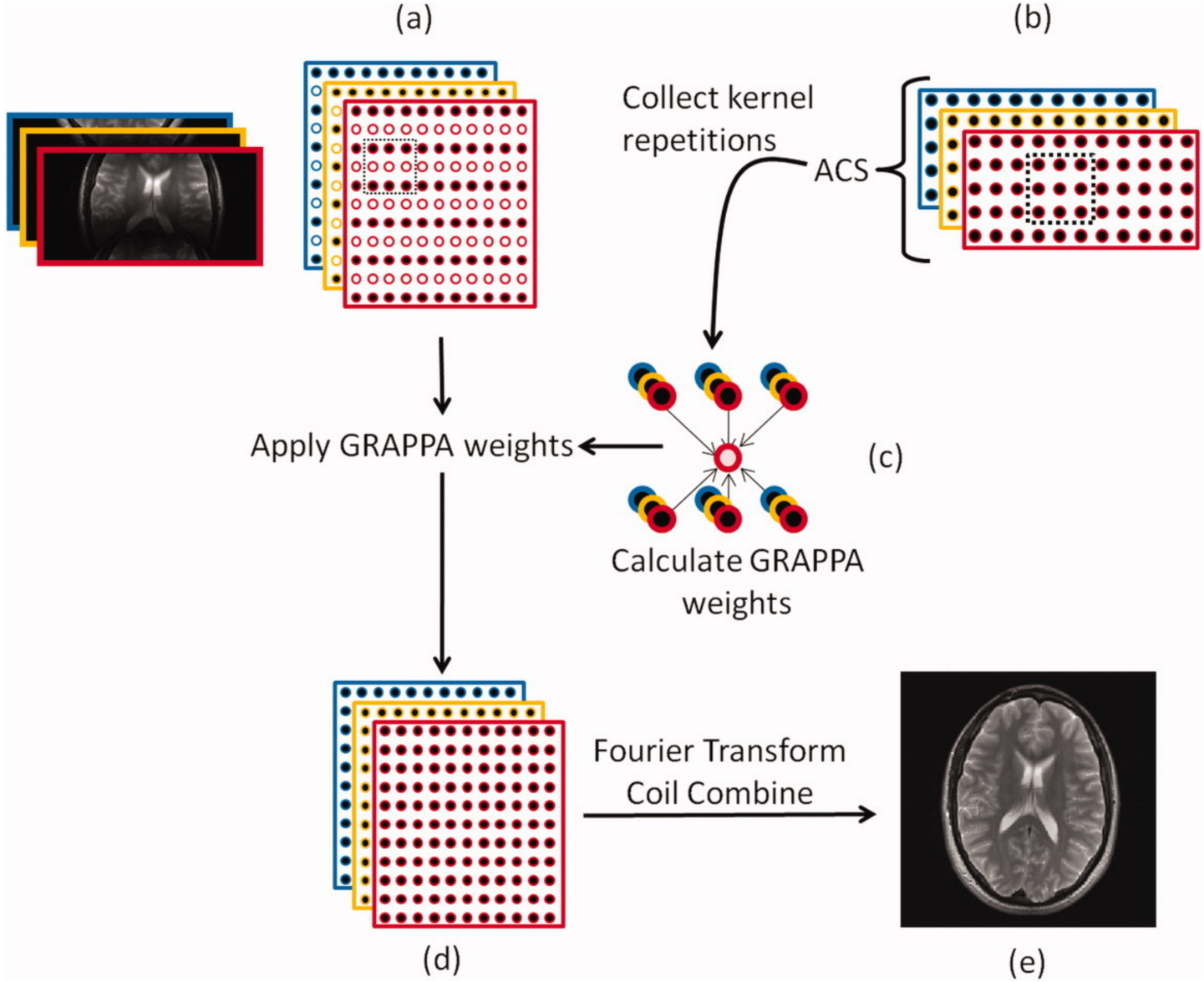
GRAPPA



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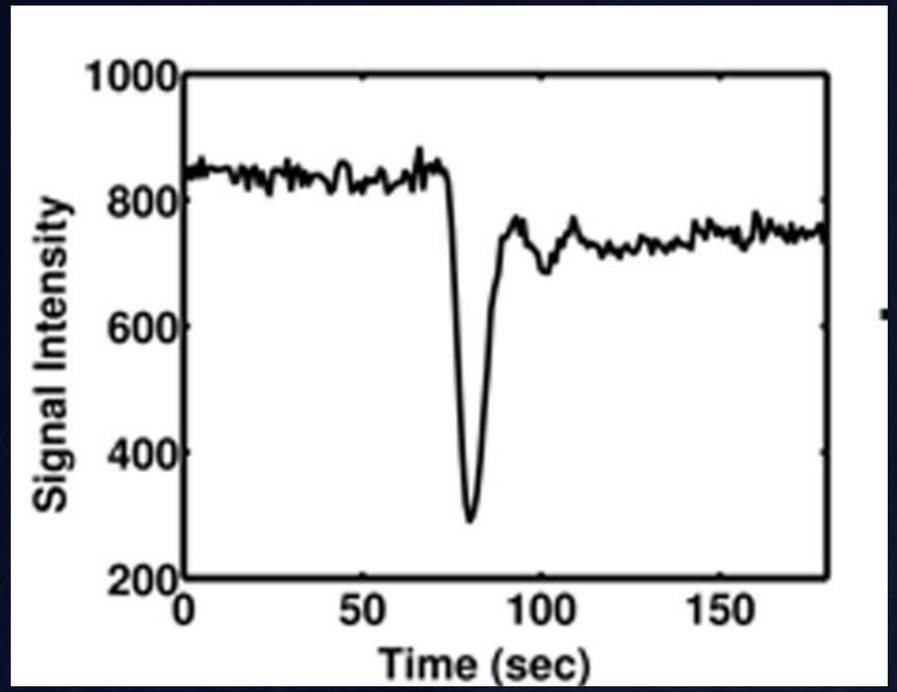
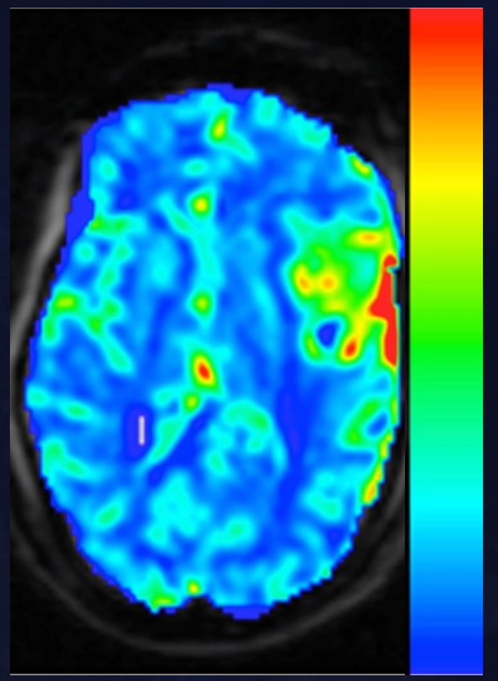
Clinical Perfusion using DSC MRI

Inject CA

Dynamic Imaging

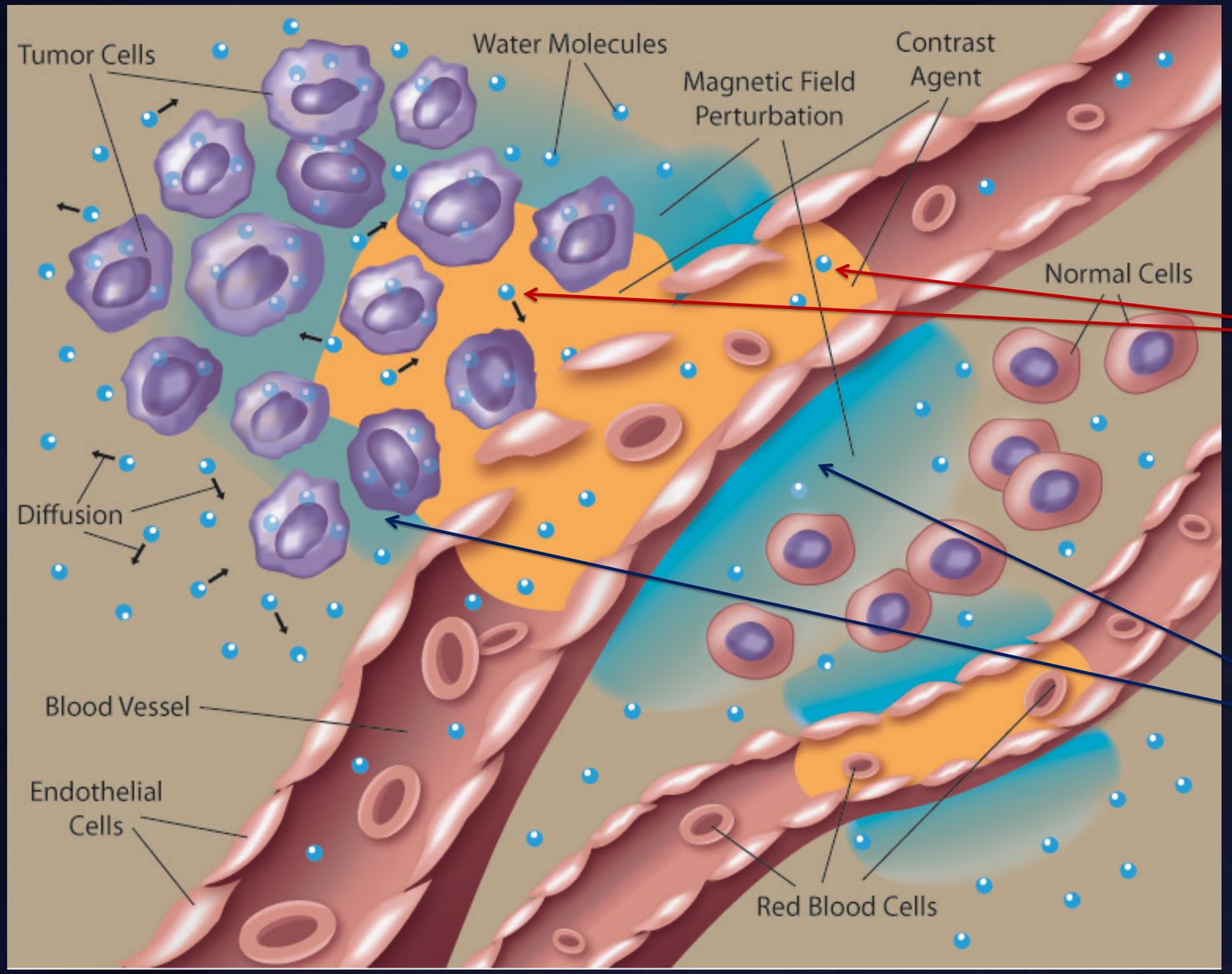
Kinetic Analysis





Blood Volume

Slide Courtesy : C Chad Quarles PhD, Barrow Neurological Institute



T_1 effects

(direct interaction)

T_2^* effects

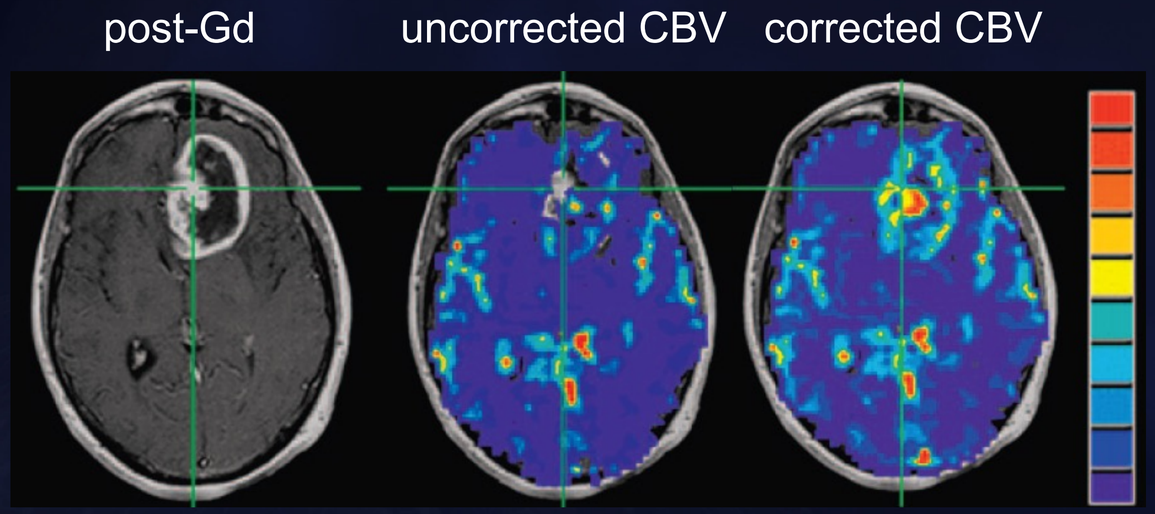
(through space)

Slide Courtesy : C Chad Quarles PhD, Barrow Neurological Institute

Clinical challenge: contrast agent leakage

- Mitigate leakage effects
  - Leakage correction [1]
  - Preload dosing
    (requires two contrast injections)

- Standardized DSC-MRI protocols [2]
  - Longer TEs (25-35ms)
  - Moderate TRs (<1.5s)
  - Moderate flip angles (FA, 60-70°)
  - Preload dose: ⇩ sensitivity to T_1 leakage effects



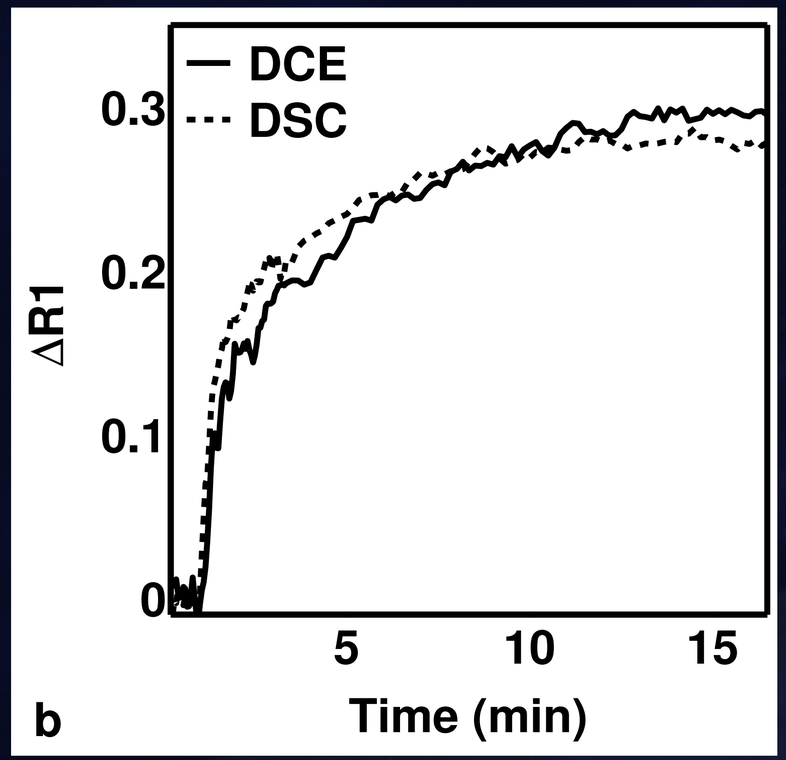
Standard DSC-MRI Protocol:

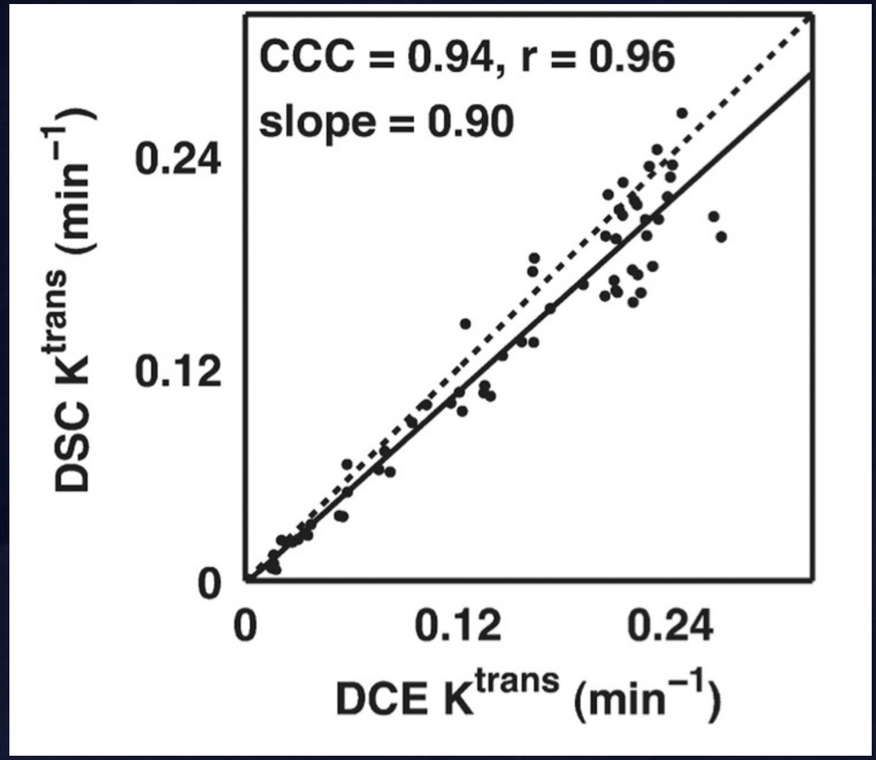
[1] Boxerman JL, et al. AJNR 2006;27(4):859-867.
[2] Welker K, et al., *AJNR* 2015 36:E41–E51.

Slide Courtesy : Ashley Stokes PhD, Barrow Neurological Institute

Multi-Echo DSC-MRI

- Eliminates T1 leakage effects
- Enables T1 and T2* quantification – simultaneous DSC/DCE

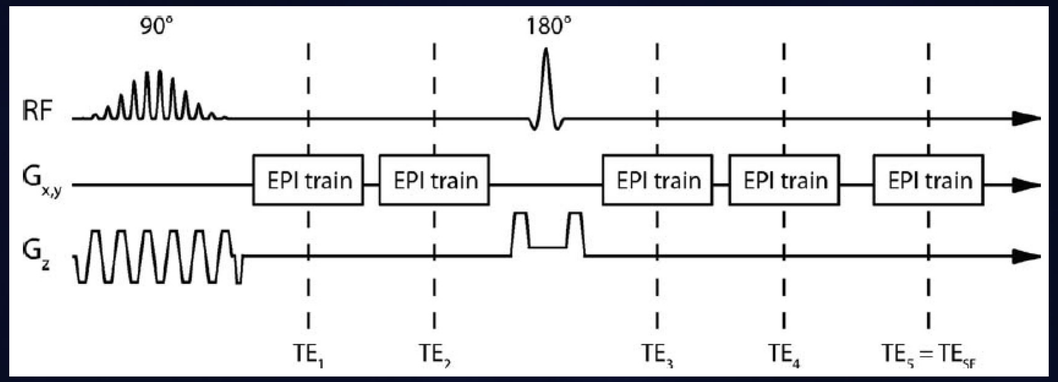


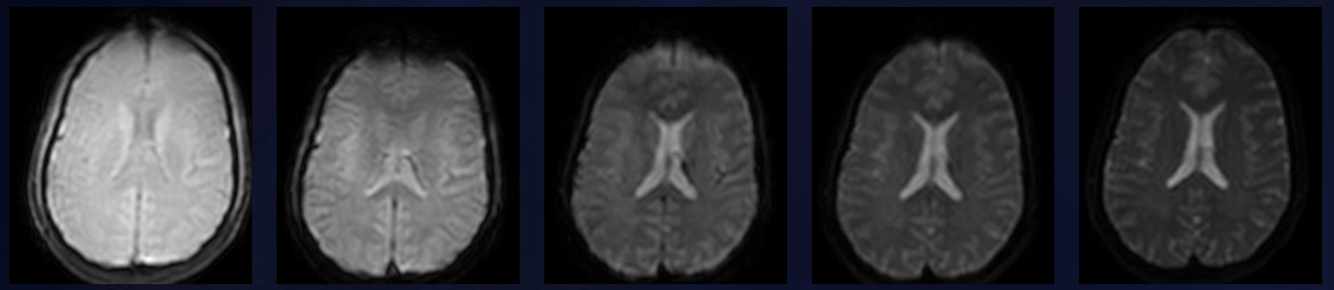


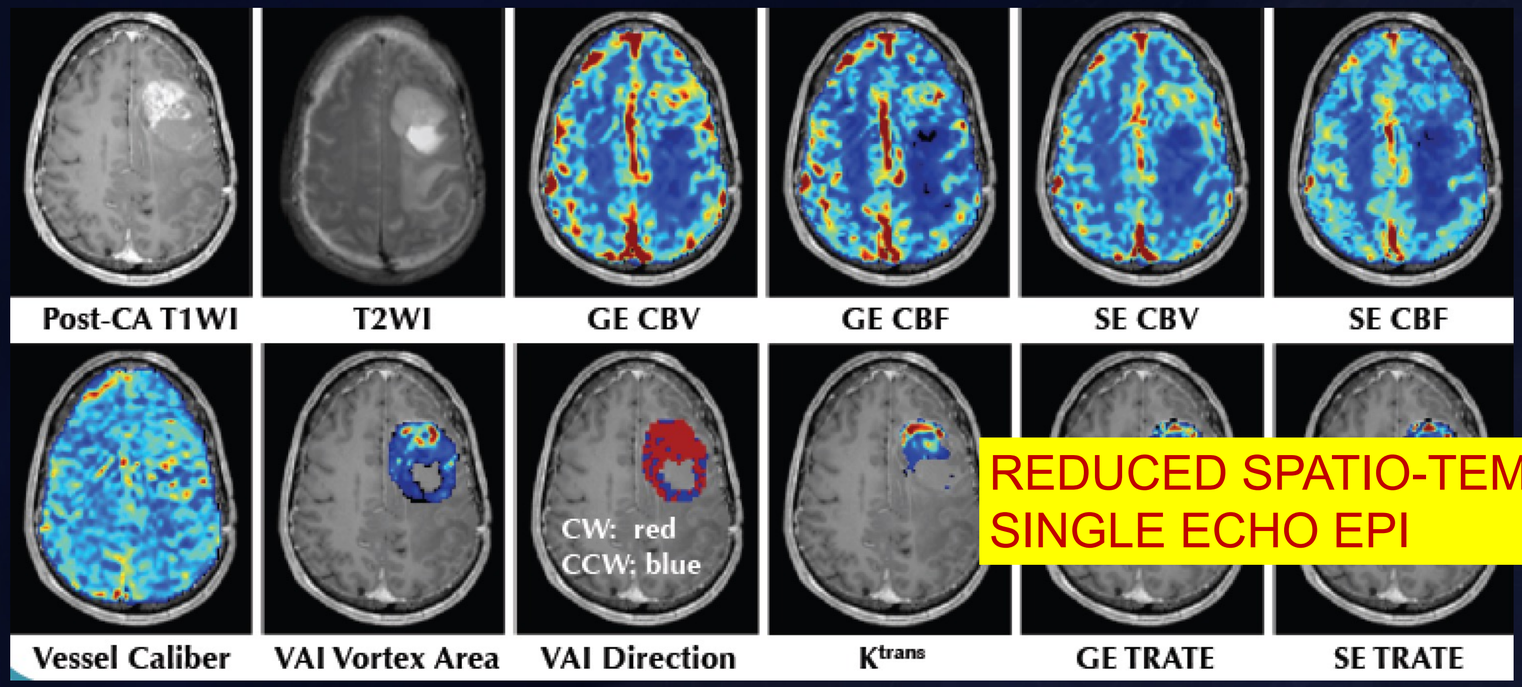
Quarles et al, MRI 2012

Slide Courtesy : C Chad Quarles PhD, Barrow Neurological Institute

Multi-echo spin and gradient-echo (SAGE)







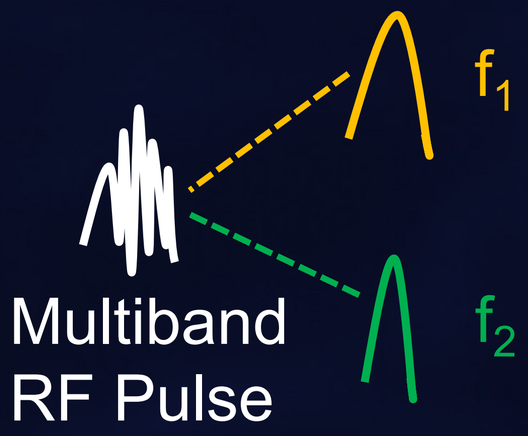
- ✓ Total and microvascular CBV, CBF, MTT, TTH
- ✓ Vessel size and vessel architectural imaging
- ✓ K^{trans} *and* v_e
- ✓ Cellularity

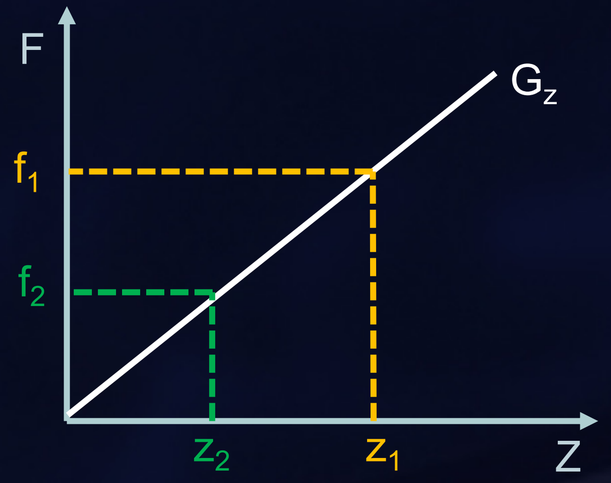
REDUCED SPATIO-TEMPORAL COVERAGE WHEN COMPARED TO SINGLE ECHO EPI

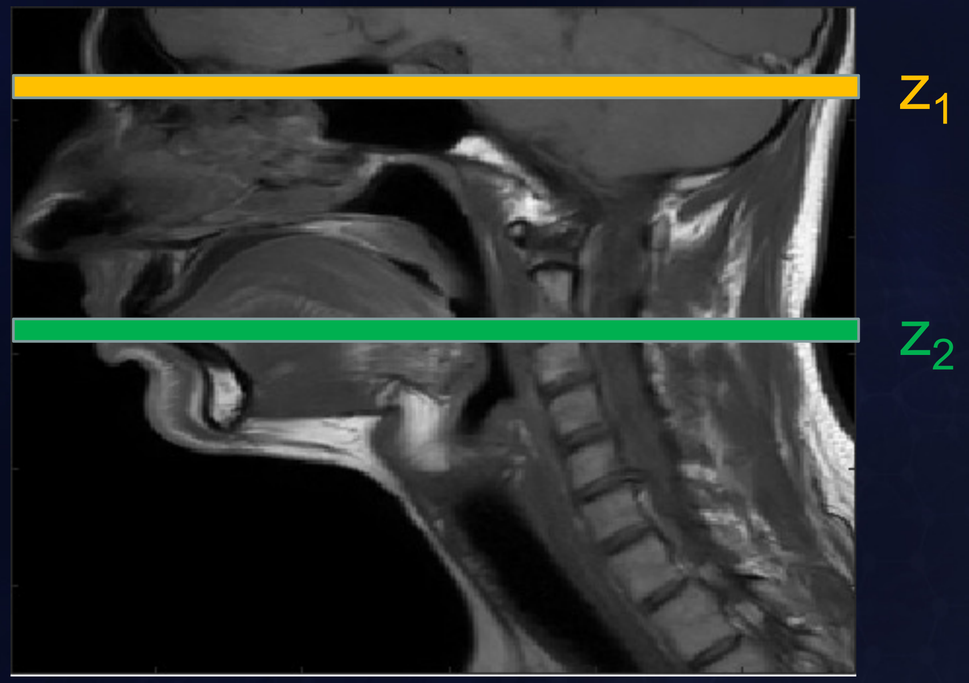
[1] Stokes et al. *MRI* 2014 32(10):1181. [2] Skinner et al. *MRI* 2014 32(10):1171. [3] Stokes et al. MRM 2016 75(1):356. [4] Stokes et al. MRI 2016 34(9):1248. [5] Semmineh NB, et al. *MRM* (2015) 74(3):772.

Slide Courtesy : C Chad Quarles PhD, Barrow Neurological Institute

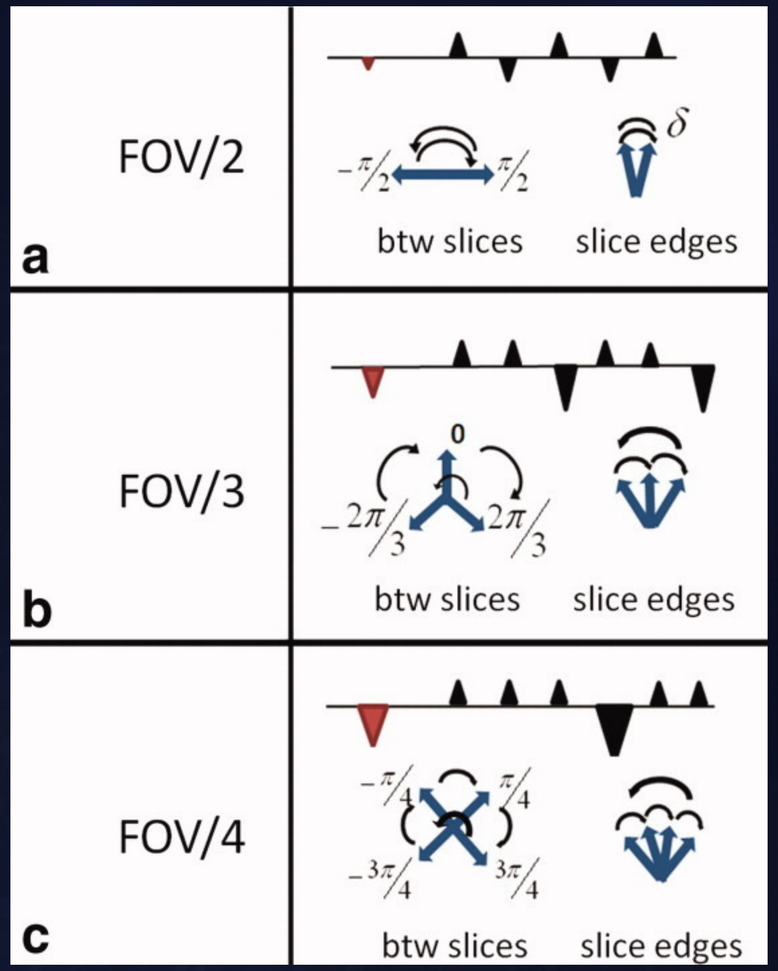
Simultaneous Multi-Slice (SMS) / MultiBand (MB)





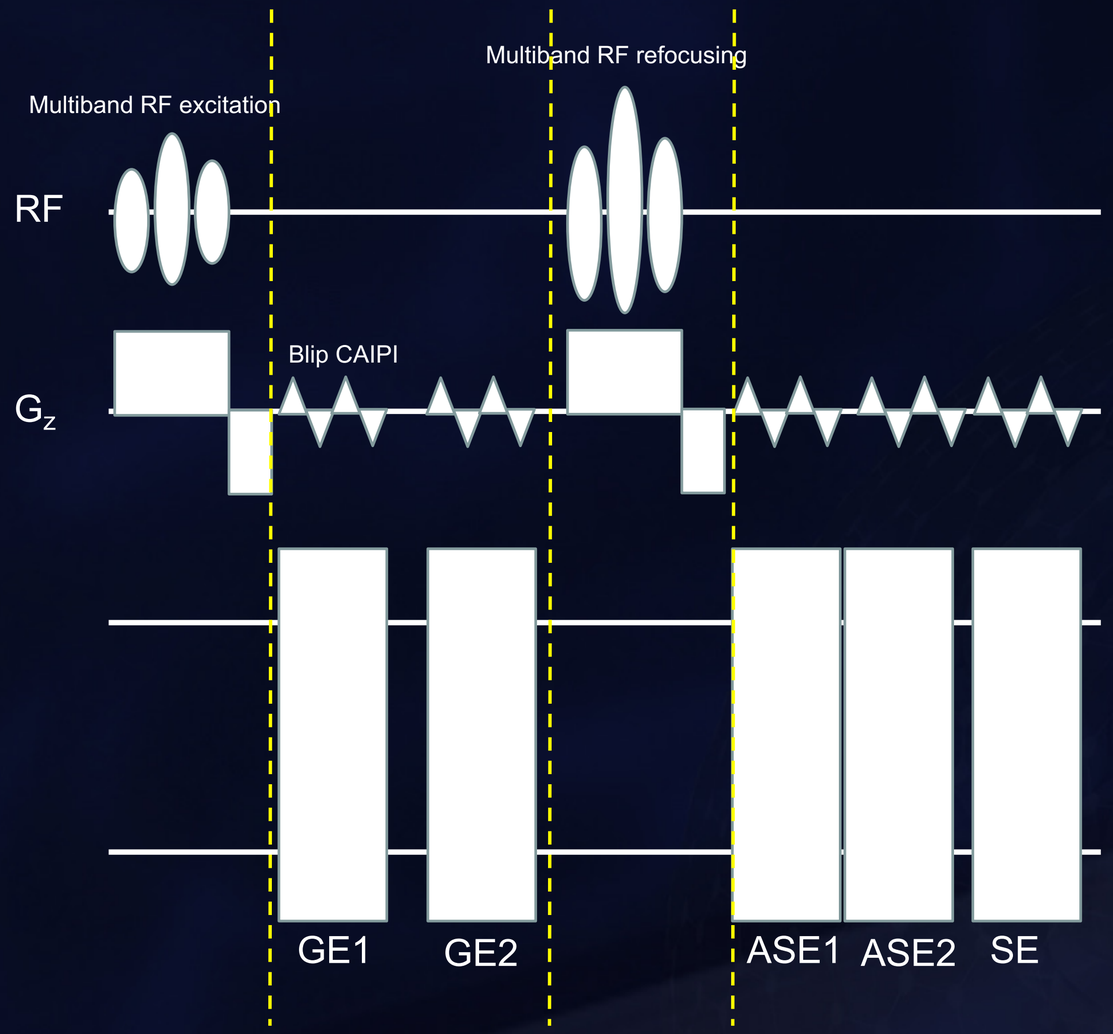


Slices must be spaced adequately apart to resolve superimposition



Setsompop, K., Gagoski, B.A., Polimeni, J.R., Witzel, T., Wedeen, V.J. and Wald, L.L. (2012), Blipped-controlled aliasing in parallel imaging for simultaneous multislice echo planar imaging with reduced *g*-factor penalty. Magn. Reson. Med., 67: 1210-1224. https://doi.org/10.1002/mrm.23097

MultiBand-SAGE EPI

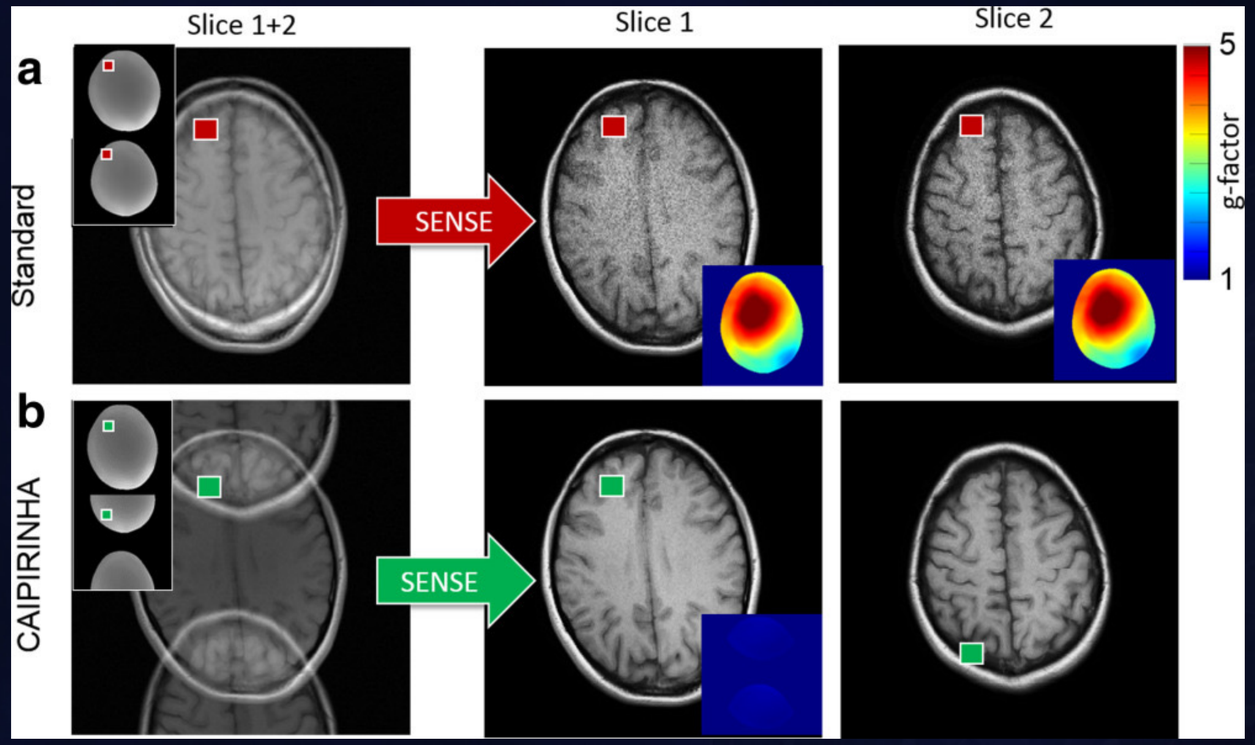


Parameter	Traditional SAGE	Multiband SAGE
# of echoes	5	5
TE1 – TE5 (ms)	8.8/26/55/72/90	8.7/26/54/71/88
TR(ms)	1800	1800
Spatial resolution (mm^3)	3.16 x 3.16 x 5	3.16 x 3.16 x 5
Temporal resolution (ms)	1800	1800
Partial Fourier	0.75	0.75
SENSE	2	2
Multiband factor	N/A	2
FOV (mm^2)	240 x 240	240 x 240
# slices (single package)	15	30

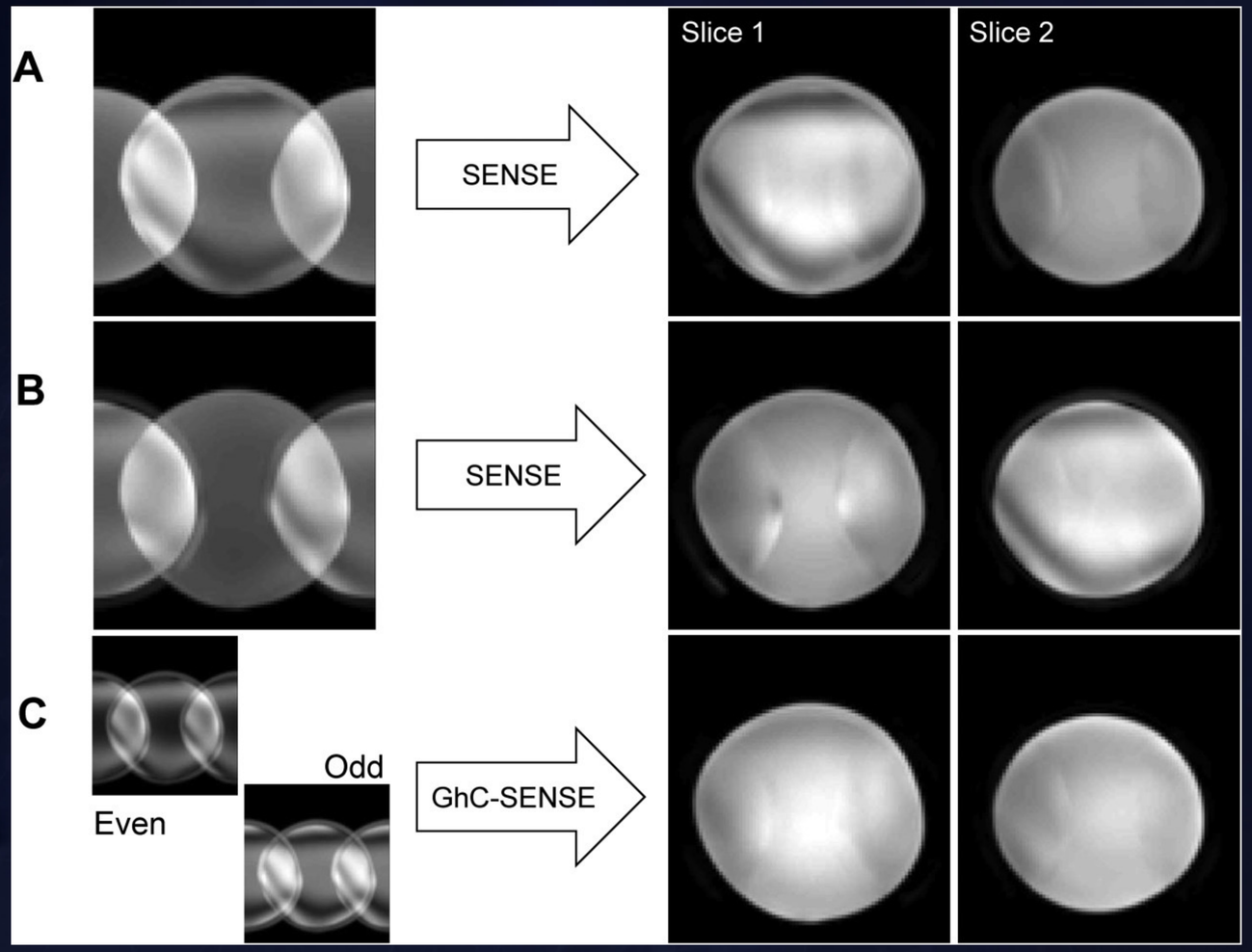
- Extended spatial coverage with MB-SAGE when compared with Traditional SAGE
- With fixed spatial coverage temporal resolution increases with MB factor

Ragunathan S et al. Proc. Intl. Soc. Mag. Reson. Med. 29 (2021)

Multiband SENSE with Nyquist Ghost Correction

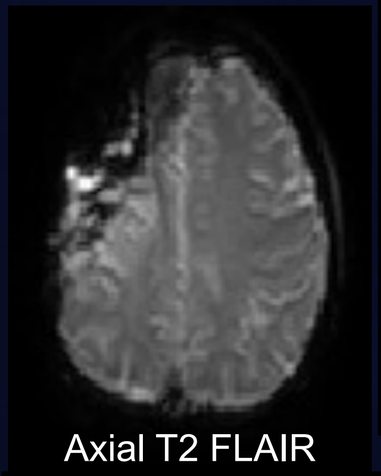


Barth M, Breuer F, Koopmans PJ, Norris DG, Poser BA. Simultaneous multislice (SMS) imaging techniques. *Magn Reson Med*. 2016;75(1):63-81. doi:10.1002/mrm.25897

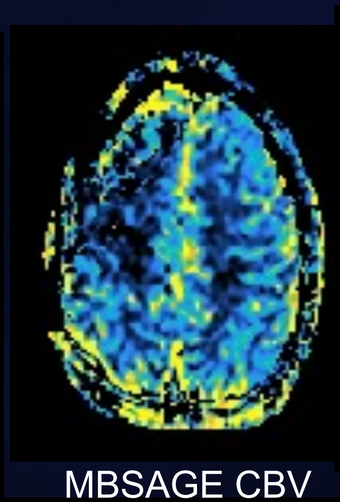


Hennel, F., Buehrer, M., von Deuster, C., Seuven, A. and Pruessmann, K.P. (2016), SENSE reconstruction for multiband EPI including slice-dependent N/2 ghost correction. Magn. Reson. Med., 76: 873-879. https://doi.org/10.1002/mrm.25915

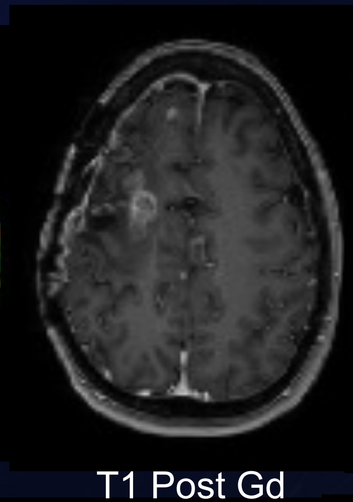
MultiBand-SAGE EPI



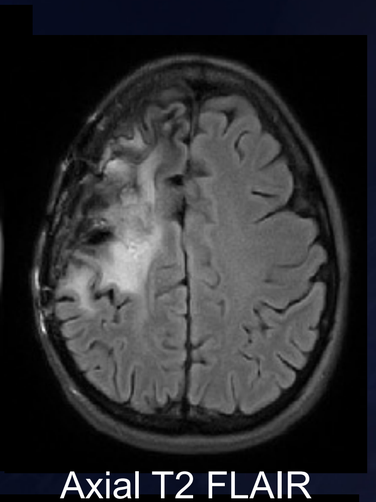
Axial T2 FLAIR



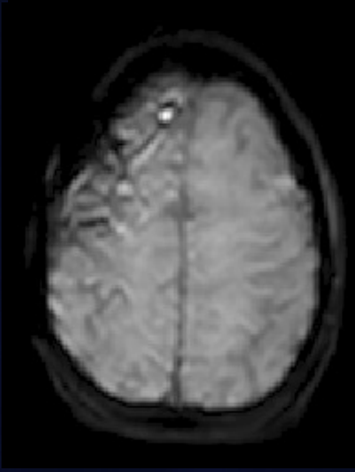
MBSAGE CBV



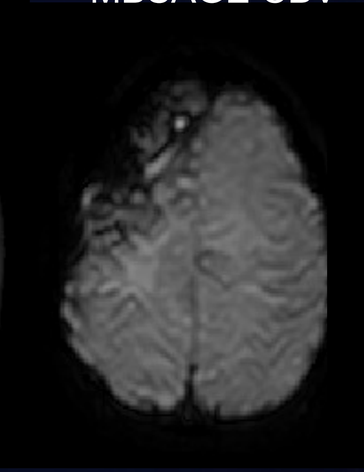
T1 Post Gd



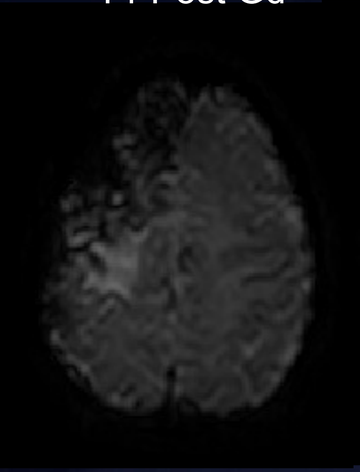
Axial T2 FLAIR



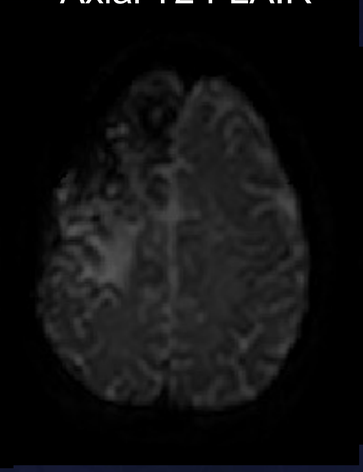
MBSAGE Echo1



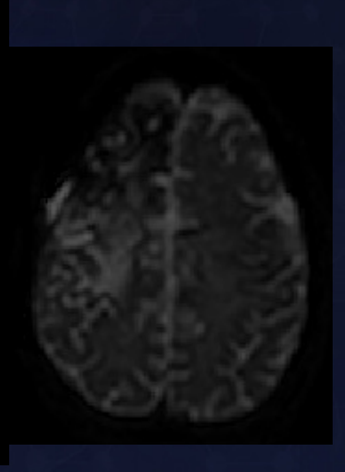
MBSAGE Echo2



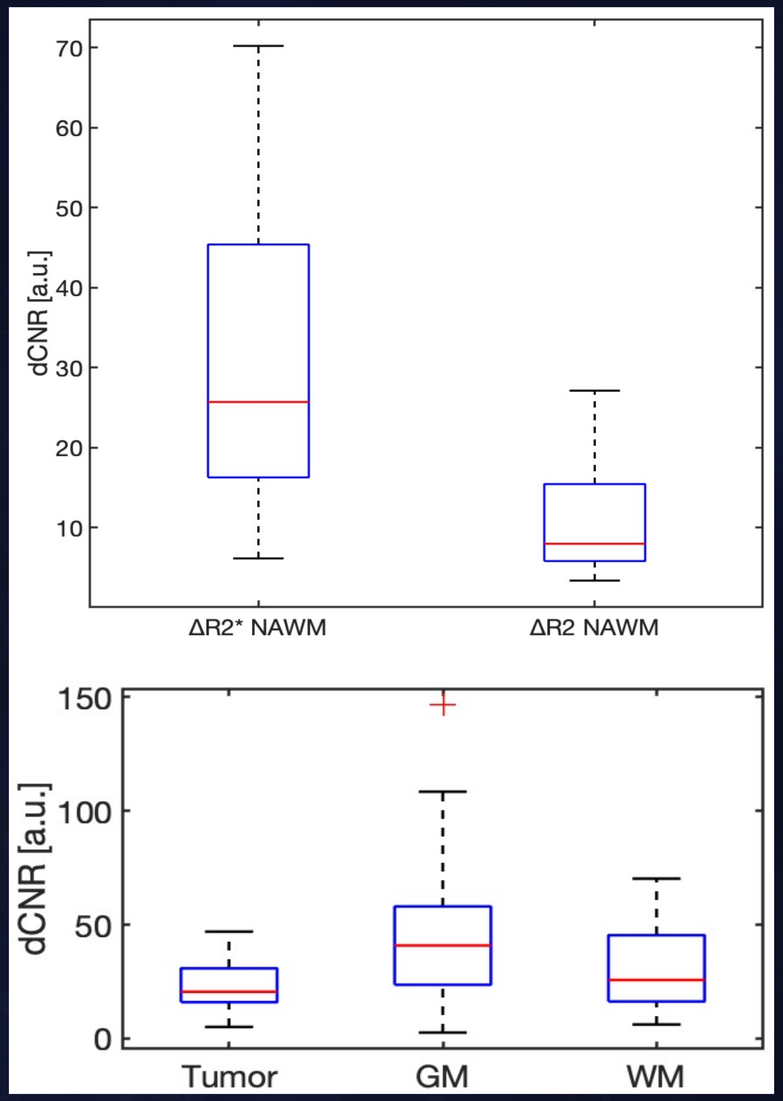
MBSAGE Echo3



MBSAGE Echo4



MBSAGE Echo5



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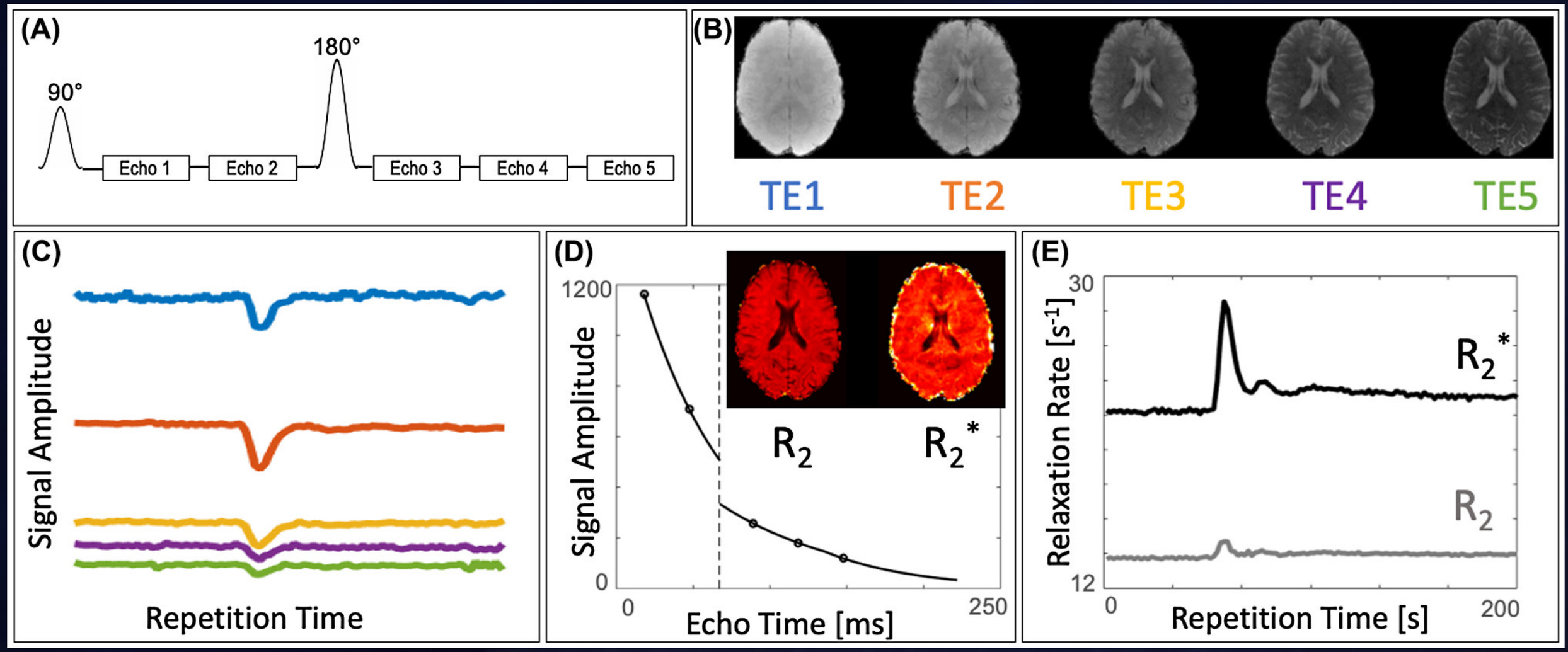
Accelerated whole-brain perfusion imaging using a simultaneous multislice spin-echo and gradient-echo sequence with joint virtual coil reconstruction

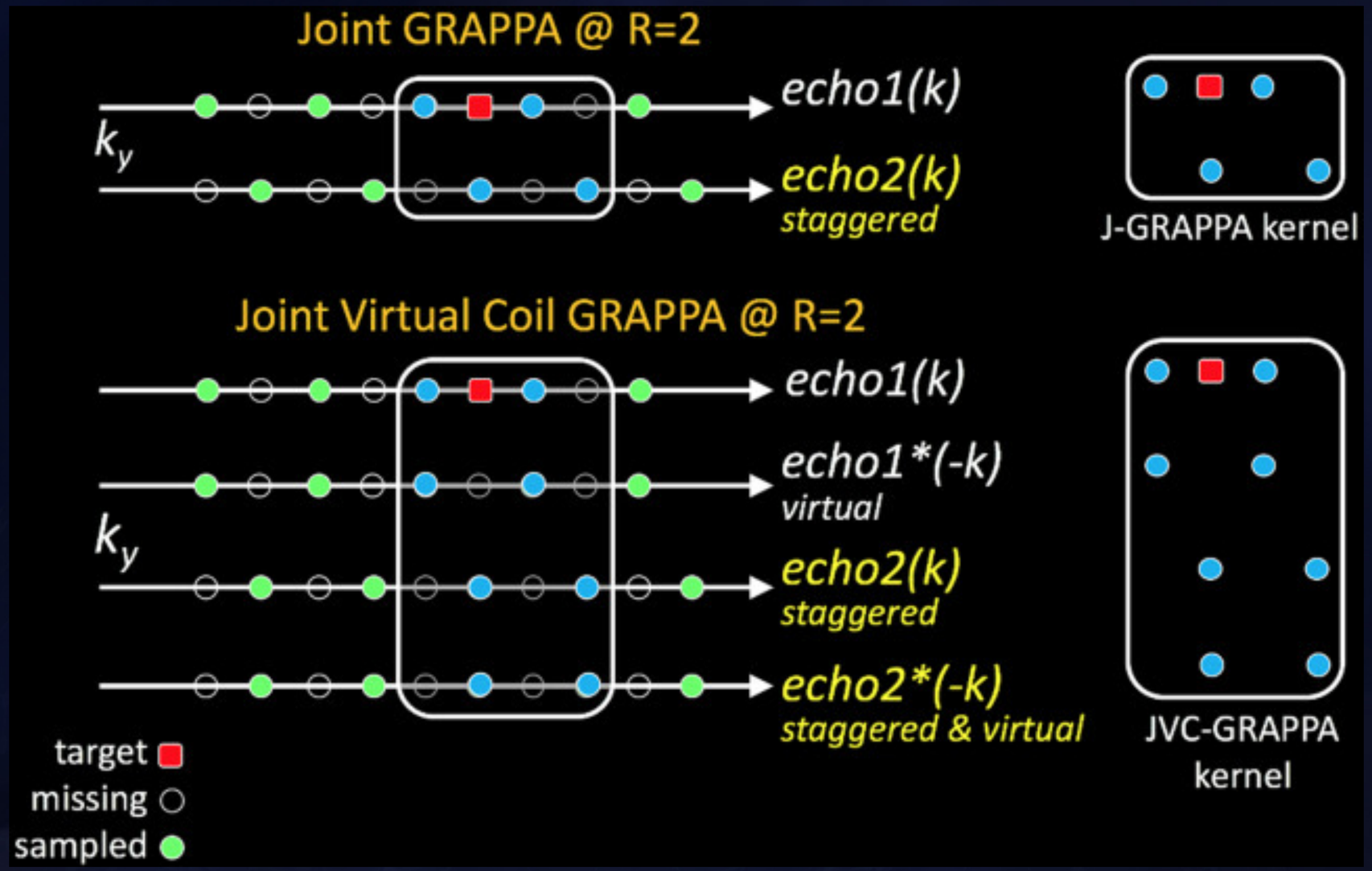


Manhard, MK, Bilgic, B, Liao, C, et al. *Magn Reson Med*. 2019; 82: 973– 983. https://doi.org/10.1002/mrm.27784

Joint Virtual Coil GRAPPA (JVC-GRAPPA)

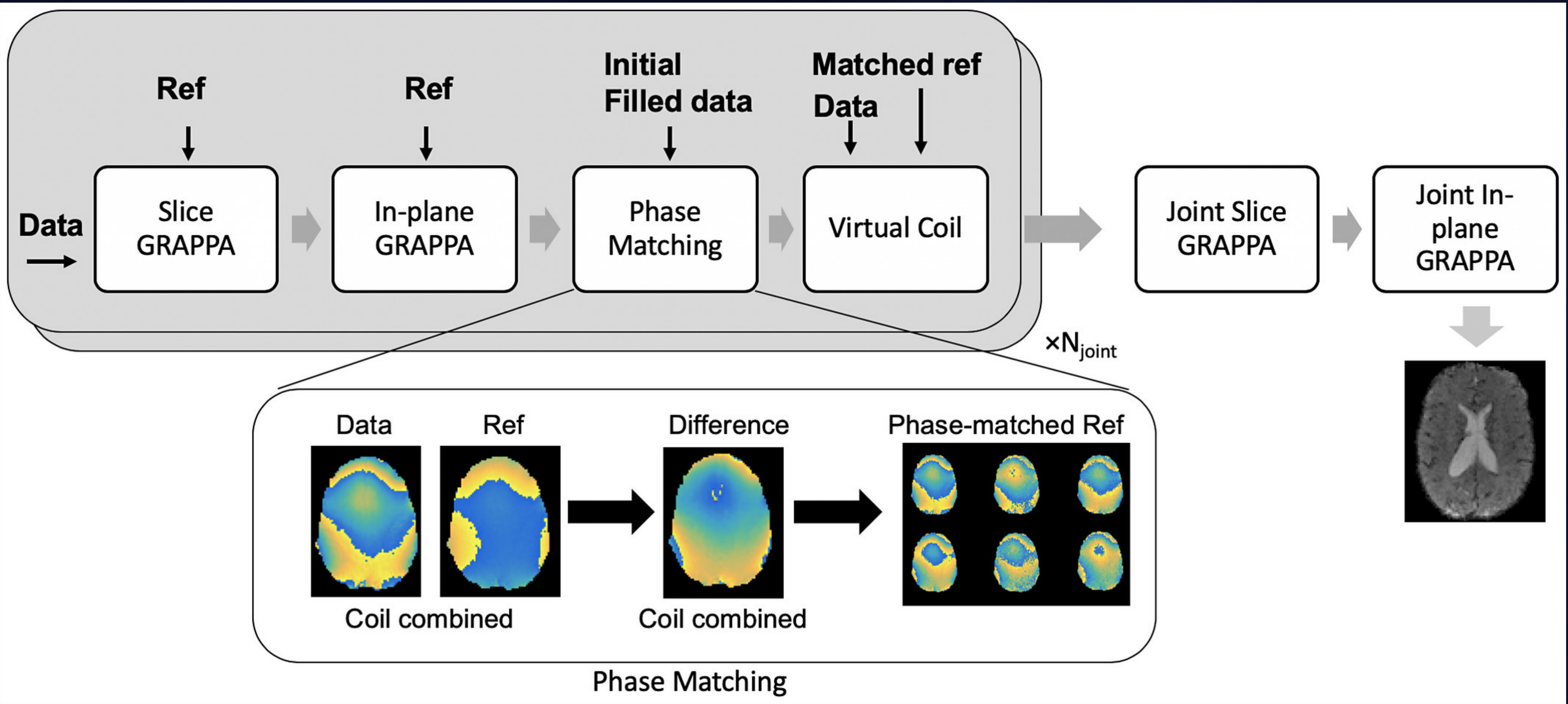
 # channels = 2 x N_c x N_e

N_c - number of coils
N_e - number of echoes



Bilgic, B., Kim, T.H., Liao, C., Manhard, M.K., Wald, L.L., Haldar, J.P. and Setsompop, K. (2018), Improving parallel imaging by jointly reconstructing multi-contrast data. Magn. Reson. Med., 80: 619-632. https://doi.org/10.1002/mrm.27076

JVC GRAPPA Reconstruction with Phase Matching



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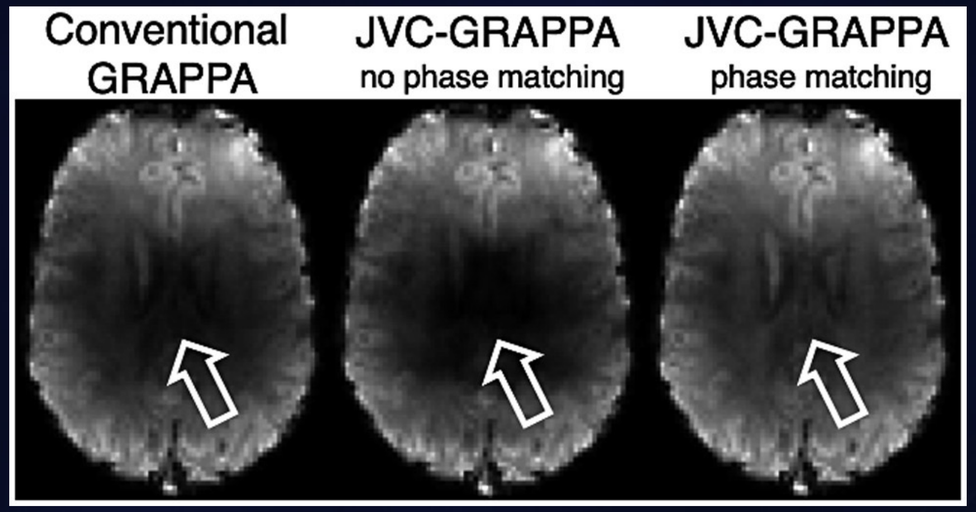

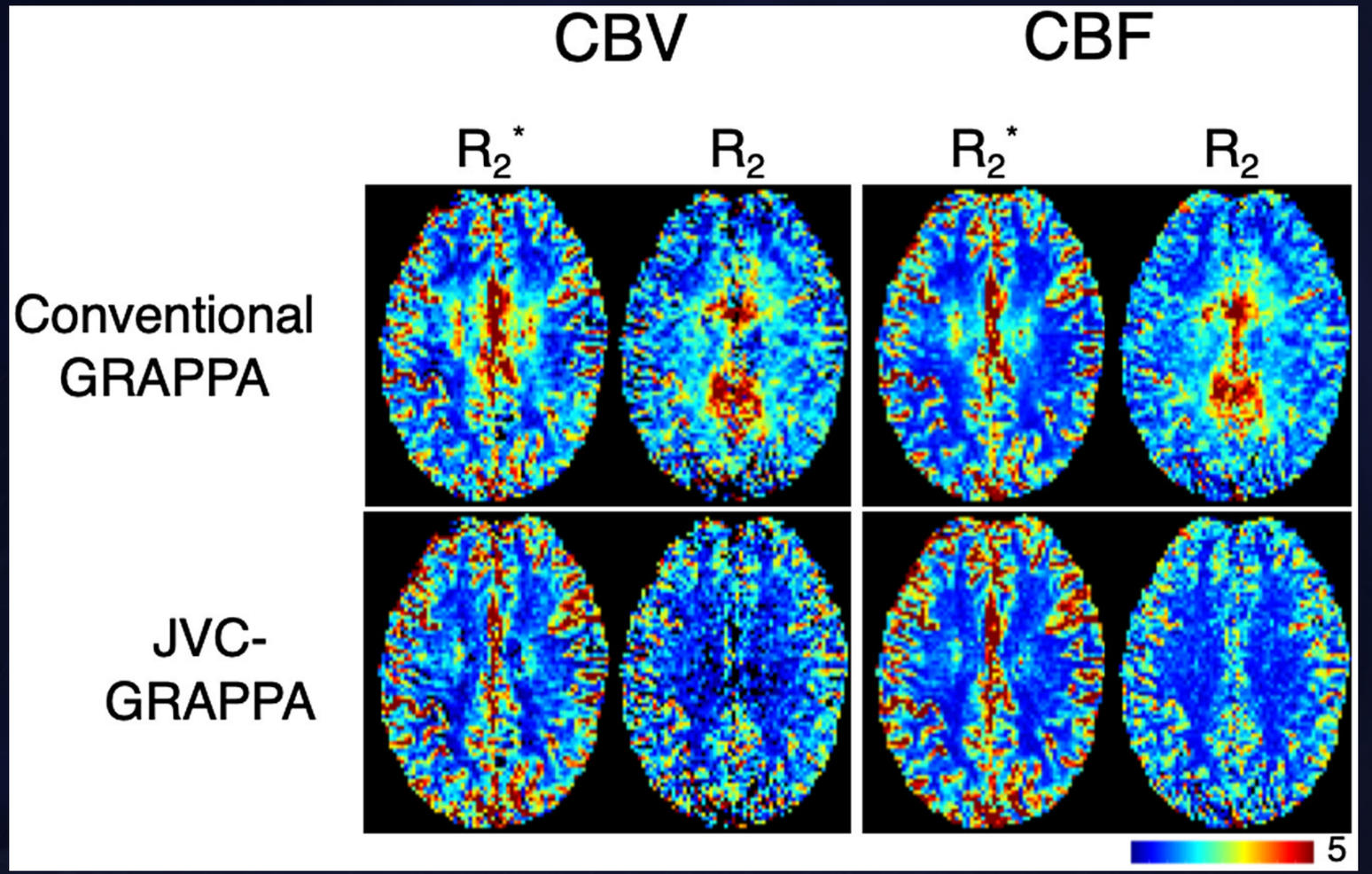

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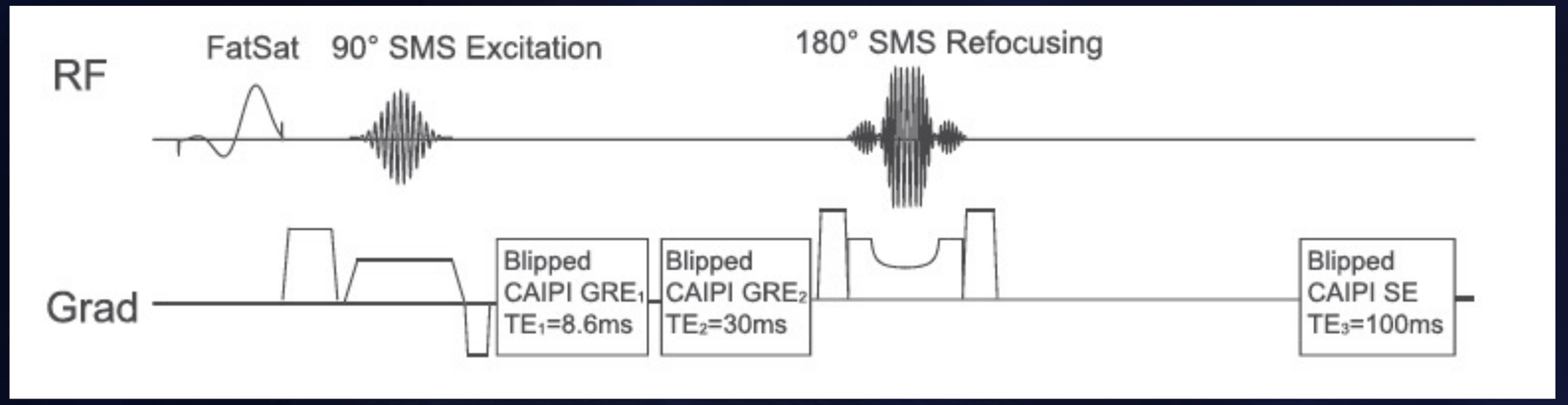
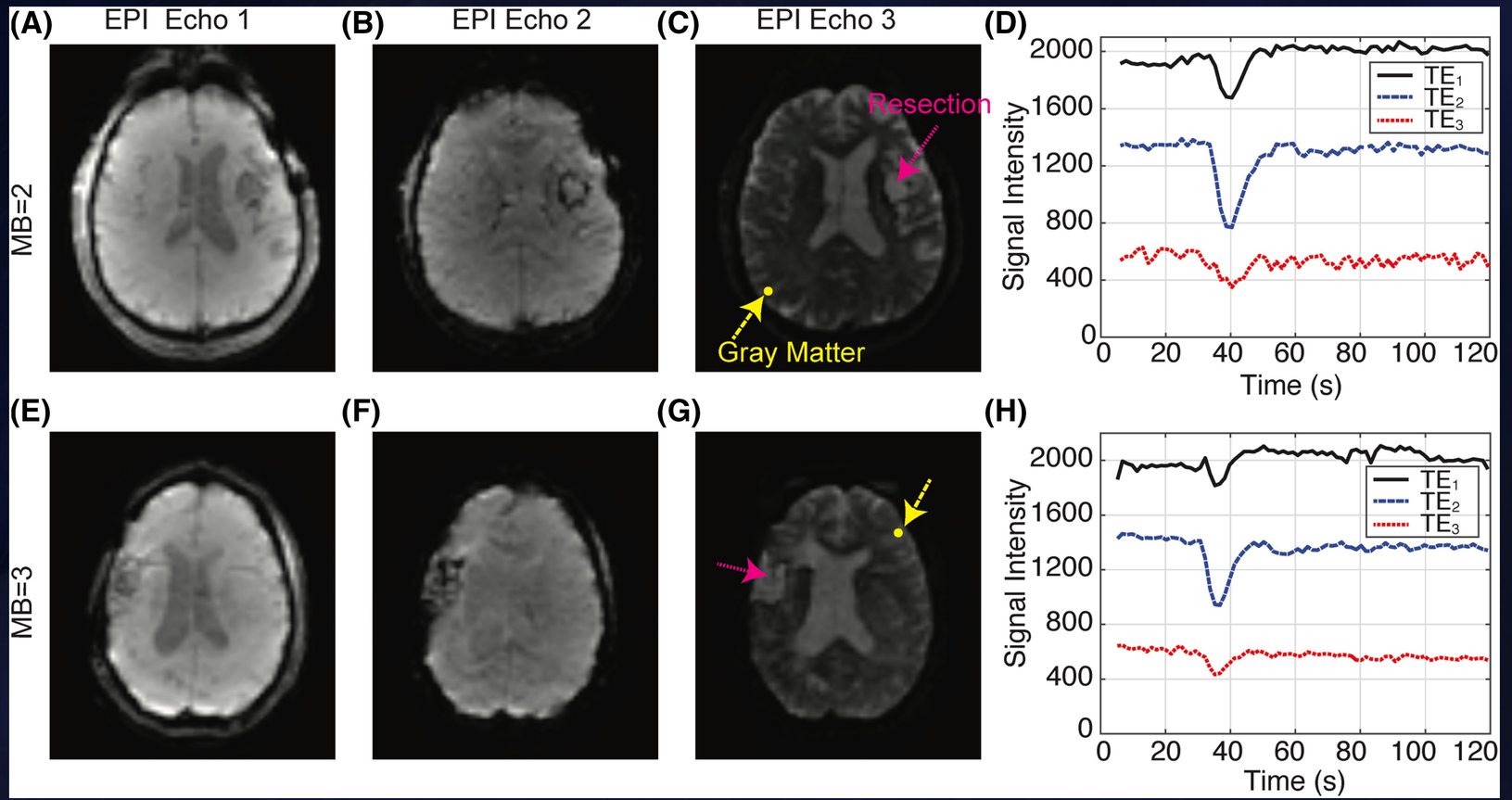
Simultaneous multi-slice spin- and gradient-echo dynamic susceptibility-contrast perfusion-weighted MRI of gliomas





Han, M, Yang, B, Fernandez, B, et al. . *NMR in Biomedicine*. 2021; 34:e4399. https://doi.org/10.1002/nbm.4399

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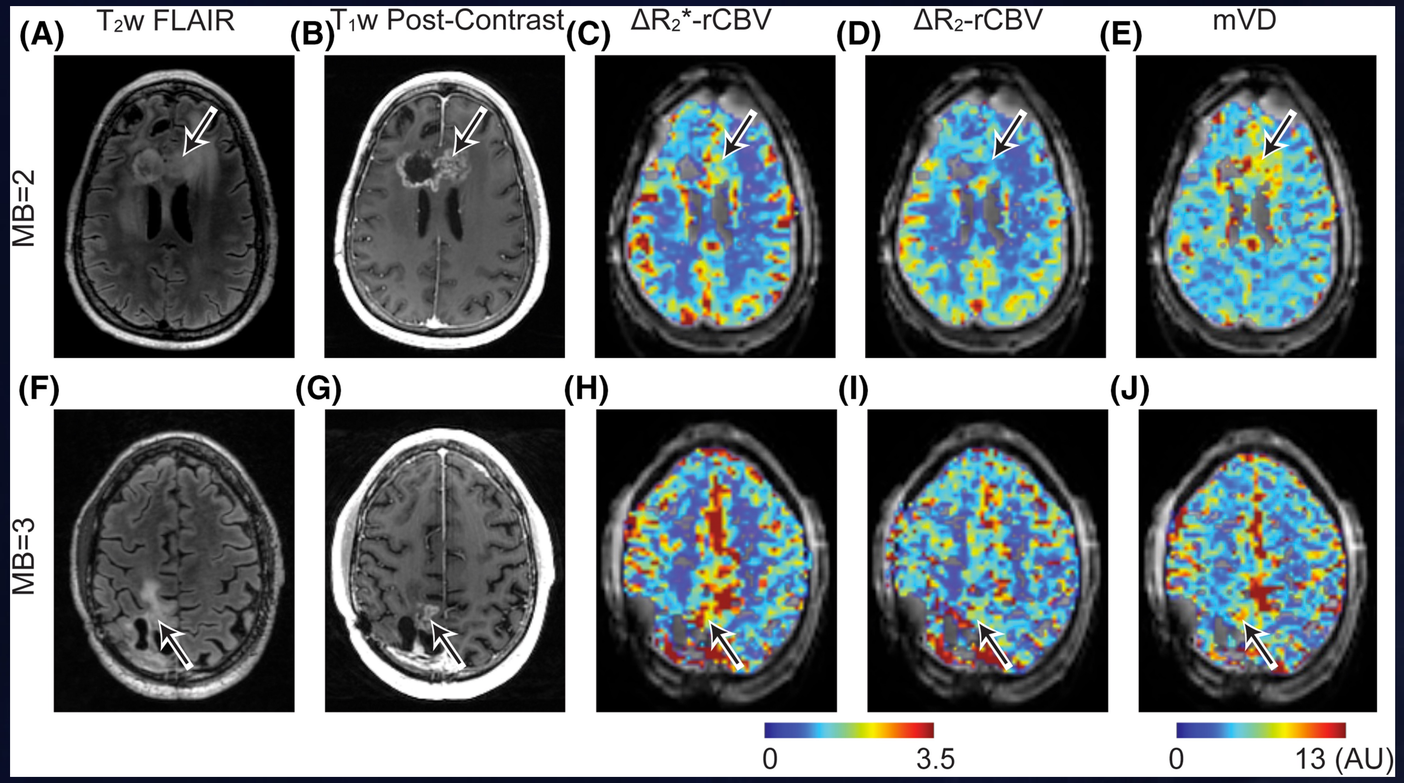

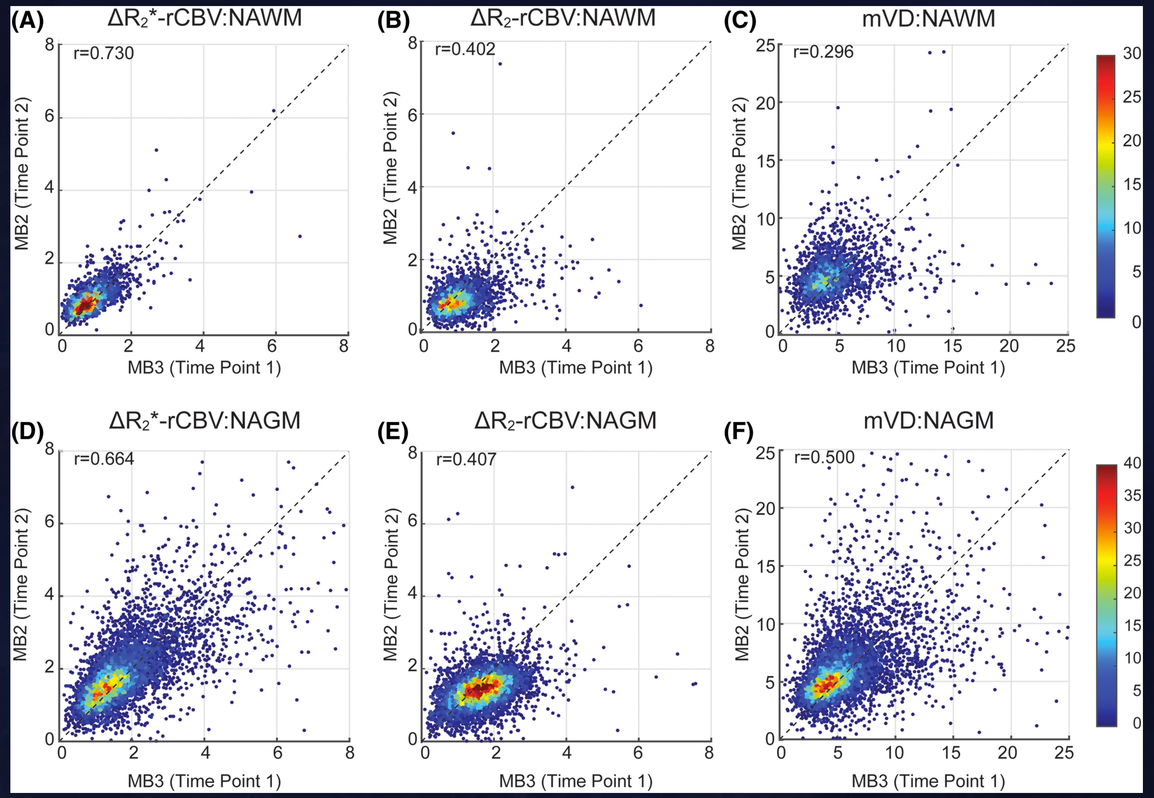

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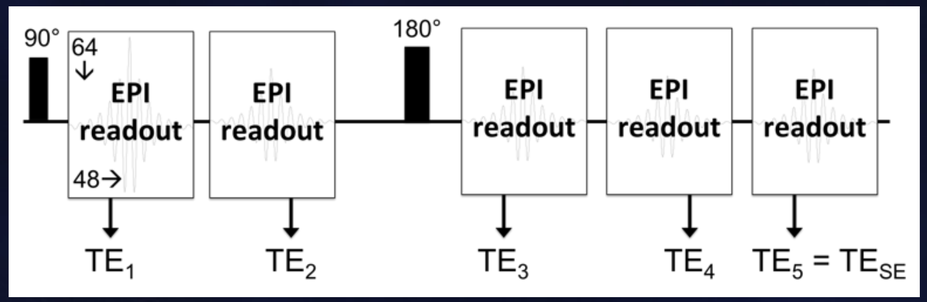
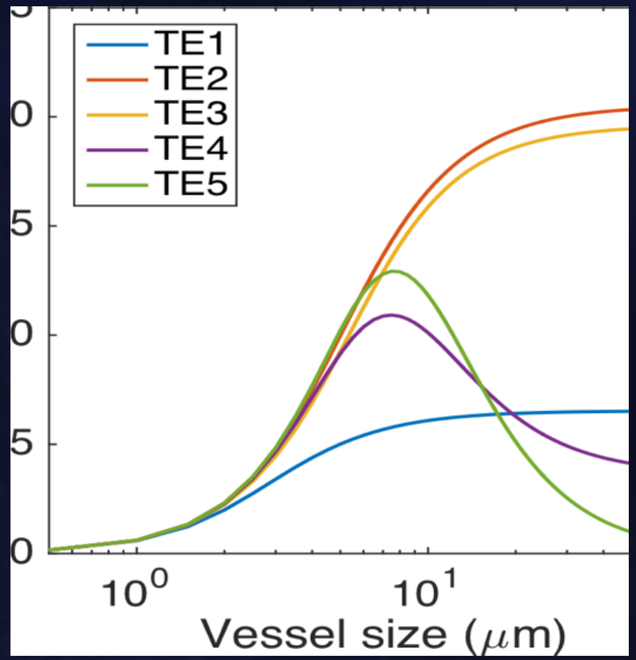
SAGE-based fMRI

- SAGE-fMRI combines multi-(gradient)-echo (MGE) and spin-echo (SE) advantages
  - Less sensitive to susceptibility effects
  - Improved BOLD sensitivity via multiple echoes [1-2]
    - Quantify T_2^* or echo-weighting combinations
  - Less sensitive to large draining veins
  - Improved spatial specificity via multiple contrasts





Sensitivity to vessel size

Hypothesis: SAGE-fMRI will improve signal fidelity, BOLD sensitivity, and spatial localization of activation

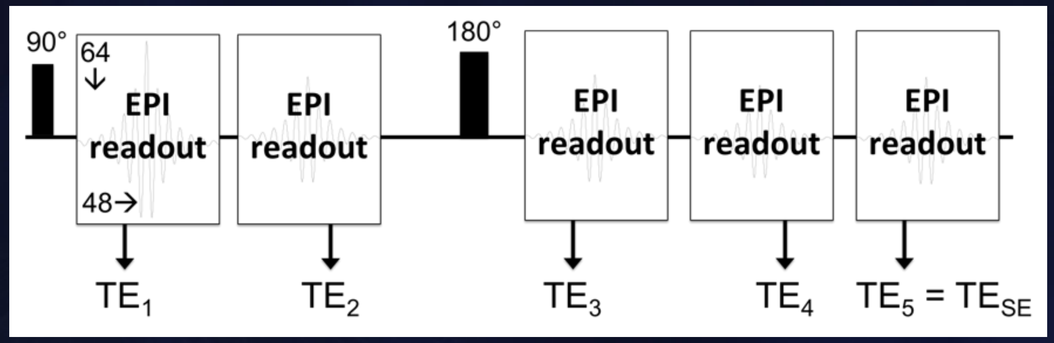
D = 1e-3 mm^2/s, ς = 5%,
$\Delta\chi$ = 0.264 ppm

[1] Kundu P, et al., PNAS 2013. Posse S, et al., MRM 1999. Poser BA, et al., MRM 2006.
[2] Norris DG, et al., Neuroimage 2002. Binney RJ, et al., Cerebral Cortex 2010.

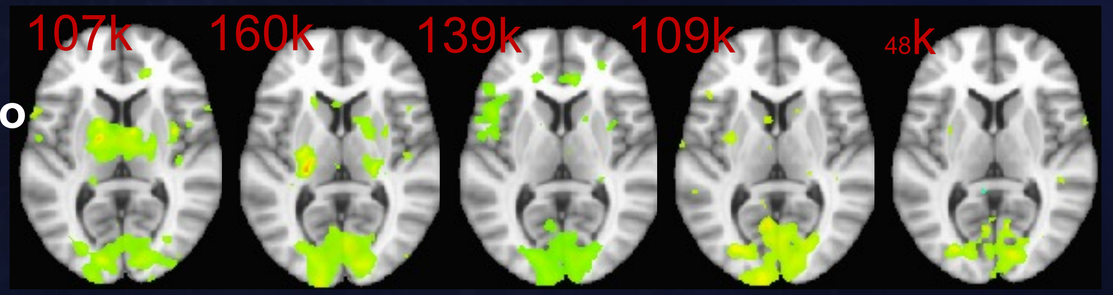
Slide Courtesy : Ashley Stokes PhD, Barrow Neurological Institute

Development of SAGE-based fMRI

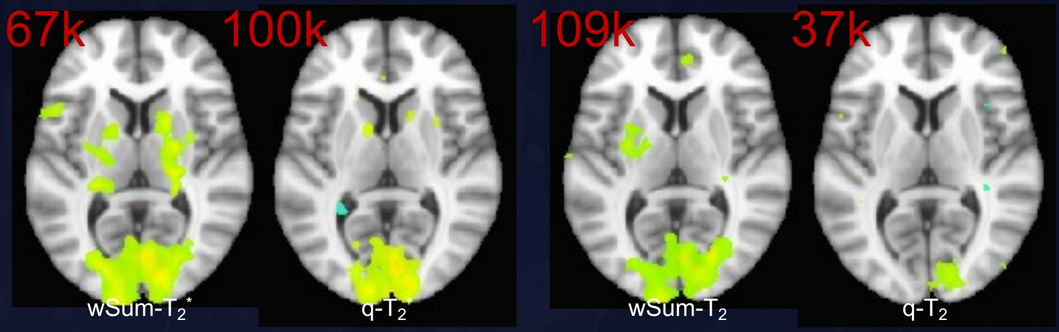
- Advantages of SAGE-fMRI
  - Less sensitive to susceptibility effects
  - Improved BOLD CNR via multiple echoes
    - $T_2^{(*)}$ or echo-weighting combinations
  - Yet to be seen:
    - Improved spatial localization via multiple contrasts
- Future work
  - Apply SAGE-fMRI in Alzheimer's disease using memory paradigms
  - Further improvements in optimizing multi-echo combinations
  - Biophysical basis of multi-contrast fMRI signals and noise



Single-echo analysis



Multi-echo SAGE analysis

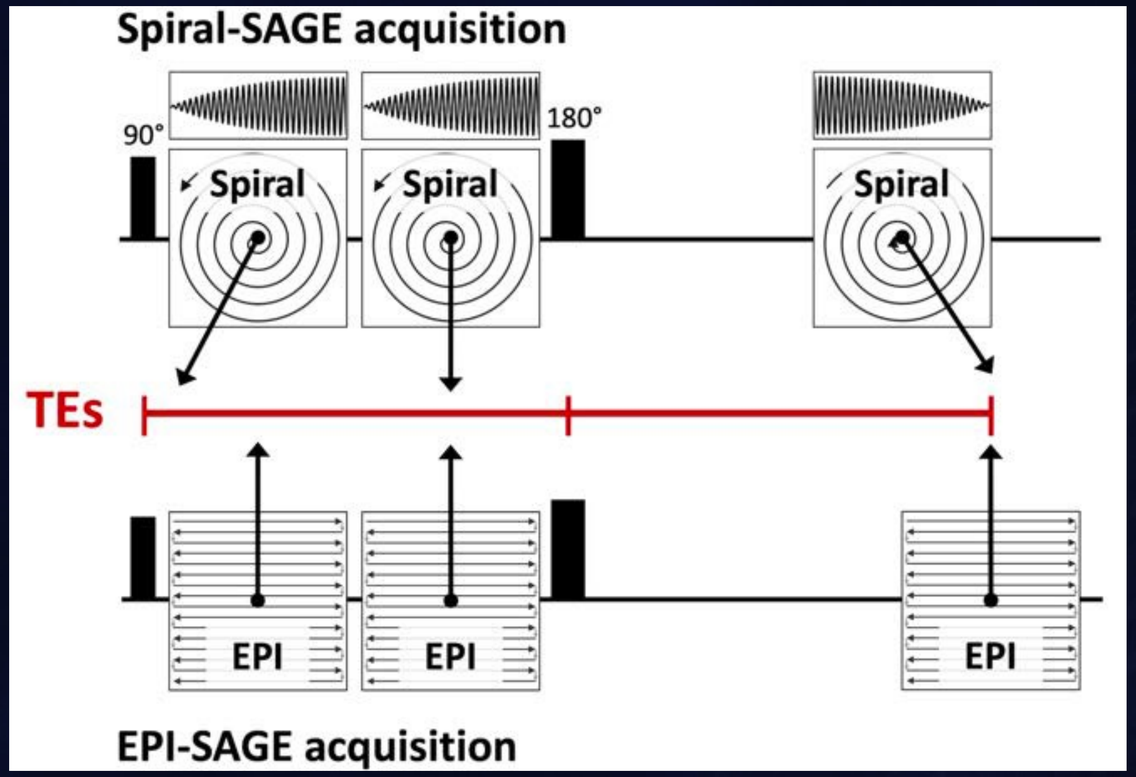


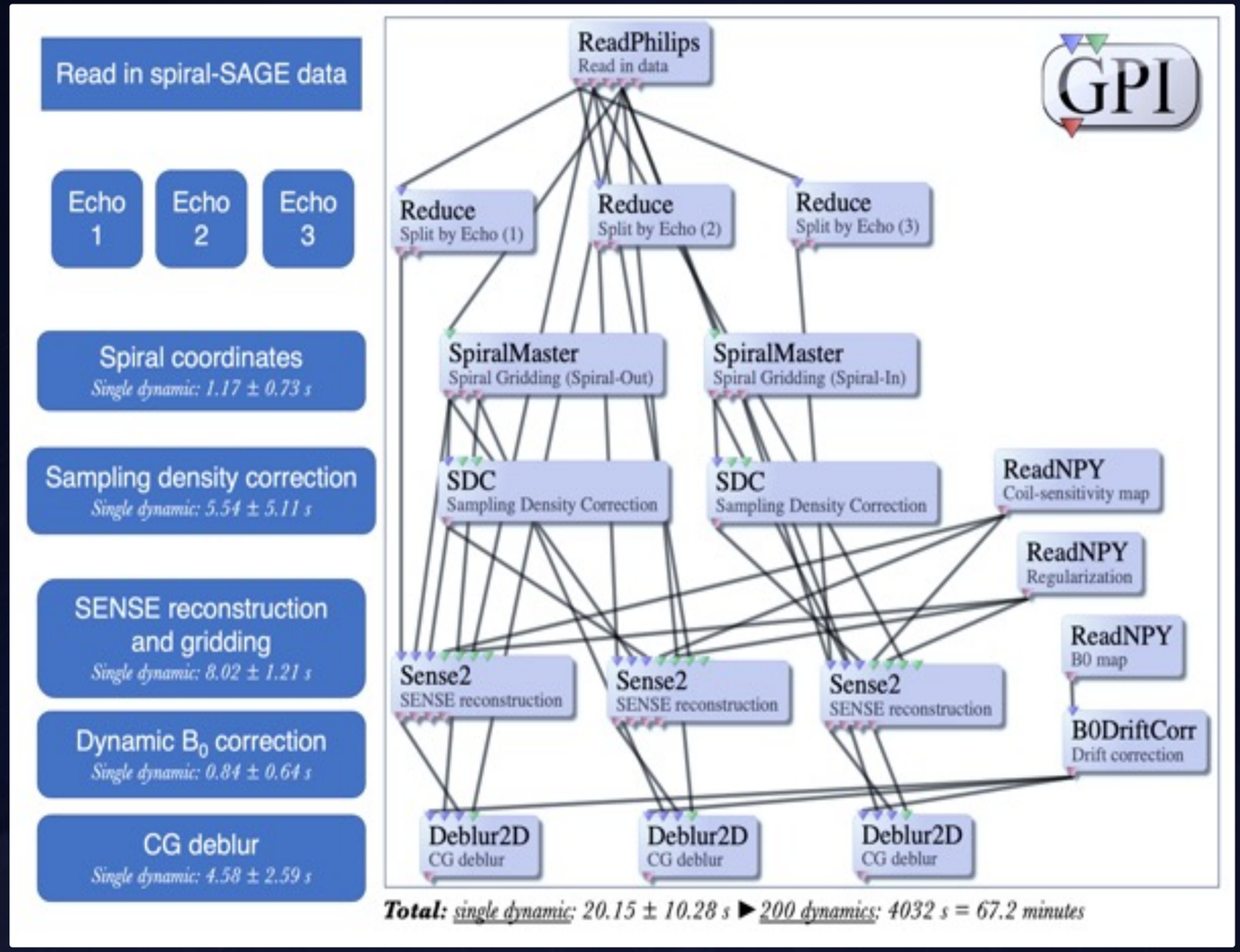
#s in red indicate # significant voxels for each method

Analysis by Dr. Maurizio Bergamino

Slide Courtesy : Ashley Stokes PhD, Barrow Neurological Institute

Spiral SAGE MRI





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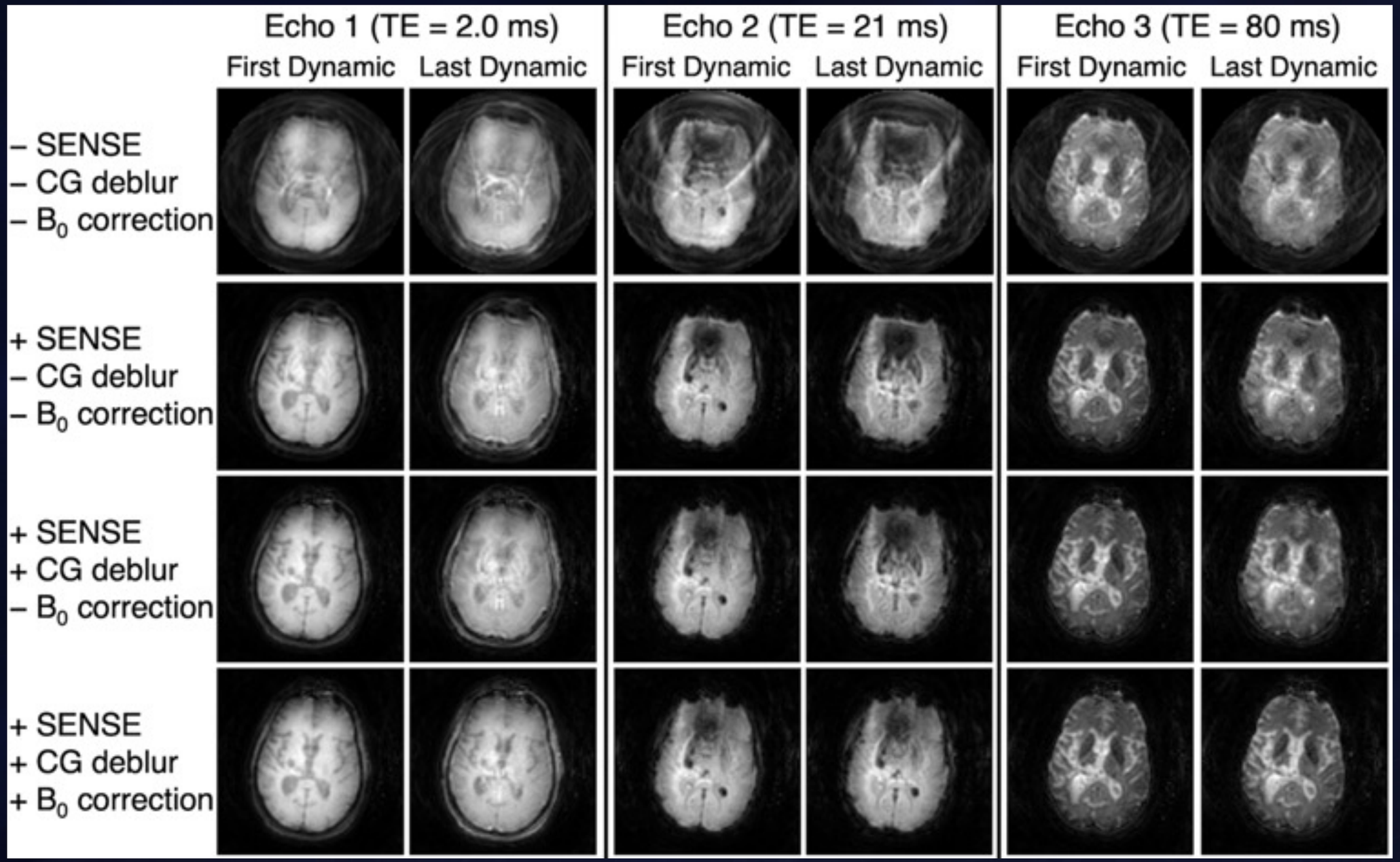
Spiral SAGE MRI



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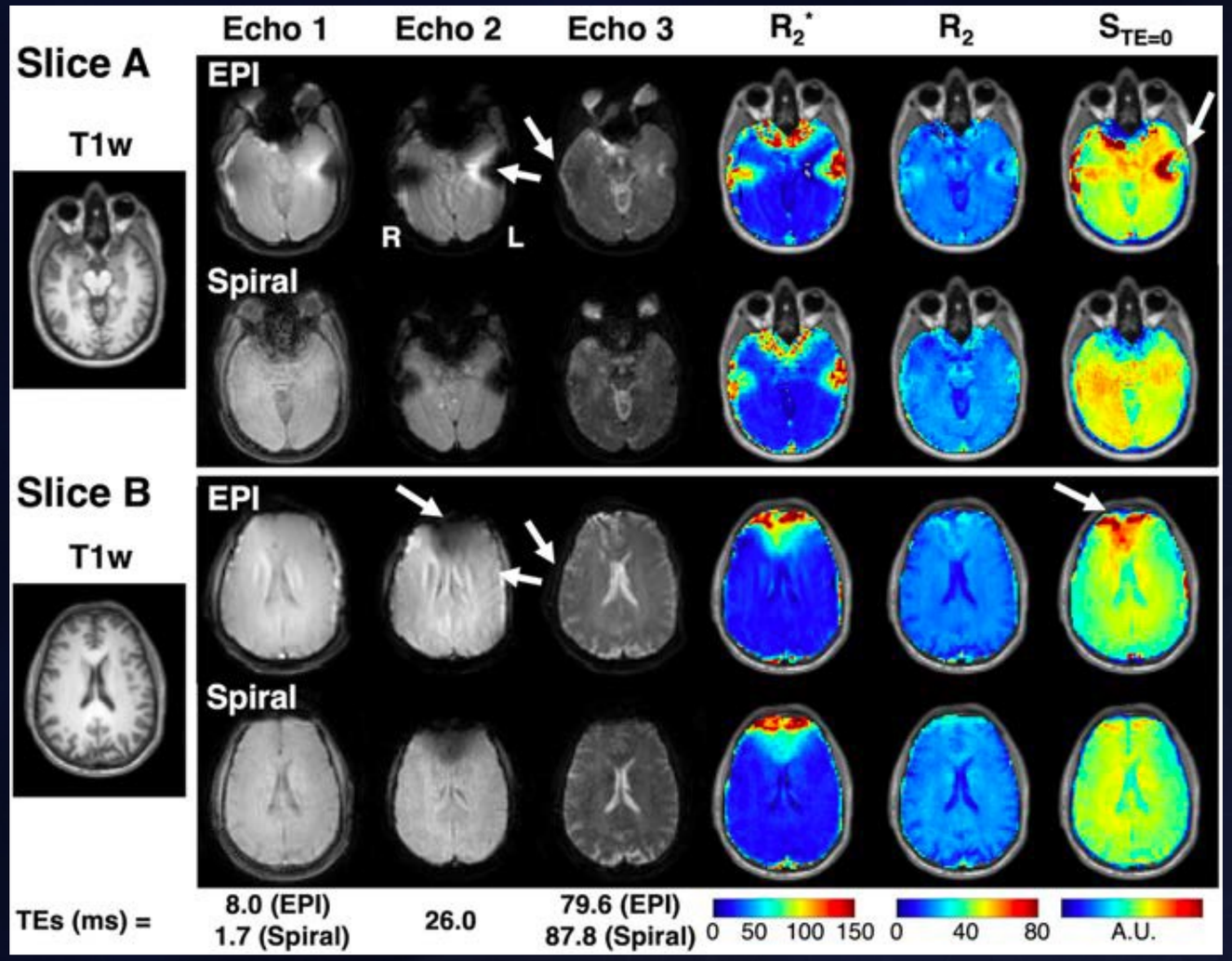
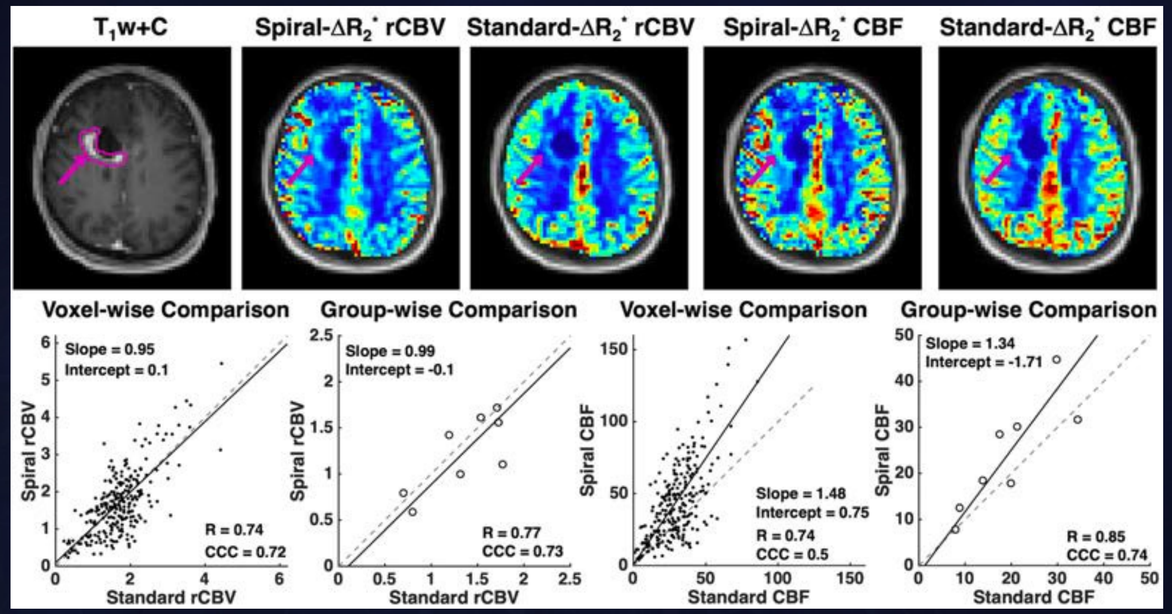
Spiral SAGE MRI





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Summary

- Advantages of SAGE over single echo DSC MRI
  - Combined DCE/DSC information
  - Vessel size index / mean vessel diameter
- SMS/MB + Parallel Imaging
  - Same spatiotemporal coverage as clinical DSC MRI
- SAGE applications to fMRI for improved BOLD CNR
- Non-Cartesian implementations of SAGE for efficient k-space coverage

Acknowledgements

Barrow Neurological Institute

- **Dr. Chad Quarles**
- Dr. Laura Bell
- **Dr. Ashley Stokes**
- Dr. Natenael Semmineh
- Dr. Zhiqiang Li
- Lori Steffes
- Sharmeen Maze

Philips Healthcare

- Dr. Melvyn Ooi
- Dr. Ryan Robison

Research Support

- NIH
- Philips Healthcare