Simulation of bSSFP Pulse Sequence with Stack-of-Stars K-space Sampling

Group 4
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Balanced Steady-State Free Precession (bSSFP): Background

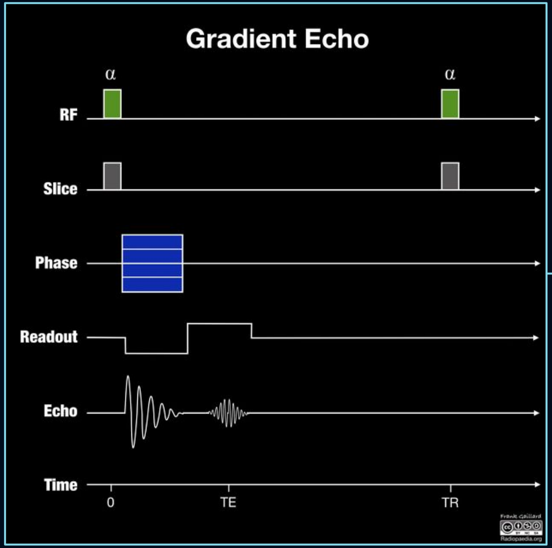


Figure 1. Gradient Echo [a]

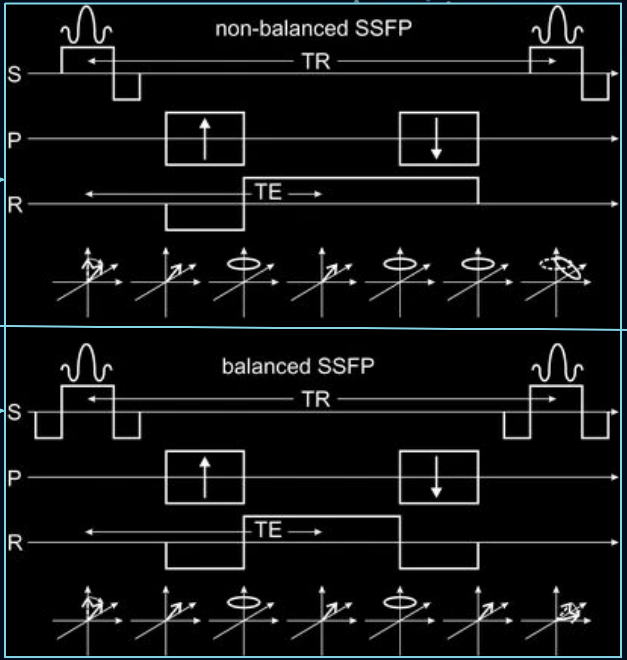


Figure 2. SSFP & bSSFP [2]

What is a Steady-State Signal?

- Rapid & Periodic RF
- Balance Between Excitation and Relaxation
- Time to reach Steady-State
- Signal Dependence on T1, T2, TR & Flip angle (< 90^0 for higher overall signal)

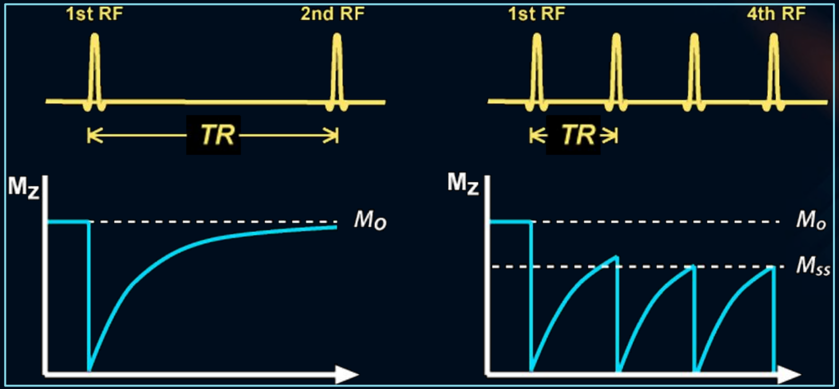


Figure 3. Steady State Magnetization [b]

What are Balanced Gradients?

- +ve & -ve Gradient Lobes cancel out over TR
- Across all 3 axes: slice-selection, phase encoding, frequency encoding
- Refocus dephasing caused by gradient fields
- Preserving coherent transverse magnetization across successive TRs

$$\int_0^{TR} G(t)\,dt = 0$$

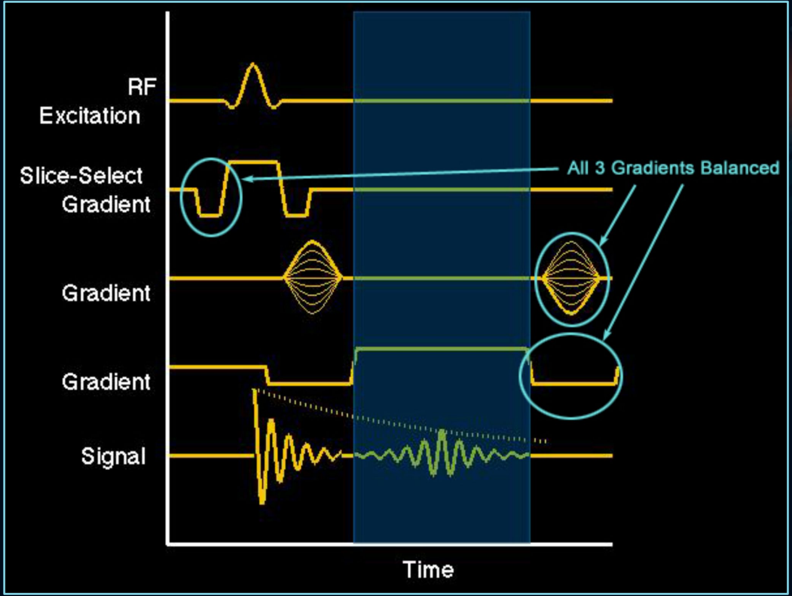


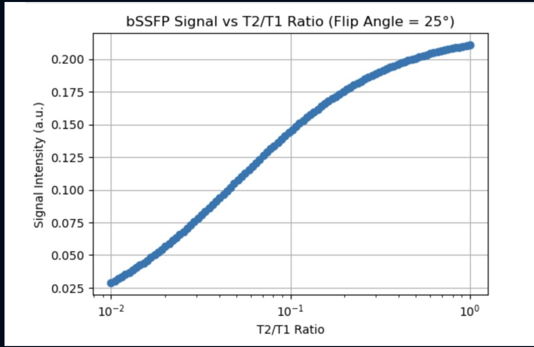
Figure 4. Balanced Gradients [c]

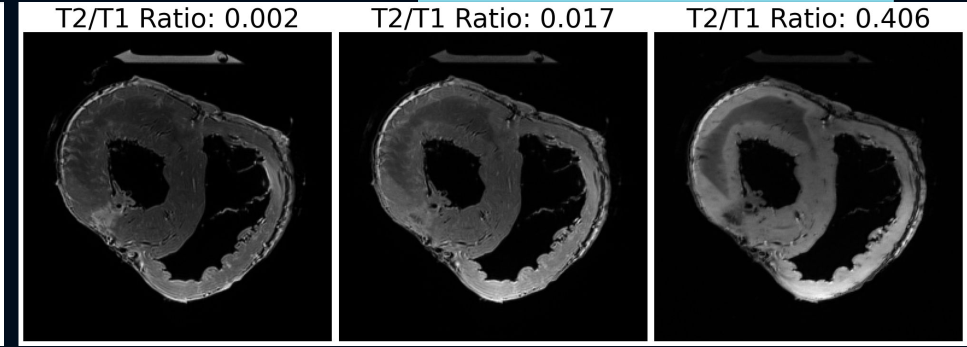
Effects of T2/T1 Ratio on Signal Strength

- bSSFP signal is proportional to the T2/T1 ratio of tissues
- Higher ratio = better contrast
- Strong and stable signal with high SNR

Table 1. T2/T1 for different tissues [3]

Tissue	T2/T1
Arterial Blood	0.21
Fat	0.3
Muscle	0.05





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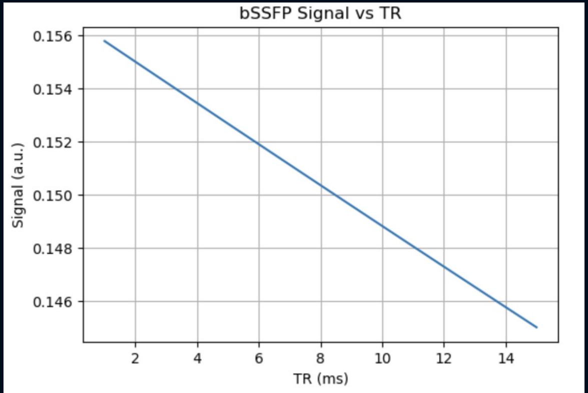
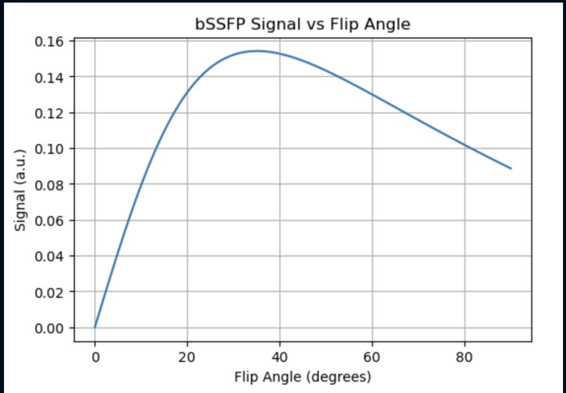
Dependence of bSSFP on Imaging Parameters

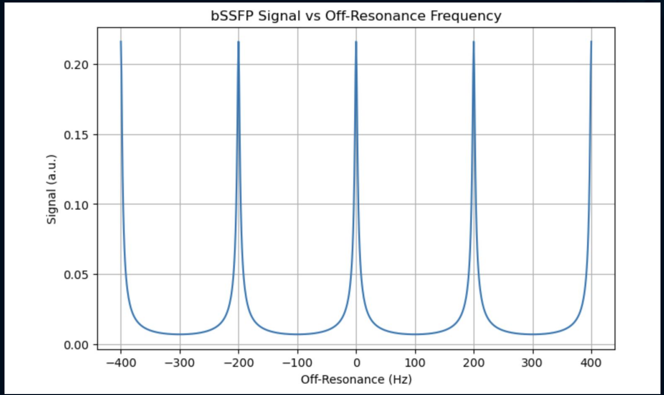
Repetition Time (TR): Determines banding artifact frequency.

Flip Angle: Affects signal intensity and contrast.

Off-Resonance: Influences artifact visibility and band placement.







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Simulation

Dataset and Known Imaging Parameters

Ex Vivo Porcine Heart DT MRI Dataset [1] - Stanford CMR group

Imaging system: Siemens Magnetom Prisma fit → 3T scanner

T1 protocol: FLASH 3D

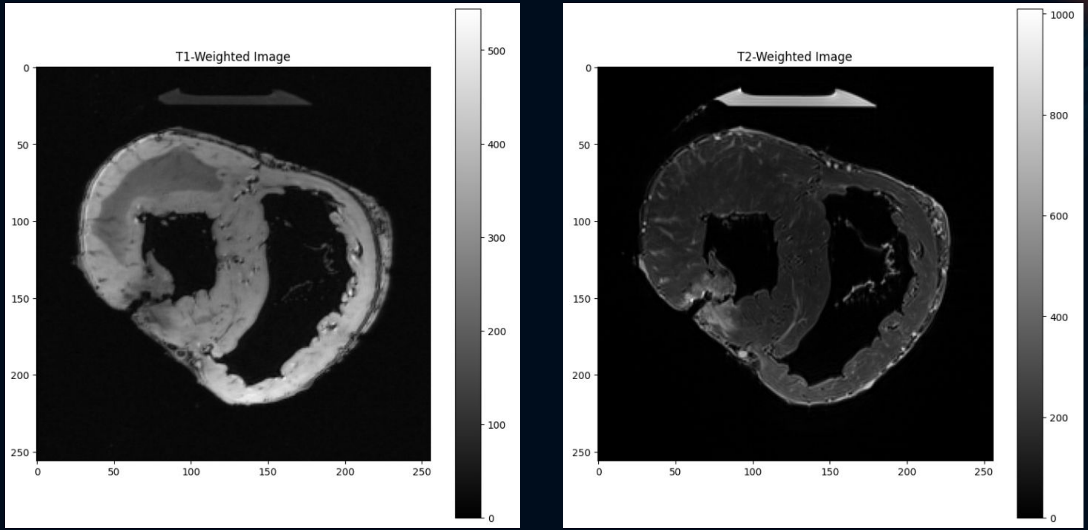
T2 protocol: TSE 3D

Number of slices: 240

Repetition Time: 12 ms

Echo Time: 3.15 ms

Flip Angle: 25°



Visualization of our dataset

Modeling Steady-State Magnetization

Bloch equations show the evolution of magnetization over time

$$\frac{dM_x}{dt} = \gamma\left(M_y B_z - M_z B_y\right) - \frac{M_x}{T_2},$$
$$\frac{dM_y}{dt} = \gamma\left(M_z B_x - M_x B_z\right) - \frac{M_y}{T_2},$$
$$\frac{dM_z}{dt} = \gamma\left(M_x B_y - M_y B_x\right) - \frac{M_z - M_0}{T_1}.$$

We can simplify this by assuming Bx, By and Bz = 0

$$\frac{dM_x}{dt} = -\frac{M_x}{T_2},$$
$$\frac{dM_y}{dt} = -\frac{M_y}{T_2},$$
$$\frac{dM_z}{dt} = \frac{M_0 - M_z}{T_1}.$$

M_i = Magnetization along the i axis, i ∈ {x,y,z}

B_i = External magnetic field components along the i axis, i ∈ {x,y,z}

M_0 = Equilibrium Magnetization

T1 = Longitudinal Relaxation Time

T2 = Transverse Relaxation Time

Modeling Steady-State Magnetization

RF pulses rotate the magnetization by the flip angle α

If this is repeated every TR → Magnetizations stabilize

Relaxation equation	Steady-state equation
$M_z(t+TR) = M_0 + (M_z(t) - M_0)e^{-TR/T_1}$	$M_z^{SS} = M_0 \frac{1 - E_1}{1 - E_1 \cos\alpha}$
$M_{xy}(t+TR) = M_{xy}(t)e^{-TR/T_2} + iM_{xy}(t)\sin(\alpha)$	$M_{xy}^{SS} = \frac{-M_0 E_2 \sin\alpha}{1 - E_2 \cos\alpha}$

Modeling Steady-State Magnetization

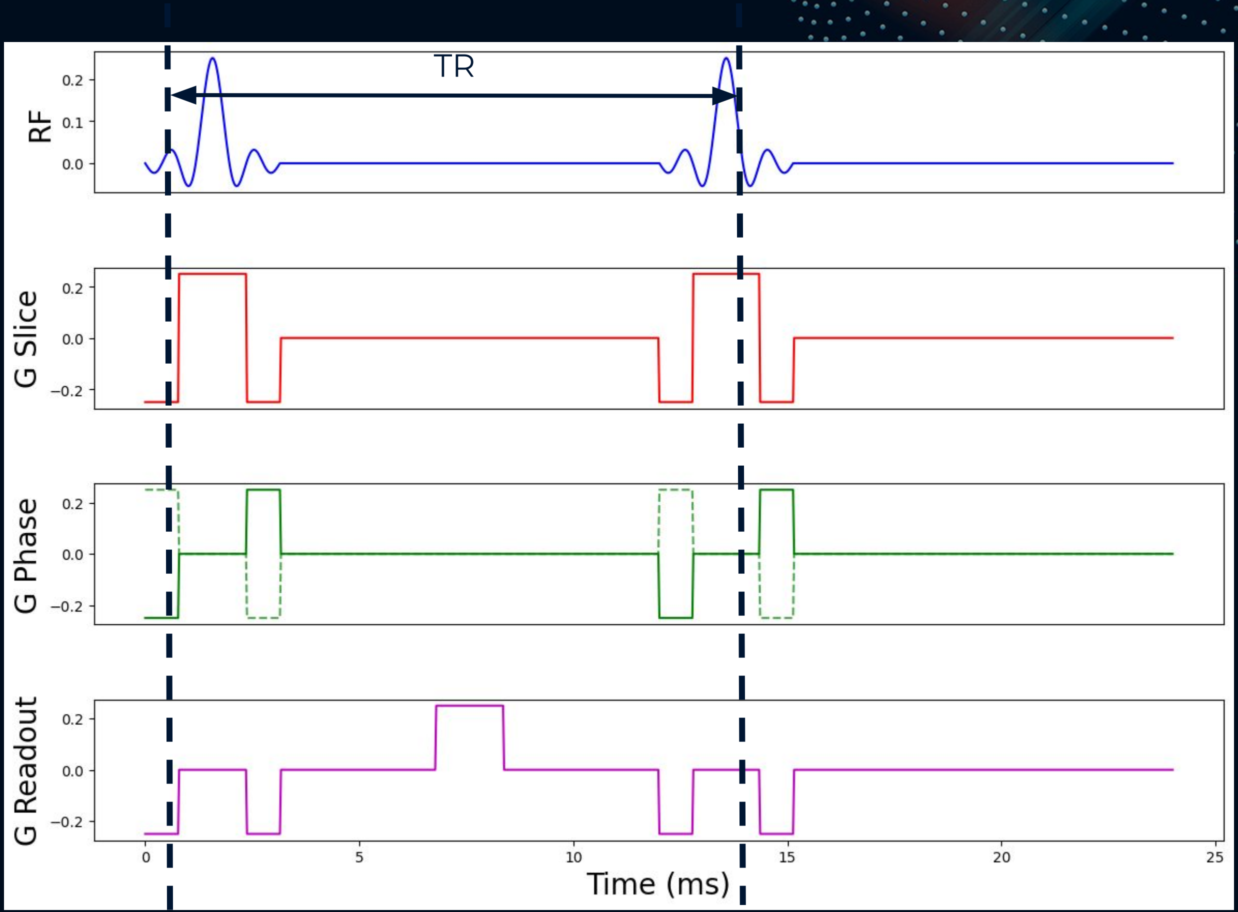
Combine the 3 steady-state equations into the full steady-state magnetization

$$M_{SS} = \frac{M_0(1 - E_1)}{1 - E_1 \cos\alpha} + i\frac{-M_0 E_2 \sin\alpha}{1 - E_2 \cos\alpha}.$$

Consider the magnitude of this magnetization [2]

$$|M_{SS}| = M_0 \cdot \frac{\sin\alpha \cdot \sqrt{E_2(1 - E_1)}}{1 - (E_1 - E_2)\cos\alpha - E_1 E_2}.$$

where $$E_{1,2} = e^{-\mathrm{TR}/T_{1,2}}$$



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Modeling Off-resonance Effects

Generate off-resonance frequency map (Δf)

$$\Delta f \sim \mathrm{Uniform}(-100, 100)\ \mathrm{Hz}$$

Phase accumulation across voxels

$$\phi = 2\pi\Delta f \cdot \frac{\mathrm{TR}}{1000}$$ **where TR is in seconds**

bSSFP signal modification

$$S_{\mathrm{off}} = S \cdot e^{i\phi} \quad \rightarrow \quad S = M_0 \cdot \frac{\sqrt{E_2 \cdot (1 - E_1)} \cdot \sin(\alpha)}{1 - (E_1 - E_2) \cdot \cos(\alpha) - E_1 \cdot E_2} \cdot e^{i\phi}$$

Assumptions/Modifications for the Simulation

Synthetic T1 and T2 map generation

- Synthetic T1 range: 250-1500 ms
- Synthetic T2 range: 40-200 ms

Maps do not consider tissue-specific T1 & T2 scaling

- Uniform, linear scaling for all tissues

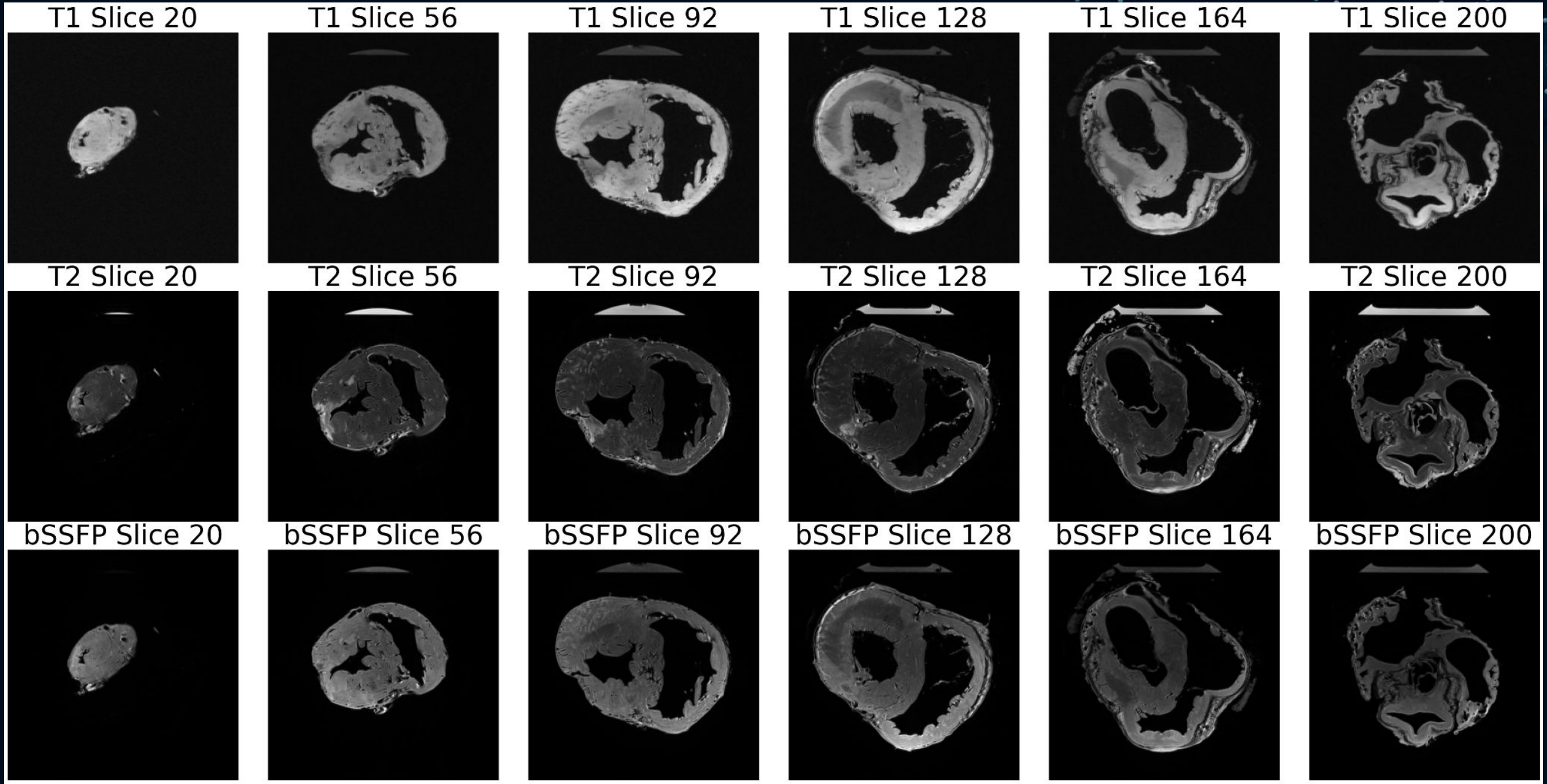
M_0 does not reflect true proton density distribution

- M_0 = unscaled T1 image

Off-resonance effect is modeled uniformly across all tissues

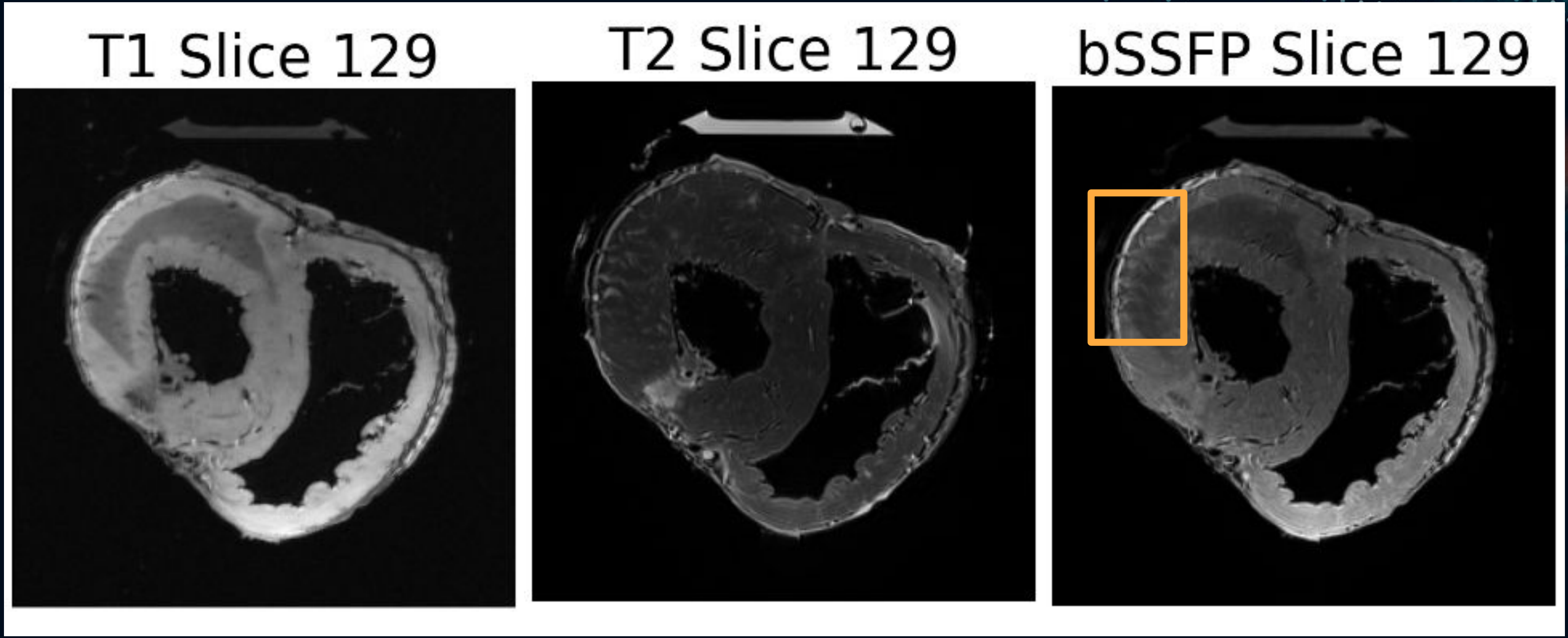
- Dynamic effects (heart beating and breathing) are also ignored

Results: Images after bSSFP



Visualization of our results

Results: Images after bSSFP



Visualization of our results

Stack-of-Stars (SoS) K-space Sampling

Golden-angle radial sampling in xy plane + Cartesian sampling along z axis [5]

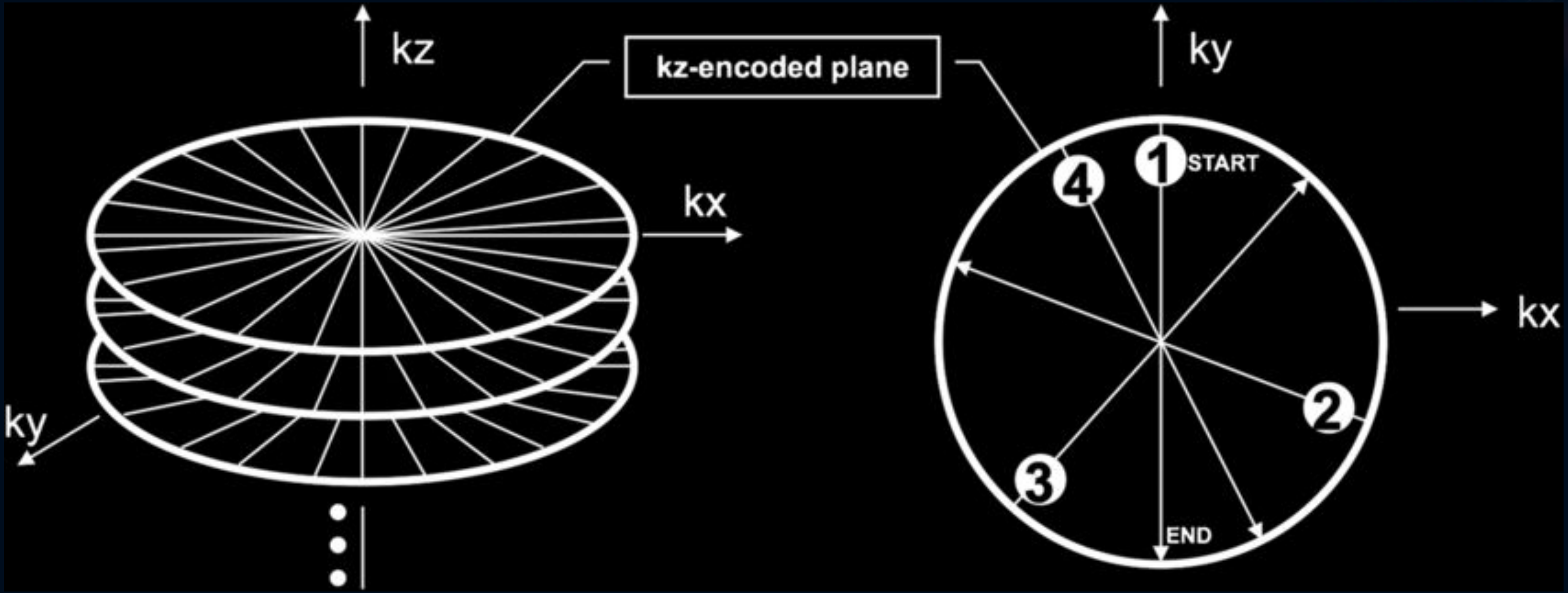
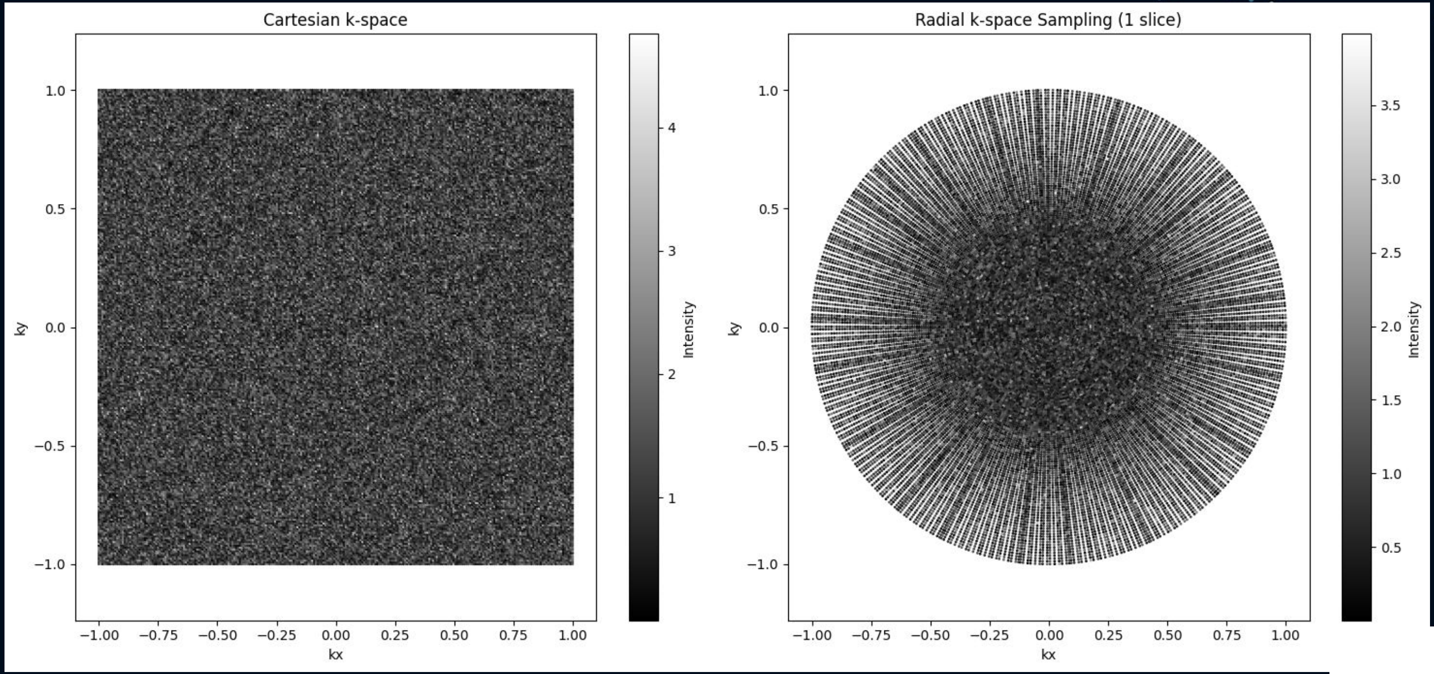


Fig 5. Illustration of 3D k-space “stack of stars” trajectory

Stack-of-Stars (SoS) K-space Sampling

Golden-angle radial sampling in xy plane + Cartesian sampling along z axis [5]



$$N_{\text{spokes}} \approx \pi \times \frac{FOV}{\Delta x}$$

Number of spokes = 400, Golden angle = 112.5° [6]

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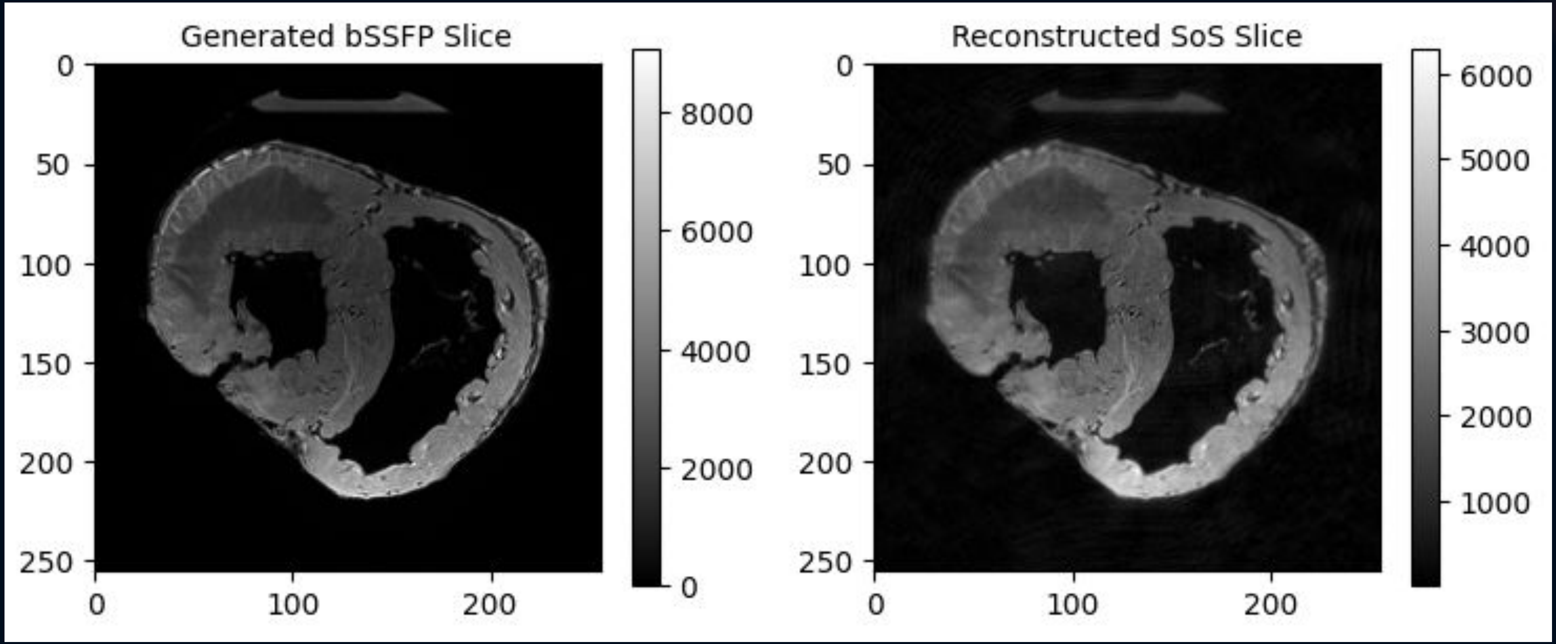
Results: Reconstruction of the SoS Sampled Image

Reconstruction method: Inverse Fourier Transform of K-space image



Visualization of our results

Strengths of bSSFP

- **High SNR Efficiency**
- **Unique Contrast Characteristics**
  - No Contrast Agents Needed
- **Fast imaging Capabilities**
- **Good Depiction of Blood vessel and Fluid Visualizations**
  - Used for functional cardiac imaging, cerebrospinal fluid flow

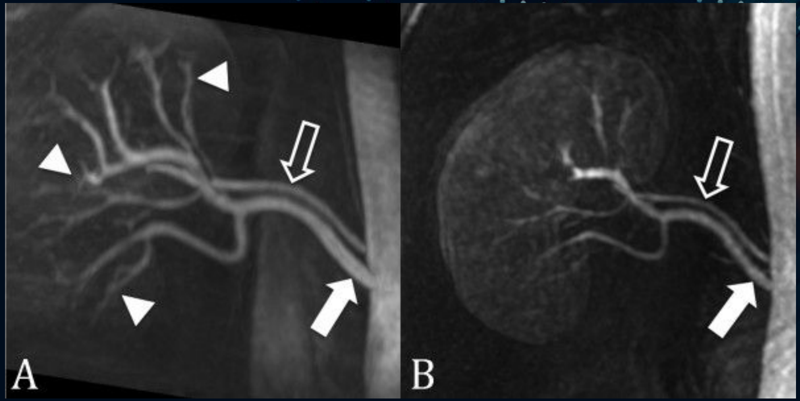


Fig 6. Non-contrast-enhanced SSFP MRA (left) contrast-enhanced MRA (right) [d]

Challenges in bSSFP

- **Susceptibility to Off-Resonance Effects:**
  - Banding Artifacts
  - Field Inhomogeneity Sensitivity
  - Can do phase cycling to mitigate
- **B1 Inhomogeneity and Flip Angle Variations:**
  - Non-Uniform Flip Angles
- **Need to do advanced shimming**

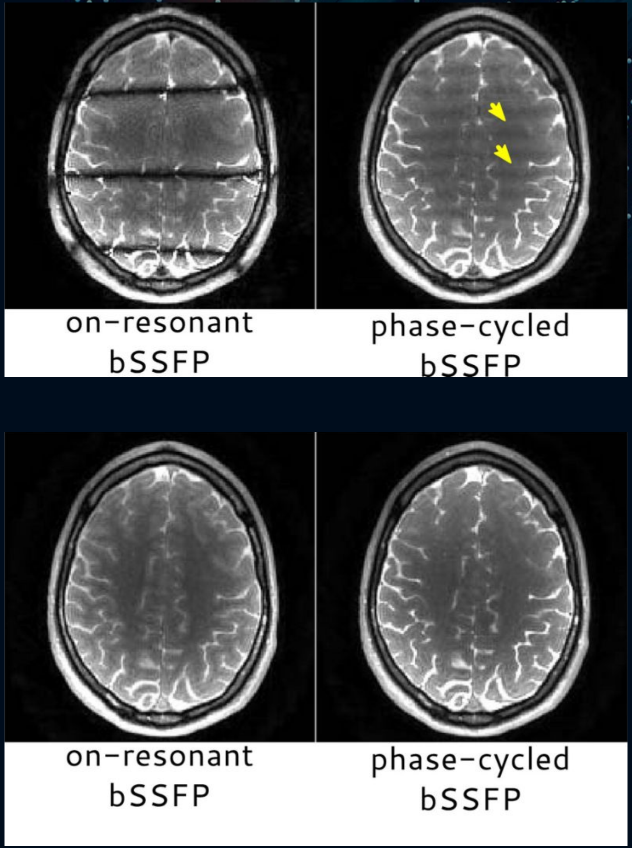
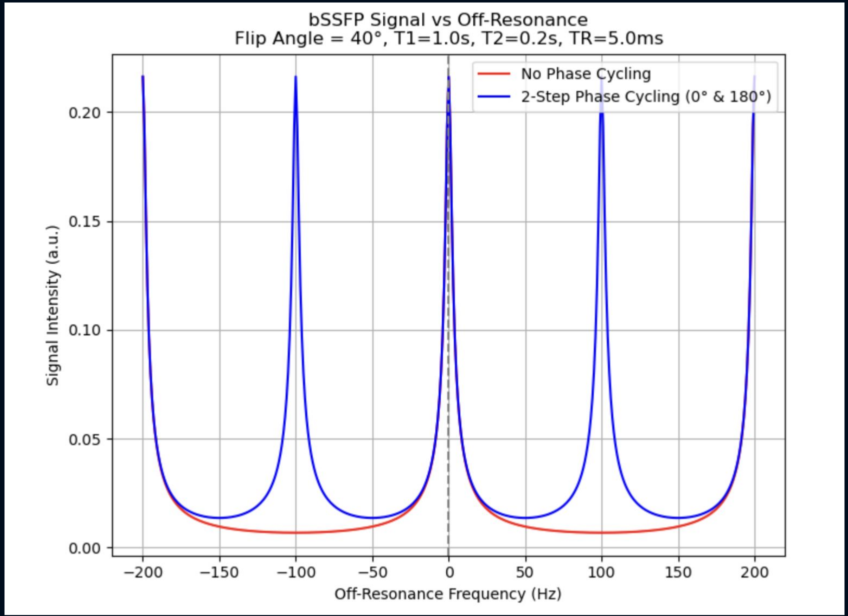


Fig 7. Without shimmed field (top) and with shimmed field (bottom) [e]

Off-Resonance Effects and Phase Cycling

Series of RF pulse phases that differ by specific increments (usually 90° or 180°) between successive RF pulses in the sequence. → Dephase the signal that contribute to artifacts



Generated as part of our simulation

References

[1] Ex Vivo Porcine Heart DT MRI Dataset
Accessed from: https://med.stanford.edu/cmrgroup/data/ex_vivo_dt_mri.html Accessed on: 11/19/2024

[2] Bieri, Oliver, and Klaus Scheffler. "Fundamentals of balanced steady state free precession MRI." Journal of Magnetic Resonance Imaging 38.1 (2013): 2-11.

[3] https://mriquestions.com/ssfp-mra.html#/

[4] Feng, Xue et al. “Non-Cartesian balanced steady-state free precession pulse sequences for real-time cardiac MRI.” Magnetic resonance in medicine vol. 75,4 (2016): 1546-55. doi:10.1002/mrm.25738

[5] https://mriquestions.com/k-space-trajectories.html#/

[6] Zhou, Ziwu, et al. "Golden-ratio rotated stack-of-stars acquisition for improved volumetric MRI." Magnetic resonance in medicine 78.6 (2017): 2290-2298.

Images

[a] https://radiopaedia.org/articles/gradient-echo-sequences-1?lang=us

[b] https://mriquestions.com/how-is-signal-higher.html#/

[c] Overview of MRI Pulse Sequences and Image Acquisition - N. Yanasak, PhD Department of Radiology and Imaging Augusta University - https://amos3.aapm.org/abstracts/pdf/127-35665-418554-127775-1650906372.pdf

[d] Hartung, Michael P., Thomas M. Grist, and Christopher J. François. "Magnetic resonance angiography: current status and future directions." *Journal of Cardiovascular Magnetic Resonance* 13.1 (2011): 19.

[e] Roeloffs, Volkert, et al. "Frequency-modulated SSFP with radial sampling and subspace reconstruction: A time-efficient alternative to phase-cycled bSSFP." *Magnetic Resonance in Medicine* 81.3 (2019): 1566-1579.

[f] Hu, Houchun H., et al. "Post-contrast T1-weighted spine 3T MRI in children using a golden-angle radial acquisition." *Neuroradiology* 61 (2019): 341-349.

Our Code

https://github.com/186shades/mri-bSSFP-simulation

THANK YOU!