Project 2 Proposal: Simulation of bSSFP pulse sequence with Radial and Stack-of-Stars k-space Sampling

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Introduction

Magnetic Resonance Imaging (MRI) is a powerful, non-invasive diagnostic tool which offers detailed insights into soft tissue structures. However, its long acquisition time poses significant challenges, including patient discomfort, motion artifacts, and limited throughput in clinical settings. These issues are especially problematic in dynamic imaging scenarios like cardiac MRI.

Balanced Steady-State Free Precession (bSSFP) [3][4] mitigates MRI's long acquisition times by providing rapid imaging with excellent soft tissue contrast, ideal for cardiac MRI. Paired with advanced k-space sampling methods like radial and stack-of-stars (SOS) trajectories, bSSFP enhances motion robustness and reduces scan times [2]. Radial sampling ensures sharp contrast with reduced artifacts, while stack-of-stars enables efficient 3D imaging, making bSSFP a powerful tool for dynamic and real-time cardiac imaging.

Our goal is to simulate and evaluate the bSSFP sequence combined with various k-space sampling strategies (that haven't been discussed in the class or as part of our assignments), such as radial and stack of stars, using digital phantoms and, tentatively, real heart models. We will compare the quality of reconstructed and ground-truth images using image similarity metrics.

Objectives

The objectives of this project are:

- Going over the theory of bSSFP
- Simulating a bSSFP (balanced steady-state free precession) pulse sequence
- Modeling off-resonance and gradient spoiling effects; plotting the off-resonance profile
- Combining the bSSFP signal acquisition strategy with SOS k-space sampling on real data
- Reconstructing MRI images from sampled k-space data using Inverse Fourier Transform
- Discussing alternative, advanced methods for efficient/accurate reconstruction
- Comparing reconstructed images with fully sampled ground-truth images

Dataset

We will be using the "Ex Vivo Porcine Heart DT MRI Dataset" [1] from Stanford's Cardiac MRI Group. Specifically, we plan to use the following data for our simulations:

- A series of T1-weighted DICOM images
- A series of T2-weighted DICOM images
- Metadata about the acquisition protocol including FoVs, TR, TE, flip angle etc.

Theoretical discussion

We plan to study and discuss:

- The physics behind balanced gradients and the resulting pulse sequence diagrams
- The concept of steady-state signal, due to repeated excitation and relaxation
- The effects of high T2/T1 ratio of signal strength
- Dependence of bSSFP on imaging parameters
- Banding artifacts and potential mitigation strategies
- Strengths and limitations of the method

Methodology

bSSFP Pulse Sequence Simulation

Our step-by-step approach to the simulation includes:

1. Defining simulation parameters and data processing

   We plan to use imaging parameters such as the repetition time (TR), echo time (TE), and flip angle (α) from the dataset's acquisition protocol metadata. Tissue-specific relaxation properties (T1 and T2) will be derived by normalizing the corresponding DICOM image series, followed by the creation of a tissue property map for each image. The normalized intensity of the T1-weighted image will be used as a proxy for the proton density (M0), since the dataset does not contain any PD-weighted images.

2. Modeling the steady-state magnetization

   We plan to compute the steady-state signal (M_{SS}) for bSSFP based on tissue relaxation properties and imaging parameters. We will use a series of equations from [8] for this:

   $$M_{SS} = M_0 \frac{\sqrt{E_2(1-E_1)\sin\alpha}}{1-(E_1-E_2)\cos\alpha - E_1 E_2} \quad \text{with} \quad E_{1,2} = e^{-TR/T1,2}$$

   Under the assumption that TR<<T1,T2 (which should hold true for our dataset since it contains biological tissues imaged at 1.5T, with TR = 3.15 ms), this equation simplifies to:

$$M_{SS} = M_0 \frac{\sin\alpha}{1+\cos\alpha+(1-\cos\alpha)\left(T1/T2\right)}$$

We will simulate the steady-state signal with both these equations and compare the results; this will act as a sanity check for our assumption that TR<<T1,T2.

Finally, we will incorporate off-resonance/gradient spoiling effects at this step and visualize the off-resonance profiles for our simulated bSSFP signal.

3. Defining the stack-of-stars k-space sampling strategy [5][6]

   We will generate spokes radiating outward from the k-space center and use the golden angle θ = 111.25° to distribute spokes uniformly, ensuring maximum coverage of k-space. This will constitute uniform radial sampling in the kx-ky plane (in each slice). We will extend this along the kz axis with Cartesian sampling, for efficient 3D acquisition using the stack-of-stars sampling strategy.

4. The final step of our simulation would be populating the k-space matrix with the simulated bSSFP signals.

Reconstruction

We will implement a baseline reconstruction using the Inverse Fourier Transform to reconstruct sampled k-space images into the image space. We have chosen not to try more complicated reconstruction methods (such as those associated with compressed sensing or deep learning techniques) in the interest of time, and because we want to focus on bSSFP theory and simulation aspects for this project. We will, however, do a theoretical exploration of advanced reconstruction techniques that may work better for SOS.

Image Similarity Metrics

We will be comparing the reconstructed images obtained using different sampling strategies on the basis of:

- Peak Signal-to-Noise Ratio (PSNR) - calculated as the ratio between the maximum possible power of a signal and the power of corrupting noise (noise is known since we determine the additive noise profile)

- Mean Square Error (MSE) - calculated as the average squared difference between the estimated (reconstructed, sampled k-space image) and actual values (unsampled ground truth image)

Visualize a Simple Application of bSSFP

Our background reading has informed us that bSSFP images have a better contrast than either T1 or T2 images because their contrast is characterized by the ratio of T2 and T1. We would like to visualize this difference in contrast, before applying image processing techniques to verify whether blood vessels are easier to extract from bSSFP images as compared to pure T1- or T2-weighted images.

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

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