Real-Time Spiral Cardiac Imaging using Balanced SSFP with Ultra-Short Variable-Density Spiral Imaging

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Introduction

Real-time cardiac MR imaging is being used or investigated for evaluation of ventricular and valve function, catheter tracking, and scan localization. Steady state free precession (SSFP) imaging has become a standard sequence for the evaluation of cardiac anatomy and function. Spiral imaging is a very efficient technique, providing a good trade-off between spatial and temporal resolution. This work investigates the design and implementation of variable-density spiral balanced SSFP for high temporal and spatial resolution real-time imaging.

Background

Balanced SSFP sequences use fully-refocused gradient waveforms to achieve a high signal level [1] and excellent contrast between blood and myocardium [2]. Balanced SSFP requires a repetition time (TR) under 5 or 6 ms for cardiac imaging, to avoid dark band artifacts. Spiral imaging allows rapid image acquisition due to efficient k-space coverage, and exhibits good flow and motion properties [3] due to oversampling of the k-space center.

Variable-density spiral imaging can be used to reduce image acquisition time by undersampling high spatial frequencies [4], in a similar manner to undersampled projection reconstruction [5].

Figure 1 shows a variable-density spiral balanced SSFP imaging sequence, and the corresponding k-space trajectory. All gradient waveforms have zero area and zero first moment over a sequence [6]. The TR is kept short to avoid signal loss. Within these constraints, we design moment-nulled waveforms to achieve a good trade-off between spatial and temporal resolution, with minor undersampling artifacts.

Variable-density spiral waveforms are designed numerically by enforcing sampling-density and gradient amplifier constraints at each time point [7]. Several techniques for rewarder design are given in [8]. Here we use numerical optimization techniques [7,9].

Sequence Design

The spiral sampling density can be an arbitrary function of k-space radius. Here we use either a uniform density (FOV=24 cm) or variable density that decreases linearly with k-space radius (corresponding to FOV = 24 cm at k = 0 decreasing to FOV = 12 cm at k = k₉₀₉₀). We determined the spatial-temporal resolution trade-off as follows:

1. A spiral readout and 3-axis moment-nulled rewinder were designed to achieve the spatial resolution and FOV.
2. The number of interleaves (N) was adjusted, and step 1 repeated to find the minimal N with TR less than 5.5 ms.
3. Using N and TR, the temporal resolution was calculated.

Figure 2 shows the temporal vs spatial resolution for uniform and variable-density spiral trajectories designed using this procedure.

Experimental Validation

On several normal volunteers, we tested a variable-density spiral design with the following parameters:

- N = 18 interleaves
- 1.6 mm in-plane resolution
- 100 ms temporal resolution (10 true frames per second)
- 24 cm FOV, decreasing linearly to 12 cm at high spatial frequencies
- 7 mm slice thickness
- 60° flip angle
- 5.4 ms TR

We imaged long-axis and short-axis cardiac views of several normal volunteers using a 5-inch surface coil and a GE Signa LX scanner with 40 mT/m, 150 mT/m/ms gradients.

Results and Discussion

Figure 3 shows systolic and diastolic frames from short-axis and long-axis cardiac views. Excellent contrast is seen between blood and myocardium in all cases. Some motion artifact is seen in frames acquired during systole, likely due to the 100 ms temporal window. However the frames during diastole are extremely clear, as evidenced by the clear depiction of the RCA in the short-axis view.

Like other radial imaging schemes, spiral balanced SSFP benefits from speed improvements over the k-space center on each acquisition. At 1.6 mm spatial resolution, the coverage requires only 25% of the acquisition time of a full-covering Cartesian scan while providing 20% higher SNR efficiency.

There are numerous factors to consider when selecting an imaging trajectory (such as Cartesian, PR, spiral, echo-planar imaging). Here we compared the spatial-temporal resolution trade-off and SNR efficiency of the fastest trajectories. However, artifacts from motion, off-resonance and perhaps parallel imaging techniques will differ with trajectory type as well as the degree of undersampling. Although we have shown the potential of variable-density spiral trajectories for real-time balanced SSFP, a full imaging comparison is still necessary.

Conclusion

Using a combination of ultra-short variable-density spiral readouts and balanced SSFP, we are able to achieve temporal resolution that is comparable to results obtained using parallel-imaging-accelerated Cartesian scanning [10], but with significantly improved spatial resolution (half the pixel size). The combination of variable-density spiral imaging with parallel imaging could further increase frame rates.

References