

# Shells With Integrated Radial and Spiral (SWIRLS): An improved shells k-space trajectory

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## Introduction

The shells trajectory is a 3D non-Cartesian trajectory that samples k-space data on the surfaces of a series of concentric spheres. It has been shown to have many favorable properties such as efficient k-space coverage, variable sampling density, motion correction, spherical center-out ordering, and maximal speed for acquiring the center of a 3D k-space (1,2). The implementation of the shells trajectory typically uses interleaves helical spirals to cover the spherical shells (1). Due to the hardware constraints on gradient slew rate, the helical spirals cannot reach the poles of the sphere. The previous solution to this problem is to acquire an additional one or two helical-spiral interleaves that cover the “polar icecap” part of k-space. That strategy, however, is temporally inefficient and can lead to phase discontinuities in the k-space data at the boundary of the polar icecap due to off-resonance effects. A single, continuous readout from between the two poles is desirable for shells sampling to minimize image blurring and ghosting. For in-plane 2D sampling, a related solution has been proposed to achieve center-out k-space trajectory by using a hybrid sequence combining radial lines and spirals (3,4). These ideas can also be generalized to the 3D spherical shells by developing a three-staged trajectory. The proposed trajectory is referred to SWIRLS.

## Methods

Due to spherical symmetry, the design of the SWIRLS trajectory only need to consider the hemisphere that starts from the equator of the sphere and ends at one pole. As with its 2D counterpart, “WHIRL”, the SWIRLS trajectory has three stages. In the first stage, the trajectory inherits the constant linear velocity sampling spiral design from the previously-reported shells trajectory (1,2). That yields nearly uniformly distributed data points and covers the equatorial part of the spherical surface. As the trajectory approaches the slew rate limit, the trajectory begins the second stage, which uses the maximal gradient slew rate to change the gradient orientation so that the helical spiral trajectory is curved to radial direction. In the final stage, the trajectory moves towards the pole of the sphere with maximum allowable gradient amplitude. Figure 1 schematically shows one single interleave design. Based on a single trajectory, the remaining interleaves were generated by azimuthal rotation. The number of interleaves is determined by Nyquist requirement. An iterative algorithm was implemented with MATLAB to find the suitable number of points spent in stage two and three. The readout length was kept constant, while the data points allocated in stage two and three were determined by the slew rate limits. The gradient waveform files were pre-generated for each shell and pre-loaded to the MR scanner for use.

The SWIRLS pulse sequence adapted from a 3D fast spoiled gradient echo sequence was implemented on both a 1.5 T and a 3T scanner (GE Signa, v14.0, Milwaukee, WI). The maximum gradient amplitude and slew rate are 40mT/m and 150T/m/s, respectively. An undersampling scheme was used by limiting the number of interleaves for the peripheral shells with large radii (1). A phantom experiment was done on the 1.5T scanner with a single channel head coil to test the performance of the trajectory. A resolution panel was placed along the axial plane inside of the phantom. The nominal FOV was chosen to be 24 cm<sup>3</sup> and the spatial resolution was 1.1 mm in each direction. The TR was 7.5 ms, the flip angle was 7°, and the readout length was 4 ms for 512 samples, resulting in a  $\pm 62.5$  kHz sampling bandwidth. A total of 110 shells were acquired. A single channel head coil was used. The acquisition time was 1 minutes and 50 seconds. Human head images were also acquired from a healthy volunteer under and IRB approved protocol. The imaging parameters were the same as described for the phantom study, except it was acquired on the 3T scanner and with an 8-channel head coil.

## Results

Figure 2 shows one reformatted axial image from the phantom experiment. Generally good image quality and high spatial resolution were achieved. Figure 3 shows the results from the human subject. Both coronal and sagittal plane were shown. Only minor undersampling artifacts were observed.

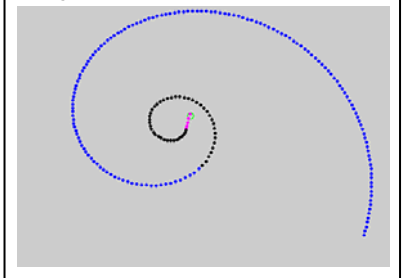
## Conclusion

We have demonstrated an optimized shells sampling method, SWIRLS. Both phantom and in vivo experiment demonstrate the initial feasibility of this method. SWIRLS yields better temporal efficiency compared to the previous “polar ice cap” shells trajectory design. The ability to generate a single interleave that covers the surface of a sphere from pole-to-pole provides convenience in customizing the trajectory for a variety of applications. The future direction includes applying this trajectory to 3D magnetization prepared imaging (5) and to optimize it for CE-MRA applications.

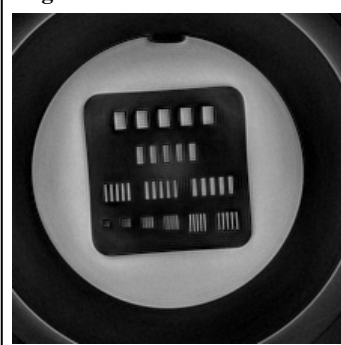
## References

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**Figure 1:** Schematic illustration of the SWIRLS trajectory. Only half of one interleave were shown. The three stages are marked with blue (stage 1: isotropic constant linear velocity spiral), black (stage 2: transition from spiral to radial) and purple (stage 3: radial).



**Figure 2:** Phantom Results



**Figure 3:** Sagittal and coronal slices of the head

