# Spiral Phyllotaxis: A Better Way to Construct a 3D Radial Trajectory in MRI


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## INTRODUCTION

In the recent years, radial 3D acquisition has been prominently discussed in the field of cardiac MRI. While this method features excellent results with undersampling [1], the self-navigating properties of the trajectory can be exploited advantageously [2]. Hence, the radial trajectory has to be interleaved in such a way that the first readout of every interleave starts at the top of a sphere which defines the shell covering all readouts. If this is done sub-optimally, the image quality might be degraded by eddy currents effects, because the phase encoding gradients are switched with rapidly changing moments for successive readouts. Moreover, computationally expensive density compensation needs to be performed if the distribution of the readouts on the sphere is not uniform. In this work, an innovative 3D radial trajectory based on a spiral phyllotaxis pattern [3] is introduced which features optimized interleaving properties: 1) if the number of interleaves is a Fibonacci number, interleaves of the trajectory self-arrange in such a way that eddy currents effects are significantly reduced, 2) an overall uniform readout distribution is preserved which facilitates simple density compensation. The spiral phyllotaxis trajectory was compared to a conventional Archimedean spiral in phantom experiments. Furthermore, navigator gated whole-heart coronary imaging was performed in 6 healthy volunteers with both trajectories.

## METHODS

In order to exploit the self-navigating properties of 3D radial MRI, the trajectory has to be arranged so that the first readout of every interleave is oriented in superior-inferior direction [2]. If, to achieve this, an Archimedean spiral trajectory is arranged in such a way that for *m* interleaves every *m*-th readout is assigned to a particular interleave, the image quality might be degraded by eddy currents effects. Exploiting the self-arranging properties of spiral phyllotaxis, a novel 3D radial trajectory is introduced which intrinsically features smooth gradient waveforms if interleaved with a Fibonacci number. The novel trajectory was derived from [3]: the azimuthal angle $\varphi_n$ and the polar angle $\theta_n$ for the *n*-th readout of a total number of *N* are defined as:

$$\varphi_n = (2\pi/360°)\cdot n\cdot\varphi_{gold};\quad \theta_n = \pi/2\cdot\sqrt{n/N};\quad \varphi_{gold}\cong 137.51°.$$

Besides the optimized interleaving properties, the trajectory preserves an overall uniform distribution of the readouts which keeps the density compensation function simple for gridding reconstruction [4].

The new trajectory was implemented on a 1.5 T Magnetom Avanto scanner (Siemens AG, Healthcare Sector, Erlangen, Germany) and was compared to an Archimedean spiral trajectory in phantoms and in-vivo. Data acquisition was performed: 1) non-interleaved as the reference data and 2) interleaved in the way which was described at the beginning of this section. The phantom experiments were performed with body coil. For signal reception in-vivo, a total of 12 elements of a body matrix coil anterior and the spine matrix coil posterior were selected. Whole-heart coronary imaging was performed in 6 healthy volunteers after informed consent. The in-vivo measurements were cardiac triggered and respiratory gated with a crossed-slice spin echo navigator placed on the dome of the right hemidiaphragm. In all experiments non-selective, T2-prepared, fat-saturated, balanced SSFP imaging was performed with the following parameters: TR/TE 3.0/1.51 ms, FOV $(220\text{ mm})^3$, matrix $192^3$, voxel size $(1.15\text{ mm})^3$, flip angle 90° and receiver bandwidth 898 Hz/Px. A total of 12818 radial readouts were acquired in 377 heartbeats for an overall undersampling ratio of 22%. Image reconstruction was performed online with a gridding algorithm [4] featuring identical settings for all datasets.

Eddy currents effects in the interleaved Archimedean and the interleaved spiral phyllotaxis images were evaluated in direct comparison to the reference image data. The in-vivo images were also evaluated with regards to SNR, CNR and vessel sharpness of the RCA as described in [5].

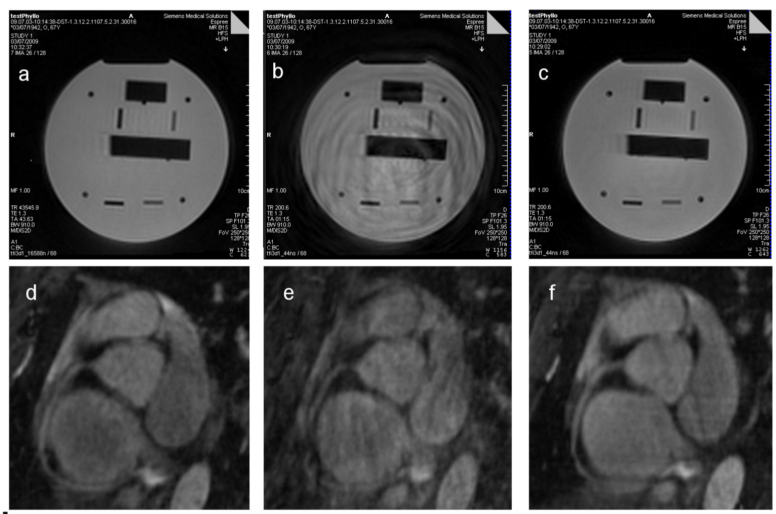

**Figure 1: Phantom results (a,b,c) and reformatted images of the RCA (d,e,f) are depicted for the 3 different trajectories. Reference images which were acquired with a non-interleaved 3D radial Archimedean trajectory (a, d) were compared to an interleaved version (b, e). In the latter case, the image quality was degraded by eddy currents effects. In images which were acquired with the novel 3D radial phyllotaxis trajectory (c. f) the overall image quality was restored. This trajectory features superior interleaving properties while the overall uniform sampling distribution is preserved.**

## RESULTS

Compared to the non-interleaved reference data set (Fig. 1a) phantom images were degraded by artifacts when data acquisition was performed with the interleaved Archimedean trajectory (Fig. 1b). The image quality was restored when the interleaved phyllotaxis trajectory was used (Fig. 1c). Only little residual artifacts were observed in phantoms.

Quantitative analyses of in-vivo results showed deterioration in SNR and CNR of the interleaved Archimedean acquisition (Fig. 1e) in comparison to the non-interleaved reference (Fig. 1d). SNR and CNR decreased respectively from 5.71±1.41 to 4.17±1.05 and from 2.46±0.94 to 1.81±0.83. The quantitative analysis of the phyllotaxis acquisitions (Fig. 1f) with values of 6.42±1.71 and 2.96±1.16, for SNR and CNR, revealed superior image quality compared to the non-interleaved Archimedean trajectory. This trend seemed to be confirmed since the vessel sharpness of the RCA was reduced from 0.68±0.12 to 0.64±0.14 comparing the non-interleaved and interleaved Archimedean spiral, and was restored to 0.74±0.13 with the novel trajectory.

## DISCUSSION AND CONCLUSION

The smooth gradient waveforms featured by the phyllotaxis trajectory avoid eddy currents effects and, thus, allow for interleaved respiratory gated whole-heart coronary imaging with highly undersampled data. Moreover, the presented method is intrinsically prepared for self-gated cardiac MRI. In conclusion, the novel 3D radial phyllotaxis trajectory proved to be a promising alternative to the conventional Archimedean trajectory. The trend towards a general improvement of the image quality observed in-vivo and the application for self-navigation techniques will be subject to further investigation.

## REFERENCES


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