

## A Simple Acquisition Strategy to Remove Off-Resonance Blurring in Spiral Imaging

**Introduction:** Spiral  $k$ -space trajectories have many advantages over traditional rectilinear sampling schemes, some of which are better acquisition efficiency, less stringent hardware requirements, and better flow performance. The major hurdle to wide-spread adoption of spiral trajectories has been their poor off-resonance performance, and much effort has been expended to correct for off-resonance effects in image reconstruction. Here, we show that using a redundant spiral-in-out sampling scheme naturally corrects for the most severe off-resonance image artifacts during image acquisition.

**Theory:** The standard implementation of spiral-in-out trajectories is in a so-called “non-redundant” scheme. In this approach, each spiral-out arm fills in the conjugate  $k$ -space location of the spiral-in arm. An alternative approach is to acquire each in-out interleaf twice; once in each direction through  $k$ -space and average the data (Fig.1). It can be shown that the signal arising from such an approach is

$$s(t) = \int m(\mathbf{r}) e^{-j2\pi k_r(t)\mathbf{r}} \cos[\Delta\omega(\mathbf{r})t] d\mathbf{r}$$

where  $\Delta\omega(\mathbf{r})$  represents off-resonance. This equation implies a relatively benign cosine amplitude modulation of the signal for small-to-moderate off-resonance values, rather than the more serious phase modulation that arises with spiral-out trajectories in the presence of off-resonance. Figure 2 shows a single line through the 2D simulated point-spread-functions (PSFs) for a spiral-out, standard non-redundant in-out, and redundant in-out trajectories with and without off-resonance. For all simulations, number of interleaves = 24, field of view = 300 mm, total readout duration 6.4 ms. Moderate off-resonance with spiral-out trajectories causes a well-known broadening of the main PSF lobe, while in non-redundant spiral-in-out it causes strong rings whose location is dependent on the number of interleaves being used, but little broadening of the PSF main lobe. Redundant scanning removes these rings and leaves the narrow main lobe, resulting in an excellent PSF for spiral imaging.

**Methods:** A resolution phantom was scanned on a 1.5 T Siemens Avanto scanner with a gradient-echo spiral sequence with a spiral-out trajectory and a redundant spiral-in-out trajectory. Acquisition parameters were: number of interleaves 14 (28 for spiral-in-out), spiral duration 10 ms, in-plane FoV 300 mm, slice thickness 5.0 mm. To examine off-resonance performance, the sequences were run once with a good shim applied, and again with the receive frequency manually tuned 40 Hz off-resonance. Images were gridded and Fourier-transform reconstructed with no off-resonance correction applied to either dataset.

**Results:** The redundant spiral-in-out trajectory shows excellent robustness to off-resonance (Fig.3). Indeed, the off-resonance performance is such that the use of advanced off-resonance correction techniques in image reconstruction did not appreciably improve the image above naïve gridding in this case (not shown).

**Discussion:** For moderate values of off-resonance, the  $k$ -space signal experiences a benign cosine windowing, which accounts for the small broadening of the PSF shown in Figure 2c and the slight blurring in Figure 3d. For larger off-resonance values (or for long readout lengths), the cosine modulation will begin nulling important frequencies in  $k$ -space as a function of  $k$ -space radius, resulting in image artifacts. This limits the use of redundant spiral-in-out scanning to areas which can be well-shimmed or to short readout durations; at least until additional methods can be developed to address this issue. This technique also corrects for concomitant field effects through the same mechanism described above.

It should be noted that the redundant spiral-in-out trajectory necessarily requires twice the number of interleaves as a spiral-out trajectory to achieve a similar resolution. The spiral-in-out trajectory is a natural method for spin-echo and turbo spin echo (TSE) sequences since it aligns the gradient echo with the spin echo. For slab-selective 3D spiral TSE imaging, at least, we have combined the redundant acquisition with the RF-chopped second average with no penalty in scan time, and have obtained good results both in phantoms and *in vivo*.

**Conclusion:** Redundant spiral-in-out trajectories with proper symmetry are naturally resistant to blurring caused by inhomogeneity and concomitant gradients. They can be used for both gradient-echo and spin-echo acquisitions.

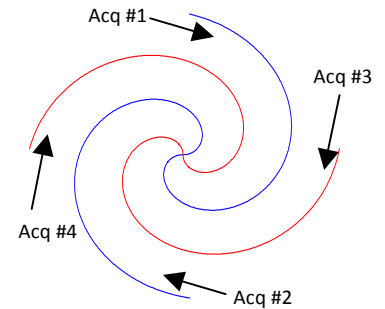


Figure 1. Redundant 2-interleaf spiral-in-out trajectory.

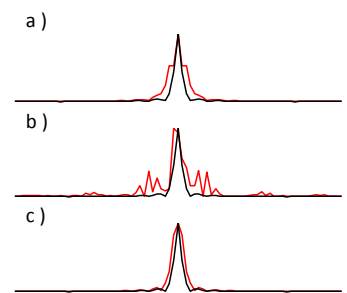


Figure 2. Spiral trajectory PSFs. a) spiral-out. b) non-redundant spiral-in-out. c) redundant spiral-in-out. Black = on resonance. Red = 100 Hz off-resonance.

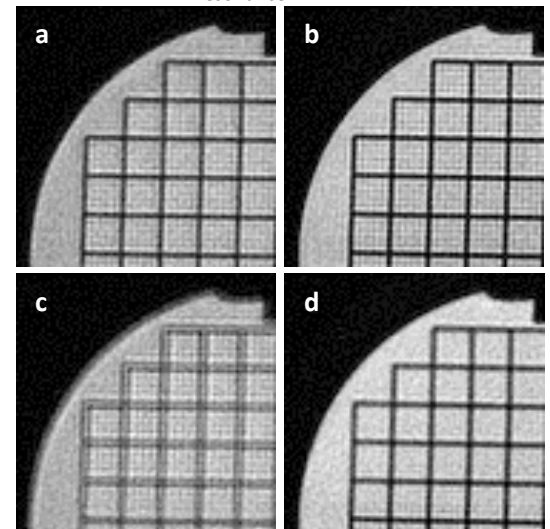


Figure 3. a) Spiral-out and b) spiral-in-out on-resonance. c) Spiral-out and d) spiral-in-out 40Hz off-resonance.

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