Tiny Golden Angles: A Small Surrogate for the Radial Golden Angle Profile Order

Stefan Wundrak[1,2], Jan Paul[1], Johannes Ulrici[2], Erich Hell[2], and Volker Rasche[1]
[1]*Ulm University, Ulm, Baden-Württemberg, Germany,* [2]*Sirona Dental Systems, Bensheim, Hessen, Germany*

Introduction: In golden angle radial MRI a constant azimuthal radial profile spacing of 111.246...° guarantees a nearly uniform azimuthal profile distribution for an arbitrary number of radial profiles and was recently used in various real-time imaging methods [1]. However, in combination with balanced SSFP sequences the large azimuthal angle increment leads to strong image artifacts, due to the varying eddy currents introduced by the rapidly switching gradient scheme [2].

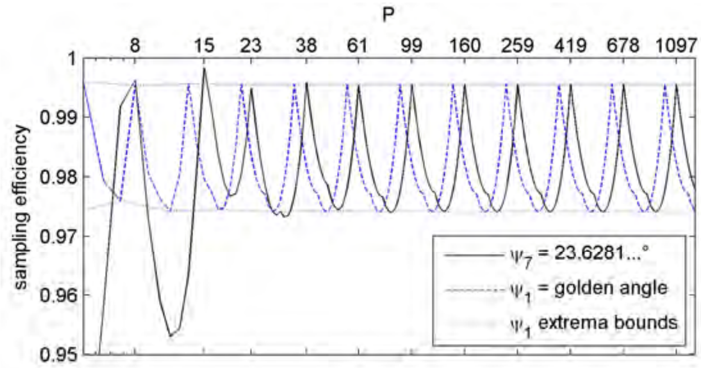

Figure 1: The sampling efficiency for ψ_7 compared to the golden angle ψ_1 (log scale on x-axis).

Methods:

Tiny Golden Angles: We introduce the sequence of angles $\psi_N = \pi/(\tau + N - 1)$ where $\tau = (1+\sqrt{5})/2$ is the golden ratio. The first two members are the well-known golden angle ψ_1 and the complementary small golden angle ψ_2. We call all angles $\psi_{N>2}$ T*iny Golden Angles* (TyGA) and show that these angles (49.750…°, 32.039... °, 27.198... °, 23.628...°, ...) have the same optimal sampling efficiency $SE_P^{\psi} = SNR_{\psi}/SNR_{uni}$ as the golden angle for an arbitrary reconstruction window P > 2N, where SNR_{uni} is the optimal signal to noise ratio for a uniform radial sampling scheme (see [1] for details).

Acquisition: Short-axis cardiac datasets from one healthy volunteer were acquired on a Philips 3T Achieva using a 32 channel coil array. A balanced SSFP sequence in combination with a radial trajectory using the golden angle ψ_1, and the new tiny golden angles ψ_3, ψ_5, and ψ_7 was used. The parameters were TE / TR = 1.15 / 2.3 ms, flip angle = 43°, pixel bandwidth = 2688 Hz, spatial resolution = 2.74 x 2.74 x 8 mm³ and 124 x 124 pixel. A reference image was acquired using a constant radial increment of 3° which leads to a uniform trajectory if a multiple of P = 60 radial profiles are used for reconstruction.

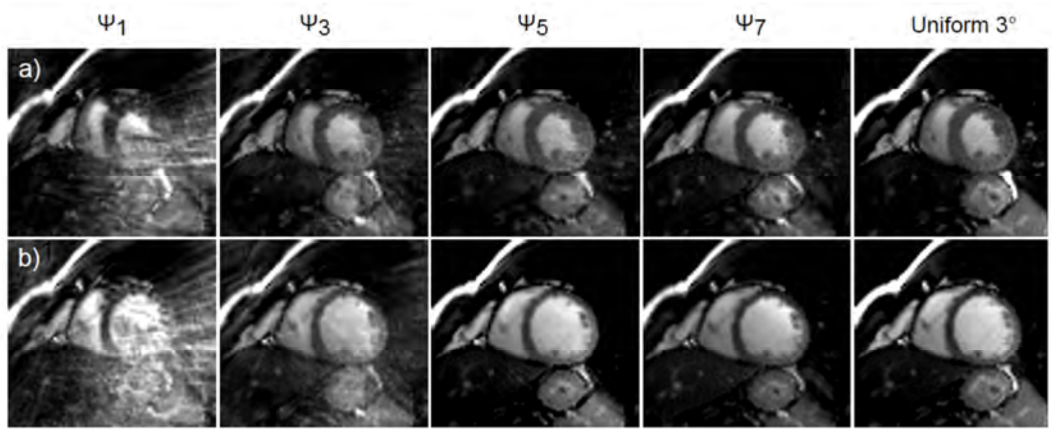

Figure 2: Cardiac short-axis view scanned multiple times using a b-SSFP sequence and a radial trajectory with different constant angle increments ψ_N.

Results: Figure 1 shows the sampling efficiency for ψ_7 compared to the golden angle ψ_1. If the reconstruction window is P > 2N = 14 the sampling efficiency stays practically within the bounds of the golden angle ψ_1. The peak sampling efficiencies are located at members of the modified Fibonacci sequence $G_1^N = 1; G_2^N = N; G_n^N = G_{n-1}^N + G_{n-2}^N$. Figure 2a shows the systole reconstructed with 60 radial profiles. The image acquired with the golden angle azimuthal increment ψ_1 shows strong image artifacts. The image artifacts are reduced if the angle gets smaller (ψ_3, ψ_5) and the image that was acquired with the smallest angle ψ_7 exhibits an artifact level visually comparable to the reference image. The enddiastolic phase (Fig. 2b) was reconstructed with 120 radial profiles (due to the longer resting phase) and shows the same artifact reduction at the smallest angle increment ψ_7.

Conclusion: It has been shown that the proposed radial profile order yields similar properties as the well-known golden angle acquisition order, but shows improved performance for balanced SSFP sequences with respect to eddy-current related artifacts. Some of these angles were reported previously in the field of theoretical biology and the distribution uniformity of leaves [3].

References: [1] Winkelmann S, et al. IEEE Trans. Med. Imaging, vol. 26, no. 1, pp. 68–76, Jan. 2007. [2] Bieri O, et al., MRM, vol. 54, pp. 129–137, 2005. [3] Marzec C, Kappraff J, Journal of Theoretical Biology, vol. 103, pp. 201–226, 1983.