A Golden Angle of 68.75° improves gradient spoiling in radial GRE

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Introduction: Radial imaging (Projection imaging) has favorable properties for dynamic processes due to the continuous sampling of the center of *k*-space. In these applications a continuous series of image frames is generated. If projection angles of views that contribute to a single image frame are in monotonously increasing ("linear") order, the center time of the image frame can be selected freely, but the minimum temporal footprint for a frame is dictated by the time required to measure the views covering 180° or 360°. This restriction can be relaxed with a quasi-random sequence of projection angles, which allow retrospective selection of center time and temporal width of image frames. The tradeoff between temporal resolution, signal to noise, and artifact level can be made retrospectively in reconstruction. within the capabilities of the image reconstruction algorithm to deal with undersampling. The most popular quasi-random view ordering scheme is based on a constant angular increment with the value of the Golden Angle (*GA*).

Since Golden Angle imaging was introduced in MR [1], based on [2] and [3], values for *GA* typically used in the MR literature are 111.25° for symmetric readouts [4,5], and 222.49° for half-echo readouts [6]. Golden Angles are based on the Golden Ratio, which describes a specific bisection of a problem-specific measure, e.g., of a distance, an area or an angle. Therefore, for every geometric problem, characterized by an angle α, a pair of equivalent Golden Angles exists [1]:

$$GA^{\alpha}_{small} = \frac{\alpha}{2} * \left(3 - \sqrt{5}\right) \quad \text{and} \quad GA^{\alpha}_{large} = \alpha - GA^{\alpha}_{small} = \frac{\alpha}{2} * \left(\sqrt{5} - 1\right)$$

With $\alpha = 360°$ for a general problem:
$\Rightarrow GA^{360}_{small} = 137.51°$, $GA^{360}_{large} = 222.49°$

With $\alpha = 180°$ for a point-symmetric problem:
$\Rightarrow GA^{180}_{small} = 68.75°$, $GA^{180}_{large} = 111.25°$

MR data, acquired with symmetric echoes, is (at high receiver bandwidths) independent of the sign of the projection direction and *k*-space coverage is point symmetric. Therefore GA^{180}_{small} and GA^{180}_{large} are equivalent with respect to *k*-space coverage. However, these angles are not equivalent with respect to spin dynamics because the resulting imaging gradients are different and their pattern is not point symmetric. Therefore, for phenomena depending on the signed imaging gradients, GA^{360}_{small} and GA^{360}_{large} should be equivalent, but not GA^{180}_{small} and GA^{180}_{large}.

An important example for this is radial spoiled GRE: The in-plane gradient spoilers are typically rotated with the projection direction, and their efficiency is reduced for large advance angles. To avoid artifacts from incomplete spoiling, the spoiling scheme must be modified and/or spoiling moments must be increased which slows down the sequence [7]. We hypothesize that image quality will be higher for GA^{180}_{small} than for GA^{180}_{large}, due to increased spoiling efficiency .

Methods: A radial gradient-spoiled GRE sequence and inline radial image reconstruction program, utilizing GPU-based CG-SENSE [8], was in-house modified to support the Golden Angle sampling scheme with the above choices for the *GA* value. The spoiling direction was rotated together with the views. Measurements with all four values of *GA* were conducted with a structured phantom on a 3T scanner (MAGNETOM Skyra, Siemens AG, Erlangen, Germany). Half-echo acquisition was used and enough views per image were acquired to make image quality independent of the variation of the angular sampling pattern. Measurement parameters were: slice orientation: sagittal, FOV = 300 mm x 300 mm, resolution: 1.56 mm x 1.56 mm x 10mm, TE = 1.1ms, TR = 3.0ms, bandwidth = 1530 Hz/pixel, 20 repetitions, flip angle = 12°, views per image = 65.

Results: The images in fig. 1 show, to a varying degree, the ring-shaped image artifacts described in [7] as arising from incomplete spoiling. The intensity of the artifact is increasing with the *GA* value. For GA^{360}_{small} and GA^{360}_{large}, the artifact appears identical, because the sense of rotation does not affect spoiling; for GA^{180}_{small} it is nearly invisible.

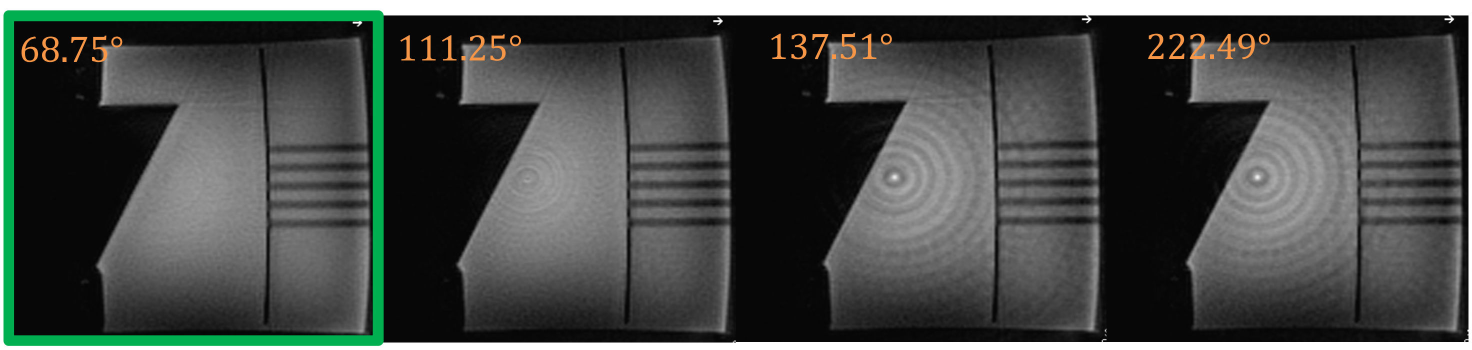

Fig. 1: radial GRE images (frame 19 of 20) for various advance angles, from left to right: GA^{180}_{small}, GA^{180}_{large}, GA^{360}_{small}, and GA^{360}_{large}.

Discussion and Conclusion: The experiment clearly demonstrates that the spoiling efficiency of gradient spoilers, rotating together with the projections, can be increased by selecting GA^{180}_{small} instead of the commonly used GA^{180}_{large}. The improved efficiency can in turn be invested in smaller spoiling moments which in turn will increase the frame rate.

References: [1] Winkelmann S et al., IEEE Trans Med Imaging. 2007, 26(1):68-76. [2] Koehler T, Proc. IEEE Nucl. Sci. Med. Imag. Conf., 2004, M10-200.
[3] Kasantsev IG et al., Electr. Notes Discrete Math., vol. 20, pp. 205–216, 2005. [4] Ehses P et al., Magn Reson Med, 2013, 69: 71–81.
[5] Hansen MS et al., Magn Reson Med, 2012, 68: 741–750. [6] Konstandin S, Schad LR, Magn Reson Med 70:791–799, 2013.
[7] Vakil P et al., JMRI, 2012, 36: 249-258. [8] Sorensen, TS et al., IEEE Transactions on Medical Imaging , 28 (12): 1974-1985, Dec. 2009