"Be nice to your gradients!" Useful gradient modifications for SPI

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Introduction: Single Point Imaging (SPI) is a MRI technique with pure phase encoding which avoids artifacts such as off-resonance blurring [1]. SPI requires long and strong gradients as k-space samples are acquired with continuously ramped gradients which results in excessive heating of the gradient coils. Gradient heating can affect the gradient fields [2], and detailed heating models have been proposed [3, 4]. As the gradients are also active during RF excitation, additionally an unwanted slice selectivity is imposed. Post processing schemes have been proposed for eliminating the slice selection [5]. Here, we introduce a novel k-space ordering for SPI which avoids keeping a gradient active at high levels for long times and a new approach in sequence design which limits the gradient level during excitation while maintaining continuous gradient ramp feature of SPI as a silent sequence. The methods in this study are demonstrated in SPI, yet, they are applicable to other hard pulse sequences.

Materials and Methods: All measurements are conducted on a 1.5T clinical MR system (Symphony, Siemens AG, Erlangen). Three SPI sequences are tested with continuously ramped gradients with different k-space ordering: standard step-wise ordering (Seq. 1), modified to have a rectangular-spiral ordering at each 2D slice (Seq. 2), and samples of k-space are ordered such that the 3D k-space is divided into cubic shells and each shell is travelled following contours in a saddle-like trajectory (Seq. 3). Gradient waveforms that show significant difference are shown in Fig. 1. Temperature information is obtained from sensors placed in gradient coil connectors (Fig. 3). Heating is tested with sequence parameters TR = 6.4 ms, effective TE = 0.3 ms, 64x64x64 samples, FOV = 240 mm.

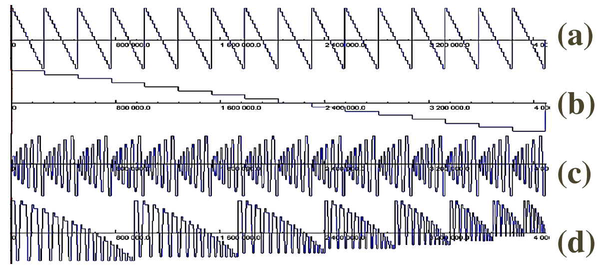


Figure 1: Gradient waveforms for Gy of Seq. 1 (a), Gz of Seq. 1 (b), Gx of Seq. 2 (c), Gz of Seq. 3 (d)

Additionally, the gradient amplitude was lowered during RF excitation as shown in Fig. 2. The gradient level amplitude during readout is re-calculated to:

$$G_{Actual} = (G_{Standard} \cdot t_p - G_{Limit} \cdot t_p/2)/(t_p - t_{ramp}/2),$$

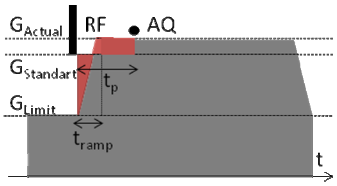


Figure 2: Limitation of gradient level on RF excitation. G_{Actual} is re-calculated.

where $G_{Standard}$ is the gradient level before modification, t_p is acquisition delay after RF excitation, G_{Limit} is the limited gradient level and t_{ramp} is the ramp duration. Note that the effective TE increases due to the limited slew rate. Bloch equation simulations are performed for slice profile calculation at the maximum field strength of the sequence. Imaging experiments are done with TR = 2 ms, FOV = 340 mm, 64x64x64 samples, effective TE = 0.3 ms, α = 1° using a receive-only flexible loop coil (Ø 25 cm) and rubbers as phantom (T_2^* = 600 µs). SPI images with regular and limited gradient strength are reconstructed for comparison (Fig. 4).

Results: The temperature measurements during sequence execution shows that with standard step-wise k-space ordering (Seq. 1), higher temperatures are measured than with the reordered sequences 2 and 3 (Fig. 3). While sequences 1 and 2 could not be executed by the MR system due to a cooling system warning, Seq. 3 could finish data acquisition without interruption. Gradient waveforms for three directions in Seq. 3 are similar as well as the measured increase in temperature. Therefore, the modified sequence can be performed with more extreme parameters compared to standard version. Results also show that gradient coil heating not only depends on the instant current levels but also on k-space ordering since the cooling system has a non-negligible time constant.

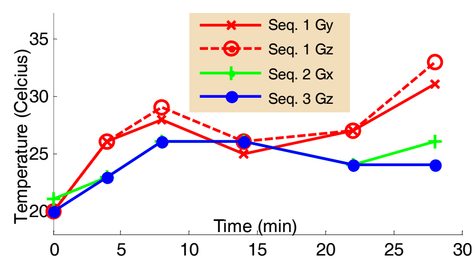
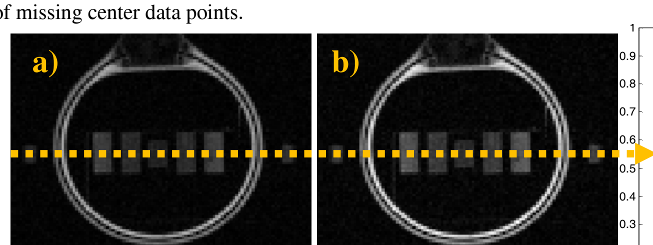


Figure 3: Temperature measurements for four different gradient waveforms shown in Fig. 1

The Bloch simulations show that the slice profile improves with the limited gradient amplitude, and even at the edges of the FOV an excitation of 80% is achieved. In Fig. 4 one can see that the limited gradient amplitudes provide a smoother signal distribution over FOV. The additional effect of the gradient limitation on gradient heating was minor for TR = 6.4 ms.

Discussion: The proposed k-space ordering is more gradient-friendly in a way that strong discontinuities in the k-space are avoided leading to a reduction of gradient-induced eddy currents. Furthermore, the gradient coils carry less energy per unit time. Although temperature measurements do not represent actual gradient coil temperatures and many interfering parameters are ignored, the results clearly show that an optimal ordering of k-space can reduce gradient heating. In the future we will optimize k-space ordering with search algorithms instead of intuitive k-space trajectories.

Lowering the gradient level during RF excitation improves the excitation profile while maintaining the low acoustic noise levels of the continuous gradient sequences since gradients are not switched off completely. Limiting gradient amplitudes can also be applied to projection reconstruction sequences such as ZTE [4]. Here, low gradient amplitudes might result in lower number of missing center data points.



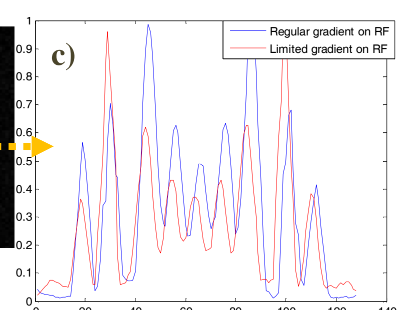


Fig. 4: Comparison of sequences with regular gradient level (a) and gradient level halved on RF (b) resulting in a smoother slice (c)

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