Cog-Wheel Imaging: A Rapid Echo Shifted Technique

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Introduction

Increasing scanning efficiency is one of the driving forces for the development of new MRI techniques. Echo shifting(1,2) has proven useful in numerous applications requiring long echo time in combination with high image resolution. Echo shifted sequences allow for TE>TR and typically operate in the regime of $TE \approx kTR$ with k=2..5. The MUSIC technique(3) presents a limiting case of echo shifting, when all slices of the slice package are sequentially excited following by a single rewinding and a common readout gradient (Fig. 1).

Here a new echo shifted gradient echo (GRE) technique is proposed, which similarly to MUSIC has $TE \gg TR$, but in contrast to that intrinsically incorporates spoiling and shifting gradients, requires no common rewinding gradient and allows number of slices to exceed k.

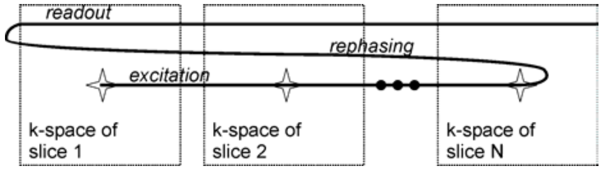

Fig. 1. *Arrangement of k-spaces in the MUSIC technique(3).*

Methods

The arrangement of k-spaces for individual slices for the proposed technique, dubbed cyclic orbital gradient (COG), is shown in Fig. 2. For the sake of compacting the figure dephaser gradient moments are scaled down. Following the excitation themagnetisation is dephased and a readout gradient is applied which, however, is not meant to generate an echo at this point. Thereafter the next slice is excited and the same two gradients are applied, but this time rotated by a certain angle. The sequence is repeated without generating echoes until the number of slices excited reaches the shifting factor, k. The crucial point is that the spoiler gradient and the angles are calculated for the readout gradient to refocus the magnetisation excited in slice 1 and produces the first echo on the k-th TR. The sequence continues (dashed line) exciting new slices and refocusing previously excited ones. In contrast to other echo shifted methods the number of slices here is not limited to multiples of k, since the next slice to excite does not have to be slice 1, but rather the next slice in the package. The calculation of the gradient moments and angles is detailed in Fig. 3. For the given spatial resolution, number of projections, number of slices and k-space isolation (which define $\alpha_{\min}$ and β) $\alpha \geq \alpha_{\min}$ is searched to satisfy the echo condition. Another ingredient needed to achieve an echo on the k-th cycle is the requirement for the total gradient moment in the slice selection direction be zero. This is achieved by alternating the slice selection polarity. For this reason, in the current implementation the COG sequence only accepts odd shifting factors.

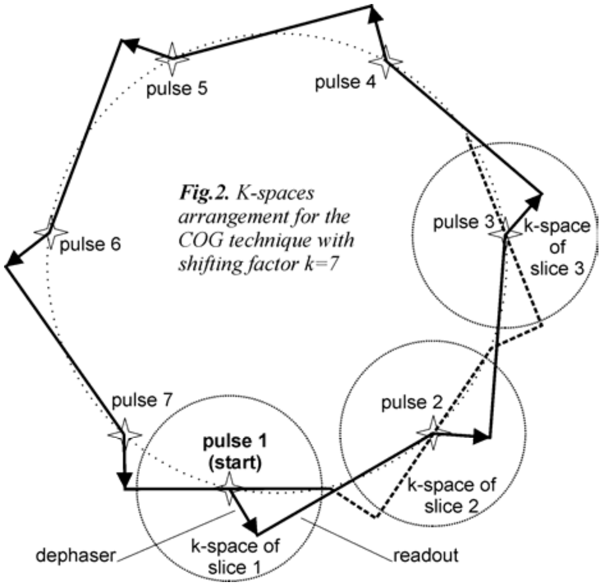

Fig.2. *K-spaces arrangement for the COG technique with shifting factor k=7*

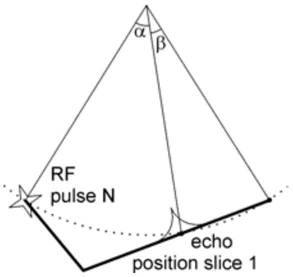

Fig. 3. *Calculation of the COG gradient moments based on the geometric considerations. Angle β is defined from the required readout moment; α controls the separation between k-spaces and is adapted to the echo condition: $k\alpha+(k-1)\beta=360°$. On the subsequent TR the gradients are rotated by the angle $\alpha+\beta$.*

The COG technique was implemented on a 1.5T Sonata system (Siemens Medical Solutions, Germany). Test imaging and calibration experiments were performed in a homogeneous doped water phantom. The volunteer was scanned in accordance with the IRB regulations.

<u>Trajectory correction:</u> Due to its extended character the COG k-space trajectory is likely to deviate from the ideal one. In projection reconstruction (PR) MRI eddy currents and gradient delays result in the typical problem of being unable to hit the k-space centre with every projection. For COG, due to the error accumulation on every TR, this results in the trajectory to become a spiral instead of a circle and no projections to hit the k-space centre, leading to inconsistencies in k-space and signal cancellation. Secondly, due to the untypically long for PR TEs susceptibility gradients may cause notable k-space centre shifts. However, because these shifts remain constant for all projections, regrinding the data produces a consistent k-space with a shifted centre, resulting in the suboptimal SNR but no image artefacts.

For trajectory calibration RF excitation was disabled for all slices but one. Low amplitude phase encoding gradients were overlaid on the trajectory and stepped to achieve independent phase encoding for every projection angle. 2D k-space data acquired for every projection angle were analysed to calculate the correction factors. The corrections were found to be independent on the projection angle and were applied via modifying the dephasing gradient.

<u>Image reconstruction</u> was performed offline in Matlab (The Mathworks, USA) using complex inverse Radon transform. Reconstruction included following steps. An initial image with a suboptimal SNR was reconstructed based on the raw projections acquired. From the image thus produced, projections were calculated via forward Radon transform. These projections were then used to calculate the first order phase correction to the raw data. Phase correction accounted for the residual trajectory imperfections, shim drifts and subject motion. From the corrected data the final image with the improved SNR was reconstructed.

Results and Discussion

The result of the in vivo imaging experiment is presented in Fig. 4. The image quality is acceptable bearing in mind the high spatial resolution of 1×1×2 mm. SNR of the COG image reconstructed from the phase-corrected data (Fig. 4) is notably higher than that of a FLASH image with the comparable acquisition parameters (data not shown).

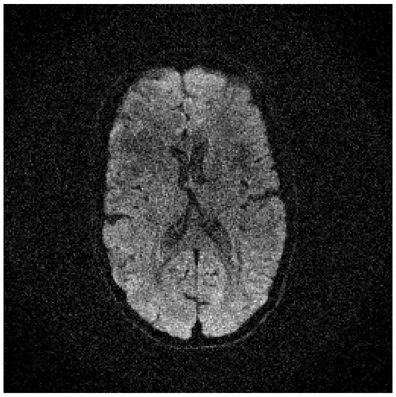

Fig. 4. *Slice through the brain of a normal volunteer.*

Measurement parameters: TR=3.8 ms, k*=17, TE=63.5 ms, flip angle 32°, 256^2 image matrix, NP=407 (full k-space for the matrix), 52 slices, 2 mm slice thickness, 0.4 mm gap, FOV 256 mm; TA=82 s.*

Presented here is the novel rapid 2D encoding scheme for susceptibility weighted imaging which drives the echo shifting idea to its limit. The efficient use of dephasing and readout gradients eliminates the need for large dephasing-rephasing gradient pairs typically required by the echo-shifted sequences. The extreme efficacy of the sequence comes, however, at the price of loosing the flexibility of the imaging parameter choice. Thus, parameters like TR, TE, image resolution, number of slices, etc become linked and cannot be changed without affecting the others. COG is intrinsically a high resolution technique because readout gradients are used for separating signals from the neighbouring k-spaces. Reducing spatial resolution requires a dephaising gradient increase to maintain the signal separation which leaves TR virtually constant. The proposed encoding scheme is not limited to a 2D slice selective case; extending COG to a 3D encoding technique similar to PRESTO(2) seems feasible.

References: [1] Moonen CTW et.al. MRM 1992; 26:184-189 [2] Lui G et al. MRM 1993; 30:68-75 [3] Loenneker T et al. MRM 1996; 35:870-874