# Improvements on Single-shot STEAM with Optimised Signal Shaping for Diffusion Weighted Imaging at High Fields

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**Introduction:** It was recently shown that a diffusion weighted Single-shot Stimulated Echo Acquisition Mode (DW ss-STEAM) pulse sequence is an alternative to the standard DW EPI at high fields [1-3]. By designing variable flip angles (vFA) for centric *k*-space acquisition without RF spoiling, more signal is utilised than usual. The iterative vFA-algorithm is based on the Extended Phase Graph formalism (EPG) (e.g. [4]). Unfortunately, the diffusion-weighted images thus obtained often suffer from severe image artefacts caused by tiny gradient-moment inaccuracies in the DW-preparation (DW errors). These unpredictable deviations impede the coherent summation of all available transverse phase states. However, this drawback can be circumvented by a slight change of the pulse sequence and use of advanced signal shapes with beneficial vFAs that display a reasonable compromise between SNR and resolution. Preliminary results of a basic experiment finally demonstrate the possibility to correct for the DW errors and so to derive the advantage of the advanced signal shapes in combination with full coherent summation.

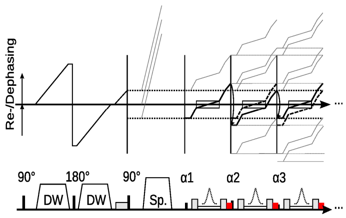


*Fig. 1 Schematic phase graph and pulse sequence of the new DW ss-STEAM sequence. Red marked gradients separate odd- and even-parity echoes.*

**Methods:** Coherent coincidence of transverse phase states is ensured by matched spoiler gradients. A slight modification of the former pulse sequence allows for completely artefact-free DW image acquisition by separating direct spin echo contributions from the primary stimulated echoes (extra dephasing gradient moments, marked red in Fig. 1). The correspondingly adjusted vFA-algorithm produces complex vFAs for sensible signal shapes and improved SNR (increased initial flip angles during *k*-space centre readout, see Fig. 2).

Utilising a cylindrical white matter phantom (T1=767ms, T2=102ms at 3T), the possible signal gain with four different signal shapes (constant, moderate exponential decay, Hann and Gaussian with 0.3$k_{max}$ confidence interval) and three acceleration factors using GRAPPA parallel imaging is systematically investigated on a 3 Tesla SIEMENS system with a 12 channel receive head-coil. The feasibility of such improved DW ss-STEAM sequence for DW studies is demonstrated in an *in vivo* experiment on a 4T SIEMENS system with an 8 channel receive head-coil applying the ss-STEAM sequence with a Hann shape that offers a good point spread function.

A final experiment on the 3T scanner utilising a large spherical phantom containing a solution of $NiSO_4$ + NaCl demonstrates how a simple adjustment of the second DW gradient can potentially help to correct for the actual DW errors and thereby to facilitate the highest SNR gain by combining advanced signal shapes with full coherent summation. The complex STEAM readout module is therefore replaced by a dephasing and rephasing gradient to obtain a simple gradient echo following the identical DW-module with globally excited magnetisation. Both the DW as well as the readout is performed on all three physical axes leading to 9 DW signals in comparison to 3 non-DW signals. The actual DW gradient error should be expressed in an echo time shift if readout is on the DW-axis and a signal reduction if readout is on the orthogonal axes due to incomplete or additional rephasing.

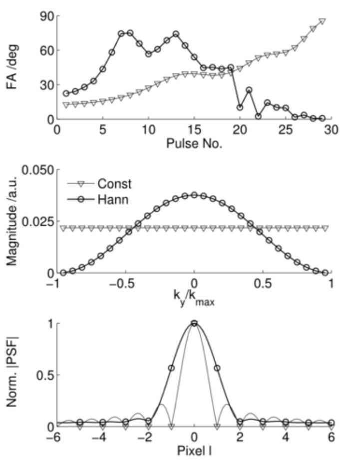


*Fig. 2 Complex vFA trains, corresponding signal shapes and PSFs (simulation, T1/T2=1200/75ms assumed).*

**Results:** The possible white matter SNR gain using the actual ss-STEAM version with advanced signal shapes is depicted in the bar-plot of Fig. 3. The SNR increase with higher acceleration factor (R) is remarkable. Overall, a Hann shape performs approximately twice as well as a constant shape and apodises the image moderately at the same time. Note that the pale bars, denoted "R3+SE", reflect the case of full coherent summation incorporating also the contribution of the direct spin echoes that are currently shifted out of the acquisition window. The images for the principal eigenvector map shown in Fig. 4b were obtained using the Hann shape and 12 approximately uniformly distributed DW-directions [5] within 26:10min total acquisition time (50 slices, 2mm isotropic, 12/4 averages for b=0/700 s/mm$^2$). The Hann shape was shown previously to yield comparable white matter SNR as EPI in similar acquisition time *in vivo* at 4T (Fig. 4a, 1:17min EPI, 1:37min ss-STEAM).

The effect of the erroneous DW gradient moment on the echo signal is demonstrated in Fig. 5 for DW in z-direction with b=600s/mm$^2$ and readout on x-, y,- and z-direction. The blue and red dots correspond to non-DW and DW data without gradient correction, respectively. The according curves are obtained by a cubic spline interpolation to achieve better estimates of the echo maxima. From the echo time difference (18.6μs) it follows that the erroneous gradient moment amounts only approximately 0.05ms·mT/m. By naively trying to correct for that error with an additional moment of 0.03ms·mT/m (corresponding to a hypothetical prolongation of the second DW gradient of only 1μs!), the echo time approaches the correct time on the z-axis (green curve) and the echo height on the orthogonal axes increases in agreement with the theory. This indicates that such an approach may be suited to do DW ss-STEAM without neglect of available signal (cf. 3, "R3+SE").

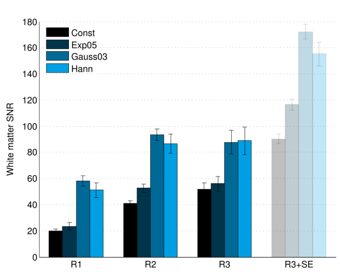


*Fig. 3 White matter phantom results for different signal shapes and iPAT acceleration factors.*

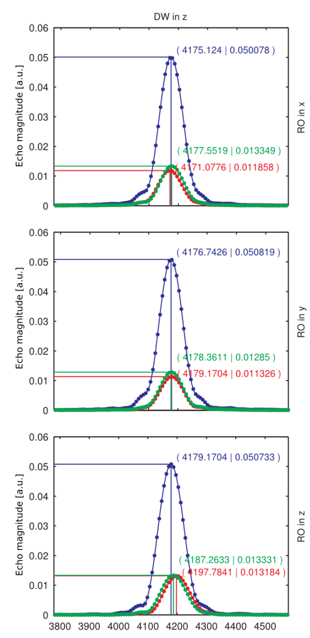


*Fig. 5 Globally excited and refocused echo without DW (blue) and b=600s/mm$^2$ (red) leading to interferences with the former sequence. The green curve demonstrates almost successful correction.*

**Discussion/Conclusion:** Although currently forced to restrict the signal gain by separation of two main phase graph pathways, it was shown that the EPG-based vFA-algorithm in combination with an adequate signal shape, such as the Hann-filter, and iPAT offers reasonable image quality for DTI at high fields (4T) without geometrical distortions in EPI-comparable acquisition times. Furthermore, the current investigations on the correction of DW gradient errors point out a possible circumvention of the pathway separation to obtain a further SNR increase of a factor of two.

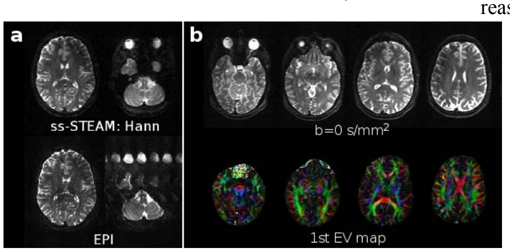


*Fig. 4 In vivo results at 4T. a) ss-STEAM with Hann compared to EPI (non-DW). b) Examples from a DTI experiment using ss-STEAM with Hann.*

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**References:** [1] Nolte, U. G. et al., MRM,2000,44(5):731-736; [2] Finsterbusch et al., MRM,2002,47:611-615; [3] Stöcker, T. et al., MRM,2008,61:372-380; [4] Hennig, J., CMR,1991,3:179-192; [5] Stirnberg, R. et al., Proc.Intl.Soc.MRM,17,2009