# On the Diffusion Sensitivity of 2D- and 3D-Turbo Spin Echo Sequences


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**INTRODUCTION AND MOTIVATION:** A common assumption in literature is that fast / turbo spin echo sequences (FSE/TSE) do not demonstrate any distinct diffusion weighting, since the permanent refocusing of magnetization does not lead to noticeable diffusion effects. This statement, however, does actually refer to standard TSE imaging with 180° refocusing pulses. The use of low refocusing flip angles, as used for specific absorption ratio (SAR) mitigation, introduces considerable fractions of dephased transversal and longitudinal magnetization components. These experience higher diffusion sensitivity due to $b \sim k^2$, with k being a measure for dephasing (e.g. 'k-space'). Furthermore, modern types of 3D-TSE sequences such as SPACE or CUBE [1] use very long RF pulse trains with variable flip angles. This work investigates therefore the effective diffusion sensitivity of such contemporary TSE sequences by using a recently published extended phase graph (EPG) approach [2-4].

**METHODS:** The framework for assessing diffusion effects within the EPG calculus was implemented into MATLAB scripts [2-4]. Based on these scripts the timing and necessary RF pulse and gradient objects for TSE sequences with both 2D and 3D acquisition modes were defined accordingly to the acquisition parameters given below. The refocusing flip angles were generally kept different for each RF pulse object to allow for variable flip angle sequences. Idealized rectangular gradient shapes were assumed, since the difference compared to 'real' trapezoidal shapes was shown to be completely negligible for multi-pulse sequences [5]. – For the simulation of realistic 2D-TSE imaging, the following protocol parameters were presumed: FOV=220mm, matrix=256x256, TE=80ms, ESP=8.0ms, ETL=11 or greater, BW=264Hz/px, duration RF pulses=2.56ms. The refocusing pulses had a constant user-defined flip angle $\alpha$ between 0° (no refocusing) and 180° (full refocusing). – For the simulation of realistic 3D-TSE imaging a similar geometry was assumed: FOV=220mm, matrix=256x256x256. The other adapted parameters were TE=440ms, ESP=4.0ms, ETL=220, BW=781Hz/px, duration RF pulses=0.7ms. An adequate refocusing flip angle schedule for extended echo train TSE imaging was generated similar to [1]. For signal simulations a representative virtual tissue with the biophysical MR properties T1=1000ms, T2=100ms, and apparent diffusion coefficient ADC=0.001mm$^2$/s was introduced.

**RESULTS:** Figure 1, left side, depicts the resulting signal response of a 2D-TSE sequence in dependence of its constant refocusing flip angle $\alpha$. The response is clearly dominated by the maximal achievable signal intensity of a TSE sequence without diffusion [6]. On the right side the resulting net b-factor of the TSE is shown. For high flip angles the diffusion weighting is completely negligible. However, stronger diffusion effects become visible for quite low refocusing flip angles in 2D-TSE.

Figure 2 demonstrates the diffusion sensitivity of a modern 3D-TSE sequence with very long echo trains, generated by RF pulses with optimized variable flip angle schedules, being different around the central RF pulse / center echo (left chart). The center chart depicts the resulting total b-factor in dependence of the echo number. Noticeable diffusion sensitivity accumulates along the echo train. For the center echo, which usually provides the main contrast of an image, the b-factor is approximately 88mm$^2$/s. On the right side of Fig. 2 the partial diffusion sensitivity between consecutive echoes of such a 3D-TSE sequence is displayed. This partial effective b-factor per interval is very different from echo to echo. Particularly, a peculiar oscillatory response can be observed. The partial contributions for the total b tend to decrease towards the later echoes in the echo train.

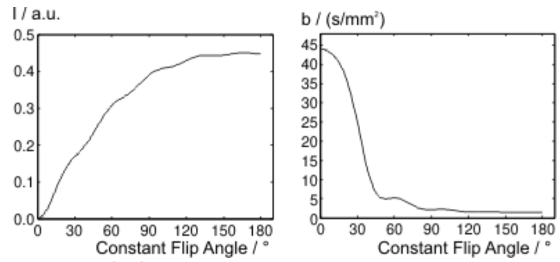


**Fig. 1:** *Left*: Simulated signal response measured with a typical 2D-TSE sequence depending on the constant flip angle for the representative tissue. *Right*: Dependence of the net b-factor on the flip angle. For low flip angles the diffusion weighting becomes more pronounced.

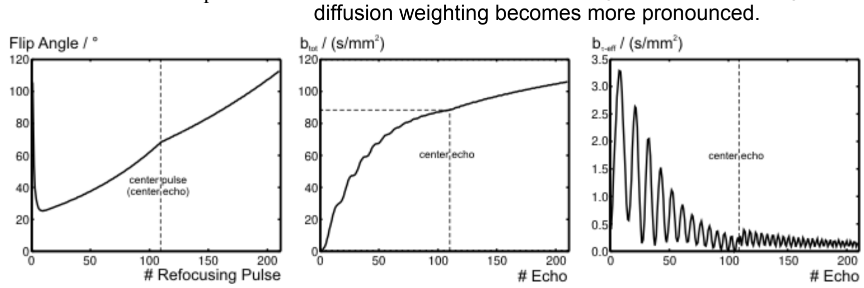


**Fig. 2:** Diffusion sensitivity of a 3D-TSE sequence with variable flip angles and extended echo trains, known as acronyms such as SPACE, CUBE etc. from literature or vendors. *Left*: Typical variable flip angle schedule for such a sequence type. *Center*: Total b-factor the 3D-TSE sequence demonstrates for a given echo. The important center echo demonstrates a b-factor of 88 mm$^2$/s. *Right*: Partial b-factors "from echo to echo", i.e. between adjacent echoes. These contributions vary considerably and show a striking oscillatory response arising from the spin system.

**DISCUSSION:** Low refocusing flip angles create larger fractions of either well dephased transversal or 'stored' longitudinal magnetization. Both types are quite sensitive to diffusion effects, since $b \sim k^2 * t$. This fact explains the notably increasing b-factor for very low flip angles (Fig. 1). However, such low flip angles are usually avoided in 2D-TSE imaging.

Even more interesting are 3D-TSE implementations such as SPACE or CUBE due to their extended RF pulse trains with variable flip angles down to 30° or even 20°, as demonstrated in Fig. 2. Indeed, these 3D-TSE sequences show distinct diffusion sensitivities in the approximate range of b=80…100mm$^2$/s. Note that these b-factors already cause signal attenuation due to intra-voxel incoherent motion (IVIM) effects in conventional diffusion weighted imaging (DWI). The partial b-factors in Fig. 2, right side, show an eye-catching oscillatory response whose nature is unknown, yet. The tendency to lower values for later echoes may be explained by the increasing flip angles, resulting in a higher coherence (less dephasing) of the spin system. The interruption of the regular frequency oscillations coincides with the location of the center echo (Fig. 2, right chart). This observation may be explained by the discontinuity of the derivative of the flip angle schedule at the center pulse (Fig. 2, left chart). The spin system is quite sensitive for such changes and, thus, 'is out of sync' for a few pulses. This assumption is supported by the fact that the resultant of the partial b-factor temporarily increases again, although the actual flip angle is not lower, indicating a temporary partial loss of coherence of the spin system, i.e. a partial withdrawal from the initially prepared static pseudo steady state (SPSS) [6]. Note that these investigated partial b-factors in Fig. 2, right side, are not simply additive from echo to echo.

To conclude, contemporary 3D-TSE sequences with extended echo trains and variable low flip angles (such as SPACE and CUBE) exhibit a distinct diffusion sensitivity that should generally be accounted for in discussions about signal and contrast properties.


**REFERENCES:** [1] Magn Reson Med 60 (2008) 640-649 [2] J Magn Reson 78 (1988) 397-407 [3] Conc Magn Reson 3 (1991) 125-143 [4] J Magn Reson 205 (2010) 276-285 [5] Proc ISMRM 19 (2010) 1605 [6] Magn Reson Med 37 (1997) 176-184