Resolution-Related Diffusion Damping in Fast Spin Echo Sequences

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Introduction. We have recently shown that the tissue-fluid contrast of nonbalanced steady state free precession (SSFP) shows an unexpected strong sensitivity on resolution (1): an increase in the spatial resolution goes with an increase in spoiling moments leading to a pronounced diffusion damping of fluids. Clearly, this effect is not confined to SSFP, but can affect the contrast of other multi-pulse sequences that show resolution dependent spoiling moments, such as RARE (TSE, FSE) (2,3). In this work, we will show that RARE sequences show a similar fluid-tissue contrast modulation as nonbalanced SSFP.

Materials and Methods. Diffusion effects in multi-pulse experiments or RARE sequences are calculated using an extended phase graphs (EPG) formalism including diffusion (diffusion coefficient D), as stated in any detail elsewhere (4). A setup of a RARE sequence is shown in Fig. 1 using equally spaced refocusing pulses (echo-spacing ESP; flip angle α; and echo time TE). In contemporary RARE sequences, transverse states are dephased prior to any refocusing pulse from frequency encoding (by the amount of 2π) and some additional spoiler gradients (by the amount of π) along Gx (see Fig. 1). As a result, the overall spoiling moment (M_0) depends on the resolution (Δx), as well as on the required spin dephasing ($p\cdot\pi$; in Fig. 1: p = 3) according to

$$M_0(p,\Delta x) = (p\cdot\pi)/(2\pi)\cdot(42.6\times\Delta x)^{-1} \qquad [1]$$

The relative signal loss (ΔS) in RARE sequences will be analyzed as a function of the resolution and the echo-time for tissues (T_1/T_2 ~ 1500ms/50ms, D ~ 1.0μm^2/ms) and fluids (T_1/T_2 ~ 4000ms/2000ms, D ~ 2.5μm^2/ms) according to

$$\Delta S_{p=3}(\Delta x, T_{1,2}, D) := \left(S_0(T_{1,2}) - S_{p=3}(\Delta x, T_{1,2}, D)\right)/S_0(T_{1,2}) \qquad [2]$$

where $S_0 := S_{p=3}(\Delta x\rightarrow\infty, T_{1,2}, D)$ is the signal free of diffusion effects. In a second step, the prominent T_2 contrast (C) between fluids (S_{fluid}) and tissues (S_{tissue}) is analyzed as a function of the resolution according to

$$C_{p=3}(\Delta x) := \left(S_{fluid}(\Delta x) - S_{tissue}(\Delta x)\right)/\left(S_{0,fluid} - S_{0,tissue}\right) \qquad [3]$$

Results & Discussion. The resolution-related effect of diffusion on the signal of RARE sequences is shown in Fig. 2 as a function of TE, the refocusing pulse (α) for tissues and fluids. Clearly, diffusion damping is increased with decreasing Δx (increasing M_0, see Eq. [1]), as well as with decreasing α (from the refocusing of higher order modes). Moreover, fluids become more strongly attenuated, as compared to tissues. Generally, from the constrained phase history (as compared to nonbalanced SSFP) the resolution-related diffusion damping regime depends on TE, and becomes relevant for tissues only for Δx ~ 50 – 100μm or below (ΔS > 10%), whereas for fluids, a significant signal loss sets in for Δx ~ 200 – 300μm or below. From this, the prominent T_2 contrast between fluids and tissues is expected to flatten for RARE with a resolution Δx < 200μm (Fig. 3).

Diffusion damping in RARE (TSE, FSE) was analyzed as a function of the resolution (assuming a dephasing of 3π / voxel), the echo-time (TE), and of the flip angle (α) of the refocusing pulse. It is, however, evident that any increase in the spoiling moment (e.g., by additional spoiling moments along the slice direction, or by an increase in the dephasing moment from 3π to 4π) leads to increased diffusion-damping effects.

Conclusion. For RARE sequences, the resolution-related diffusion damping regime is expected to set in for resolutions Δx < 200μm. This regime appears, even with state-of-the-art ultra-high field systems, just on the limit for in-vivo human RARE imaging, but becomes frequently exceeded for small animal imaging using in-plane resolutions typically ranging from 50 to 200μm.

References. **1**. Bieri O et al; Proc. ISMRM 2011; p. 379. **2**. Hennig, J. J. Magn. Reson. 1988; 78: 397-407. **3**. Hennig J et al. MRM 1986; 3: 823-833. **4**. Weigel et al. J. Magn. Reson 2010; 205: 276-285.

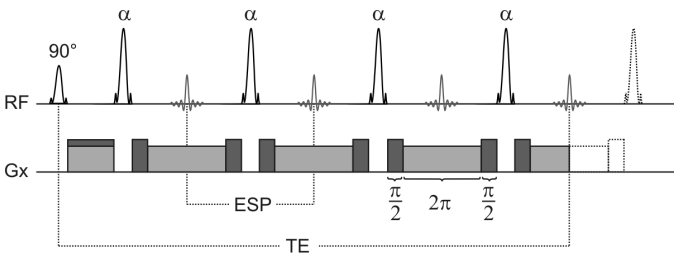

Figure 1: Sequence diagram of a RARE sequence (TSE, FSE). Spoiler gradients in read direction induce a dephasing of (at least) 3π / readout.

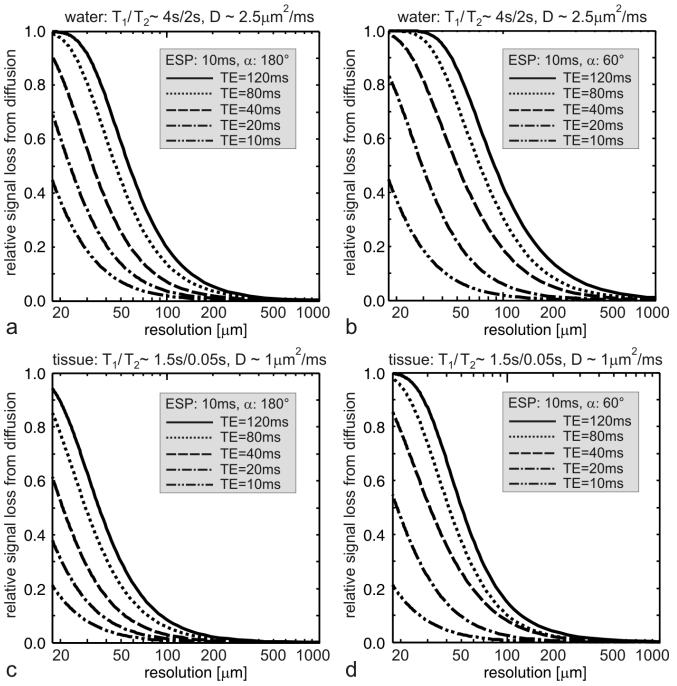

Figure 2: Signal loss from diffusion in a RARE sequence as a function of resolution (spoiling moment, see Fig. 1) for fluids (a,b) and for tissues (c,d). Frequently, from SAR limitations at ultra-high fields, the flip angles of the 180° - refocusing pulses are reduced (α << 180°) and imaging is performed in the static pseudo steady state.

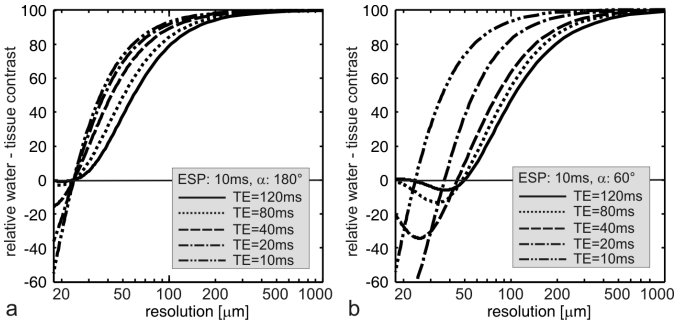

Figure 3: Contrast between fluids and tissues as a function of resolution (spoiling moments, see Fig. 1). With increasing spatial resolution, the signal from fluids gets more strongly attenuated than the one from tissues (see Fig.) and subsequently the prominent water-tissue contrast of T2w-TSE is lost for resolutions ~ 20 – 50 μm or even inverted (< 20 – 50 μm).