The Impact of Finite RF Excitation on Steady State Free Precession

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Introduction. For quantitative imaging a detailed understanding of the pulse sequence's signal behavior is of fundamental importance. Although SSFP signal theory is based on the concept of instantaneous radio-frequency (RF) rotation [1], and thus being in contradiction to any real sequence implementation, SSFP theory is generally well-accepted and unquestioned. To clear things up, SSFP signal behavior for finite RF pulses is analyzed.

Theory & Methods. During RF excitation, the steady-state of balanced SSFP (bSSFP; on-resonance alternating excitation) describes a "zenithal" movement (see Fig. 1a). Intuitively, this results in an overestimation of transverse relaxation (T_2) effects, since during its zenithal residence time ζ (i.e., the time the steady-state needs to cross its longitudinal alignment) no T_2 decay takes place on the magnetization. This suggests the following heuristic modification to the common E_2 factor of SSFP signal formulae to take into account finite RF effects:

$$M_{xy}^{+} = M_0 \cdot \frac{\sin\alpha \cdot (1-E_1)}{1-(E_1-E_2)\cdot\cos\alpha - E_1E_2} \quad [1], \qquad E_2 = e^{-TR\cdot R_2} \xrightarrow[RF]{finite} \tilde{E}_2 = e^{-(TR-\zeta T_{RF})\cdot R_2} > E_2 \quad (\forall T_{RF}, \zeta > 0) \quad [2]$$

Simulations base on numerical integration of the Bloch equations and were assumed to represent the "true" SSFP signal values (S0). S0 is opposed to the signal (S) derived from common SSFP formulae without (Eq. [1]) or with incorporation of finite RF effects (Eq. [2]) and deviations, $\Delta S = (S0 - S)/S0$, are given in percentile units. *Imaging Experiments* were performed on a 1.5 T system (Siemens Espree) and 3D acquisitions (2x2x2mm resolution) with non-slice selective hard pulses were performed to guarantee constant flip angle profiles. The TR was fixed to 5ms allowing RF pulse durations between 300 – 3000µs. In order to circumvent any possible issues from magnetization transfer [2], imaging experiments were performed on aqueous probes only, with (i) T2/T1 = 267ms /292ms ~ 1 and (ii) T2/T1 = 51ms/467ms = 0.11 << 1. S0 is estimated using extrapolation to $T_{RF} \to 0$.

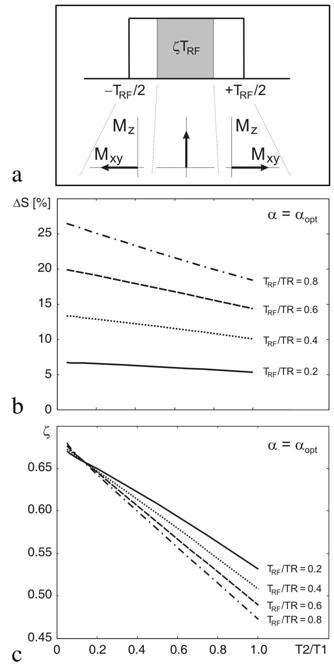

Fig. 1: (a) The steady state passes through a longitudinal alignment during RF excitation. The mean zenithal residence time, ζT_{RF}, is indicated as gray shaded area. (b) As a result, transverse relaxation is overestimated leading to increasing deviations of bSSFP signal from Eq. [1] with increasing T_{RF}/TR. (c) Corresponding zenithal periods to achieve $\Delta S(\zeta) \to 0$.

Results & Discussion. The limit of $T_{RF} \to 0$ leads to SSFP signal intensities independent on RF pulse durations (Eq. [1]), but it is self-evident that any finite excitation process violates the assumption of instantaneous rotation. Numerical simulation revealed that ΔS depends on T_2/T_1 and T_{RF}/TR only (not shown). Figure 1b summarizes ΔS from Eq. [1] as a function of T_2/T_1 (for $\alpha_{opt}=\cos^{-1}[(\varepsilon-1)/(\varepsilon+1)]$, $\varepsilon=T_1/T_2$) and relative RF pulse durations (T_{RF}/TR). The zenithal periods (ζT_{RF}, see Eq. [2]) to achieve $\Delta S(\zeta) \to 0$ depend linearly on T_2/T_1 and show some slight dependency on T_{RF}/TR (Fig. 1c). Linear fitting of ζ as a function of T_2/T_1 and T_{RF}/TR suggests

$$\zeta(\lambda := 1 + T_{RF}/TR, \tau := R_1/R_2) \approx (16 - 3\lambda\tau)/24 \qquad [3]$$

over a wide range of sequence and tissue related imaging parameters. Eq. [3] was estimated from $\alpha=\alpha_{opt}$ and thus its validity for other α must be tested. Figure 2a demonstrates excellent correspondence over the whole range of flip angles and RF time portions exemplarily for T_2/T_1=0.1 using the proposed E_2-substitution (Eq. [2]). Deviations from Eq. [1] (ΔS) and Eqs. [1-3] (ΔS*) are displayed in Figs. 2b,c for moderate RF pulse fractions (20%). Generally, ΔS increases with increasing flip angle and decreasing T_2/T_1 ratio and can reach 10 – 12% for tissues exhibiting considerable differences in relaxation times, such as muscles, but are quite limited for probes having similar relaxations properties (T_1~T_2). However, for considerable RF time portions (80%, whether this seems to be practically feasible or not), deviations are very much substantial and can lead to a more than two-fold signal increase (ΔS > 50%, see Fig. 2a) as compared to the signal prediction according to Eq. [1]. This is in contrast to Fig. 2c, where ΔS* is less than 1% for customary flip angles over the whole range of T_2/T_1.

Conclusion. Finite RF pulses may have a considerable impact on SSFP. Generally, finite RF pulses lead to an increase in steady-state magnetization for all flip angles, off-resonances and relaxation rates. This increase can be very much substantial, especially when the RF pulse extends over a considerable portion of the TR time. Correction of SSFP signal is thus indicated for all quantitative methods that use highly diverging flip angles, changes in the RF pulse duration or in TR.

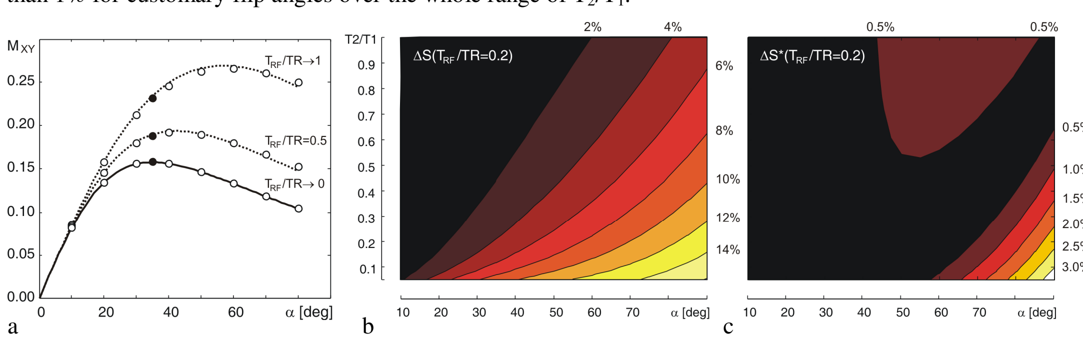

Fig. 2: (a) Impact of finite RF (T_{RF}/TR) on bSSFP steady-state as a function of flip angle α for T2/T1=0.1 (the filled circle indicates the optimal flip angle for the given T2/T1). Deviations increase with increasing α and T_{RF}/TR. (b) Signal deviations between numerical simulations and Eq. [1] (DS) and (c) between numerical simulations and Eqs. [1-3] for moderate RF time portions (T_{RF}/TR=0.2) as a function of α and T2/T1.

References. [1] Haacke et al., Magnetic Resonance Imaging, Wiley (1999). [2] Bieri O et al., MRM 58 (2007).