Superbalanced Steady State Free Precession

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Introduction. Finite radio-frequency (RF) excitation pulses can give raise to considerable signal deviations from the "common" steady-state free precession (SSFP) theory in the transient and steady state (see Fig. 1)(1,2), which may impair the accuracy of common SSFP-based quantification techniques (3-5). Here, a generic approach for intrinsic compensation of finite RF pulse effects is introduced, based on balancing transverse relaxation effects during finite RF excitation (similar to flow or motion compensation of gradient moments), resulting in a superbalanced SSFP sequence free of finite RF pulse effects in the transient and in the steady state, irrespective of the RF pulse duration, relaxation times and flip angles.

Theory. Accumulation of relaxation effects during RF excitation depends to leading order and for sufficiently small flip angles only on the spatial path of the magnetization (cf. Eq. [3] in Ref. (1)),

$$\Delta M_{xy}^{+} \approx -\frac{T_{RF}}{T_2}\left\langle \hat{m}_{xy}\right\rangle^{+} M_{xy}^{-}, \text{ where } \left\langle \hat{m}_{xy}\right\rangle^{+} := \frac{1}{M_{xy}^{-}T_{RF}}\int_0^{T_{RF}} M_{xy}(t)dt \qquad [1]$$

is the time-average of the normalized transverse magnetization trajectory, as generated by the action of the RF pulse. Consequently, finite RF pulse effects are predicted to become ineffective for

$$\left\langle \hat{m}_{xy}\right\rangle^{+} \overset{!}{\approx} 1 \qquad [2]$$

(where the exclamation mark indicates that this is a requirement). A balanced SSFP sequence featuring an RF pulse, which fulfills the constraint given by Eq. [1] is said to be superbalanced (sb), since not only gradient moments are fully refocused, but in addition RF pulses are balanced to compensate for finite RF pulse effects. Like flow-compensation of gradient moments, any RF pulse shape can, in principle, be balanced for relaxation effects from the addition of bipolar RF pulses of zero nominal flip angle, as exemplarily given in Fig. 2 for a rectangular, i.e. non-slice selective, hard pulse.

Materials & Methods. Measurements and calibrations were performed on a clinical 1.5T system equipped with actively shielded magnetic field gradient coils. In-vitro SSFP scans were performed in 3D with a TR = 10msec and 4mm isotropic resolution (64×64×64 imaging matrix) on an aqueous probe (0.25mM MnCl; T_1 = 455msec, T_2 = 50msec) with a flip angle $\alpha = 90°$, allowing RF pulse durations to range between 500µs and 8700µs.

Results & Discussion. Finite difference simulations (not shown) predict balancing for symmetrically compensated hard RF pulses with

$$\left\langle \hat{m}_{xy}\right\rangle^{+}_{hard} \overset{!}{\sim} 0.9 \qquad [3]$$

with negligible dependency (<1% residual signal modulations) for flip angles 0° < α < 70° and relaxation time ratios $0.05 < \Lambda^{-1} < 1$. In-vitro scans (Fig. 3) reveal for non-balanced RF pulses a considerable increase in signal (+124%), whereas superbalanced SSFP proves to be resistant against RF pulse elongation (+2%). These findings are in agreement with simulations and thus validate the proposed finite RF compensation concept. Hence, after compensation, the signal of a superbalanced SSFP sequence follows the common SSFP signal theory. Superbalancing of SSFP, however, generally leads to an increase in SAR from the addition of bipolar RF pulses of nominal zero flip angles. Superbalancing of SSFP will be extended to slice selective RF pulses and its impact on quantitative SSFP techniques will be analyzed and discussed.

Conclusion. Generic compensation of finite RF pulse effects in SSFP, termed superbalancing, was introduced, which can be applied to any arbitrary RF pulse shape to restore the SSFP signal theory to the limit of quasi-instantaneous RF pulses. Superbalancing is thus indicated for all quantitative SSFP techniques where finite RF pulse effects might be expected or where elongated RF pulses are used.

References. [**1**] Bieri O & Scheffler K. MRM 2009. [**2**] Bieri O. MRM 2010 (in press). [**3**] Crooijmans HJ, Scheffler K & Bieri O. MRM 2010 (in press). [**4**] Gloor M, Scheffler K, Bieri O. Proc. ISMRM 2010: p. 5143. [**5**] Ehses P, Gulani V, Yutzy S, Seiberlich N, Jakob P, Griswold M. Proc ISMRM 2010: p. 2969.

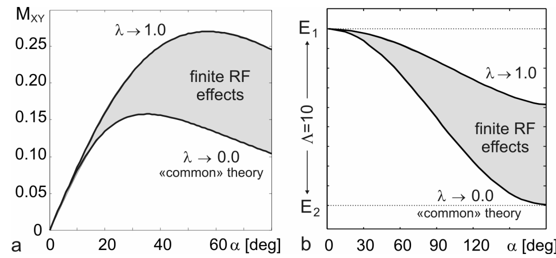

Figure 1: Range of finite RF bSSFP effects in (a) the steady state and (b) the transient phase demonstrated for tissues (with $\Lambda := T_1/T_2 \sim 10$) as a function of the fractional RF pulse duration $\lambda := T_{RF}/TR \rightarrow 0$.

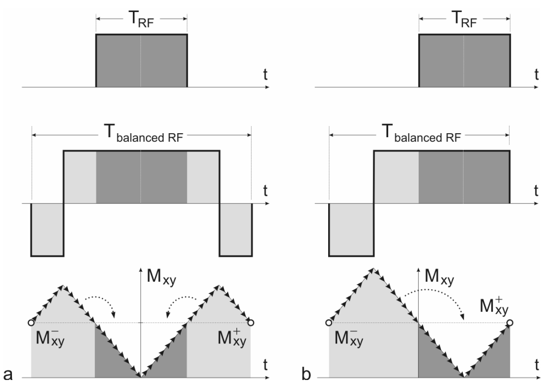

Figure 2: Principle of RF pulse balancing, exemplarily demonstrated for non-slice selective excitations (hard RF pulses with $<m_{xy}> \sim 0.5 << 1$, shown in dark gray). The requirement in Eq. [1] can be fulfilled by the addition of bipolar RF pulses (indicated in light gray)with zero nominal flip angle: (a) symmetrical compensation or (b) asymmetric compensation.

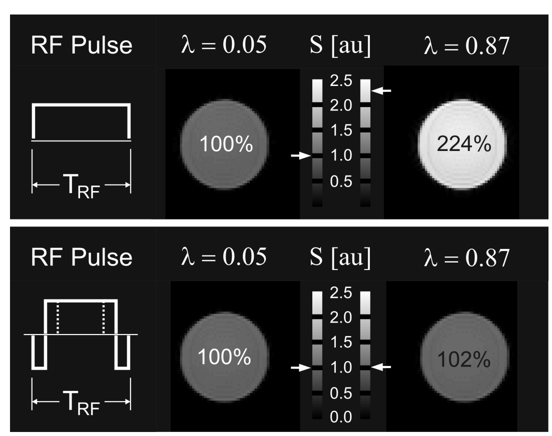

Figure 3: Range of finite RF bSSFP signal modulations in the limit of $\lambda := T_{RF}/TR \rightarrow 0$ and $\lambda \rightarrow 1$ for an aqueous probe with $\Lambda \approx 10$ (0.25mM $MnCl_2$). (top) hard RF pulses. (bottom) Balanced hard RF pulses (see Fig. 2a) compensate finite RF pulse effects and thereby restore the signal to the Freeman-Hill theory, independently on the RF pulse duration.