On the use of steady-state equations to estimate signal intensities in 2D TrueFISP imaging

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Introduction The signal intensity of a TrueFISP sequence is often described by steady-state formulas [1] and can be used for studying contrast properties [2], flow effects [3], or even for relaxometry [4]. Unlike in spoiled gradient echo sequences, the signal intensity is strongly affected by the phase advance (β), which determines the off-resonance rotation of the magnetization vector within a single TR. In 2D-imaging, a slice excitation profile should be considered that has a variation in magnitude, determined by the RF pulse shape, but also in phase, which is caused by imperfect refocusing of magnetization through the slice [5]. The latter effect results from the slice selective excitation process and cannot be incorporated correctly in steady-state formulas, because they consider the excitation to occur instantaneously. Nevertheless, little has been reported about the validity of using steady-state formulas to predict the signal intensity in 2D TrueFISP images.

Aim: In this study, methods using TrueFISP steady-state formulas are proposed that can be used to calculate steady-state profiles and corresponding signal intensities. The results were compared with measurements as well as full Bloch-simulations that describe the change of the slice profile towards steady-state including every excitation. This comparison will give insight under which conditions steady-state formulas are applicable to describe 2D TrueFISP signal behavior.

Materials and Methods *In vitro* experiments were performed on a 6.3T experimental MRI scanner (Bruker BioSpin MRI GmbH, Ettlingen, Germany) on a phantom tube containing an aqueous $MnCl_2$-solution. T_1 and T_2 value were 1210±50 and 98±2 ms, respectively. A TrueFISP sequence (TR/TE = 4.0/2.0 ms) with a Gaussian shaped RF pulse was applied as a slice profile imager with the read-out gradient parallel to the slice selection direction and a non-FT reconstruction in phase encoding direction. Steady-state slice profiles were measured after 500 dummy pulses and the steady-state signal intensity was determined by integration over the slice profiles. Steady-state slice profiles were also calculated using Bloch simulations. A Hard Pulse approximation [6] was used to simulate the effect of each excitation. That means that the RF pulse and concurrent slice selection gradients were treated as alternating blocks or “hard pulses” of the RF and gradient field describing the temporary rotations of the magnetization vector. Between consecutive pulses, relaxation effects and precession were taken into account. The value for the RF phase advance (β^{RF}) was varied to get different frequency responses. We have named this the *HP-method*. The steady state magnetization is often described by the following steady-state formula: $M^{SS} = A^{TE} R_\alpha [(I - A^{TR} R_\alpha) B^{TR}] + B^{TE}$, where M^{SS} is the steady-state magnetization vector (M_x, M_y, M_z), I a 3x3 identity matrix and R_α the RF rotation around the x-axis with flip angle α. $A^{\Delta t}$ and $B^{\Delta t}$ are free precession matrices, which are a function of T_1, T_2 and β and where $E_{1,2} = \exp(-\Delta t/T_{1,2})$. Steady-state formulas were applied in two different ways for calculating the steady-state slice profiles. *SSmethod1* used the Hard Pulse approximation to calculate the slice excitation profile after a single RF pulse. From this, both the distribution of flip angles and phase variations were derived. These were inserted in the steady-state formulas as α and β, respectively. β^{RF} was added in A^{TR} to simulate an RF phase advance. *SSmethod2* only considered the distribution of flip angles, while neglecting the phase variations.

$$A^{\Delta t} = \begin{pmatrix} E_2\cos(\beta) & E_2\sin(\beta) & 0 \\ -E_2\sin(\beta) & E_2\cos(\beta) & 0 \\ 0 & 0 & 1 \end{pmatrix}, B^{\Delta t} = \begin{pmatrix} 0 \\ 0 \\ (1-E_1) \end{pmatrix}$$

Results Measured steady-state slice profiles (signal magnitude and phase) and those obtained with the simulation methods are shown in Fig. 3 for two different values of the RF phase advance (0˚ and 180˚ degrees). Results from the *HPmethod* (Fig. 3b) match very well with those measured (Fig 3a), except sometimes for regions far from the centre of the slice. However, not all features of the steady-state slice profiles obtained by the *HPmethod* and measurements were reproduced by the simulation methods based on steady-state formulas (Fig 3c,d). Both methods showed no decrease in maximum signal intensity at high flip angles in case of β^{RF} = 180˚ (Fig. 3, see *). The asymmetrical phase profile seen for β^{RF} = 0˚ (Fig. 3a, see +) could not be simulated with *SSmethod2*, but it was obtained with *SSmethod1*. In case of β^{RF} = 180˚, a flat phase profile was measured for all flip angles, which indicated that the refocusing nature of the TrueFISP sequence [1] at this value for β^{RF} also applied to phase variations within the slice excitation profile. This effect was also noted for all simulation methods. Fig. 4 shows the measured and simulated signal intensities as function of the flip angle for different values of β^{RF}. The *HPmethod* represents the measured curves to a high degree. From Fig. 4b, it can be seen that for each value of β^{RF} and in a range of flip angles close to the optimal flip angle, *SSmethod1* and *SSmethod2* give almost equal predictions of the signal intensity as compared to the *HPmethod*. Only at large flip angles, the signal intensities were overestimated by the methods based on steady-state equations, which is in line with observations in the steady-state slice profiles. This overestimation was least for β^{RF} = 180˚. Although *SSmethod2* was not able to simulate asymmetries in the phase profile (Fig. 3d), the signal intensity could still be similar in those cases. This was the result of large side lobes of opposite phase that compensate for the signal in the centre.

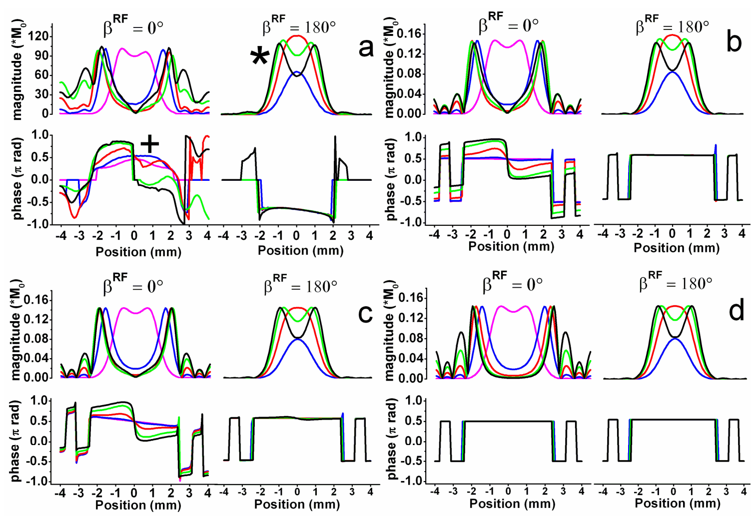

Figure 3: Measured (a) and simulated (b,c,d) steady-state slice profiles. Various flip angles were used: 1˚ (magenta), 10˚ (blue), 30˚ (red), 60˚ (green), 90˚ (black). Different simulation methods were performed: HPmethod (b), SSmethod1 (c), SSmethod2 (d).

Discussion The formation of steady-state slice profiles in 2D TrueFISP sequences and the corresponding signal intensities were described via measurements and reproduced accurately with Bloch-simulations. The use of steady-state formulas did not always result in correct predictions of the steady-state signal intensity, which was explained by deviations in the steady-state slice profiles. However, good estimations were obtained for flip angles close to the optimal flip angle and for values of β^{RF} > 60˚. This was even valid for the method in which the phase variation in the slice excitation profile was not taken into account. In conclusion, this study has shown under which circumstances steady-state formulas can be used to estimate signal intensities in 2D-TrueFISP images, which can be very useful in cases when simulations are used to fit measured data.

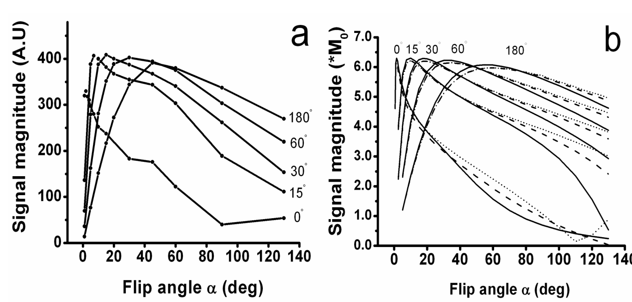

Figure 4: Measured (a) and simulated (b) signal intensities as function of the flip angle. Three methods were used in the simulations: Hard Pulse method (solid), SSmethod1 (dashed), SSmethod2 (dotted).

References [1] Scheffler et al. Eur Radiol 13:2409-18 (2003); [2] Dharmakumar et al. Phys Med Biol 52: 3261-32 (2007); [3] Markl et al. MRM 50: 892-903 (2003); [4] Deoni et al. MRM 49: 515-526 (2003); [5] Haacke et al. Wiley-Liss (1999); [6] Subramanian et al. Proc SMRM 1986 p.1452-1453