Simultaneous T1 and PRF MR Thermometry: Optimization of Flip Angles

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Introduction

MR thermometry is an important tool to monitor the efficiency and safety of different thermal treatment methods. Two temperature-sensitive MR parameters are used for temperature calculations: the proton resonance frequency shift (PRF) and longitudinal relaxation time change (T1) [1]. A combination of these two methods might allow for a more precise temperature monitoring for example in fat where PRF techniques alone fail. Recently, the influence of MR noise on temperature calculations was evaluated for both methods [2]. In this work, we present simulations and analytical calculations on the optimal flip angle for MR thermometry with simultaneous PRF and T1 measurements.

Materials and Methods

MR signal simulations were performed with the software package Matlab R2012a. First, the complex MR signal without noise was calculated using the signal equation for a spoiled gradient echo sequence (FLASH):

$$S = M_0 \cdot sin\alpha \cdot \frac{1-e^{-TR/T_1}}{1-cos\alpha \cdot e^{-TR/T_1}} \cdot e^{-TE/T_{2^*}} \cdot e^{i\Delta\varphi}. \qquad (1)$$

Here, M_0 is the initial magnetization, α is the flip angle, TR is the repetition time, TE is the echo time, $T1$ is longitudinal relaxation time, $T2^*$ is the apparent transverse relaxation time, and $\Delta\varphi$ is the temperature-dependent phase. Next, complex Gaussian noise was added yielding a Rician distribution of the signal magnitude [3]. From the complex signal with noise the temperature was calculated using two methods:

$$\text{PRF:}\ \ T_{PRF} = \frac{\Delta\varphi}{\gamma \cdot \alpha_{therm} \cdot B_0 \cdot TE}, \text{ and} \qquad (2)$$

$$\text{T1:}\ \ T_{T1} = \frac{T1 - T1_{ref}}{m} + T_{ref}, \text{ where } m = \left[\frac{-TR}{\ln\left(\frac{S - M_0 \cdot sin\alpha \cdot e^{-TE/T_{2^*}}}{S \cdot cos\alpha - M_0 \cdot sin\alpha \cdot e^{-TE/T_{2^*}}}\right)} - T1_{ref}\right] \cdot \frac{1}{T - T_{ref}}. \qquad (3)$$

Here, γ is the gyromagnetic ratio, α_{therm} is the PRF thermal coefficient, B_0 is the static magnetic field, and $T1_{ref}$ is the longitudinal relaxation time at reference temperature T_{ref}. The signal to noise ratio (SNR) was calculated by dividing absolute of signal without noise by absolute of noise.

The following parameters were used for the simulation: $T = 50°$ C, $T_{ref} = 20°C$, $T1_{ref} = 685$ ms, $T_2^* = 50$ ms, $m = 13$ ms/°C, $\gamma = 2.675\cdot10^8$ rad/(s·T), $\alpha_{therm} = 0.01\cdot10^6$ 1/°C, $B_0 = 1.5$ T, $TE = 20$ ms, $M_0 = 1$, $TR = 30$ ms. The calculations were repeated 100000 times and mean and standard deviation of the temperature were computed for each method for flip angles from 1° to 90°. Temperatures and SNR were plotted as a function of flip angle (Fig. 1).

Results

Figure 1 shows that the optimal SNR is achieved at the Ernst angle $\alpha = 13°$ for the T1(T=50°C) = 1105 ms. The PRF simulation shows that the temperature errors of PRF method are smallest for the highest SNR, as this minimizes the errors in the phase calculation.

For the *T1*-based calculations the smallest error of ±1.6° C is found at $\alpha = 23°$ (Fig. 1C), whereas a significantly larger uncertainty of $T_{T1} = 50.1\pm2.1°$ C is found at the Ernst angle. T1-based temperature calculations are not only sensitive to SNR but also to the rate of signal change with *T1*: $\partial S/\partial T1$. Thus, the optimal flip angle for the T1-method is found where $\partial S/\partial T1$ is maximal, i.e. $\partial(\partial S/\partial T1)/\partial\alpha = 0$. Inserting Eq. 1 finally yields

$$\alpha = arccos\left(\frac{2-e^{TR/T_1}}{2e^{TR/T_1 - 1}}\right). \qquad (4)$$

With the parameters above the optimal flip angle is 23° which is in excellent agreement with the calculations shown in Fig. 3.

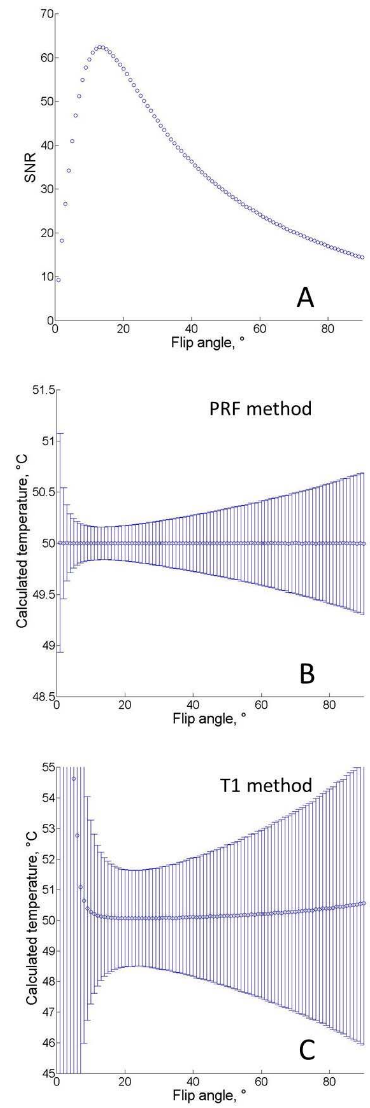

Fig. 1: A. SNR as a function of flip angle α. B. Temperature calculated with the PRF method as a function of flip angle α. C. Temperature calculated with the T1 method as a function of flip angle α.

Discussion

The simulations and calculations show that the optimal flip angle is not the same for the both methods. Even though the error increases for PRF method when the flip angle increases beyond the Ernst angle, for $\alpha = 23°$ it remains small (±0.2°) when the optimal flip angle for the T1 method is applied. On the other hand, the T1-based temperature calculations show a higher uncertainty at the Ernst angle (Fig. 1C). Thus, for this set of parameters a higher flip angle as given in Eq. 5 is the optimal choice to minimize the T1 error for both methods. In the future, the optimal signal preparation strategies that allow stronger T1 weighting will be studied to make full use of the temperature information contained in the MR signal.

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References:

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