Modified balanced SSFP sequence for better temperature sensitivity

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INTRODUCTION: Safety and efficacy of tumor treatment using high intensity focus ultrasound (HIFU) requires accurate temperature measurement throughout the thermal procedure. The proton resonance frequency shift (PRF) method is currently the best method for achieving this goal, since it is independent of tissue type, easy to perform and has a high temporal resolution. Recently, it has been shown that an unbalanced steady-state free precession (ub-SSPF) sequence is suitable for temperature monitoring in moving objects although the measurement can be noisy and subject to random measurement errors [1]. In this work, we investigate how the noise in temperature measurements can be reduced by variations to this new ub-SSFP sequence.

THEORY: In the PRF technique, the image phase is proportional to the temperature and the quality of the temperature can be expressed in terms of the phase signal to noise ratio (SNR) or the phase change divided by the standard deviation of the phase change. To account for possible signal averaging, efficiency is defined as the SNR/(acquisition time)$^{1/2}$. Since the phase difference images are proportional to the temperature dependent PRF change and the echo time TE, it can be converted to a temperature change by: $\Delta\phi = \gamma\alpha BoTE\Delta T$

The phase uncertainty can be related to image SNR [2] by the expression: $\sigma(\Delta\phi) = \frac{1}{SNR}$. Finally, image SNR is proportional to voxel size, the square root of the total acquisition time, and the signal level for a given sequence, which decreases exponentially with TE. Hence the $SNR_{\Delta\Phi}$ dependence on the echo time can be written as

$$\mathrm{SNR}_{\Delta\phi} = \frac{\Delta\Phi}{\sigma(\phi)} = SNR * \gamma\alpha BoTE\Delta T \propto \gamma\alpha Bo\Delta T\ (\Delta x\Delta y\Delta z)\sqrt{N_x N_y N_{acq}\Delta t}\ \mathrm{TEexp}^{-\frac{TE}{T_2^*}} \quad (1)$$

Differentiating the $\mathrm{SNR}_{\Delta\phi}$ expression with respect to TE yields the optimal TE in the temperature dependent phase imaging, which is $TE = T_2^*$. Because T_2^* of most tissues is longer than TR values typically used in SSFP (10 to 25 ms), one goal was to modify ub-SSFP to obtain the maximum TE value possible. The ub-SSFP sequence was created by increasing the prephasing and the dephasing gradient such that the area of each are equal to α times half of the area of the readout gradient $(1 < \alpha < 2)$. The new echo time is given by: $TE' = TE + \frac{\alpha-1}{2}\tau$, where τ is the time duration of the flat top of the readout window and TE is the echo time of standard b-SSFP. This modification of the b-SSFP sequence splits the b-SSFP signal into two echoes, one primarily a gradient echo and the second primarily a spin echo as described in [1]. The two k-space halves can be reconstructed separately, leading to 2 phase images which are temperature sensitive as shown in Fig1. A second goal was to investigate the efficiency of the ub-SSFP sequence as a function of flip angle and readout bandwidth (which also changed TE and TR).

METHODS: All MR imaging was performed on a Siemens TIM Trio 3T MRI scanner. For the SNR efficiency calculation, two images were acquired with each of the following parameter sets: 256x128 imaging matrix, 2.0x2.0x3.0 resolution, and various (TR and TE') values that were changed by changing the bandwidth for each value of the flip angle.

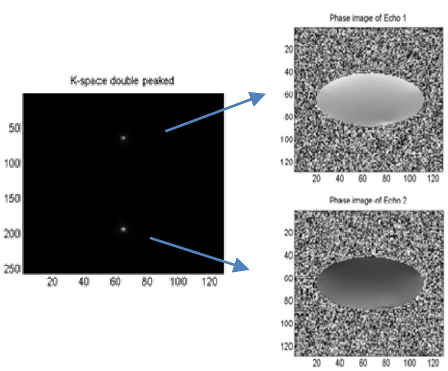

Fig 1: k-space (above) and resulting phase images from each echo

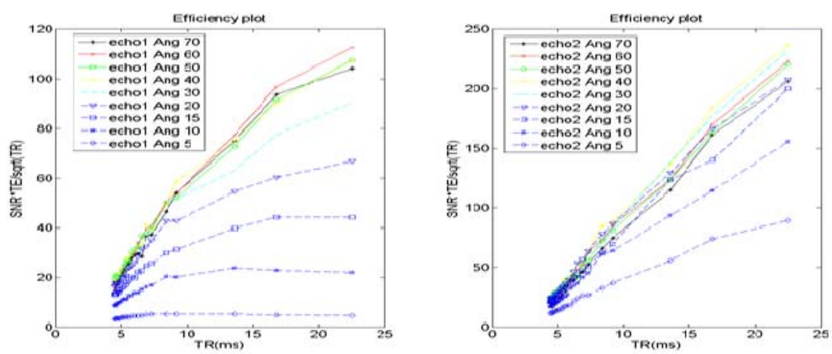

Fig 2: Plot of efficiency time TE' as function of TR for different flip angles. Efficiency increases through decreases in receiver bandwidth (increase TR). Echo 2 has better SNR efficiency than echo 1.

RESULTS: SNR efficiency results for 2-D ub-SSFP sequence are presented in Fig 2. Echo 2 (the gradient echo) has higher SNR efficiency than echo 1 and therefore has better temperature sensitivity. As a function of the flip angle, the efficiency plot shows saturation around flip angle 20 for small TR values and 40 for large TR values. These results demonstrate that temperature measurement efficiency can be greatly increased by using a flip angle close to 40 degrees and a bandwidth consistent with a relatively long TR. Because longer TR decreases the contribution of stimulated echoes, future work is necessary to determine the efficiency of this technique relative to the various forms of PRF with the conventional GRE sequence.

References: [1] Bruno Madore and al. ISMRM 2009, p.441, [2] Thomas Conturo and al. MRM 15, 420-437, 1990

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