A simple and fast flip angle calibration method

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Introduction

Quantitative MR techniques such as variable flip angle (VFA)[1] , DESPOT1 [2], quantitative T_2 [3] etc. rely on the accuracy with which the true flip angle is known. Although spatial inhomogeneity of flip angles is expected at high fields (>1.5T) due to B_1 field inhomogeneities and uneven slice profiles, accurate estimates of true flip angle are important even at lower field strengths. Most methods relying on flip angle knowledge assume the nominal flip angle to be equal to the true flip angle for lower field strengths. For the higher field strengths, extra scans are often required to assess the flip angle calibration [4] or flip angle error [5] before useful information (eg. longitudinal relaxation, T_1) can be extracted.

Assessment of the true flip angle, α^{true}, can be accomplished using a double-angle method [1,4]. This method, whether using spin-echo or spoiled gradient recalled echo (SPGR) images, relies on data acquired for a long repetition time, TR, ($TR > 5T_1$) and for at least two flip-angles (α and 2α). These requirements make the necessary scans prohibitively long. To overcome this time limitation, fast imaging techniques such as echo-planar (EPI) or spiral have been used. However, fast imaging techniques are inherently sensitive to main field inhomogeneities which can introduce another source of errors. Furthermore, there is an expected mismatch between the slice profiles associated with 2D fast imaging techniques ard the 3D VFA methods [4]. These issues result in undesirable inaccuracies associated with variable flip angle measurements.

In this paper, a different approach is used to determine the flip angle calibration factor. It relies on the acquisition of several SPGR scans (which can be 2D or 3D) at short TR (TR~T1/10). This new method exploits the quasi-linear relationship between signal intensity and flip angle for large (~180°) flip angles.

Theory

For an SPGR scan, the signal intensity (SI) as a function of α^{true}, TR and T_1 is given by :

$$SI = B\ \mathbf{sin}(\alpha^{true})\frac{1-E_1}{1-\mathbf{cos}(\alpha^{true})E_1} \qquad \text{Eq.[1]}$$

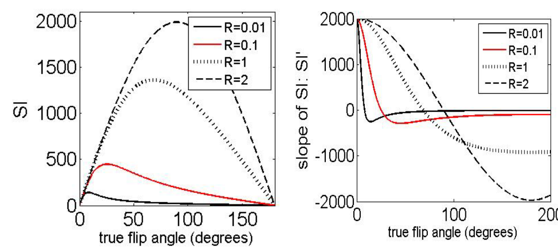
where $E_1 = \mathbf{exp}(-TR/T_1)$ and B incorporates the effects of coil sensitivity, T_2^* decay and proton density. The double angle (DA) method makes use of the fact that for long TR (TR>5T$_1$) , $E_1 \approx 0$ and $SI \approx B\ \mathbf{sin}\,\alpha^{true}$. Therefore, obtaining the signal for a nominal flip angle, α^{nom}, and twice that flip angle and taking a ratio of respective signal intensities : $\lambda = SI(2\alpha^{true})/SI(\alpha^{true})$, the true flip angle can be determined: $\alpha^{true} = a\mathbf{cos}(\lambda/2)$ [4]. The calibration factor, k, is then given by: $k = \alpha^{true}/\alpha^{nom}$, assuming that α^{true} and α^{nom} maintain a linear relation for all values of flip angle (this is believed to hold for values at least up to 120°)[4]. This calibration factor is subject and coil dependent and must therefore be determined for every scan. In general, the double angle method is usually performed for a single pair of angles (60°, 120°) and hence the linear relation is determined from a single point along the α^{true} vs α^{nom} line (at $\alpha^{nom} = 60°$).

Methods

The proposed method makes use of the properties of the full relation between SI and α^{true}, given by Eq.[1] while taking advantage of the knowledge of the null point of the SPGR signal, occurring for $\alpha^{true} = 180°$. Writing $\alpha^{true} = k\,\alpha^{nom}$, Eq.[1] can be rewritten as an expression for SI as a function of three unknowns: k, B and T_1. Unfortunately, the use of this equation alone is not enough to uniquely determine the wanted parameters [2]. However, the derivative $\partial SI/\partial\alpha^{nom}$ can be used to uniquely determine k. Taking the derivative of Eq.[1]. gives:

$$SI' = \frac{\partial SI}{\partial\alpha^{nom}} = \frac{Bk(1-E_1)}{(1-\mathbf{cos}\,k\alpha^{nom}E_1)^2}(\mathbf{cos}\,k\alpha^{nom} - E_1) \qquad \text{Eq.[2].}$$

Fig.1 a. SPGR signal variations b.

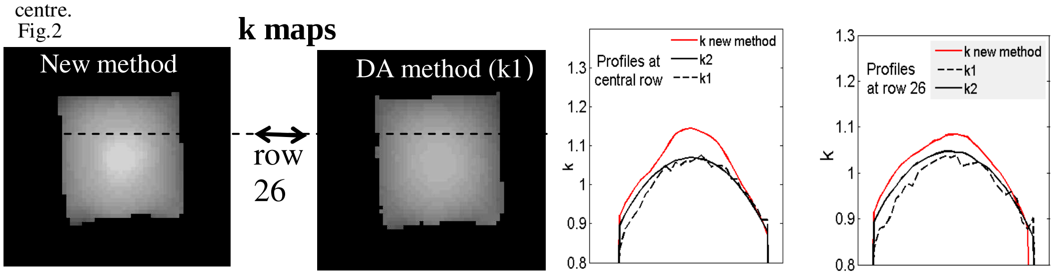


Plots of SI' vs α^{true} for several values of $R = TR/T_1$ (Fig.1b) show that for small values of R, the relationship between SI and α^{true} (Fig.1a), as α^{true} approaches $180°$ can be approximated by a straight line with negative slope. This allows the x-intercept ($k\,\alpha^{nom} = 180°$) to be extrapolated from a simple line fit at α^{true} close to $180°$. Given the expected range of k values (0.8< k <1..2) , data points of $SI(130° \le \alpha^{nom} \le 180°)$ were used. A Least Squares Minimization was used to fit that data to a straight line on a pixel-by-pixel basis. The estimated x-intercept yielded regionally varying k values (k -map). A smoothing filter was used to minimize discontinuities between the pixel-wise data fitting algorithm because k is known to vary smoothly. Fortunately, the linear relationship requirement favors small R values thus, short TR. Although several data points need to be taken, a shorter scan time (~5min) can be achieved than for a single data point resulting from 2 long TR scans for the DA method (22min). R was chosen such that the slope of SI' vs α^{nom} is flat near $180°$ and non-zero while trying to maximize the signal to avoid noise contamination. For this work, the selection of $R = 0.1$ was used (red lines).

Results

For proof of principle, this method was tested on a homogeneous water phantom doped with $MnCl_2$ at 3T (Signa, GE Healthcare).2D-SPGR data were obtained for flip angles varying from 130° to 170° in steps of 5°. Up to five complex averages were performed for data points associated with large flip angles and small signal (3mm slice). The T_1 of the phantom was expected to be close to 900*ms* hence a $TR = 90ms$ was used. Three other scans ($\alpha^{nom} = 30°, 60°, 120°$) with long TR, ($TR > 5T_1$) were also performed to assess the spatial variation of k resulting from the DA SPGR method [3]. Three such scans allowed the determination of two estimations of k : k_1 and k_2 for the flip angle pairs: (30°, 60°) and (60°, 120°) respectively. The calibration term determined using the new method is in close agreement with the DA results (Fig.2). A slight over-estimation is observed, particularly in the centre.

Fig.2



Conclusion

A simple new method for obtaining B_1 inhomogeneity profiles or flip angle calibration maps has been demonstrated. It requires scanning at short TR ($TR \le T_1/10$) and fitting the data to a line. The result is in close agreement with the long DA method. A smaller TR could be used although more signal averaging may be required to compensate for the noisier signal. Optimization of the TR selection and number of required data points is expected to further reduce the required scan time.

References: [1] Stollberger & Wach, *MRM* 35, 1996 [2] Deoni et al., *MRM* 49, 2003 [3] Sled & Pike, *MRM* 43, 2000 [4] Wang et al., *JMR* 182, 2006 [5] Cheng & Wright, *MRM* 55, 2006