A flip-angle-optimized 3D FLASH sequence for fast dynamic T1 mapping

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Target audience: MR physicists, (radiologists)

Purpose: Fast T_1 mapping is of considerable interest for many different MRI applications. In particular, for the rapid quantification of contrast-agent concentrations, fast dynamic T_1 mapping methods with temporal resolutions in the order of seconds are required. The purpose of the present study was to optimize and evaluate a fast three-dimensional T_1 mapping approach based on the variable flip angle (VFA) technique, in which the acquisition of only a single 3D FLASH data set for each time point is sufficient.

Theory: The conventional VFA technique is based on the acquisition of at least two FLASH data sets with different flip angles (FA).[1] For dynamic applications, this approach can be modified by combining a longer baseline acquisition with several FAs and a fast repeated acquisition with only a single FA.[2] The signal intensity, S_{dyn}, of these single-FA (1FA) acquisitions with FA α_{dyn} can be used to determine $T_{1,\mathrm{dyn}}$ by inversion of the well-known FLASH equation (neglecting the $T_2{}^*$ dependence for sufficiently short echo times):

$$E_1 = \exp(-\mathrm{TR}/T_{1,\mathrm{dyn}}) \approx [M_0 \sin(\alpha_{\mathrm{dyn}}) - S_{\mathrm{dyn}}] \,/\, [M_0 \sin(\alpha_{\mathrm{dyn}}) - S_{\mathrm{dyn}} \cos(\alpha_{\mathrm{dyn}})].$$

The optimal FA, α_{dyn}, for the dynamic phase can be determined by minimizing the statistical error of $T_{1,\mathrm{dyn}}$. Assuming sufficient time for a precise and accurate measurement of the baseline parameters, $T_{1,0}$ and in particular M_0, and, thus, considering only the influence of errors of the measured dynamic signal intensity, S_{dyn}, the statistical error of E_1 is $\Delta E_1 = |\partial E_1/\partial S_{\mathrm{dyn}}|\ \Delta S_{\mathrm{dyn}} = [1 - E_1 \cos(\alpha_{\mathrm{dyn}})]^2 \,/\, [M_0 \sin(\alpha_{\mathrm{dyn}})\ (1 - \cos(\alpha_{\mathrm{dyn}}))] \cdot \Delta S_{\mathrm{dyn}}$. This expression as function of α_{dyn} (for given E_1) has a unique minimum defining the optimal FA for dynamic T_1 measurements (see Fig. 1):

$$\alpha_{\mathrm{dyn,opt}} = \arccos[(2E_1-1)/(2-E_1)].$$

It is interesting to note that $\alpha_{\mathrm{dyn,opt}}$ lies always above the Ernst angle $\alpha_{\mathrm{Ernst}} = \arccos(E_1)$ by about 33 % to 73 %.

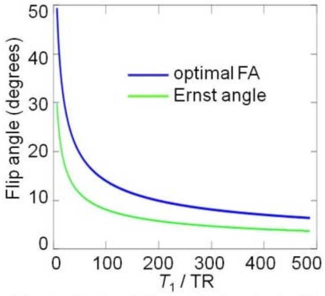

Fig. 1: Optimal flip angle for single-FA T_1 mapping over T_1 / TR.

Methods: The proposed single-FA method was evaluated in phantom measurements at a 3-Tesla whole-body MRI scanner using a phantom with stepwise increased concentrations of Gadolinium contrast agent. To evaluate the optimal FA, α_{dyn}, VFA measurements were performed at each step with α_{dyn}=2.5°, 5.0°, 7.5°, 10.0°, 12.5°, 15.0°, 17.5°, 20.0°, 22.5°, 25.0°, and 30.0° (other parameters: TR=7.0 ms, TE=3.0 ms, matrix=128×128×48, bandwidth=391 Hz/pixel); B_1 was measured for FA correction.[3] As reference, T_1 was determined using a saturation-recovery (SR) measurement. Using all flip angles for the baseline measurement and only a single one for the dynamic 1FA measurements, T_1 maps were calculated for 7 increasing Gd concentrations. The statistical error of the method was assessed using the standard deviation of the T_1 map; the systematic error was assessed using the relative deviation from the SR reference measurement.

Results: The statistical error (standard deviation of T_1 map) as a function of α_{dyn} for different relaxation times, T_1, is shown in Fig. 2 together with the (appropriately scaled) theoretical curve $\Delta E_1(\alpha_{\mathrm{dyn}})$. The minima of both the measured errors and the theoretical curve agree well and increase from about 7° for T_1=2870 ms to 30° for T_1=140 ms. The determined T_1 values of the SR and 1FA measurement with α_{dyn}=12.5° (which is the mean value of $\alpha_{\mathrm{dyn,opt}}$ over the T_1 range from 140 to 2870 ms) are listed in Table 1:

Table 1: Measured T_1 values (saturation recovery, SR, and single-FA, 1FA, approach)

Reference (SR): T_1 (ms)	2873	1643	986	787	410	232	140
1FA (α_{dyn}=12.5°): T_1 (ms)	2988	1651	959	749	390	227	144
Relative deviation (%)	+4.0	+0.5	–2.7	–4.9	–4.9	–2.0	+2.8

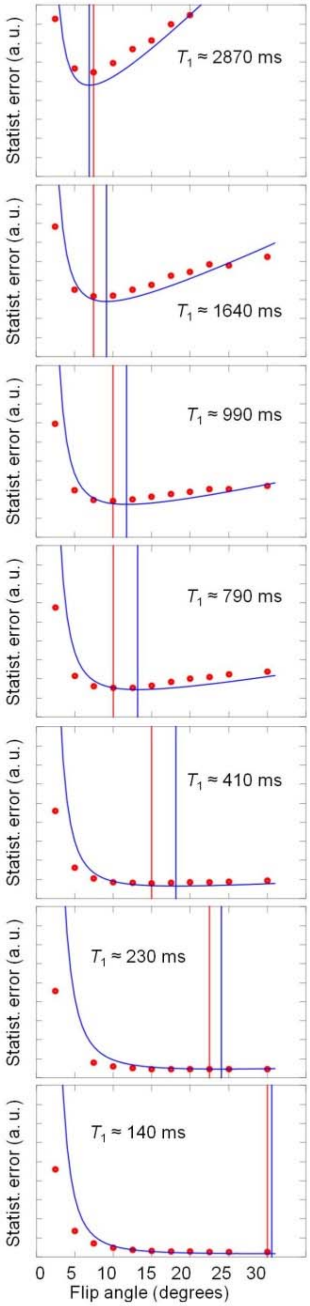

Fig. 2: Measured statistical error (standard deviation in T_1 maps, red circles) and scaled theoretical statistical error (ΔE_1, blue line). The minima of experimental and theoretical errors are indicated by colored vertical lines.

Discussion: The proposed 1FA technique provides accurate T_1 values (within ±5%). Remaining deviations might be related to neglected $T_2{}^*$ influences and imperfect B_1 correction. The theoretically derived optimal FA for the 1FA approach, $\alpha_{\mathrm{dyn,opt}}$, is confirmed by the evaluation of the statistical error of the parameter maps.

Conclusions: Fast dynamic T_1 mapping is feasible acquiring only a single 3D FLASH data set for each time point in combination with a longer baseline measurement. The optimal FA for the dynamic series can be determined depending on the expected range of T_1 values using the derived equation for $\alpha_{\mathrm{dyn,opt}}$ shown in Fig. 1. In particular when implemented with ultra-fast dynamic acquisition techniques such as TRICKS [4] or TWIST [5], the temporal resolution of T_1 mapping can be dramatically improved.

References: 1. Fram EK et al. Magn Reson Imaging. 1987;5:201. **2.** Brookes JA et al. Br J Radiol. 1996;69:206. **3.** Yarnykh VL. Magn Reson Med. 2007;57:192. **4.** Korosec FR et al. Magn Reson Med. 1996;36:345. **5.** Song T et al. Magn Reson Med. 2009;61:1242.