# Fast dynamic measurements of $T_1$ relaxation times: influence and correction of $T_2$* effects

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**Target audience:** MR physicists

**Purpose:** To analyze and correct the influence of contrast-agent induced $T_2^*$ relaxation effects on the accuracy of fast dynamic 3D $T_1$ measurements with a combined variable-flip-angle (VFA)/single-flip-angle (1FA) method.

**Theory:** Fast dynamic 3D $T_1$ mapping (e.g. to quantify the passage of contrast agent through tissue) can be performed by combining an initial longer (pre-contrast) baseline measurement with several different flip angles and a subsequent single-flip-angle (flip angle: $\alpha_{\text{dyn}}$) measurement during the dynamic phase.[1,2] The VFA baseline measurement is used to determine $S_0E_{2,0} = S_0\exp(-\text{TE}/T_{2,0}^*)$ and $E_{1,0} = \exp(-\text{TR}/T_{1,0})$; e. g., by fitting the measured signals to the spoiled-gradient echo (FLASH) signal equation. Dynamic $E_{1,\text{dyn}} = \exp(-\text{TR}/T_{1,\text{dyn}})$ and, thus, $T_{1,\text{dyn}}$ can be determined as [2]

$$E_{1,\text{dyn}} = [S_0E_{2,\text{dyn}}\sin(\alpha_{\text{dyn}}) - S_{\text{dyn}}] \,/\, [S_0 E_{2,\text{dyn}}\sin(\alpha_{\text{dyn}}) - S_{\text{dyn}}\cos(\alpha_{\text{dyn}})], \qquad (1)$$

if $T_2^*$ effects are neglected (i. e., assuming $E_{2,\text{dyn}} \approx 1$, which is justified for sufficiently short echo times TE and not too high $T_2^*$-shortening concentrations of the contrast agent). However, this approximation is no longer valid at high concentrations of contrast media, and a more accurate approach for $T_1$ quantitation is required: The influence of the contrast-agent concentration $c$ on $R_1$=1/$T_1$ and $R_2^*$=1/$T_2^*$ is $R_1 = R_{1,0} + c\cdot r_1$ and $R_2^* = R_{2,0}^* + c\cdot r_2^*$. Thus, $c = (R_1 - R_{1,0})/r_1$ and (the following is the principal idea of the proposed approach) $R_2^*$ can be expressed as a function of $R_1$: $R_2^* = R_{2,0}^* + (R_1 - R_{1,0})\cdot r_2^*/r_1 = R_{2,0}^* - \lambda R_{1,0} + \lambda R_1$ with $\lambda = r_2^*/r_1$. Consequently, $S_0E_{2,\text{dyn}} = S_0E_{2,0}\cdot E_{1,0}^{[-\lambda\cdot(\text{TE/TR})]}\cdot E_{1,\text{dyn}}^{[\lambda\cdot(\text{TE/TR})]}$, i.e., $S_0E_{2,\text{dyn}}$ can be expressed using known quantities from the baseline measurements ($S_0E_{2,0}$ and $E_{1,0}$), the sequence parameters (TE/TR), and the contrast-agent-specific property $\lambda = r_2^*/r_1$. Combining this expression for $S_0E_{2,\text{dyn}}$ with Eq.(1), we obtain the expression

$$E_{1,\text{dyn}} = \frac{S_0E_{2,0}\cdot E_{1,0}^{[-\lambda\cdot(\text{TE/TR})]}\cdot E_{1,\text{dyn}}^{[\lambda\cdot(\text{TE/TR})]}\cdot\sin(\alpha_{\text{dyn}}) - S_{\text{dyn}}}{S_0E_{2,0}\cdot E_{1,0}^{[-\lambda\cdot(\text{TE/TR})]}\cdot E_{1,\text{dyn}}^{[\lambda\cdot(\text{TE/TR})]}\cdot\sin(\alpha_{\text{dyn}}) - S_{\text{dyn}}\cos(\alpha_{\text{dyn}})} \qquad (2)$$

for the unknown $E_{1,\text{dyn}}$, which must be solved numerically because of the rational exponent $\lambda\cdot$(TE/TR).

**Methods:** *Simulations:* Measurements (TE = 2 ms, TR = 5 ms) with typical relaxation times ($T_1$ = 1000 ms, $T_2^*$ = 50 ms) and contrast agent concentrations between 0 and 10 mmol/L ($r_1$ = 5.2 $s^{-1}$/(mmol/L), $r_2$ = 6.1 $s^{-1}$/(mmol/L) as for gadobutrol[3]) were simulated for 10 initial flip angles $\alpha$ = 3°, 6°, 9°, …, 30° and for 3 different "dynamic" flip angles $\alpha_{\text{dyn}}$ = 18°, 24°, 30°. $R_{1,\text{dyn}}$ was determined (a) neglecting $T_2^*$ effects, (b) with the proposed exact $T_2^*$ correction, and (c) with an approximate correction assuming $\lambda\cdot$(TE/TR) ≈ 0.5. *Phantom measurements:* $T_1$ mapping with the proposed method (with and without correction) was performed in a liquid phantom with stepwise increasing concentrations of gadobutrol (3D FLASH sequence, TR: 7 ms, TE: 3 ms, matrix: 128×128×48, 12 VFA flip angles between 2.5° and 30°; the 1FA flip angle was set to 20°).

**Results:** *Simulations* (Fig. 1): Without $T_2^*$ correction (dashed lines), the calculated values of $R_1$ were systematically too low (i. e., $T_1$ too long) with a mean relative deviation of $R_1$ (over all contrast-agent concentrations) of –20.0 % for $\alpha_{\text{dyn}}$ = 18°, –14.7 % for $\alpha_{\text{dyn}}$ =24°, and –11.8 % for $\alpha_{\text{dyn}}$ =30°; the relative deviations became greater than 5 % for $R_1$ > 11/s (c > 2 mmol/L) for $\alpha_{\text{dyn}}$ = 18°. With the exact $T_2^*$ correction, all mean deviations were below 1 ppm. With the approximate correction (i. e., setting $\lambda\cdot$(TE/TR) = 0.5), the mean errors were +4.7 % for $\alpha_{\text{dyn}}$ = 18°, +2.0 % for $\alpha_{\text{dyn}}$ = 24°, and +1.2 % for $\alpha_{\text{dyn}}$ = 30°, i. e. still up to an order of magnitude smaller than without correction. *Phantom measurements* (Fig. 2): The maximum $R_1$ deviations (for the 2 highest concentrations of gadobutrol) between 1FA measurement and VFA reference were –5.0% and –6.4% without correction and –2.7% and –1.6% with the proposed correction.

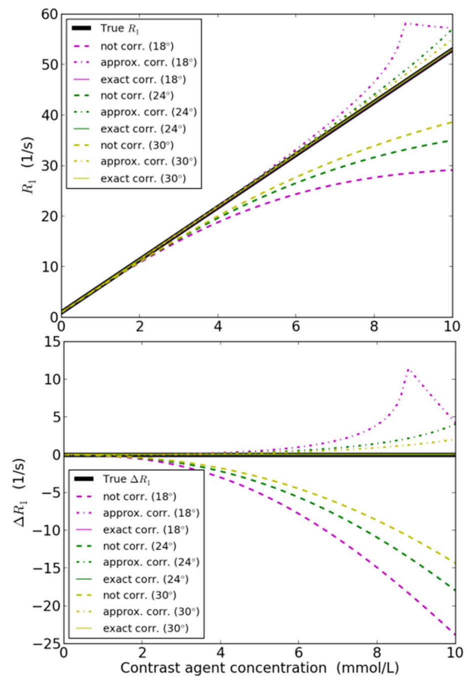


**Fig. 1:** Simulation results: $R_1$ (top) and $\Delta R_1$ (bottom) as a function of the contrast agent concentration. "Exact correction" results lie exactly on the reference.

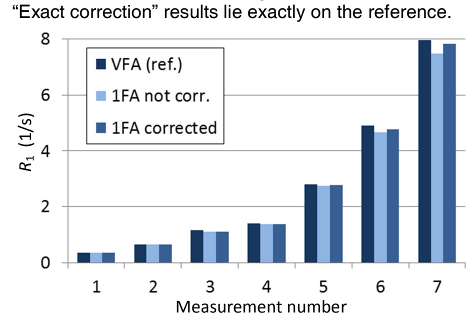


**Fig. 2:** Phantom measurements of $R_1$ at seven increasing concentrations of the contrast agent.

**Discussion:** According to our results, $T_2^*$ effects become relevant for 1FA $T_1$ mapping at tissue concentrations of contrast agent of about 2 mmol/L (i. e., $R_1 - R_{1,0}$ of 10/s); this threshold, however, depends strongly on the chosen sequence parameters, and particularly on TE and the flip angle. The approximate correction with $\lambda\cdot$(TE/TR) = 0.5 may be sufficient for many practical purposes and has the additional advantage that it results in a cubic equation for $(E_{1,\text{dyn}})^{1/2}$, which can be solved in principle analytically using Cardano's method.

**Conclusion:** Our results indicate that a correction of $T_2^*$ effects substantially reduces the systematic errors of 1FA $T_1$ measurements at high concentrations of contrast agents (e. g. during the first pass of a contrast agent bolus).

**References: 1.** Brookes JA et al. Br J Radiol. 1996;69:206, **2.** Dietrich O et al. Magn Reson Med. 2014 (epub, DOI: 10.1002/mrm.25199) , **3.** Rohrer M et al. Invest Radiol 2005;40:715