# Relaxation Time Calculations using an Inversion-Recovery Steady-State Free-Precession (IR-SSFP) Sequence — A Comparison of Single and Dual Acquisition Methods

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Introduction The rapid and accurate quantification of relaxation times in cardiac MRI is now possible with the introduction of segmented Inversion Recovery Steady-State Free Precession (IR SSFP) sequences[1]. A method developed by Schmitt *et al.*[2] used a single IR-SSFP acquisition to calculate both $T_1$ and $T_2$, and applied this to measurements in the brain. One requirement of this method is that the longitudinal magnetisation must have sufficient time to recover (of the order of five seconds), which means it may not be suitable in cardiac imaging. An alternative method that involves two IR-SSFP acquisitions at different flip angles may not have this requirement; however, the need for an extra acquisition cannot be justified unless this method can produce more accurate measurements under conditions typically seen in cardiac imaging. The aim of this work is to compare these two methods in phantoms and see if there is any value in using this alterative technique.

Theory The signal time course of an IR-SSFP sequence follows an exponential recovery from an initial state $-S_o$ to a final steady-state signal $S_{ss}$ with a time constant $T_1^*$. This can be rewritten with the introduction of a parameter INV, which is equal to $1+(S_o/S_{ss})$. Schmitt [2] demonstrated that $T_1$ and $T_2$ can be calculated using the following equations: $T_1 = T_1^* \cos(\alpha/2)\cdot(\mathrm{INV}-1)$, $T_2 = T_1^* \sin^2(\alpha/2)\cdot(1-(\cos(\alpha/2)/(\mathrm{INV}-1)))^{-1}$ where $\alpha$ is the SSFP flip angle.

For the case where acquisitions at two different flip angles ($\alpha_1$ and $\alpha_2$) are used, $T_1$ and $T_2$ can be calculated using the equation, right, where '-1' denotes the inverse matrix. This method only needs two $T_1^*$ values in order to quantify $T_1$ and $T_2$. Since it does not require the calculation of INV, it may be more accurate in situations where there is incomplete recovery of longitudinal magnetisation during the acquisition.

$$\begin{pmatrix} \frac{1}{T_1} \\ \frac{1}{T_2} \end{pmatrix} = \begin{pmatrix} \cos^2(\alpha_1/2) & \sin^2(\alpha_1/2) \\ \cos^2(\alpha_2/2) & \sin^2(\alpha_2/2) \end{pmatrix}^{-1} \begin{pmatrix} \frac{1}{T_1^*(\alpha_1)} \\ \frac{1}{T_1^*(\alpha_2)} \end{pmatrix}$$

Methods All measurements were performed on a 1.5T Magnetom Avanto (Siemens Healthcare, Erlangen, Germany). Twelve Eurospin (Diagnostic Sonar, Livingston, UK) agarose gel phantoms with a wide range of calibrated $T_1$ (230—1720 ms) and $T_2$ (53—216 ms) values were scanned using a standard IR-SSFP sequence with the following parameters: TR/TE = 3.35/1.44 ms, Slice thickness = 8 mm, FOV = 250×250 mm, matrix = 192×192, number of segments = 9 and triggering every second heartbeat. A simulated ECG trace was set to run with five RR intervals (600, 800, 1000, 1400 and 2000 ms). For each R-R interval, five acquisitions were run at flip angles from 10° to 50 in 10 increments. All data was analysed using Matlab (2012b, MathWorks, Natick, US). Region of interest analysis was performed, followed by curve fitting using the Levenberg-Marquardt algorithm with a three-parameter fit to a custom equation. The For the single acquisition method the fitting parameters were $S_{ss}$, INV and $T_1^*$. $T_1$ and $T_2$ were calculated using the formulae from Schmitt *et al.* The alternative method used $S_{ss}$, $S_o$ and $T_1^*$ as its fitting parameters; $T_1$ and $T_2$ values were calculated for all ten flip angle combinations. All values were then compared against calibrated values obtained from IR-Spin-Echo and multi-echo Spin echo experiments. Limits of Agreement (LoA) were calculated using the Bland-Altman method.

Results Curve fitting was successful in all cases ($R^2$ >0.998) with the exception of the longest $T_1$ gel ($T_1$ = 1719 ms). This data was excluded from further analysis. Both curve fitting methods yielded similar values for $T_1^*$ and $S_{ss}$, and INV values from the single acquisition fit were shown to be in keeping with values calculated using $S_{ss}$ and So values. For the single acquisition method, the most accurate $T_1$ and $T_2$ measurements were obtained using a flip angle of 50 , and for the dual acquisition method, a flip angle combination of 20° and 50° gave the best results. For an RR interval of 1000 ms, Bland-Altman analysis (Figure 1) shows that for $T_1$, the dual acquisition method has a far greater accuracy (mean difference: 1.7 ms; LoA: -3.4—6.7 ms) relative to the calibrated values than the single acquisition method (mean difference: -78.9 ms; LoA: -277.9—120.1). There was a marked under-estimation of $T_1$ with the single acquisition method for long $T_1$ gels. A similar pattern is seen at longer RR intervals, but with improved LoAs (mean difference: -19.4 ms; LoA: -67.8—28.9). In the case of $T_2$, however, both methods over-estimated the true $T_2$ value (51.7 ms for single acquisition vs. 21.3 ms for dual acquisition), but the LoA for the dual acquisition method (4.2—38.4 ms for an RR interval of 1000 ms) were still better than the single acquisition method (LoA: -60.1—163.5 ms).

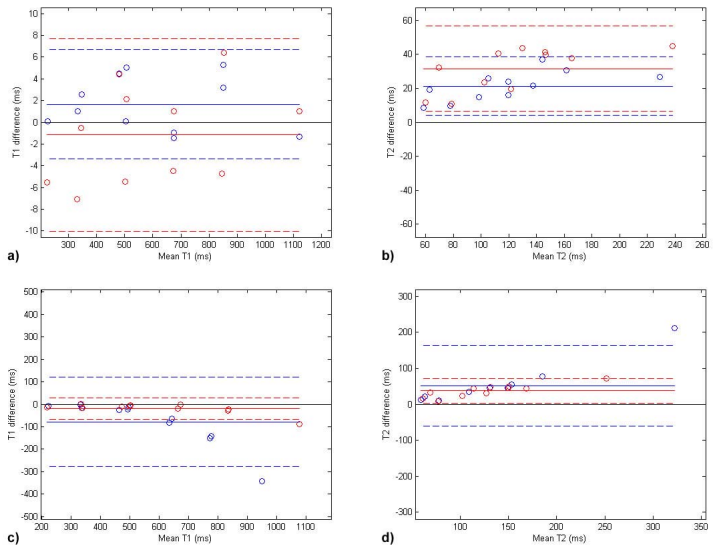


Figure 1. Bland-Altman plots a) $T_1$, dual acquisition, b) $T_2$, dual acquisition, c) $T_1$, single acquisition, d) $T_2$, single acquisition. Blue represents 1000 ms RR interval data and red 2000 ms RR interval.

Discussion An alternative method for measuring $T_1$ and $T_2$ using two acquisitions has been demonstrated that has superior accuracy to a method using a single acquisition over a wide range of $T_1$ and $T_2$ values. The equations used to derive $T_1$ and $T_2$ using the single acquisition method, are only valid in cases where full relaxation has taken place, hence the reason for the marked deviations for long $T_1$ or $T_2$ values and short RR intervals. The dual acquisition method can therefore be used in cardiac imaging where scans must be acquired in a single breath-hold, and subjects may have very short RR intervals. However, the disadvantage of this method is the need to perform two acquisitions, which for a subject would introduce additional variability from mis-registration, breathing artefacts etc. that would negate any benefit of using this method. However, it may still have value in situations where motion is not an issue (e.g. neuro, MSK etc.), but running with a significantly shorter recovery time (e.g. 1—2 s using the dual acquisition method compared to 5 seconds with the single acquisition method) could still be advantageous. Note that no corrections were made for flip angle variations across the slice profile.

Conclusion A dual acquisition method for measuring $T_1$ and $T_2$ was compared with a single acquisition method in phantoms and was found to give superior accuracy in situations where the downside of performing two acquisitions can be offset by reduced scan time. Further work is needed to establish whether this can be applied in vivo.

[1] Scheffler K and Hennig J. (2001) *Magn Reson Med*, 45 (4): 720-723

[2] Schmitt P *et al.* (2004) *Magn Reson Med*, 51 (4): 661-667