A Systematic Technique for Echo Truncation in MRI-Based R2* Calculations for Liver Iron Quantification Which Reduces Systematic and Random Error

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Purpose

Multi-echo gradient echo MRI techniques for measuring the R_2* relaxation rate have emerged as clinical methods for measurement of hepatic iron concentration (HIC). These techniques involve a T1-weighted acquisition of 12-20 echoes with the shortest echo times possible, followed by a log-linear fit to the magnitude signal intensity data using a least-squares fitting algorithm (1,2). The least-squares method assumes a symmetric (Gaussian) distribution of noise in the measured data, however the noise distribution in magnitude signal intensity data is in fact asymmetric (Rician) (3). This asymmetry results in a positive bias in the measured magnitude signal intensity values and is the cause of the "noise floor" phenomenon, where the magnitude of the MR signal decays to some fluctuating positive value for very long echo times.

$$SI(echo) = R(SI(0) * e^{-R_2^* * TE}, \sigma) \quad [1]$$

$$R(v,\sigma) = \sqrt{[(\sigma * N_1(0,1) + v]^2 + [\sigma * N_2(0,1)]^2} \quad [2]$$

$$CV(RMSE) = \frac{\sqrt{\left[R_2^*(known) - \overline{R_2^*}\right]^2 + V}}{R_2^*(known)} \quad [3]$$

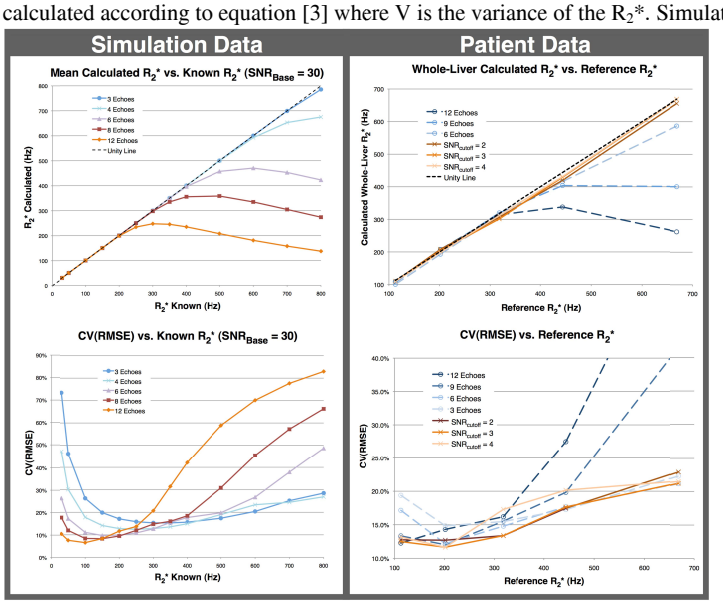
As a result, the use of the least-squares algorithm can lead to a systematic bias in the solution when the value of the measured signal approaches that of the noise floor. Similar difficulties applying the least-squares fitting algorithm have been described with (ADC) calculations in diffusion-weighted imaging (4). We examine the propagation of both systematic and random error in the multi-echo R_2* measurement problem, using both Monte Carlo simulations and measured patient data. We propose an automated paradigm to minimize measurement error without *a priori* knowledge of R_2*, using progressive estimations of the local SNR at each echo time in the MR acquisition.

Materials and Methods

Our institutional review board approved this retrospective Health Insurance Portability and Accountability Act–compliant study. For the patient data portion, five data sets were selected from a database of patients who had undergone liver R_2* measurements with a range of reference R_2* values of 113-669 Hz, approximating the range of abnormal R_2* values encountered clinically at our center.

R_2* calculation techniques – We refer to the "fixed echoes" technique as the use of a predetermined number of echoes in the R_2* fitting problem. SNR_{Base} is the calculated SNR at an echo time of 0 ms according to [1]. The "variable echoes" technique refers to the customized choice of a number of echoes on a voxel-by-voxel basis. The choice of echo number in the variable echoes technique is based on an estimate of local SNR for each voxel at each acquired echo time, calculated as the SI of a voxel divided by the standard deviation of SI values in a 5x5 region of neighboring voxels. The number of echoes used in this technique is chosen as the number of echoes for which, in that voxel location, the estimated SNR value is greater than a predetermined value SNR_{cutoff}.

Monte Carlo Simulation – The MR signal measured by a multi-echo T1-weighted gradient echo sequence was simulated according to equations [1,2], where $R(v,\sigma)$ is a function which adds noise with a Rician distribution to the simulated data. We simulated signal intensity measurements for echo times TE(n) where TE(1) = 1ms, number of echoes = 12, and echo spacing = 0.9 ms, based on one of our 1.5 T clinical MRI systems. Simulations were performed for R_2*$_{known}$ = 30-800 Hz and SNR_{Base} = 10-70, and a least-squares log-linear fit was performed for each combination of R2*$_{known}$ and SNR_{Base}, with 100,000 simulations performed for each pair of for R_2*$_{known}$ and SNR_{Base}. The mean and variance of the resultant R_2*$_{calc}$ value distribution were calculated for each combination of R_2*$_{known}$ and SNR_{Base}. These were compared against the R_2*$_{known}$ values to determine the systematic error, and the total error CV(RMSE) calculated according to equation [3] where V is the variance of the R_2*. Simulations were performed for the fixed echoes technique for a range of n = 3-12 echoes, and for the variable echoes technique for SNR_{cutoff} = 2-7.



Patient Data – R_2* maps were calculated from image data obtained with a 1.5 T clinical MRI system, with parameters identical to those described for the simulation, using both the fixed and variable echoes techniques. Since our simulation data showed that systematic error was lowest when the 1st-3rd echoes were used to calculate R_2*, we took the mean whole-liver R_2* calculated using those echoes as the reference standard. The distribution of R_2* values within the whole-liver ROI was considered to represent the standard deviation of the values for that patient calculated with the particular technique, and systematic and total error calculated using the same method employed for the simulation data.

Results

Monte Carlo Simulation – Systematic underestimation of R_2*$_{calc}$ was observed for the fixed echoes technique when R_2*$_{known}$ values were high and a large number of echoes was used. Total error tended to be high for low R_2*$_{known}$ values when few echoes were used, due to large amounts of random error. For the variable echoes technique, no significant systematic error was observed across the range of simulated values. Total error was lower for the variable echoes technique compared with the fixed echoes technique for any fixed number of echoes and any SNR_{cutoff} value.

Patient Data – Similar trends were observed in the patient data evaluation, with the exception that the variable echoes technique did not universally outperform the fixed echoes technique with regard to total error. However, the best case of the variable echoes technique (SNR_{cutoff} = 3) did outperform the best case of the fixed echoes technique (number of echoes = 6), with lower total error across the range of reference whole-liver R2* values. No systematic errors were observed for the variable echoes technique, while systematic underestimation of R_2*calc was observed for the fixed echoes technique when larger numbers of echoes were used, including the best case for total error (number of echoes = 6).

Conclusion

In R_2* calculation from a multi-echo gradient echo acquisition, systematic errors in the R_2* solution can result from the use of a large number of echoes, while random errors increase from the use of too few echoes. The errors in such a calculation method can be reduced by use of a systematic technique to optimize the number of echoes used in each calculation.

References

1. Wood JC et al. Blood 2005;106(4):1460-1465.
2. Hankins JS et al. Blood 2009;113(20):4853-4855.
3. Gudbjartsson H et al. Magn Reson Med 1995;34(6):910-914.
4. Kristoffersen A. Magn Reson Med 2011.