Estimation of T2* in Severe Iron Overload Patients with Weighed Least Squares T2*-IDEAL

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Introduction Hepatic iron overload is a common chronic liver disease. Excess irons shorten the T2* of liver from above 20ms [1] to shorter than 1ms [2]. MRI has been shown to have excellent sensitivity to the presence of iron with T2* weighted sequences [3]. Liver to muscle (L/M) and liver to fat (L/F) signal intensity ratios offer reliable means to characterize liver iron content [3], however they are qualitative in nature and sensitive to coil sensitivity and B_1 inhomogeneity. Direct measurement of T2* may be a more attractive approach to assess iron concentration independent of pulse sequence parameters. We have previously demonstrated that R2* (1/T2*) mapping can be achieved simultaneously with water-fat separation using a multi-echo acquisition and a T2*-IDEAL reconstruction algorithm [4]. With the T2*-IDEAL technique, the confounding factor of fat is removed from the estimation of T2*.

A typical T2*-IDEAL acquisition collects 6 or more echoes as rapidly as possible [4]. In the presence of very short T2* decay, the images collected at later echoes are dominated by noise, which, as shown below, can lead to substantial errors in R2* mapping and water-fat separation using the T2*-IDEAL algorithm. In this work, we introduce a weighted least squares algorithm during the iteration of the T2*-IDEAL reconstruction, which automatically decreases the impact of later, noise-dominated echoes. Using this approach, we will show that T2* can be effectively estimated to as short as 1ms.

Methods The T2*-IDEAL algorithm utilizes the concept of "complex fieldmap" to combine the B_0 fieldmap (ψ) and R2* into one parameter: $\hat{\psi} = \psi + j \cdot R_2^* / 2\pi$. The signals can be modeled as $\mathbf{s} = \mathbf{D}(\hat{\psi}) \cdot \mathbf{A} \cdot \boldsymbol{\rho}$, where $\mathbf{s}$ is the signal vector collected at multiple echo times ($\mathbf{t}$). $\mathbf{D}(\hat{\psi}) = diag(e^{j2\pi\hat{\psi}\mathbf{t}})$, a diagonal matrix representing the modulation from the fieldmap and T2* relaxation. $\mathbf{A}$ is a matrix characterizing the signal evolution of water and fat, and has the form of $\mathbf{A} = \begin{bmatrix} 1 & e^{j2\pi\Delta f \mathbf{t}} \end{bmatrix}$ [5]. $\boldsymbol{\rho} = \begin{bmatrix} w & f \end{bmatrix}^T$ denotes water and fat. The signal is a nonlinear function of the unknowns ($\hat{\psi}, \boldsymbol{\rho}$). To apply weighted least squares in the T2*-IDEAL iteration, the following steps are followed:

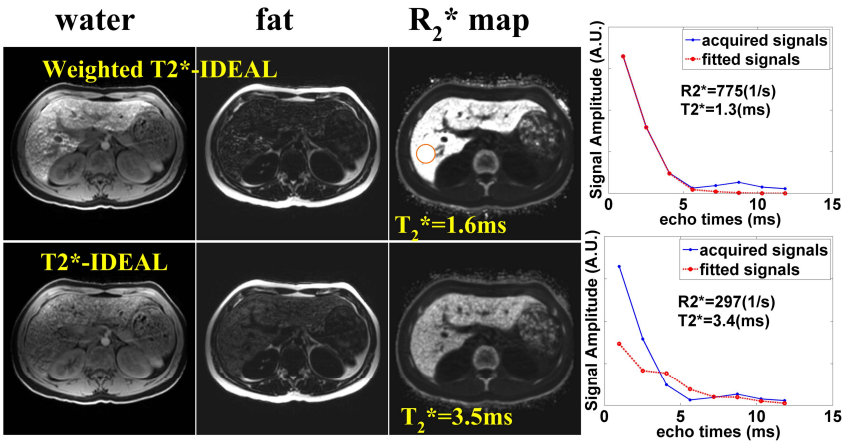

Figure 1: Results from a liver patient with severe iron overload: water, fat, R2* map and fitting of a typical liver pixel. Weighted T2*-IDEAL shows accurate fitting while the original T2*-IDEAL results in substantial errors in both T2* and water-fat separation.

1). Initialize the current estimate of the complex fieldmap $\hat{\psi}_c$ with a first-guess value, e.g. 0.

2). Generate the weights according to the R2* portion of the $\hat{\psi}_c$: $\mathbf{W} = diag(e^{-2R_{2c}^* \mathbf{t}})$.

3). Demodulate the signal with the complex fieldmap: $\tilde{\mathbf{s}} = \mathbf{s} \cdot \mathbf{D}(-\hat{\psi}_c)$

4). Calculate current estimates of water and fat using **weighted** least squares inversion: $\boldsymbol{\rho}_c = (\mathbf{A}' \cdot \mathbf{W} \cdot \mathbf{A})^{-1} \cdot \mathbf{A}' \cdot \mathbf{W} \cdot \tilde{\mathbf{s}}$

5). Calculate the cost function: $C = \mathbf{s} - \mathbf{D}(\hat{\psi}_c) \cdot \mathbf{A} \cdot \boldsymbol{\rho}_c$

6). Following the Gauss-Newton search algorithm, the cost function can be approximated to the first order as the multiplication of the Jacobian matrix (J) and the increment terms in the unknowns. We apply another **weighted** least squares inversion to estimate the increment terms: $[\Delta\hat{\psi}, \Delta\boldsymbol{\rho}]^T = (J' \cdot W \cdot J)^{-1} \cdot J' \cdot W \cdot \mathbf{C}$

7). Update the fieldmap: $\hat{\psi}_c := \hat{\psi}_c + \Delta\hat{\psi}$, if it has not converged, repeat starting at step 2.

Note that Step 3 implies the demodulation of the T2* relaxation from the source signals, i.e. multiplying the signals and the noise by $e^{R_2^* \mathbf{t}}$. Therefore, if the weighted least square algorithm is not applied, substantial errors may result from the exponentially magnified noise.

Multi-echo data were acquired in patients with liver iron overload using an investigational version of the 3D-SPGR sequence on a 1.5T scanner (HDx, GE Healthcare, Waukesha, WI). Informed consent and permission from our Institutional Review Board (IRB) were obtained. Both the original T2*-IDEAL and weighted T2*-IDEAL reconstructions were performed using the same source data. The goodness of fit from the two reconstruction methods was examined in representative pixels in the liver.

Results Figure 1 shows results from a scan of a patient with severe iron overload. Water, fat and R2* maps from the weighted T2*-IDEAL (top row) and original T2*-IDEAL (bottom row) are shown, along with the plots of signal fitting in a representative liver pixel. With the weighted T2*-IDEAL, the fitted signals (dashed red) follow the acquired signals (solid blue) extremely well, particularly at early echoes with better SNR. In contrast, the original T2*-IDEAL results in substantial errors in the measured T2*. The erroneous T2* further leads to incorrect water-fat separation, reflected as the baseline fat signal in the liver. The TE of the first echo is 1.0 ms and echo spacing is 1.6 ms for this scan. Eight echoes were collected in a 19-sec breath-hold with parallel imaging acceleration of 2.

Simulations were performed to study the range of T2* in which the weighted T2*-IDEAL should be applied. The echo times from the liver scan shown in Figure 1 and a pure water pixel were used. Signals were generated with increasing T2* (1ms to 10ms) and Gaussian distributed noise with SNR of 20, which were then processed by the original T2*-IDEAL and weighted T2*-IDEAL algorithms. This was repeated 10000 times and the averaged T2* values were plotted (Figure 2). When T2* is short, the weighted T2*-IDEAL significantly outperforms the original T2*-IDEAL. T2* is over-estimated with the original T2*-IDEAL, consistent with the observation from the liver study. Both methods estimate T2* very well when T2* is longer than approximately 4ms.

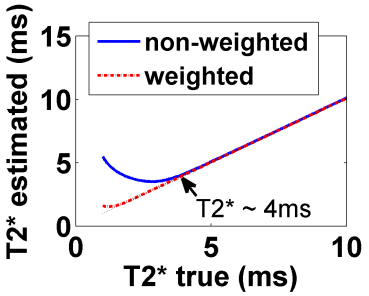

Figure 2: Simulations to study the range of T2* in which weighted T2*-IDEAL outperforms the original T2*-IDEAL.

Discussion and Conclusion We have shown that in order to use T2*-IDEAL for estimation of very short T2*, consideration must be given to the fact that the SNR is not the same for all echoes. In our approach, the weighted least squares fitting is applied during the iterative T2*-IDEAL reconstruction. The weights are calculated based on the noise variance in the source images after the T2* demodulation. As a result, the acquisition can simply collect as many echoes as possible within the allowed scan time, and the weighted T2*-IDEAL automatically accounts for the SNR difference between the echoes. In conclusion, weighted T2*-IDEAL makes it possible to accurately quantify very short T2* in the presence of severe iron overload.

References

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