Noise Performance of IDEAL considering Relaxation and Multiple Spectral Peaks of Fat

S. VAN ZYL[1], P. BÖRNERT[2], H. EGGERS[2], AND M. M. MORLOCK[1]

[1]HAMBURG UNIVERSITY OF TECHNOLOGY, HAMBURG, GERMANY, [2]PHILIPS RESEARCH EUROPE, HAMBURG, GERMANY

INTRODUCTION

Water/fat resolved MR imaging is gaining considerable interest in a number of clinical applications. Chemical shift encoding-based imaging approaches, like three-point Dixon [1] or IDEAL [2], provide high quality water/fat separation. Both approaches treat the spectral composition of water and fat as idealized single peak spectra with infinite signal lifetime. However, in reality, relaxation effects are always present. Therefore, Yu et al. [3] proposed to incorporate a common $T2^*$ for water and fat into the signal model ($T2^*$-IDEAL). Moreover, the fat spectrum is much more complicated. Human fatty tissue contains methyl, methylene and olefinic methine protons in different concentrations and compositions [4,5]. Recently, Brodsky et al. [6] proposed a separation algorithm that takes the multi-peak nature of fat into account. The fat spectrum in this multi-peak (MP)-IDEAL approach is considered to be spatially invariant and normalized.

In this paper, these refinements to the original IDEAL approach are studied with respect to model limitations and noise performance.

METHODS AND MATERIALS

The estimation of fat and water $\{\rho_f(\mathbf{r}), \rho_w(\mathbf{r})\}$ and the field map $\psi(\mathbf{r})$ requires the acquisition of three different echoes centered at TE_n. At each echo, the signal for a voxel containing water and fat with P spectral components under the influence of $T2^*$ can be written as [6,7]:

$$s_n(\boldsymbol{r}) = \left(\rho_w(\boldsymbol{r}) + \sum_{p=1}^{P} \rho_f(\boldsymbol{r}) a_{f,p} e^{i\Delta\omega_{f,p} TE_n}\right) e^{i2\pi\psi(r)TE_n} e^{\frac{TE_n}{T_2^*}} \quad \leftrightarrow \quad \boldsymbol{s}(\boldsymbol{r}) = \boldsymbol{A_r}\boldsymbol{\rho}(\boldsymbol{r}) \quad \wedge \quad \sum_{p=1}^{P} a_{f,p} = 1,$$

where $\Delta\omega_{f,p}$ and $a_{f,p}$ are the resonance frequencies (with respect to water) and the relative proportions of the p^{th} peak of fat. To characterize $T2^*$-IDEAL and MP-IDEAL, the noise performance was investigated in this work using the Cramér-Rao bound (CRB) **[7]**. The results were independently verified using Monte Carlo simulations. For this purpose, 256 noise realisations (σ_s= 0.1) were carried out on images with varying fat/water ratios (from 0-1) at equally spaced echo time increments (ΔTE) over 0.1-9.1 ms (0-4π). Each algorithm was analyzed in separate simulations neglecting B_o field inhomogeneities. For T2*-IDEAL, different T2* values from 5 - 1000 ms were assumed, considering a two-line w/f spectrum (chemical shift @ 1.5 T: 220 Hz). For MP-IDEAL, T2* was ignored, and the number of spectral fat peaks was varied from 1 to 3. The frequencies and the amplitudes considered are approximated from **[5]** ($\Delta\omega_f$ = [220 160 -55] Hz, a_f = [0.75 0.15 0.1]). Additionally, for both algorithms, the actual w/f estimation accuracy was evaluated and the impact of realistic spectral properties (like T2*, p = 3) was studied using the standard IDEAL approach. Phantom measurements with water and sunflower oil were made on a 1.5 T clinical scanner (Achieva, Philips Healthcare) at differernt ΔTE to confim seleted simulation results.

RESULTS

The NSA (number of signal averages) obtained by T2*-IDEAL for w/f magnitude estimates is plotted in Fig. 1 as a measure for the SNR performance of the algorithm. The same NSA behavior is obtained for water and fat, since their T2* was identical. At long T2* values, the NSA behavior is hardly changed compared to standard IDEAL. In contrast, short T2* values cause a drastic drop in NSA, especially at large ΔTE. Similar to standard IDEAL, optimal echo shifts are obtained at ΔTE = 1.5 ms (2π/3). However, for T2* = 7.7 ms the maximal NSA is reduced already by a third. Short ΔTEs are therefore essential.

Results from MP-IDEAL are shown in Fig. 2. The NSA behavior for water (blue) shows small variations to standard IDEAL as the number of fat peaks increases. However, a large NSA decrease is observed for fat (yellow) when using the more realistic 3-peak model. This is caused by the changed condition of the pseudo-inverse of $\boldsymbol{A_r}$, which depends in detail on the fat amplitudes a_f and its frequencies $\Delta\omega_f$ (see Fig. 3). As a consequence, it has been found that non-equispaced encoding times may lead to higher NSA. All the CRB results have been confirmed by Monte Carlo results, which agreed very well with the theoretical results and are not explicitly shown. More importantly, phantom measurements have confirmed that the NSA for fat is smaller when decomposed using MP-IDEAL. In Fig. 2, these sample points are shown by crosses, supporting experimentally the CRB and Monte Carlo results obtained.

It has been found, that the w/f estimation accuracy for T2*-IDEAL is not significantly influenced by T2* effects. MP-IDEAL, on the other hand, improved the w/f estimation accuracy considerably, but showed a strong dependence on the accuracy of the chosen fat spectrum.

CONCLUSION

The investigations made have highlighted the importance of short encoding increments ΔTE. In both approaches, NSA was drastically reduced for fat estimates. The application of standard IDEAL to a multi-peak spectra has shown that larger NSA values can be obtained, but at the cost of accuracy. It is therefore stressed that with the use of IDEAL or MP-IDEAL a trade-off between noise efficiency and estimation accuracy has to be considered.

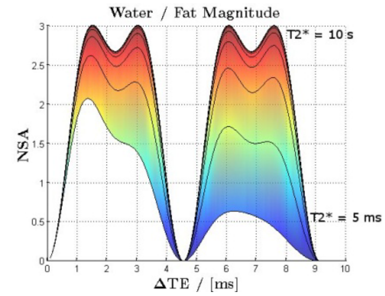

Fig. 1: NSA obtained for water and fat magnitude estimates with T2*-IDEAL. The impact of the *exp(-TE/T$_2^*$)* decay is clearly visible.

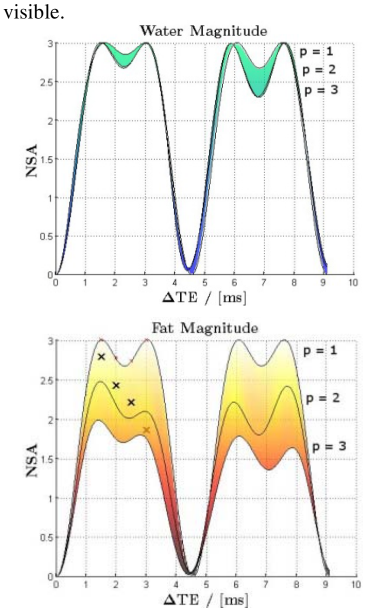

Fig. 2: NSA obtained for water (blue) and fat (yellow) magnitude estimates with MP-IDEAL. The dots indicate measurements.

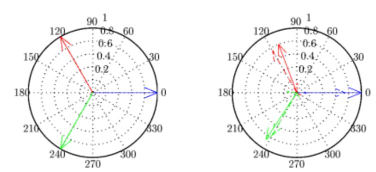

Fig. 3: Echo distribution of IDEAL (left) in comparison to MP-IDEAL (right) at ΔTE = 1.5 ms. Due to the multi-peak nature of the fat spectrum, the fat signal amplitude and the numerical condition is changed.

REFERENCES

[1] Glover et el. *MRM* 1991;18:371-383
[2] Reeder et el. *MRM* 2004;51:35-45
[3] Yu et al. *JMRI* 200;26(4):1153-61
[4] Bydder et al. ISMRM 2007;1632,
[5] Ren et al. *JLR* 2008,49:2055-2062
[6] Brodsky et el. *MRM* 2008;59:1151-1164
[7] Pineda et el. *MRM* 2005;54:625-635