Effects of T1, T2, and Spectral Complexity on In- and Out-of-Phase Imaging: A systematic approach by computer simulation

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INTRODUCTION: In- and out-of-phase imaging is used to quantify fat in tissues that contain fat and water, e.g. liver [1-3] . The observed signal shows time-dependent oscillation, which results mainly from the signal interference between the water peak at 4.7ppm and the dominant fat $(CH_2)_n$ peak at 1.3ppm. Under the assumptions of (a) equal T1 or small T1/TR, (b) long T2, (c) one fat spectral peak, (d) no B_0 inhomogeneity, and (e) no additional susceptibility effect, fat fraction can be estimated as:

$$f = (IP - OP)/2IP \quad \text{.....[Eqn. 1]}$$

where IP is the 1st in-phase echo, and OP is the 1st out-of-phase echo. In practice, however, these assumptions may not hold, in which case the method is prone to systematic errors. Using computer simulation, the errors due to these effects were modeled using realistic values of T1, T2, and the lipid MR spectrum. For simplicity and expository purposes B_0 field and other inhomogeneity effects were not considered here.

METHODS: MR spectroscopy was performed on corn oil using a spin-echo sequence with long TR (3sec) at 9 different TEs. Four major peaks (**Table 1**) were identified in accord with prior knowledge, and the peak areas were estimated using AMARES algorithm [4, 5] after correcting for T2 decay.

$$s(TE) = \left| P_w \exp\left(\frac{-TE}{T2_w^{(*)}}\right)\left[\frac{(1-\exp(-TR/T1_w))\sin\alpha}{1-\exp(-TR/T1_w)\cos\alpha}\right] + \exp\left(\frac{-TE}{T2_f^{(*)}}\right)\left[\frac{(1-\exp(-TR/T1_f))\sin\alpha}{1-\exp(-TR/T1_f)\cos\alpha}\right]\sum_{n=1}^{N} P_n \exp(i\omega_n TE)\right| \quad \text{.....[Eqn. 2]}$$

P_w, P_n	proton densities of water and n^{th} fat component
$T1_w$, $T1_f$, $T2_w$, $T2_f$	T1, T2 values of water, and each of fat components
α, ω_n	Flip angle and frequency of n^{th} fat component

The MR signal was modeled as a sum of signals of various frequencies (**Eqn 2**), the water and the dominant CH_2 peaks in the 2-component model, and the water and the four main fat peaks in the 5-component models, with P_n's weighted by the observed peak areas (**Table 1**). Fat components were assumed to have common $T1_f$ and $T2_f$ values, which may differ from those of water. The signal intensity over time after excitation was generated with varying fat fraction, given by $(P_1+P_2+\ldots)/(P_w+P_1+P_2+\ldots)$, from 0 to 1. Six different cases were simulated for each of 2- and 5-component models: (A) long T1 and long T2 to simulate an ideal situation where **Eqn. 1** is accurate, (B) $T1_w \neq T1_f$, to isolate the T1 effect, (C) $T2_w \neq T2_f$, to isolate the T2 effect, (D) $T1_w \neq T1_f$ and $T2_w \neq T2_f$, to simulate an asymmetric spin-echo sequence, (E) $T1_w \neq T1_f$ and $T2^*_w \neq T2^*_f$, to simulate a gradient-echo sequence, (F) $T1_w \neq T1_f$, short $T2^*_w$ and $T2^*_f$, to simulate a short T2* environment (e.g. Fe overload) in a gradient-echo sequence. The fat fraction was estimated by **Eqn. 1**, and plotted against the true fat fraction defined by the simulation. Due to fat-water dominance ambiguity of the IP-OP method, the fat fraction could only be given as modulo min(f, 1-f). The error of the fat quantification was illustrated as deviation from the diagonal lines, which represent exact correspondence between estimated and true fat fraction. For all simulations, flip angles were 20° and 70°, and TR = 150msec.

Figrue 1

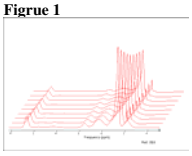


Table 1: Major Fat Spectral Peaks

ppm	Relative Area (P_n)
5.3	0.2
2.1	0.4
1.3	1
0.9	0.2

RESULTS: The simulations illustrate the following observations: (1) T1 effects, including high flip-angle, generally cause overestimation of fat fraction (**Fig. 2 and 3, B, D-F**). (2) T2 effects cause underestimation of fat in low-fat range, and overestimation in high-fat range (**C-F**). (3) The 5-component model predicts significant fat-fat interference effects, which may lead to fat quantification errors (**Fig. 3**). (4) The IP and OP fat quantification method is reliable accurate when the fat fraction approximates 50%. (5) Short T2* environments may produce large errors.

Figure 2: Two-Component Model.

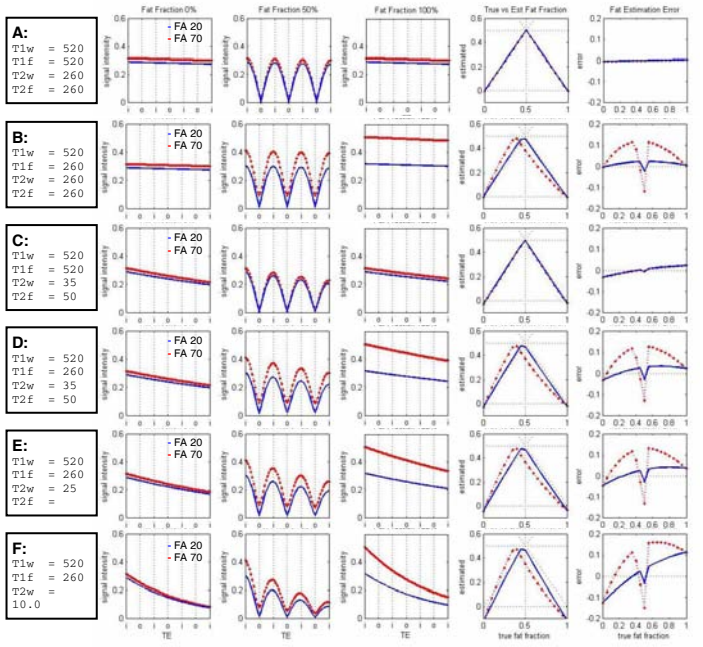
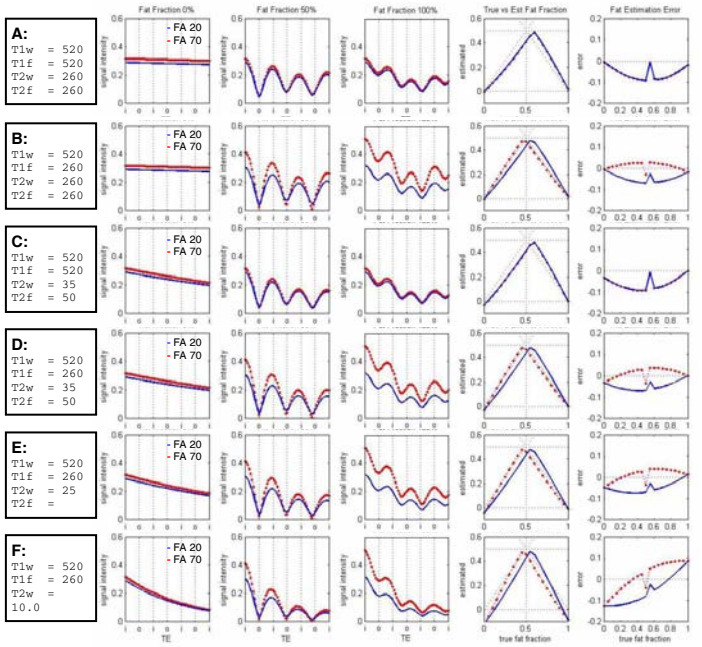


Figure 3: Five-Component Model.



CONCLUSION: (1) A simple Dixon IP-OP fat quantification may be inaccurate over realistic values of T1, T2, (or T2*), and it is prone to systematic errors due to these effects. (2) The previously under-recognized effect of fat-fat interference (due to its multiple spectrum components) can contribute to the errors in fat estimation.

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