Multi-Resolution Non-Iterative Field Map Estimation for Water and Fat Separation

W. Lu[1], G. E. Gold[1], H. Yu[2], and B. A. Hargreaves[1]

[1]Dept. of Radiology, Stanford University, Stanford, CA, United States, [2]Global Applied Science Laboratory, GE Healthcare, Menlo Park, CA, United States

Introduction: Water and fat separation methods based on chemical-shift induced phase such as IDEAL [1] and fast multi-echo sequences [2] are of great clinical interest. Multi-echo sequences, which are less sensitive to subject motion, enable highly SNR efficient water/fat separation. However, increased echo-spacing ($\Delta\mathrm{TE}$) in multi-echo sequences imposes great challenges on existing Dixon methods. IDEAL works less robustly when $\Delta\mathrm{TE}$ is long (i.e., through $\Delta\mathrm{TE}$ accrued phase between water and fat $>\pi$). Hence the application of existing methods is limited with multi-echo sequences: *short echo-spacing dictates large readout bandwidth and/or low spatial resolution, hence degraded image quality*. In this work we show longer echo-spacing limits the range of field map values that can be unambiguously resolved. Based on the study, we propose a non-iterative field map estimation method that works robustly with multi-echo sequences.

Theory: Let us model the images $\mathrm{I_n}$ (n=1,2,3) acquired at echo times $\mathrm{TE_n}$ as follows:

$$\underbrace{\begin{pmatrix} I_1\\ I_2\\ I_3\end{pmatrix}}_{S} = \underbrace{\begin{pmatrix} e^{j2\pi\psi TE_1} & 0 & 0\\ 0 & e^{j2\pi\psi TE_2} & 0\\ 0 & 0 & e^{j2\pi\psi TE_3}\end{pmatrix}}_{\Psi(\psi)} \underbrace{\begin{pmatrix} 1 & e^{j2\pi\Delta f TE_1}\\ 1 & e^{j2\pi\Delta f TE_2}\\ 1 & e^{j2\pi\Delta f TE_3}\end{pmatrix}}_{A} \underbrace{\begin{pmatrix} W\\ F\end{pmatrix}}_{\Gamma},$$

where W: water, F: fat, Δf: chemical shift, and ψ: field map. For a given field map estimate $\hat{\psi}$, its associated water and fat estimates $\hat{\Gamma}$ can be obtained optimally in a least-squares sense, i.e., $\hat{\Gamma} = A^{\dagger}\Psi(\hat{\psi})^{-1}S$. For each estimate $\hat{\Gamma}$ there is an estimation error $J(\hat{\psi}) = \left\|(AA^{\dagger}-I)\Psi(\hat{\psi})^{-1}S\right\|$, which can be used as a cost function to be minimized for locating the optimal field map value.

Fig.1 depicts a plot of a typical $J(\hat{\psi})$ that shows two prominent characteristics—multiple local minima and periodical pattern. Due to multiple local minima, iterative searches may not converge or may converge to erroneous local minima. Furthermore, it can be shown that the fundamental period of $J(\hat{\psi})$ is $1/\Delta\mathrm{TE}$, i.e., $J(\hat{\psi})=J(\hat{\psi}+1/\Delta\mathrm{TE})$. Hence, the longer the echo-spacing $\Delta\mathrm{TE}$, the narrower the range of field map values that can be resolved.

Methods: By exploiting the characteristics of the cost function $J(\hat{\psi})$, we propose a non-iterative field map estimation method that consists of two modules. Module I *multiple local minima searches* limits the search of the field map values within one period. Multiple local minima within a single period are located by applying multiple golden section searches. Upon completion of Module I, each pixel has several possible field map values, of which only one is selected by Module II *field map smoothing*. Specifically, Module II first identifies a reliable starting pixel of which the field map value is numerically close to the global median of all field map estimates and the spatial location is close to the centroid of the foreground mask. Subsequently the field map is progressively grown such that no abrupt change between neighbouring field map values is allowed.

To improve computational efficiency and estimation robustness, the non-iterative method is only applied at the coarsest level of a multi-resolution pyramidal structure, in which each pixel at a coarse level corresponds to a group of 4 pixels at next finer level. Hence a coarse resolution field map is magnified by a factor of 2 as an initial field map for the next finer resolution. Initial field map values $\hat{\psi}_{init}$ are evaluated based on the cost function $J(\hat{\psi}_{init})$. Large $J(\hat{\psi}_{init})$ indicates the initial estimate from the coarser level is inaccurate and need to be refined based on its neighbouring field map values. This coarse-to-fine field map propagation significantly reduces computational cost and corrects erroneous field map estimates obtained from the non-iterative method.

Results: The proposed method has successfully separated water and fat for various anatomical regions acquired with multi-echo sequences at both 1.5T and 3T. Fig.2 shows sagittal and coronal maximum-intensity projections of a lower-leg multi-echo bSSFP acquisition [3] at 3T using a single coil with $\mathrm{TR} = 11.8\mathrm{ms}$, $\mathrm{TE}_{1,2,3} = 2.3, 5.3, 8.4\mathrm{ms}$, flip 30°, matrix $512\times256\times128$, and $\pm 81.3\mathrm{kHz}$ receiver bandwidth. Despite of $8\pi/3$ relative phase between water and fat during $\Delta\mathrm{TE}$, excellent water/fat separation enables depiction of the arterial structure. Fig.3 shows the result of an axial slice of an abdomen acquired at 1.5T using an 8-channel coil with $\mathrm{TR} = 14\mathrm{ms}$, $\mathrm{TE}_{123} = 3.5, 6.7, 9.8\mathrm{ms}$, flip 10°, matrix $256\times144\times28$ with phase FOV ratio $.75$, and $\pm 41.5\mathrm{kHz}$ receiver bandwidth. Uniform water and fat separation throughout the abdomen is achieved for all slices, which covered the entire liver in a 42s breath-hold. Fig. 4 shows the separation results of an ankle acquired at 3T with $\mathrm{TR} = 11\mathrm{ms}$, $\mathrm{TE}_{123} = 3.2, 5.6, 8\mathrm{ms}$, flip 30°, matrix $256\times256\times64$, and $\pm 81.3\mathrm{kHz}$ receiver bandwidth. The field map shows large field inhomogeneity present in this study has been estimated.

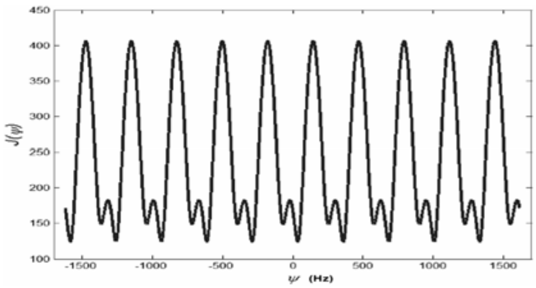

Fig. 1: A typical plot of cost function of the estimated field map value, which shows two characteristics—multiple local minima and periodical pattern.

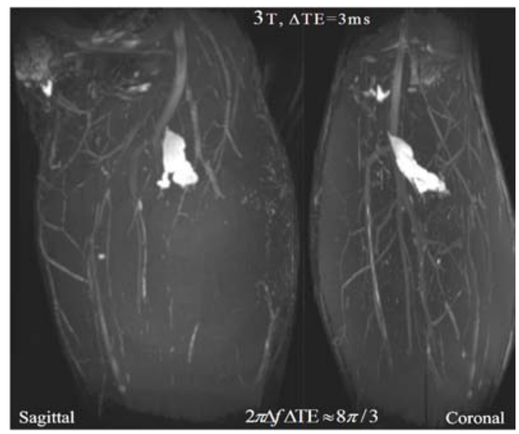

Fig. 2: Sagittal and coronal MIP images of a lower-leg study at 3T with long echo-spacing 3ms. Excellent water and fat separation enables depiction of artillery structure (bright residue is a cyst).

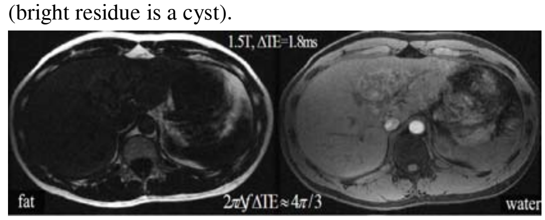

Fig. 3: Separated water and fat sample images of a liver scan. Uniform fat/water separation is achieved for all slices which cover the entire liver in a 42s breath-hold.

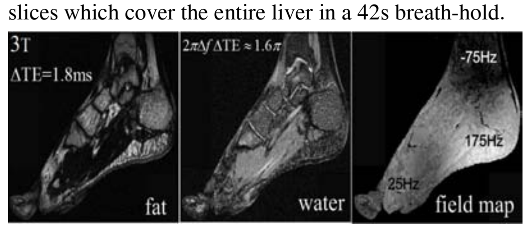

Fig. 4: Separated fat/water images and field map of an ankle study at 3T. The sample field map values show large field inhomogeneity present in this study.

Conclusion: We have analyzed the characteristics of the cost function associated with multi-point field map estimation and showed long $\Delta\mathrm{TE}$ hinders the ability of iterative methods in locating field map values. A non-iterative field map estimation method has been proposed to work robustly with multi-echo sequences in separating water and fat. Experimental results show the proposed method holds great promise to solve difficulties imposed by long $\Delta\mathrm{TE}$.

Ref.: 1. Reeder S., et al. MRM2004 51(1):123-30. 2. Wieben O., *et al.* ISMRM2005, p2386. 3. Hargreaves B., *et al.* ISMRM2006, p1940. This work is supported by NIH EB002524 and RR009784.