Phase Combination for Multi-channel RF Coils with a Dual-echo Scan in Water-Fat Imaging

Zhongxu An[1,2], Rui Li[1], Haining Liu[1], Chun Yuan[1,3], and Hua Guo[1]

[1]*Center for Biomedical Imaging Research, Department of Biomedical Engineering, School of Medicine, Beijing, China, People's Republic of,* [2]*Department of Electronic Engineering, Beihang University, Beijing, China, People's Republic of,* [3]*Department of Radiology, University of Washington, Seattle, WA, United States*

INTRODUCTION

Phase image can be a superb source of image contrast, thus it has been used in various applications such as susceptibility weighted imaging [1] and chemical shift-based water fat separation [2]. Phase images acquired by multi-channel RF coils, which are commonly used now, need to be combined optimally to maintain the phase accuracy, improve signal-noise-ratio (SNR) and reduce post-processing time (processed individually)[3]. The phase combination can be challenging because of different phase offset existing among different channels, which can vary across objects but does not change with time [4]. Currently, several means were proposed to combine multi-channel phase images [5]. However, all of them require phase unwrapping process which inevitably decreases the reliability. In this report, we propose a new method, Multi-Channel Phase Combination with In-Out phase time (MCPC-IO), to combine multi-channel phase images in phasor domain without phase unwrapping. The acquired signals can have multiple echo times but with two for in-phase and out-phase between water and fat. We successfully applied this technique in Xiang's two-point POP water-fat separation [6] and six-point IDEAL algorithm [2] with improved quantification accuracy. This MCPC-IO in water-fat separation was compared with the traditional sum of square method whose water-fat separations are processed separately among different channels before final information combination [3].

METHOD

The phasor model of an MRI image is as follows: $P_{i,L} = e^{i*(\theta_i+\psi_i+a_L+n_{i,L})}$, where ***i*****:** echo number, ***L***: channel number, $\boldsymbol{\theta_i}$**:** phase due to chemical shift (zero in fat suppressed imaging), $\boldsymbol{\psi_i}$**:** $2\pi\Delta B_0 TE_i$ (field map), $\boldsymbol{a_L}$: additional phase offset [2], $\boldsymbol{n_{i,L}}$**:** phase noise.

In our method, operation is done in the phasor domain to avoid phase wrapping [7]. The first step of this method is calculating the additional phase offset($\boldsymbol{a_L}$) by eliminating phases due to chemical shift($\boldsymbol{\theta_i}$) and field map($\boldsymbol{\psi_i}$). As the phases induced by B_0 inhomogeneity are proportional to *TE*, to remove field map from original phases, TE_{i1} and TE_{i2} (not necessary in neighbor) should satisfy $TE_{i2}=k\bullet TE_{i1}$ (*k*= 1.1, 1.2, 1.25, 1.5 or 2). When *k*=1.2, 1.25, 1.5 or 2, water and fat will be in-phase and out-phase. For example, for two neighbor echoes with TE_1 and TE_2, when TE_1 is in-phase echo time and k=1.5, then $TE_2=1.5*TE_1$, water and fat will be out of phase. So $\boldsymbol{\theta_i}$ from chemical shift and $\boldsymbol{\psi_i}$ from field map can be removed and additional phase offset can be calculated by following methods. (Note that in fat dominated pixels if $\boldsymbol{\theta_i}=-\pi$, $\exp^2(i*\boldsymbol{\theta_i})=1$)

$$Pa_L = e^{i*(a_L+n')} = P_{1,L}^{2} \bullet P_{2,L}^{-1}, \qquad (1)$$

or $$Pa_L = e^{i*(a_L+n')} = P_{1,L}^{3} \bullet P_{2,L}^{-2}, \qquad (2)$$

$$P_i^{final} = [\sum_L (P_{i,L} / Pa_L)]/[abs(\sum_L (P_{i,L} / Pa_L))] \qquad (3)$$

If $\psi_2=2*\psi_1$ (k=2), and TE_1 is the echo time of out-phase (1.15ms or 3.45ms at 3T), then TE_2 is in-phase time. Additional Pa_L can be calculated by (1).

If $\psi_2=1.5*\psi_1$ (k=1.5) and TE_1 is the echo time of in-phase (2.3ms or 4.6ms at 3T), then TE_2 is out-phase or in-phase time. Additional Pa_L can be calculated by (2). When k=1.2 or 1.25, similar calculation can also be carried out to get Pa_L.

Once Pa_L is known and then is removed from all echoes, phases from different channels , which do not have phase offset anymore, can be combined in phasor domain using (3). Magnitude images of different channels are combined by sum-of-square method, thus the final complex image is obtained to do water-fat separation.

The proposed method was tested on a phantom consisting of water and peanut oil on a 3T MRI scanner (Achieva, Philips, Best, The Netherlands) with: TR = 500 ms, TE = 1.72ms, ΔTE= 0.58ms, flip angle = 10°, FOV = 90 mm×90 mm, and image matrix = 96×64. Oblique images along water-fat interface were acquired using an 8-channel head RF coil to simulate fat variation (0-100%). Fat fraction is calculated with IDEAL [1] algorithm.

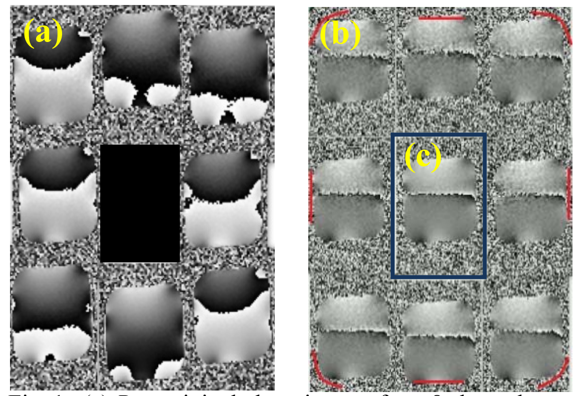

Fig. 1. (a) $P_{1,L}$, original phase images from 8 channels. (b) Phases without additional phase Pa_L. Center image (c) is 8-channel combined phase.

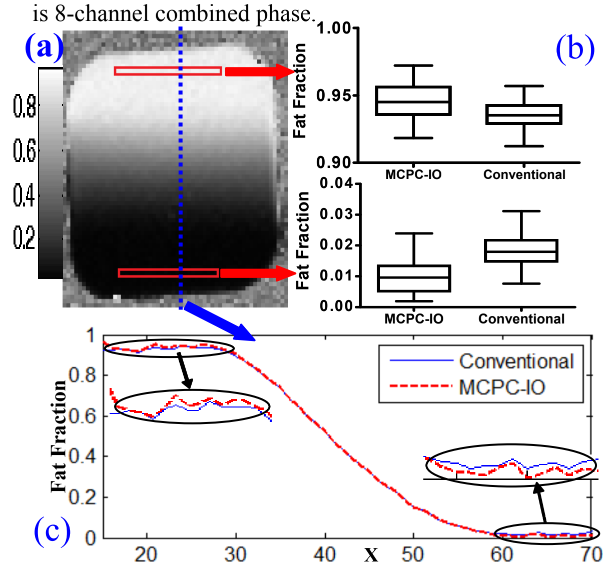

Fig.2. (a) Fat fraction. (b) Mean and standard deviation from two methods. (c) Improvement by MCPC-IO comparing with the conventional method.

RESULTS

Fig. 1 shows multi-channel phase combination using the proposed method. Once Pa_L is calculated with either equation (1) or (2), it can be removed from original phases. which are then combined into one phase image (Fig. 1c). Fig. 2 shows the comparison between the proposed MCPC-IO and the conventional method for fat fraction calculation. As it can be seen in Fig. 2b and 2c, the mean values calculated with MCPC-IO for the selected ROI are 94.6% and 1.0%, respectively, which are closer to true values than those from the conventional method (93.6% and 1.8%, respectively). To emphasize the effectiveness of MCPC-IO, smoothing widow is not used in all processes.

DISCUSSION

Bigger standard deviation of MCPC-IO is probably caused by nonuse of smoothing window when Pa_L is removed from each echo's phase. Since no phase unwrapping is needed, MCPC-IO is a much simpler solution for multi-channel phase combination in water-fat imaging. With MCPC-IO, the number of computation iteration in water fat separation can decrease dramatically. More importantly, the accuracy can be improved. In susceptibility weighted imaging**,** where $\boldsymbol{\theta_i}$ is zero, MCPC-IO is even more effective because K and TE could be chosen more flexibly to map B_0 images.

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