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

\[ P_i = e^{i(\theta_i - \eta_1 + \eta_2 + \phi)} \]

where \( P \): echo number, \( L \): channel number, \( \theta_i \): phase due to chemical shift (zero in fat supressed imaging), \( \eta_1 \): random phase offset, \( \eta_2 \): phase noise. In our method, operation is done in the phasor domain to avoid phase wrapping [7].

\[ P_{a} = e^{i(\theta_i - \eta_1 + \eta_2 + \phi_{1})}, \quad P_{b} = e^{i(\theta_i - \eta_1 + \eta_2 + \phi_{2})} \]

If \( \phi_{1} \) and \( \phi_{2} \) are 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).

\[ P_{\text{comb}} = \left[ \sum_{L} \left( P_{a}(L) / P_{b}(L) \right) \right] / \left[ \sum_{L} \left( P_{a}(L) \right) \right] \]

If \( \phi_{2} = 2 \pi \phi_{1} \) and \( \phi_{2} = 0 \), then \( \phi_{2} \) is in-phase or out-phase time. Additional phase offset due to chemical shift(\( \phi_{1} \)) can be calculated by (1).

\[ \phi_{1} = \frac{1}{2} \left( \theta_{a} - \theta_{b} \right) \]

RESULTS
Fig. 1 shows multi-channel phase combination using the proposed method. Once \( P_{a} \) 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 \( P_{a} \) 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 \( \theta \) is zero, MCPC-IO is even more effective because \( K \) and TE could be chosen more flexibly to map B0 images.