Bipolar Multi-Echo Water-Fat Separation: Phase Correction Using Parallel Imaging

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Introduction Chemical–shift based 3-point (3-pt) water fat separation techniques have seen a recent increase in clinical use [1-4]. Traditionally, each echo is acquired in a separate sequence repetition (TR), allowing flexible imaging prescriptions at the cost of tripling the minimum scan time. More recent implementations collect all echoes in one TR [5-10], significantly reducing the required scan time. “Unipolar” approaches acquire all echoes using the same gradient polarity [6], while “bipolar” approaches provide more efficient acquisitions, with data collected during both positive and negative gradient lobes [7-10]. Bipolar methods must account for phase errors that may result from eddy currents and gradient delays that may differ for positive and negative gradient lobes, disrupting the inter-echo phase consistency that is critical for water-fat separation. The correction of such phase errors is achieved by either realigning the k-space center to correct for a linear phase error [9] or collecting reference data that can be used to estimate a nonlinear phase error [7, 10], similar to phase correction techniques developed for EPI scans [11]. In this work, we introduce a novel method to correct nonlinear phase errors without an additional reference scan by utilizing parallel imaging reconstruction. The method is applied to 3-pt bipolar data to achieve uniform water-fat separation with the IDEAL water-fat separation algorithm [4].

Methods Figures 1 and 2 illustrate the method. A 3-echo 3D SPGR dataset is acquired with the gradient polarity flipped between odd and even phase encode (k_y) lines to acquire the 3 echoes (Fig. 1). These data are split into two undersampled sets, one from the even k_y lines (all of which have the same gradient polarity) and one from the odd k_y lines (all of which have gradient polarity opposite the even k_y set). Figure 2 illustrates the data processing steps for echo 1 of slice 1. Similar processing would also be completed on echoes 2 and 3 and for each slice. Referring to Fig. 2, the two aliased datasets for the first echo and slice (S_1^{even} and S_1^{odd}) are unwrapped using an externally calibrated parallel imaging method, such as SENSE or ASSET. The result is two full FOV images (S_1^+ and S_1^-). which can be viewed as images acquired with opposite gradient polarities and described as: $s_1^{\pm}(x,y) = (\rho_w(x,y) + \rho_f(x,y)\cdot e^{j2\pi\Delta f\, t_1})\cdot e^{j2\pi\psi(x,y)t_1}\cdot e^{\pm j\theta_1(x)} = s_1\cdot e^{\pm j\theta_1(x)}$, where ρ_w, ρ_f, ψ and Δf denote the water, fat, Bo inhomogeneity and chemical shift of fat, respectively. $\pm\theta_1(x)$ is the phase error that has opposite signs for positive and negative gradient polarities. To estimate $\theta_1(x)$, utilizing the fact that the phase error only varies in the read-out direction (x direction), S_1^+ and S_1^- are , projected in the phase encode direction, forming two 1D signal profiles. The phase error can be estimated by computing the phase difference of the two signal vectors, i.e. $2\theta_1(x)$, which is then processed by a phase unwrapping algorithm. The unwrapped phase is fit to a polynomial phase profile [7] to remove the effects from noise and phase unwrapping failure, resulting in an estimated polynomial phase error profile for echo 1 and slice 1 (red curve). Polynomial phase profiles of all slices and echoes can be obtained by following the same procedure. Assuming that the phase error is independent of the slice for a given echo, the median phase polynomial over all slices is used as the final phase error profile $2\theta_i(x)$ for each echo. The S_i^+ and S_i^- are then corrected by the estimated $\theta_i(x)$, resulting in phase corrected sources S_i. Finally, the IDEAL water-fat separation method can be used to decompose water and fat based on the phase corrected S_i.

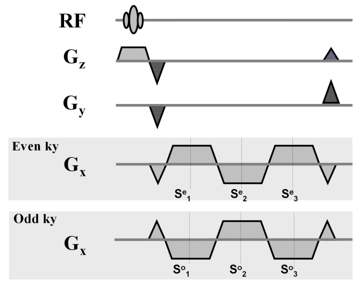

Figure 1: Sequence Diagram. Even and odd phase encode lines are acquired with opposite bipolar gradients.

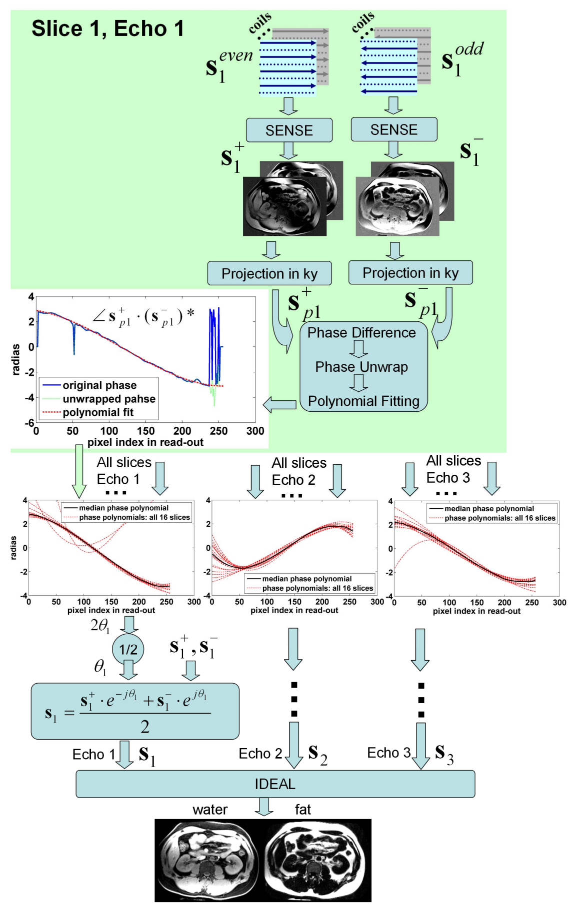

Figure 2: Flow Diagram of the Phase Correction Algorithm and IDEAL Processing.

Results Volunteers were scanned following informed consent and approval from our Institutional Review Board (IRB). Figure 3 illustrates separated water and fat images from an abdominal and a knee scans. For the abdominal scan, the polynomial phase error profiles of all slices and echoes are shown in Figure 2, and the non-linear nature of the phase error is evident. Phase error profiles from different slices agree well. The few outliers result from phase unwrapping failure. The median operation eliminates the potential destructive impact from these failures. As shown in Fig. 3, uniform water-fat separation was achieved on all slices. In contrast, water-fat separation is corrupted by the phase error if no phase correction is applied.

Discussion and Conclusion We have demonstrated that by utilizing the parallel imaging technique, nonlinear phase errors in bipolar multi-echo acquisitions can be removed. It is important to note that this method can only be used with coils and geometries that support parallel imaging. Parallel imaging may still be used for scan time reduction in conjunction with this method, however, additional acceleration needs to be achieved to estimate the phase. A k-space water-fat separation method [9] can be integrated with the proposed method to correct for the complex chemical shift effect. In conclusion, the proposed method serves as an effective approach for correction of phase errors resulting from bipolar acquisitions.

References

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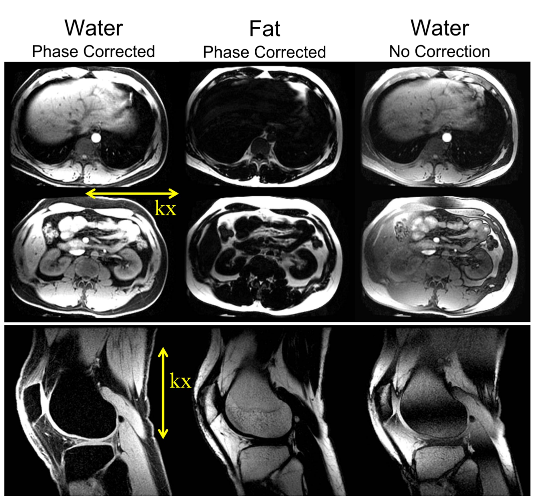

Figure 3: Results from a liver scan and a knee scan with the proposed phase correction algorithm followed by the 3-pt IDEAL method. Uniform water-fat separation is achieved. In contrast, water-fat separation is corrupted by the phase error if no phase correction is performed.