Unwrapping-based fat-suppression method for imaging scar using bipolar dual-echo acquisition

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TARGET AUDIENCE: Researchers and clinicians interested in LGE scar imaging where fat/water separation is required**.**

INTRIDUCTION: Fat-suppression is sometimes required for imaging fibrosis/scar in the heart with late gadolinium enhancement (LGE). Recently, Dixon techniques[1-4] have gained attention because they are more robust to off-resonance, resulting in uniform fat-suppression over the entire field of view compared to the conventional inversion recovery technique. Among Dixon techniques, the bipolar dual-echo (b-2pt) technique is intrinsically the fastest, making it optimal for high resolution or 3D applications. To perform b-2pt fat-suppression, phase errors due to gradient delays[5] should be removed; and if the removal is perfect, there should be no difference of conducting fat/water separation between bipolar and mono-polar acquisition. To remove the unwanted B0 off-resonance effect, the convention 2pt approach[6] maps B0 simply using unwrapping but without phase error-correction, *i.e.*, the outcome is determined by how well unwrapping performs. A recently published B0 mapping method (B0-NICE)[7] uses a magnitude-based water-mask to correct potential unwrapping error, resulting in improvement of robustness when processing mono-polar multi-echo data. In this work we hypothesize that extending B0-NICE to b-2pt acquisition (B0-NICEbd) will improve the robust of fat-suppression using unwrapping.

METHOD: The reconstructed b-2pt data from an individual channel include two complex images, I_{in} (in-phase) and I_{out} (out-of-phase). The phase term of the Hermitian product, ($I_{hp} = I_{in}\times I^*_{out}$, where * denotes conjugate operation), is the sum of phases caused by multiple sources: gradient delays (φ_{gd}), chemical-shift between fat and water (φ_{fw}, $\approx \pi$) and B0 off-resonance (φ_{b0}). The B0-NICEbd method uses the following three steps to estimate φ_{b0}, with all processing performed on a channel-by-channel basis:

Step 1. **L**inear phase error **c**orrection (using method of Ma *et al.*[5]) is first performed to remove φ_{gd} from I_{hp}, resulting in a complex image denoted as $I_{hp,LC}$.

Step 2. An initial B0 map is then generated using a 2 pt approach,[6] where the initial B0 map is defined as the (unwrapped phase term of $(I_{hp,LC})^2)/2$, where the square operation aims to achieve a near-zero φ_{fw} value (see Fig. 1a). Due to the fact that the unwrapped phase values are relative, the whole B0 map may be shifted by an unknown multiple of π (*i.e.* global-shift errors). Also, unwrapping is sensitive to noise and singularities, resulting in some π-shifted regions on the initial B0 map (*i.e.* regional-shift errors, see arrow in Fig. 1b). Without correcting these potential global- and regional-errors, entire- and/or regional-swaps may present in the water- and fat-only images.

Step 3. Finally, global and regional phase-error correction is performed using the strategy described in B0-NICE[7]: 1) *global-error* is corrected by selecting one of the $\pm\pi$-shifted and non-shifted initial B0 maps by matching the magnitude-based and phase-based fat-masks (definitions below) over the entire image; 2) *regional-error* is corrected by dividing the global-error-corrected B0 map into regions, followed by matching phase- and magnitude-based masks using the same criteria as the global-error correction but on a region-by-region basis. (Definitions: magnitude-based water- and fat-masks are generated, based on the fact that signal intensity from fat surrounding the chest wall is much higher than that from the heart for T1-weighted images (see Fig. 1c); phase-based water- and fat-masks are defined as those having a phase value of $I_{hp,LC,\ b0C}$ near zero or ±π, respectively, where $I_{hp,LC,\ b0C}$ ($=I_{hp,LC}\times\exp(-i\varphi_{b0})$) is the B0-corrected $I_{hp,LC}$.)

Fat-water separation: Once phase error-corrected B0 maps (see Fig. 1d) are obtained for each channel, water-only and fat-only images are reconstructed using the 2pt approach[6]. Final channel combination is performed using the sum of squares approach.

Data acquisition: Data sets were acquired with a 3D inversion recovery gradient echo 2pt Dixon LGE sequence at 1.5T using a five-channel cardiac coil (TE1/TE2 = 2.3/4.6 ms, out-of-phase/in-phase). Each data set includes 26 axial slices.

Evaluation: Data from three subjects were processed off-line by the fully automatic B0-NICEbd method implemented in MATLAB and an established region-growing approach[5], starting from a manually selected seed point placed in fat. The evaluation of the performance of both methods was based on avoiding fat/water swaps.

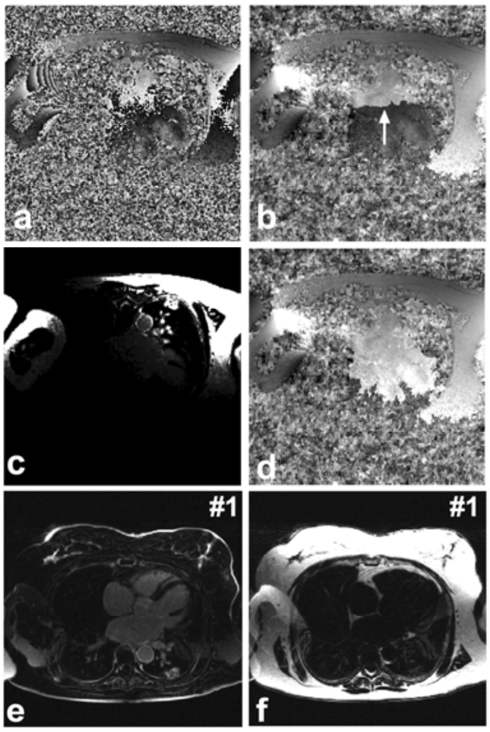

Figure 1. Central slice of Subject #1, data from channel 3: (a) linear-error corrected phase (*i.e.* phase($(I_{hp,LC})^2$), (b) initial B0, (c) magnitude, (d) final B0 map; (e) and (f) are the final water-only and fat-only images, respectively.

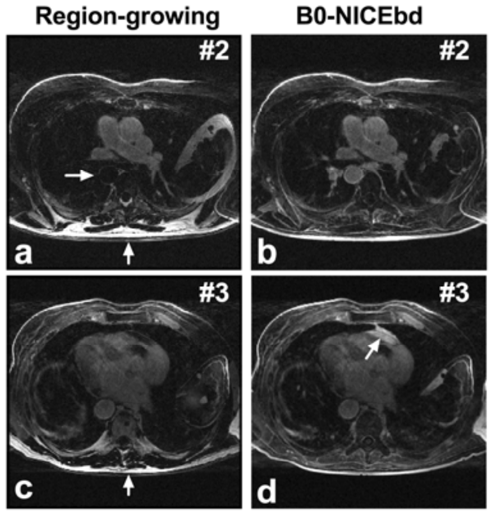

Figure 2. Comparison of water-only images using the established region growing method (a,c) and B0-NICEbd (b,d). Arrows point to the regions with fat/water swaps.

RESULTS and DISCUSSION: Figures 1a-1d illustrate some of the processing steps. For subject #1, a pair of representative B0-NICEbd fat/water images is presented in Fig. 1e and 1f, respectively; no fat/water swaps were observed in any of the slices using either method (except for parts of the aliased arms). However, as indicated by the short arrows in Fig. 2a and 2c, the region-growing approach resulted in large fat/water swap regions of 11 of 26 and 15 of 26 slices, for subject #2 and #3, respectively. More importantly, the aorta apparently disappears in the region-growing water-only image (long arrow in Fig. 2a). The aforementioned large swaps were not observed in any of the B0-NICEbd results. However, the arrow in Fig. 2d indicates that fat/water swaps may occur locally in the B0-NICEbd images (4 of 26 and 3 of 26 slices, for subject #2 and #3, respectively). Estimating a B0 map for each channel separately aims to increase the robustness of the B0-NICEbd method, because most – if not all – uncorrected regional-errors in the final B0 map are in the low SNR region and will be compensated by the sum of squares approach. When applying B0-NICEbd to mono-polar 2-pt data, step 1 can be omitted. We expect that B0-NICEbd will be able to simultaneously measure B0, T2* and fat-fraction from faster bipolar multi-echo acquisition, compared to mono-polar multi-echo acquisition. The small sample size is the major limitation of the current work.

CONCLUSION: B0-NICEbd successfully suppressed fat signal in bipolar dual-echo cardiac images.

REFERENCES: [1] Dixon, Radiology 153:189-194, 1984. [2] Shaw, et al., JMRI 40:119-125, 2014. [3] Taviani, et al., MRM 72: 718-725, 2014. [4] Boenert, et al., MRM 71:1156-163, 2014. [5] Ma, et al., MRM 60:1250-1255, 2008. [6] Coombs, et al., MRM 38: 884-869, 1997. [7] Liu and Drangova, MRM.25497.