Method for B0 off-resonance mapping by non-iterative correction of phase errors

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TARGET AUDIENCE: Researchers and clinicians interested in B0 mapping and fat-water separation.

INTRIDUCTION: Field map estimation is an essential step of the majority of Dixon fat-water separation techniques [1]. Because the B0 off-resonance map is directly related to image phase, phase unwrapping techniques are employed as a step of most B0 mapping techniques. However, perfectly unwrapped phase images are difficult to obtain, especially when data are acquired with relatively low signal-to-noise ratio (SNR) in applications where small voxels, long TEs and high readout bandwidth are required. The presence of non-contiguous regions in the field of view (islands) further complicates the unwarping. We present a robust method for B0 mapping that is not sensitive to low SNR or the presence of islands.

METHOD: The proposed phase-unwrapping-based method generates B0 maps using the following five steps:
Step 1. A raw R2* and a raw fat-fraction (FF) maps are calculated only from the magnitude, ensuring that they are not sensitive to phase-unwrapping errors. By setting the FF equal to a user-specified value (between 0 and 1), the resulting residual map is calculated by varying R2* values within a defined range; the R2* value is determined by selecting the R2* that generates the minimum residual between the measured and calculated magnitude; this is performed on a pixel-by-pixel basis. By repeating the above procedure several times with different user-specified FF values, an R2* map and a raw FF map are calculated from the weighted average of the FF used in each iteration. A water-like mask is generated by simply thresholding the raw FF map.

Step 2. A raw B0 map is generated by unwrapping the phase term (φ) of the Hermitian product (HP) between two echoes with a minimum phase difference ($\varphi_{fw,min}$) related to chemical-shift between fat and water. After φ is unwrapped, global-shift (φ_g^{un}) and local-shift (φ_l^{un}) unwrapping errors might be introduced into the unwrapped phase images, φ^{un}. It is important to remember that phase-unwrapping errors always equal an unknown multiple 2π. Secondly, a bias frequency offset introduced by the non-zero term of $\varphi_{fw,min}$ can be compensated by changing the theoretical chemical-shift values in a multi-peak fat model.

Step 3. To determine the correct number of global 2π shifts for unwrapping error correction, the method generates a set of raw B0 maps by first adding/subtracting multiples of 2π to the φ^{un}, and then using them to perform B0 correction of the HP of complex data between a pair of neighboring echoes. Histograms of the resulting B0-corrected phase images are then calculated for the water-like pixels (as defined by the raw FF mask in ***Step 1)***. The correct number of 2π shifts is the one with the highest near-zero peak on the histogram and can be used to fix the global unwrapping errors, φ_g^{un}, thereby resulting in a globally corrected B0 map.

Step 4. To correct local-shift unwrapping errors we first divide the globally corrected B0 map into multiple regions by thresholding the phase gradient, then perform a procedure similar to that used for global–error correction (***Step 3***).

Step 5. An intermediate FF map is calculated using the unwrapping-error-corrected B0 map and the raw R2* map first; it is then used to generate the final B0 map by correcting the bias frequency offset caused by ***Step 2***.

Implementation: The six-peak fat model [2] was used. Other user-defined parameters required by the algorithm are summarized as follows:

To estimate the R2* map and the initial FF map, a total of seven FF values (0.05 0.15 0.25, 0.5 0.75 0.85 and 0.95) were used. The range of R2* was set from 0 to 300 s^{-1} with an interval of 5 s^{-1}. The threshold value for identifying water-like pixels was set to 0.2. The threshold for labeling the B0 map was $\pi/2$ (***Step 3***). The final B0 map was smoothened using a 5-by-5 median filter.

Phase unwrapping was performed using PUROR [3]. Data processing was performed off-line using MATLAB on a computer with a 64-bit operating system, a 3.33-GHz processor and 8 Gb RAM. The method was evaluated using a multitude of data sets, including all data sets provided by the 2012 ISMRM Challenge. For illustration purposes in this abstract, we selected a challenging case reported on previously [4] (IDEAL acquisition, six echoes (TE1/ΔTE = 2.3/0.9 ms); raw data provided by Dr. C. McKenzie).

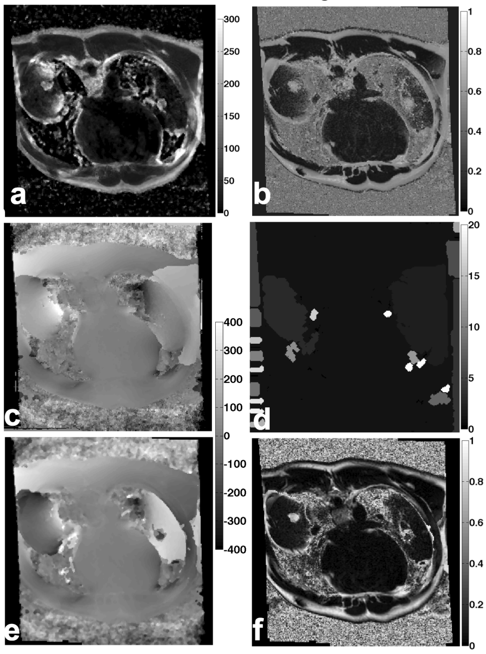

Figure 1. The proposed B0 mapping method applied to a 6-echo cardiac IDEAL acquisition. The raw R2* map (a) and the raw FF map (b) (***Step 1***); (c) raw B0 map generated from the HP between the first and sixth echoes (***Step 2***). (d) output from labeling ***Step 4***. The final B0 (e) and FF (f) maps can be compared to Fig. 5, Ref. 4.

RESULTS and DISCUSSION: The proposed B0 estimation technique generated accurate FF maps for all cases of the 2012 ISMRM Challenge. The cardiac images presented in Figure 1 show some of the processing steps and demonstrate that the proposed B0 mapping method successfully generated a smooth B0 map and reconstructed an FF map with minimal fat/water swaps. Previously [4] this same data set was analyzed using the Max-IDEAL [4], graph-cut [5] and FLAME [6] techniques, all of which resulted in greater numbers of fat/water swaps. Figure 1(d) demonstrates that the raw B0 map was successfully divided into sub-regions, which led to successful local-phase-unwrapping-error correction. The processing time for the presented case was ~ 3 seconds.

This approach is the first to demonstrate that an accurate B0 map can be generated by fixing phase unwrapping errors with information from a raw FF map estimated from the magnitude images. For high-resolution imaging acquired with multiple-echoes (number of TEs > 2), the state of art for generating accurate B0 maps is an iterative procedure (e.g. as used with IDEAL and the graph cut approaches). These approaches start with an all-zero initial B0 map and iteratively reach a final B0 map, while searching in a limited range and applying a spatial-smoothing constraint. The proposed method is entirely non-iterative is therefore very fast.

CONCLUSION: The proposed method represents a robust and rapid phase-unwrapping-based B0 mapping method.

REFERENCES: [1] Dixon, Radiology 153:189-194, 1984. [2] Hernando, et al., MRM 64:811-822, 2010. [3] Liu and Drangova, MRM 68: 1303-1316, 2012. [4] Soliman, et al., DOI 10.1002/mrm.24923. [5] Hernando, et al., MRM 63: 79-90, 2010. [6] Yu, et al., MRM 67:1065-1076, 2012.