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.

INTRODUCTION: 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 unwrapping. 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:

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.

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

3. To determine the correct number of global 2\(\pi\) shifts for unwrapping error correction, the method generates a set of raw B0 maps by first adding/subtracting multiples of 2\(\pi\) to the \(\phi_{\text{g}}\), 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 2\(\pi\) shifts is the one with the highest near-zero peak on the histogram and can be used to fix the global unwrapping errors, \(\phi_{\text{g,un}}\), thereby resulting in a globally corrected B0 map.

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).

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 smoothed 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/TE2: 2.3/0.9 ms); raw data provided by Dr. C. McKenzie).

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], graphcut [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 \(\sim 3\) seconds.

This approach is the first to demonstrate that an accurate B0 map can be generated by fixing phase unwrapping errors from information in a raw B0 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 and is therefore very fast.

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