A Parallelizable Multi-threaded and Multi-leveled Region-Growing Based Algorithm for Phase Correction in MRI

Jingfei Ma[1], Jong Bum Son[1], and John Hazle[1]
[1]*Imaging Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, United States*

Introduction: Region growing (RG) is a general and easy to implement image processing method and has been successfully used for several phase-sensitive MRI applications. Recently, a multi-threaded RG algorithm has been proposed to overcome the difficulties of phase correction when spatially isolated tissues are present (1). However, most RG algorithms are sequential by design (i.e., pixels are processed one after another and processing of each pixel relies on the results of the previously processed pixels). Hence, the efficiency of a RG algorithm does not easily benefit from the increasing availability of multi-core processors. In this work, we present a parallelizable multi-threaded, multi-leveled RG algorithm for phase correction in MRI. We demonstrate a successful application of the algorithm in two-point Dixon imaging with flexible echo times (2-5).

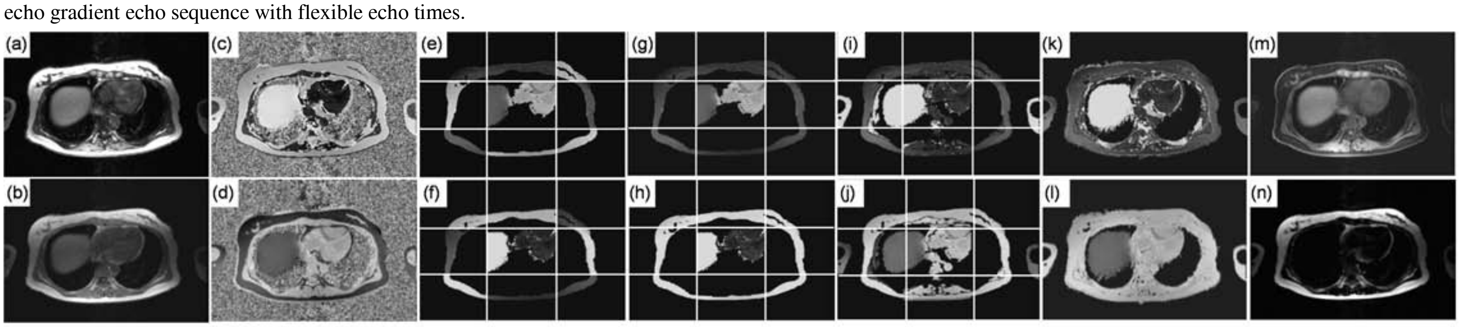
Method: The challenge of several phase-sensitive MRI is in essence to construct an output vector image O for which each pixel has the value of the corresponding pixel from either of the two input vector images A and B (1,6). The orientation of O is required to be spatially smooth and devoid of artificial discontinuities. In the case of two-point Dixon water and fat imaging, A and B can be calculated directly from the two raw complex images S_1 and S_2 that are acquired at echo times TE1 and TE2, respectively (2-5). Failure in phase correction or incorrect determination of O for certain pixels is equivalent to incorrect assignment of the pixels as water or fat-dominant, often manifesting itself as the apparent "water-fat swap" for those pixels in the final reconstructed images.

In a previously-reported RG algorithm (1), several mask images are first used to flag potential seed pixels. The RG process then starts from a seed pixel and proceeds until a pre-defined condition for the quality of the RG can no longer be met (e.g., the phase variation encountered by the RG becomes larger than a threshold) (7). One or more cumulative quality indices (e.g., q to indicate how many seed pixels visited by the RG are consistent with the initial assignment by the seed masks) are recorded for each thread of RG. New threads of RG will be performed by selecting a new seed pixel until no more seed pixels are available.

In this work, we propose the following two looped processing to further optimize the algorithm and to parallelize most of RG. In the first loop, the image is divided into multiple sub-images (e.g., 8x8). For each sub-image, an initial seed pixel is selected to start RG in which A or B of the seed pixel is separately assigned as its output vector to produce two output vector sub-images O_A and O_B. The corresponding quality indices q_A and q_B are recorded. The condition used to halt the RG is typically set to be conservatively high (e.g., the phase variation to be less than 10^o) to ensure the robustness of the sub-image RG. After RG is complete, O_A and O_B from neighboring sub-images are compared along the sub-image boundaries. If there are enough pixels within the boundary, O_A and O_B from the two neighboring sub-images will be compared for the best orientation match and then merged to form a pixel island with a unified O_A and O_B (as well as unified q_A and q_B). If there are not enough pixels within the boundary for comparison, the processed pixels from each sub-image RG will be kept as separate pixel islands with their original O_A and O_B. In a looped processing, a new RG over the pixels that have not been previously visited is started within each sub-image from a new seed pixel (if available) to generate O_A and O_B (as well as q_A and q_B), which will be compared between neighboring sub-images and with the pixel islands from the previous RG. Again, the O_A and O_B (as well as q_A and q_B) from the new RG will be compared and then merged or left as separate pixel islands depending on whether there are enough pixels within the sub-image boundaries that can be used for comparison. The process is repeated until no more seed pixels are available.

In the second looped processing, RG will be resumed by gradually relaxing the condition on the phase variation (e.g., from 10^o to 25^o in step of 5^o) from the different pixel islands that are generated in the first looped processing. At the end of each step, the pixel islands will be checked to see if they have expanded close together to allow merging the neighboring islands. After the completion of the second loop, the unified quality indices q_A and q_B for the remaining pixel islands will be compared for selecting either O_A or O_B as the final output vector O that will be used for phase correction and generation of the final water and fat separated images.

Experiment and Results: The proposed algorithm was implemented in MATLAB (MathWorks) and used for processing in vivo images that were acquired with a dual-echo gradient echo sequence with flexible echo times.



The figures above illustrate some of the described processing steps: (a) and (b) are the magnitude of the two raw images $|S_1|$ and $|S_2|$, respectively. (c) and (d) are the phase of the two vector images A and B that are calculated from S_1 and S_2, respectively. A and B are used as the initial input to the phase correction algorithm. (e) and (f) show that the phase of O_A and O_B after the first thread of sub-image RG. (g) and (h) show the phase of O_A and O_B after the results of the first thread of RG are compared along the sub-image boundaries and merged if possible. (i) and (j) show the phase O_A and O_B at the end of the first looped processing. (k) and (l) show the phase of O_A and O_B at the end of the second looped processing (when the island RG is stopped at a phase variation of 25^o). Finally, (m) and (n) are the water and fat separated images after O_B in Fig (l) was selected as the vector image O based on a comparison of the quality indices of q_A and q_B of the final pixel islands.

Discussion: The overall strategy of the proposed algorithm of phase correction is to automatically process high-quality pixels first before low-quality pixels to ensure optimal processing reliability (1, 7). With a multi-threaded and multi-leveled RG design, we showed that many of the processing steps are parallelizable and thus amenable to implementation on a platform with multi-core processors. The actual implementation of the proposed algorithm is very flexible without affecting the final results (e.g., in how many sub-images an image is divided into, how many or what seed pixels to use, what thresholds for controlling RG, and what quality indices to record). Therefore, we expect the algorithm to be generally useful in several important phase sensitive MRI applications.

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