A novel tiered, multi-threaded region growing algorithm for improved phase correction for two-point Dixon imaging

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Introduction: Recent technical advances have enabled clinical use of two-point Dixon water and fat imaging. However, a fundamental difficulty still exists in the essential step of phase correction when regions of large noise, artefacts, or isolated tissues are present (1). Here, we present a novel tiered, multi-threaded region growing algorithm to help overcome this difficulty. Successful application of the algorithm is demonstrated in processing in vivo two-point Dixon images.

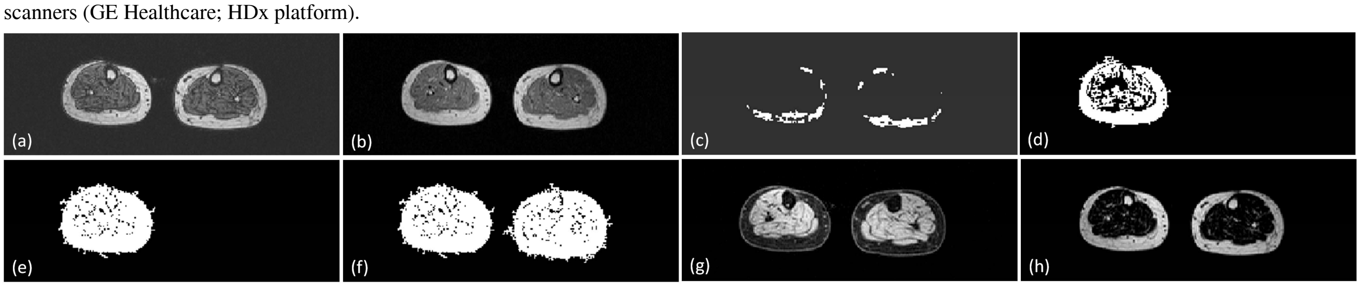
Method: The basic task of phase correction in Dixon imaging can be shown to boil down to correctly construct a vector image O whose orientation is "spatially smooth" and for a given pixel is represented by the orientation at the same pixel of one of the two input images *A* and *B* (2-5). In the context of two-point Dixon water and fat imaging, *A* and *B* can be calculated directly from the raw complex images of S_1 and S_2 that are acquired at echo times TE1 and TE2, respectively (2-5). Phase correction, or equivalently, assignment of either *A* or *B* to O on a pixel basis by requiring that the orientation of O is spatially smooth can be challenging when pixels with large noise, artefacts, or regions of signal voids are present. Failure in phase correction or incorrect determination of O for a pixel is equivalent to incorrect assignment of the pixel as water or fat-dominant, leading to the apparent "water-fat swap" in the final reconstructed images.

The proposed algorithm is based on region growing and works by first establishing several seed masks with different priority. The primary seeds are the pixels whose initial assignment of O is made using information outside the image. For example, a primary seed for an image of a slice in a 3D volume or 2D multi-slice dataset may be identified based on a tight angular correlation between *A* or *B* of the slice with O of an adjacent slice that has been already processed. The secondary seeds are the pixels that are identified as fat or water-dominant (and thus whose assignment of O can be made) using information within the image. For example, a pixel has a high likelihood of being fat-dominant if $\left|\frac{S_2}{S_1}\right|$ for the pixel falls within a narrow range of the known amplitude modulation from TE1 to TE2 for the pure fat signal. Additional restrictive criterion based on $|S_1|$ or $|S_2|$ (e.g., a fat-only pixel tend to have higher signal amplitude) may be applied in the selection of the secondary seeds. The tertiary seeds are identified as being in a "good-quality" region (e.g., small angular variation in *A* or *B* and above a certain signal amplitude) but having no initial assignment of O. It is noted that the initial assignment of O for the seeds need not be all correct. Additionally, an image may not have a primary seed (e.g., for the very first slice to be processed in a 3D dataset) or even a secondary seed.

The region growing proceeds by selecting a seed from the masks as an initial seed. The order in which an initial seed is selected is based on the priority and availability of the seeds (e.g., a secondary seed will be selected after no more primary seeds are available and before any tertiary seeds are selected). For each initial seed, two separate and independent region growing will be performed, one with O of the initial seed assigned as its *A* and the other as its *B*. The actual scheme of each region growing is based on Ref. 6 with several notable modifications. As in Ref. 6, the sequence of each region growing is such that at each step, the algorithm will visit the pixel whose angular difference between its *A* or *B* with the averaged O of its neighborhood is the smallest among all the available pixels (note that this angular difference is always between 0 and 180°). For each visited pixel, its assignment of O will be set to either its *A* or its *B* depending on which has a smaller angular difference with the averaged O of its neighborhood. Unlike the algorithm in Ref. 6 in which a single initial seed is used to visit all the pixels within an image (and thus may be forced to process pixels with noise, artefacts, and across tissue gaps before regions of high SNR), the new algorithm will be temporarily halted when there are no more pixels whose angular difference between its *A* or *B* with the averaged O of its neighborhood is smaller than a pre-defined threshold (e.g., 20°). Additionally, some quality metrics (e.g., the total number of the pixels visited and the number of the pixels whose assignment of O is consistent with the initial assignment by the seed masks) are recorded for the two independent region growing. Using these quality metrics, the results of one of the region growing is determined to be correct and accepted. If the quality metrics are indeterminate, the region growing results are selected based on which one fits in better with O from the region growing by the previous initial seeds. If this "fit-in" comparison is still inconclusive, both region growing results by this initial seed will simply be discarded or shelved until a decision can be made after region growing with other initial seeds becomes available.

In any case, all the seeds visited by each completed region growing will be de-seeded. Once region growing with an initial seed is complete, a new initial seed is selected to start a new thread of region growing with the same processing scheme until no more seeds are available. Afterwards, the condition set up in the above to temporarily halt the region growing will be removed and the algorithm will proceed with all the remaining pixels to obtain O for the entire image.

Experiment and Results: The proposed algorithm was implemented in MATLAB (MathWorks) and used for processing hundreds of in vivo images of different subjects and from different parts of the anatomy. The raw images were collected using a 3D fast spoiled gradient dual-echo pulse sequence on 1.5 Tesla whole body MRI scanners (GE Healthcare; HDx platform).



The algorithm was able to consistently reconstruct separated water and fat images in all the cases tested. The figure above illustrates some of the steps when processing an axial image of two legs: (a) and (b) are the raw images $|S_1|$ and $|S_2|$, respectively. (c) is the secondary seed mask that was generated for the fat-dominant pixels. Note that no primary seeds were used in this case. Further, the mask in (c) identified only a small portion of the fat-dominant pixels and the identification may not even be all correct. For actual region growing, the algorithm first selected an initial seed in the left leg. (d) and (e) show the pixels that were visited by the region growing when O of the initial seed was assigned as its *A* and *B*, respectively. The total number of the pixels visited was 1987 in (d) and 2896 in (e). Using the seed mask as the reference, the assignment of O was consistent for 291 seeds in (e) and was inconsistent for 289 seeds in (d). Based on this quality metrics comparison, the region growing corresponding to (e) was determined to be correct and accepted. The algorithm then selected another initial seed in the right leg and performed another thread of region growing using the same scheme. The pixels visited afterwards are shown in (f). As there were no more seeds available, the algorithm finally proceeded with all the remaining pixels, including those with low SNR and in the background. The final separated water and fat images are shown in (g) and (h), respectively.

Discussion: The basic requirement of "spatial smoothness" is intractable for phase correction while dealing with pixels of very low SNR. As a result, water and fat in well-separated regions within one image (such as two legs) may be randomly assigned. The proposed algorithm overcomes this difficulty with multi-threaded region growing. Each thread starts from one initial seed with one of the two possible assignments of O and the results are decided by comparing the quality metrics recorded during the region growing or how they fit in with the results from the previous threads of region growing. Tiered seed masks serve as a quality metric and allow more trusted regions to be processed first even when completely isolated tissue regions are present. The proposed algorithm is fully automatic and has demonstrated highly consistent results when applied for in vivo two point Dixon water and fat imaging.

References: (1) Ma J, JMRI 2008; 28(3):543. (2) Xiang QS. MRM 2006;56(3):572-584. (3) Eggers H, et al. MRM 2011; 65(1):96. (4) Berglund J, et al. MRM 2011; 65(4):994. (5) Ma J, ISMRM 2011. p. 2707. (6) Ma J, MRM 2004;52(2):415.