JIGSAW: Joint Inhomogeneity estimation via Global Segment Assembly for Water-fat separation

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Introduction: Three-point phase-sensitive water-fat separation [1, 2] is gaining great interest for producing high quality water-only and fat-only images. Key to its success is reliable estimation of field inhomogeneities, which remains difficult in many clinically important scenarios. The difficulty arises when the spectral field-of-view (i.e., the reciprocal of the echo spacing) is not sufficient to accommodate the field inhomogeneities, causing spectral aliasing, which impairs the robustness of existing techniques. This work describes a novel field map estimation technique called JIGSAW, *Joint Inhomogeneity estimation via Global Segment Assembly for Water-fat separation*. JIGSAW adapts the belief propagation (BP) [3] algorithm to produce large segments of pixels within which field map values are smooth. The field map estimation problem is then reduced to the assembly of a few large segments such that the resultant field maps are globally smooth-varying. As demonstrated with *in vivo* results, JIGSAW correctly resolves field inhomogeneities in the presence of spectral aliasing.

Theory: Feasible field map values at one pixel can be found by minimizing the associated least-squares cost function, which is periodic with the fundamental period equal to the spectral field-of-view 1/ΔTE [4], as illustrated in Fig. 1. Robust field map estimation needs to consider *all* replicas of a feasible field map inside the worst possible field inhomogeneity range $[-\psi_{max}, \psi_{max}]$ ($\psi_{max} = 1000$ Hz in our implementation). The problem is to select the correct field map value for each pixel such that the resultant smooth-varying field map consistently separates water and fat across the whole image. For computational tractability to solve this combinatorial problem, most existing techniques have to rely on the local correlations between neighbouring field map values, which are not reliable in the presence of spectral aliasing. In this work, we propose a novel field map estimation technique called JIGSAW, which adapts the sum-product belief propagation (BP) to efficiently and globally address the combinatorial problem.

The sum-product BP iteratively passes soft-decision messages among neighbouring pixels and jointly estimates the most likely field map value for each pixel. For two neighbouring pixels p and q, the message passed from p to q at the t^{th} iteration for each field map value ψ_q is computed as follows:

$$m^t_{p\to q}(\psi_q) = \sum_{\psi_p}\left(V_{pq}\prod_{s\in\mathcal{N}(p)\setminus q} m^{t-1}_{s\to p}(\psi_p)\right), \quad (1)$$

where $V_{pq} = \exp\left(-\left(\psi_p - \psi_q\right)^2\right)$, and $\mathcal{N}(p)\setminus q$ denotes the set of neighboring pixels to p other than q. After T iterations (T=30 in our implementation), a belief is computed for each feasible field map value at all pixels. Specifically, the belief for pixel q to take the field map value ψ_q is given by:

$$b_q(\psi_q) = \prod_{p\in\mathcal{N}(q)} m^T_{p\to q}(\psi_q). \quad (2)$$

Subsequently, for each pixel, the field map value with the maximum belief is selected.

On a graph without loops, the belief reflects the marginal probability for the receiving pixel to take a field map value [3]. However, the field map estimation problem deals with a 2D image grid full of loops, as shown in Fig. 2. Therefore, the belief in Eq. 2 does not yield the exact marginal, resulting in large segments of pixels within which the field map is smooth, but outside which abrupt changes remain. We propose two moves to deal with the large segments, as illustrated in Fig. 3. First, we fix the field map of a segment to the values with maximum beliefs and re-run the BP algorithm, a move called "decimation." The decimation move forces the neighbouring segments to re-compute their marginals conditioned on the fixed values. Second, the decimation move can produce a new smooth segment with abrupt changes from the fixed segment, if the influence from the latter is weaker than the influence among pixels within the new segment. A "swap" move is applied to shift each field map value in the new segment to its adjacent value in the feasible set simultaneously. The swap move retains the smoothness within the new segment but eliminates the abrupt changes, thus enlarging the fixed segment.

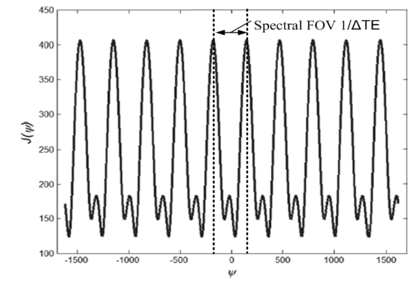

Fig. 1: Typical cost function for locating field map values, which is periodic with the period equal to the spectral FOV 1/ΔTE.

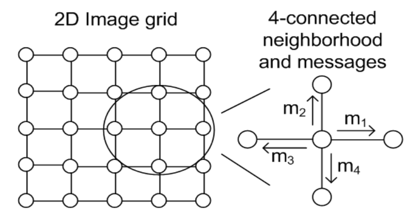

Fig.2: Illustration of BP message passing on a 4-connected 2D image grid.

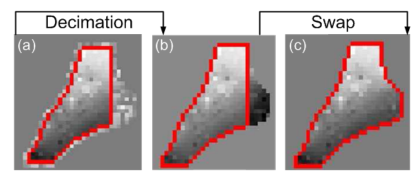

Fig. 3: The area enclosed with the red line indicates the current fixed segment. (a) shows the decimation move, which fixes field map values of a segment. (b) shows the new field map based on the recomputed beliefs conditioned on the fixed segment. A new smooth segment forms, but with abrupt changes from the fixed segment. (c) shows that the swap move eliminates the abrupt changes.

Methods: A multi-echo GRE sequence was implemented on a GE 3T scanner (GE Healthcare, WI, USA). A quadrature extremity coil was used with the following imaging parameters: TE = 3.2, 6.4, 9.6 ms, acquisition matrix 256x256x64, FOV=20x20x5 cm, receive bandwidth ±83.3 kHz, TR=11 ms and flip angle of 10º. The relatively long echo-spacing 3.2 ms leads to a spectral FOV of 312.5 Hz, which is insufficient to accommodate the present field inhomogeneities ranging from -450 Hz to 400 Hz. The spectral aliasing poses great challenge to existing field map estimation techniques. JIGSAW is applied to the down-sampled image data of 64x64 matrix size to obtain a low-resolution field map, which is then interpolated to the full-resolution for water-fat separation.

Results: Figures 3 and 4 show the comparison results of an ankle study obtained from JIGSAW and the iterative field map estimation technique currently used in IDEAL implemented on the GE scanner. The current technique produces a highly fragmented field map, which causes failure in water-fat separation. In contrast, JIGSAW correctly resolves the field maps and uniformly separates water and fat.

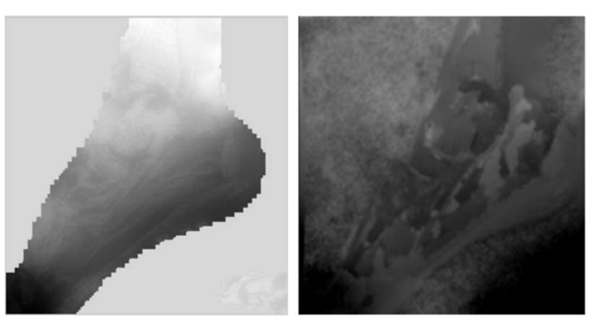

Fig. 3: Comparison of field maps of the ankle study obtained using JIGSAW and the field map estimation technique currently used in IDEAL. In contrast to the fragmented field map (right), JIGSAW produces a globally smooth-varying field map (left).

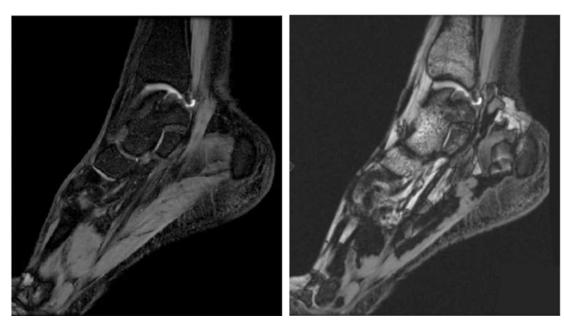

Fig. 4: Comparison of separated water images of the ankle study using JIGSAW and the current technique used in IDEAL. While the current technique (right) fails to separate water and fat, JIGSAW (left) produces the uniform water-fat separation.

Conclusion: Aliasing in spectral FOV in multi-point acquisitions arises in several clinically important scenarios, such as high-resolution imaging with multi-echo sequences, imaging at high field strengths and/or anatomies where good shimming cannot be achieved. This work proposes a novel estimation technique called JIGSAW that can efficiently resolve field inhomogeneities in the presence of spectral aliasing. JIGSAW can be easily extended to 3D with little additional complexity. A non-optimized MATLAB implementation of JIGSAW takes approximately 20 mins on a 2 GHz laptop to generate a 3D field map set with a 256x256x64 matrix size.

References: 1. An L., et al., MRM2001 46:126-30. 2. Reeder S., et al. MRM2004 51(1):123-30. 3. Yedidia J.S., et al. IJCAI2001. 4. W. Lu, et al. MRM2008 60(1):236-44.
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