Exploiting the Spectral Complexity of Fat for Robust Multi-point Water-fat Separation

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Introduction All multi-point water-fat separation methods must contend with the intrinsic challenge of water-fat ambiguity that can result in water-fat swapping. This problem arises because the signal of two chemical species, when both modeled as single discrete spectral peak, may appear indistinguishable in the presence of Bo off-resonance. Previous methods have attempted to resolve water-fat ambiguity by enforcing field- or phase-map smoothness [1-5]. Many of these algorithms are based on region growing approaches that are inherently sensitive to the physical characteristics of the object. In reality, the fat spectrum has multiple spectral peaks, which can be modeled in water-fat separation methods that use accurate spectral modeling [6]. With spectral modeling of fat ("multi-peak" model), we demonstrate that it is possible to more reliably distinguish water and fat by exploiting their spectral difference in addition to field map smoothness.

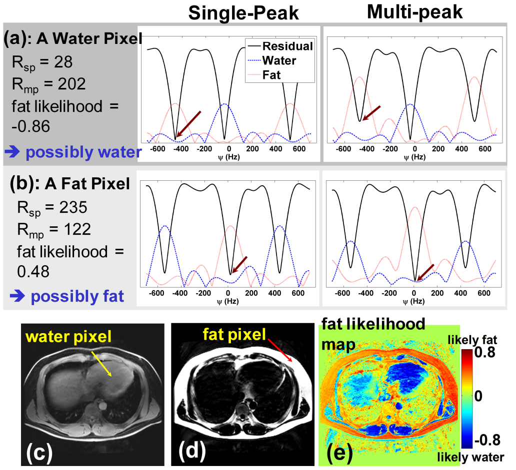

Figure 1: a fat likelihood map can be generated, based ***only*** on spectral differences between water and fat.

Methods Identification of water and fat using their spectral difference is based on the following concept: the signals of a water pixel should fit the single-peak model better while the signals of a fat pixel should fit the multi-peak model better. The goodness of the fit can be described as the "residual" of a solution (*R*) on the cost function curves [3,4]. We define a fat likelihood variable: $\mathbf{FL} = \frac{R_{sp} - R_{mp}}{\max(R_{sp}, R_{mp})}$ to describe the possibility of a pixel being fat based on the fitting residuals using the single-peak (R_{sp}) and multi-peak (R_{mp}) models. Figure 1 illustrates this idea using a 6-point (6-pt) acquisition and T2*-IDEAL reconstruction [7], where water-fat separation is performed with T2* correction. The cost function curves of the two models are shown for a water pixel (a) and a fat pixel (b). In each plot, the local minima consist of, in an alternating fashion, the true solution and the solution of a water-fat swap, as can be seen from the corresponding water/fat contents (blue/red curves). For the water pixel, the multi-peak model results in higher residual at the solution that leads to identification of a "fat pixel" (i.e. $R_{mp} > R_{sp}$, arrows), therefore FL = –0.86. On the other hand, the multi-peak model leads to better fitting than the single-peak model for the fat pixel (i.e. $R_{mp} < R_{sp}$, arrows), thus FL = 0.48. The fat likelihood value can be calculated on a pixel-by-pixel basis, forming a fat likelihood map (e). A value close to 1 (red) suggests high likelihood of being a fat pixel, whereas a value close to –1 (blue) suggests high likelihood of being a water pixel. The fat likelihood map is in general in close agreement with the true water-fat distribution (c, d).

The following steps describe a robust water-fat separation algorithm based on the fat likelihood values. The field map smoothness is also taken into consideration.

1. Start with an initial field map estimate. A simple pixel-by-pixel IDEAL approach can be used [8]. The following steps find the pixels that have water-fat swaps and re-calculate their field map values.
2. Generate a "confidence weighting map" (c_{map}) that indicates the confidence of whether the current field map estimate is correct, based on the fat likelihood value. At each pixel, the relative water and fat contents are checked against its fat likelihood value. If they are consistent, c_{map} takes the absolute value of the fat likelihood value; otherwise, a negative value is assigned. Therefore, c_{map} takes values between [-1, 1]. A value close to 1 suggests strong confidence in the current field map estimate, while a value close to –1 indicates a strong possibility of water-fat swap.
3. Generate a second weighting map by characterizing the local field map smoothness, resulting in a smoothness map (s_{map}). Starting from a "seed" pixel with the highest c_{map} value determined in step 2, where s_{map} takes the value of 1, the algorithm then follows the slowest field map gradient direction for the next pixel [2]. For each pixel at this trajectory, the s_{map} value is calculated from averaged s_{map} in its neighborhood but deducted by an amount scaled with the field map changes between the current pixel and its neighbors. Therefore, the bigger the field map varies, the faster the s_{map} loses its value. A value approaching 1 in the s_{map} represents smooth field map variation, while a value approaching 0 suggests high likelihood of water-fat swap.
4. Calculate a local averaged field map weighted by the two weighting maps. Compare this "reference" field map with the current field map to identify the pixels whose field map values need to be recalculated.
5. This completes one iteration. Repeat steps 2-4 until no pixel remain to be recalculated.

Results Figure 2 shows results from a 6-pt abdominal scan. For the initial state, a pixel-independent T_2*-IDEAL reconstruction was performed with the initial guess of 250 Hz at all pixels to simulate a significantly misplaced center frequency. Large water-fat swaps are seen at pixels with incorrect field map (arrows). In the initial c_{map} and s_{map}, the blue pixels suggest high confidence of the current field map values while the red pixels indicate high possibility of water-fat swap, in close agreement with the water/fat images. After one iteration, the majority of pixels with water-fat swap are corrected. Both c_{map} and s_{map} are updated accordingly, driving the field map correction of the next iteration. At iteration 7, the field map is completely corrected. The c_{map} is calculated based on a pre-calibrated fat spectrum [6].

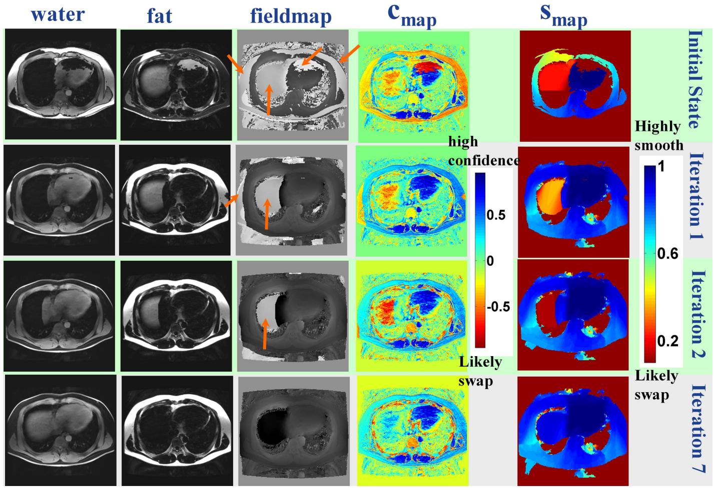

Figure 2: initial, intermediate and final images from the proposed algorithm when reconstructing a 6-pt abdomen scan. Both c_{map} and s_{map} provide reliable prediction of water-fat swap, driving the field map correction of the next iteration.

Discussion and Conclusion Conventional water-fat separation methods rely on enforcing field/phase smoothness to resolve water-fat ambiguity. We introduce a novel approach that utilizes the spectral complexity of fat to identify water and fat. Two weighting maps are generated to indicate the likelihood of water-fat swap on a pixel-by-pixel basis, based on two complementary mechanisms: spectral difference and field map smoothness. Unlike the threshold-based algorithms, these weighting maps are not directly used to make binary decision of water and fat. Instead, a "voting" process is effectively incurred with high confidence pixels intrinsically having higher voting weights. The c_{map} may enable robust separation of water and fat when there are two areas of signal separated by noise ("separate islands"), challenging for traditional region growing based algorithms. In conclusion, we demonstrate that it is possible to exploit spectral differences of water and fat to resolve their ambiguity, resulting in new opportunities to design algorithms for highly robust water-fat separation algorithms.

References
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