Single-image water/fat separation

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Introduction In MRI, fat can be hard to distinguish visually from pathology or contrast agent, due to its high signal intensity in many imaging sequences. Water and fat separation techniques provide an alternative to conventional fat suppression, and are also of interest in body composition applications. Dixon techniques [1] utilize the property of chemical shift to separate water and fat with the use of two or more source images acquired at different echo times. If field heterogeneity is negligible, water and fat can be separated with only one source image [2]. Yu et al. [3] studied water-fat separation from one source image in a heterogeneous field, with the aid of an additional reference scan, in the context of dynamic imaging. Ma [4] showed that water and fat can be separated from a single image in a heterogeneous field even without reference scans.

This work describes a straightforward single-image water-fat separation technique, that utilizes the belief propagation (BP) algorithm [5] to find the field inhomogeneity phase map. The image can be acquired at any echo time where water and fat are not in-phase or opposed-phase. However, the best SNR performance is achieved if the relative water and fat phase is an odd multiple of $\pi/2$ [3].

Methods A gradient-echo image acquired at echo time TE can be described by the following model for the complex signal in each voxel:

$$S = (w + a \cdot f)b \qquad (1)$$

where *w* and *f* are the real-valued water and fat signals. The complex phase factor *a* represents the known phase shift between water and fat at echo time TE, mostly due to chemical shift, and *b* represents an unknown complex phase factor mostly due to main field inhomogeneity. Since we have three unknown and only two known scalars in each voxel, the separation of water and fat has to rely on global information and assumptions. Here, the following assumptions are made:

A. The water:fat ratio in the majority of voxels is either 100:0 (muscle, organs) or 10:90 (adipose tissue)
B. The *b* phase map is spatially smooth
C. Voxels that contain water and fat in equal amounts are located in the interfaces between water-dominant regions and adipose tissue.

Following assumption A, two alternative *b* phase factors are obtained in each voxel; One with the phase of *S*, and one with the phase of $S/(1+9a)$. According to assumption B, one of these phase factors is picked in each voxel by imposing spatial smoothness. Specifically, finding the smoothest phase map is formulated as an optimization problem that can be solved approximately using a multi-scale BP algorithm, similar to the one described in [5].

To allow for a continuous spectrum of water:fat ratios, an averaging filter is applied to the phase map found by the BP. According to assumption C, this will have the largest effect in voxels with both water and fat, as the initial *b* phase factor in those voxels is erroneous, causing edges in the phase map. To avoid impact of noisy voxels, the averaging filter is weighted by $|S|$. This also gives less weight to water-fat interfaces, where partial signal cancellation occurs. Finally, *w* and *f* can be found in each voxel by

$$w = \mathrm{Re}(S/b) - \mathrm{Im}(S/b)\mathrm{Re}(a)/\mathrm{Im}(a) \qquad (2)$$

$$f = \mathrm{Im}(S/b)/\mathrm{Im}(a) \qquad (3)$$

where Re() and Im() are the real and imaginary operators.

Images were obtained from a volunteer subject on Philips 1.5 T and 3.0 T Achieva scanners. On the 3.0 T scanner, a 3D gradient echo (TE=1.72 ms) was acquired in 60 axial slices from the abdomen in one breathhold (13.7 s), with a voxelsize of $3.0\times3.0\times4.0$ mm^3. Additionally, a whole-body dataset was acquired in 10 stacks with 33 axial slices in each stack, with voxelsize $3.0\times3.0\times6.0$ mm^3. The breathhold time was 14.8 s, and the total imaging time was 6 min 38 s of which 4 min 10 s were due to breathing instructions, preparation phases and table movement. On the 1.5 T scanner, a 3D gradient echo (TE=1.16 ms) was acquired from the whole body in 10 stacks with 40 axial slices in each stack. The voxelsize was $3.1\times3.1\times5.0$ mm^3. The breathhold time was 13.9 s, and the total imaging time was 5 min 30 s of which 3 min 10 s were due to breathing instructions, preparation phases and table movement.

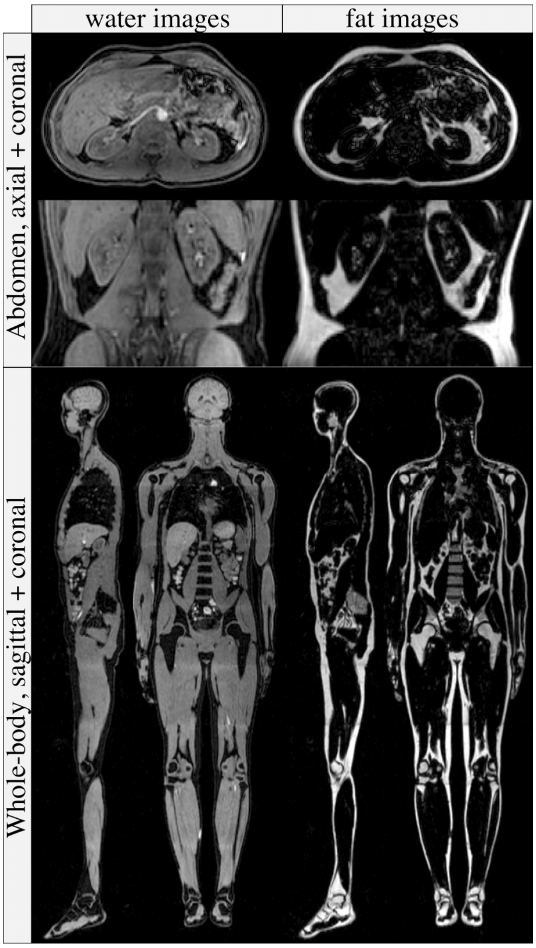

Fig 1. Water and fat separated images from the abdomen at 3.0 T, and the whole body at 1.5 T.

The three datasets were separated into water and fat images using the proposed method. To identify inaccurate water/fat separation, the resulting images were examined by a radiologist. Misregistration artifacts were localized and classified as small or large (with a maximum size of a few cm for small artifacts).

Results & Discussion Overall, the method was found to work well. Examples are shown in fig. 1. In the abdomen dataset, two small artifacts were found in the intraabdominal fat. In the 1.5 T whole-body dataset, small artifacts were found subcutaneous in the feet, legs, arms and skull. In the 3.0 T whole-body dataset, small artifacts were found in the intraabdominal fat and subcutaneous in the legs; large artifacts were found in the feet, arms, shoulders and skull. Artifacts were more frequent in the whole-body acquired at 3.0 T, than in the whole-body acquired at 1.5 T.

The resulting images are believed to be usable in body composition applications, such as measuring visceral adipose tissue, subcutaneous adipose tissue, liver, and muscle volumes. The method relies on some fundamental assumptions, which must be kept in mind. For instance, assumption A does not hold for imaging of fatty liver or bone marrow. For whole-body datasets, the large amount of overhead time could be reduced with the use of continuously moving table imaging.

Conclusion The presented method is crude but straightforward and allows water-fat separation from a single image. The initial results suggest that the method is applicable in studies of body composition. Future studies of interest include accuracy for body composition measurements, as well as feasibility in dynamic imaging and angiography background suppression.

References 1. Dixon WT. Radiology 1984;153:189-94. 2. Ahn CB, et al. Magn Reson Imaging 1986;4:110-111. 3. Yu H, et al. Magn Reson Med 2006;55:413-422. 4. Ma J. J Magn Reson Imaging 2008;27:881-890. 5. Felzenszwalb PF, Huttenlocher DP. Int J Comput Vision 2006;70:41-54.