SENSE EPI Water-Fat Imaging

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Introduction: Quantification of water and fat in tissue can improve diagnosis for some diseases such as bone marrow disease, non-alcoholic fatty liver disease, and adrenal masses. It has also been found useful in drug evaluation studies and the study of obesity-related diseases including diabetes and cardiovascular disease. In addition, water-fat imaging techniques are often used as an alternative fat-suppression technique where the fat images are simply discarded. Echo planar imaging (EPI) has been a challenge for water-fat imaging techniques including the most widely used Dixon techniques [1] due to large spatial misregistration between water and fat in the phase encoding direction. In non-EPI pulse sequences, water-fat misregistration occurs in the readout and slice selection directions, but not along the phase encoding direction. The misregistration in the readout direction is often ignored since the shift is normally less than a couple of pixels. For EPI pulse sequences, however, the water-fat misregistration along the phase-encoding direction can be very large (e.g. 25% of the field of view (FOV)), which poses a major problem for Dixon techniques. In this work, we report a new water-fat imaging technique that utilizes this spatial shift between water and fat to output separate water and fat images with a single-shot sensitivity encoded (SENSE) EPI data acquisition.

Method: Water and fat have a chemical shift of 3.4 ppm. Assume the RF frequency is tuned at the water resonance frequency, fat will be off-resonant. For an EPI pulse sequence, the small off-resonance of fat will cause a phase accumulated throughout the whole echo train. The effect of this accumulated phase along the phase encoding direction is equivalent to multiplying a linear phase factor to the fat signal in the k-space, which causes a spatial shift of fat in the image domain. Since fat precesses slower than water, fat appears to be located at a position that has a smaller magnetic field, i.e. a spatial shift in the opposite direction of the phase encoding gradients. When the polarity of the phase encoding gradients is changed, the direction of the shift will also change. The amount of spatial shift in units of pixels is the ratio between water-fat chemical shift frequency and the receiver bandwidth per pixel in the phase encoding direction. Consider scanning a subject with both water and fat (Fig. 1) using an array of n_c receive coils and an EPI pulse sequence with full FOV. A set of intermediate images a_i can be obtained by Fourier transforming the k-space data from each coil, where i refers to a particular coil. Assume water is on-resonance and fat is shifted downward. The pixel value at position (x,y) is given by $a_i(x,y) = s_i(x,y)\, w(x,y) + s_i(x,y+\Delta y)\, f(x, y+\Delta y)$, where s denotes coil sensitivity; w and f represent water and fat signals, respectively; Δy is the spatial shift of fat which is a known value for a certain pulse sequence. For pixel (x,y), two layers are superimposed, one layer is the water signal and the other the fat signal. The water signal comes from the same position as the pixel of interest but the fat signal comes from a position that is above the pixel of interest by Δy. Because the coil sensitivity maps can be obtained from reference scans, w(x,y) and $f(x, y+\Delta y)$ are the only two unknowns in the above expression and the number of equations equals the number of coils n_c. Therefore water and fat can be resolved if multiple coils are used and there are enough coil sensitivity differences between positions (x,y) and $(x, y+\Delta y)$.

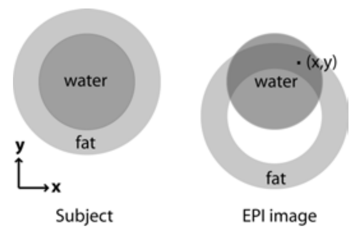

Fig. 1. *Water-fat misregistration for EPI*

When the SENSE reduction factor is greater than one, The FOV of the intermediate images is reduced. As a result, the full FOV of the subject is aliased into the reduced FOV. A pixel in the reduced FOV contains signal contribution from a number of water and fat positions in the full FOV. For the example in Fig. 2, the pixel of interest contains signal contribution from a total of four water and fat positions. Let n_t denotes the total number of water and fat positions in the full FOV for the pixel of interest. The complex coil sensitivities for n_c coils at the n_t positions form an $n_c \times n_t$ sensitivity matrix **S**, where $S_{i,j} = s_i(\mathbf{r}_j)$; Index i counts the coils, and j counts the water and fat positions; Variable $\mathbf{r}_j$ represents the (x,y) coordinate of the j-th water and fat position. Put the signal values from n_c coils for the pixel of interest in vector **a**, and assemble in vector **v** the unknown water and fat values at the n_t positions. The solution for **v** with maximum SNR is analogous to the SENSE pseudoinverse [2]: $\mathbf{v} = [(\mathbf{S}^H \boldsymbol{\psi}^{-1}\mathbf{S})^{-1}\mathbf{S}^H \boldsymbol{\psi}^{-1}]\, \mathbf{a}$, where superscript H denote conjugate transpose and $\boldsymbol{\psi}$ is the $n_c \times n_c$ coil noise correlation matrix. By repeating this procedure for every pixel in the reduced FOV, water and fat values in the full FOV are obtained. This solution is general and applies to the case where there is no SENSE phase encoding reduction as described in the previous paragraph.

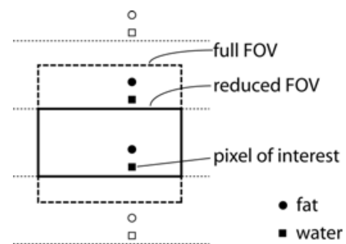

Fig. 2. *Water-fat misregistration and aliasing for SENSE EPI. A pixel in the reduced FOV (solid box) is the superposition of water and fat signals in the full FOV (dashed box). In this example, a total of four water and fat positions in the full FOV are superimposed.*

Results: Experiments of imaging water-fat phantoms were performed on a 3T Philips Achieva scanner. An eight channel SENSE head coil was used. Representative results are shown in Fig. 3. The phantom consists of an oil bottle in the middle and six water bottles surrounding it. Fig. 3(a) shows an axial slice of the phantom acquired with a turbo-spin-echo (TSE) pulse sequence, where the spatial shift of fat (0.25 pixel) is negligible. The same slice was scanned with a single-shot gradient-echo EPI pulse sequence. TE is 32.2 ms so water and fat are in-phase. However, the relative signal phase between water and fat does not matter for this technique. The full FOV is 24 cm and the acquisition matrix size is 112×112. The actual number of phase-encoding lines is 55, thus the SENSE reduction factor is about 2. The receiver bandwidth per pixel for phase-encoding is 24.1 Hz, and the spatial shift for fat is 18 pixles downward. The spatial shift for fat is 16% of the full FOV, which is common for EPI pulse sequences on 3T scanners. Fig. 3(b) shows the image of the phantom with SENSE reconstruction. We can see the fat signal shifts downward. Fig. 3(c) and (d) show the water and fat images obtained using the proposed technique. Fig.3 (e) shows the complex sum of the water and fat images. In the SENSE image reconstruction and the image reconstruction using our technique, no regularization was used. For simplicity, identity matrix was used for the coil noise correlation matrix ψ as the coils are well de-coupled.

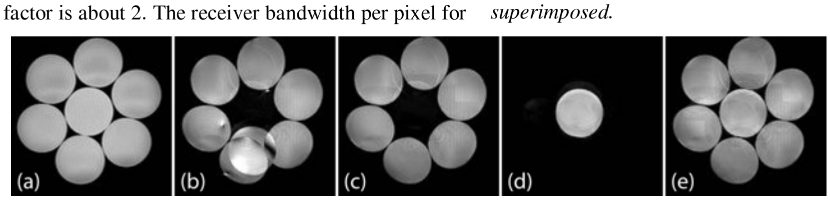

Fig. 3. *Water and fat images of a phantom. (a) Reference image acquired with a TSE pulse sequence. (b) SENSE EPI image. (c) Water image. (d) Fat image. (e) Image of water plus fat.*

Discussion: This work demonstrates the ability of generating water and fat images unambiguously with a single-shot SENSE EPI data acquisition. There is no increase in acquisition time. In fact, there is a reduction of acquisition time and SAR because of the removal of the fat-suppression pre-pulse which is routinely used for clinical EPI imaging. Scanners with higher magnetic field strength are advantageous for this technique. With a higher field strength, the spatial shift between water and fat is larger for the same receiver bandwidth, thus the sensitivity differences between water and fat positions are larger in general. In addition, the spatial phase changes in the sensitivity maps are larger for RF pulses with higher frequency thus shorter wavelength.

References: 1. Dixon WT, Radiology 153: 189-94 (1984) 2. Pruessmann K, et. al., MRM 42: 952-62 (1999)