Implementation and Noise Analysis of Chemical Shift Correction for Fast Spin Echo Dixon Imaging

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Introduction: The chemical shift displacement artifact has long been known and understood, causing a spatial shift of fat tissues with respect to water in the read-out direction with spin-warp imaging. As a result, the artifact is most noticeable at the boundary of water and fat, where either they will overlap or there is a signal void between the two tissues. Chemical shift artifact significantly degrades images at the interface of water and fat, and may interfere with correct interpretation in many applications, such as musculoskeletal (MSK) imaging [1]. In this work, we will describe a method to obtain fast spin echo (FSE) chemical-shift free images during the Dixon water-fat separation algorithm. The correction of the artifact is of particular importance at high field strength, and low bandwidth imaging where chemical shift artifact can increase markedly.

We used a recently proposed Dixon technique to obtain water and fat separated images [2]. The Dixon technique is advantageous compared to other fat suppression methods because of its relative tolerance to field inhomogeneity. In addition, it offers fat-only images as well as water-only images. We implemented an algorithm to combine fat and water images after correction for the displacement artifact, and the combined images may be valuable for anatomical reference. Using the water-fat combined images, it is now possible to perform one Dixon acquisition in place of fat saturated imaging and non-fat saturated imaging, which is used commonly in many imaging protocols. The recombination of water and fat images is an excellent opportunity to correct for chemical shift and improve diagnostic image quality. The noise performance of such combination procedure was studied.

Method: The reconstructed position of species with off-resonance frequency relative to water of Δf is shifted in the read-out direction from its true position by an amount described by $\Delta x = \Delta f \cdot Nx/(2 \cdot rBW)$. Nx is the number of pixels of the image matrix in the read-out direction. rBW is the receiver bandwidth and by convention equals half the total bandwidth ($2 \cdot rBW$), explaining the factor of 2 in the denominator. As can be seen, the chemical shift effect is most obvious at high field (increased Δf), and low bandwidth acquisitions. To correct for chemical shift, the separated fat image is shifted back by $-\Delta x$ in the read-out direction. To allow arbitrary (e.g. non-integer number of pixels) displacement, the correction is performed by multiplying each of the k-space read-out lines by a phase term $e^{j2\pi\Delta x k_x / Nx}$. The corrected fat image then is added to the water image to obtain the chemical shift free combined image.

With approval from our IRB and with informed consent, more than a dozen of healthy volunteers have been imaged on a GE Signa TwinSpeed 1.5T and a GE 3T scanner with the FSE Dixon imaging method to test the effect of chemical shift correction. These scans covered a wide range of anatomic regions including knees, ankles, wrists and shoulders.

The SNR of the combined image can be studied quantitatively. Consider a pixel with water and fat components W and F. The corresponding pixel in separated water image has a non-zero signal W and noise with standard deviation of σ_w, while in the fat image, it has signal F and noise of σ_f. The variance of the water and fat (σ^2_w,σ^2_f) for symmetric Dixon imaging [2] are given in [3]. We use r to denote the ratio, $r = \sigma^2_f/\sigma^2_w$. The noise of the real and imaginary channels of the input signals are zero mean and Gaussian distributed. We assume the noise distribution in the real and imaginary channels of the separated water or fat images are also zero mean Gaussian, which is a good approximation even though the processing in the 3-point Dixon decomposition can be nonlinear. In the magnitude images, however, the noise standard deviation can be described as $m_f \cdot \sigma_f$ or $m_w \cdot \sigma_w$ for fat and water images respectively. The scale factors, m_f and m_w, depend on the signal values and are given in [4] assuming noise in the real and imaginary channels are uncorrelated. Even if the Dixon decomposition introduced a correlation into noise in the fat and water images, after the spatial translation for correction of chemical shift the noise in the fat and water signals in a single pixel are uncorrelated. Therefore, we can expect the noise in the pixel of the combined image has standard deviation of $\sigma^2_c = \sigma^2_w (m_w^2 + r \cdot m_f^2)$. Hence, $SNR_c/SNR_w = 1/(m_w^2 + r \cdot m_f^2)^{1/2}$ (SNR_c and SNR_w represent SNR of the combined and water images). For the optimal ΔTE (1.5ms at 1.5T) [2], and a purely water pixel with high SNR ($W >> \sigma_w$, $F = 0$), $m_w \approx 1$, $m_f = 0.655$ [4] and $r = 2$ [3], thus SNR_c/SNR_w is 0.73. It has been shown that the effective number of signals averaged (NSA) of the separated water image using the 3-Pt Dixon technique in [2] is comparable to a 3-NEX acquisition at this optimal echo shift value. Therefore the NSA of the recombined image is approximately 1.6. Generally, a pixel will have both water and fat, and when the amount of the two species becomes comparable, r, m_f and m_w all approach 1 [3,4], and consequently SNR_c/SNR_w approaches 0.707.

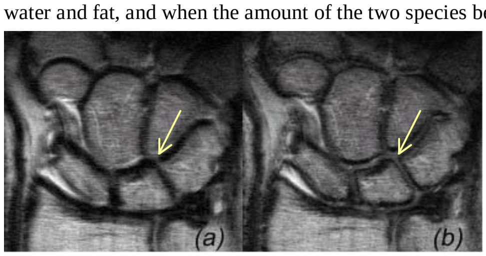

Figure 1: A FSE Dixon wrist slice at 1.5T with TEs=[-1.2, 0, 1.2]ms, *rBW*=6.94kHz and *Nx*=512. (a): the combined image without chemical shift correction; (b): with chemical shift correction.

Results: Results from 2 volunteers are shown. Figure 1 compares a portion of source image to chemical shift corrected image of a wrist. The fat in the uncorrected source image has a chemical shift of 8.11 pixels in the read-out direction (vertical) because of the low bandwidth used. The articular cartilage is seen to better advantage after chemical shift correction (arrows). Figure 2 shows images of a knee at 3T. With Nx=512 and rBW=31.25kHz, the chemical shift is 3.6 pixels in the read-out direction (vertical). The combined images without (a) and with (b) chemical shift correction are shown as well as the separated water image (c). Comparing (a) with (c), it can be seen that the articular cartilage of the proximal tibia (arrow) appears artifactually thinner in the uncorrected image than that in the water image (c) or corrected image (b).

Discussion: We have demonstrated that our correction method accurately removes chemical shift displacement artifacts, and that the SNR of the combined image is approximately 30% less than the SNR of the separated individual images. Chemical shift correction will be most useful at high field strengths and low bandwidth imaging where SNR is high, so this loss in SNR may be acceptable. In addition, a nonlinear combination method was suggested in [5] to avoid the noise amplification.

In this work, we only correct for the fat shift. However, distortion also occurs due to resonance offsets. During a Dixon acquisition, the field map, i.e. the off-resonance map of all the pixels, can be obtained. Therefore, correcting the shift caused by field inhomogeneities may also be possible.

Conclusions: We have demonstrated that chemical-shift corrected images are a useful and easily obtained side product of a Dixon FSE acquisition. Noise analysis of the combination shows that the SNR of the combined image has a moderate approximately 30% loss from the separated images, but still higher than individual source images.

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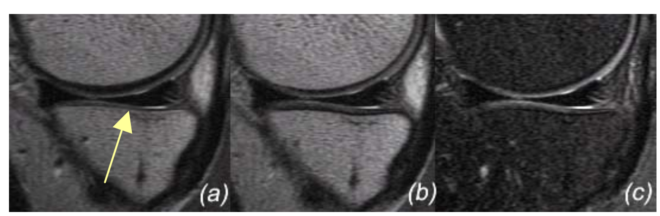

Figure 2: A FSE Dixon knee slice at 3T with TEs= [-0.6, 0, 0.6]ms, *rBW*=31.25kHz and *Nx*=512. (a): the combined image without chemical shift correction; (b): with chemical shift correction; (c) separated water image

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