Discontinuities in the distortion field: correction of the fat-shift artifact

L. N. Baldwin[1], K. Wachowicz[2], and B. G. Fallone[1,2]
[1]Department of Physics, University of Alberta, Edmonton, Alberta, Canada, [2]Department of Oncology, University of Alberta, Edmonton, Alberta, Canada

Introduction: The fat-shift artifact arising from chemical shift is one of the several types of geometric distortion affecting MR images. MR-based treatment planning is an area of increasing interest that is hampered by MR image distortion[1,2]. Various techniques for distortion correction have been investigated[3-5]; however none of these addresses discontinuities in the distortion field present at fat/water boundaries which leads to both hyper- and hypo-intense signal regions in the distorted image. Although the region affected by this artifact is minimized by increasing the strength of the read gradient, artifact size also increases in proportion to the strength of the B_0 field. As the trend towards stronger magnetic fields continues, effective correction for this artifact becomes increasingly important. The distortion correction technique presented by Baldwin *et al*[5] requires the acquisition of three images: the (distorted) treatment planning image, and two phase difference maps (one each with fat and water in-phase and out-of-phase)[3]. Here we propose a method to correct for the effects of the non one-to-one distortion field present at the interfaces between fat- and water-based tissues; it relies only on post-processing methods and does not involve the acquisition of any additional methods.

Theory: A schematic is shown in Fig. 1 where adjacent pixels contain signal from water and fat. If, for example, a 3T image is acquired with a readout bandwidth of 428 Hz/pixel, the two leftmost pixels experience the same resonance frequency and are assigned to the same location in the resultant image. In the distorted image, if fat and water are in phase, the leftmost pixel, 1′, contains the sum of the signal from pixels 1 and 2. The total signal at pixel 1′ can be expressed as

$$s_t = s_f + s_w \qquad (1)$$

where s_t is the total signal, s_f is the signal arising from the fat, and s_w is the signal arising from the water. On the contrary, pixel 3′ contains a signal void because no signal is assigned to this location. The distortion correction procedure[5] cannot distinguish the fat and water contributions to the signal in pixel 1′. Thus the "corrected" image suffers from an erroneous hyper-intense region shown in pixels 1″ and 2″ (Fig. 1C). A typical MR image can be considered to be the composite of two images: a water image and a shifted fat image. To correct for the non one-to-one distortion mapping and the resultant hyper-intense region, the image can be separated and only the fat portion of the image need be shifted. Once the fat image has been shifted to its original location, the regular distortion correction procedure can be carried out.

Methods: The fat-containing image pixels are labeled by a fat mask, M_F, which is created by subtracting magnetic field maps generated from the in-phase and out-of-phase phase difference maps. Next, pixels containing overlapped signal are labeled by an overlap map, M_O. The overlap map is generated from the distortion map by identifying locations with non-unique mapping from true to distorted coordinates. Finally, a fat-containing portion of the image is sampled and the mean fat signal intensity, s_f, is determined; the total signal at the overlapped location is separated according to Eq. (1). The fat portion of the image is shifted by Δp pixels, where

$$p = \frac{\Delta f}{\gamma \cdot G \cdot \Delta x} \qquad (2)$$

Δf is the difference in fat and water resonance frequencies, G is the read gradient strength (in mT/m), and Δx pixel resolution (in millimeters) in the direction of the chemical shift artifact. Thus, all pixels contained in the fat mask, M_F, are shifted by the amount, $-\Delta p$, where the direction of the shift is determined by the direction of the read gradient. For those pixels contained in both M_F and M_O, (i.e. $M_F \cap M_O$), only the fat portion, s_f, of the overlapped signal intensity is shifted.

Results and Discussion: A phantom containing both mineral oil (fat) and water was used to demonstrate the technique. The top third of the phantom contains oil as does the central chamber; the bottom portion of the phantom and the six small chambers contain water. The phantom was image with a gradient echo sequence at 3T using a read gradient of 2.97 mT/m, and a pixel resolution of 0.86 mm. The distorted image in Fig. 2A clearly shows the shifted fat signal; Fig. 2B shows the image following standard distortion correction and the residual hyper-intense region is indicated by the arrow. Two additional phase maps were also acquired (as described in Methods) and were used to generate the fat and overlap masks, M_F and M_O, as shown in Fig. 3. The fat signal intensity s_f, was calculated from a 50 x 50 pixel region within the top third of the phantom and was determined to be 546 ± 25. The fat shift, Δp, was calculated from Eq. (2) as 3.94 pixels. Thus, the full signal intensity of pixels identified by M_F - M_O was shifted to the left by 4 pixels, while only a portion of the signal intensity, s_f, was shifted for pixels masked by $M_F \cap M_O$. Following this pre-processing procedure, the standard distortion correction procedure is carried out. Fig. 4A shows the phantom image with only the standard distortion correction while, for comparison, Fig. 4B shows the corrected image which has been pre-processed according to the methods described above. The smeared out high signal intensity region indicated by the black arrow in Fig. 2B and visible in Fig. 4A is not present in Fig. 4B. The pre-processing steps separate the overlapped signal intensity present in the distorted image into its constituent fat- and water-based signals. Only the fat portion of the image was shifted prior to correction for the remaining types of distortion (B_0, gradient non-linearity, and susceptibility).

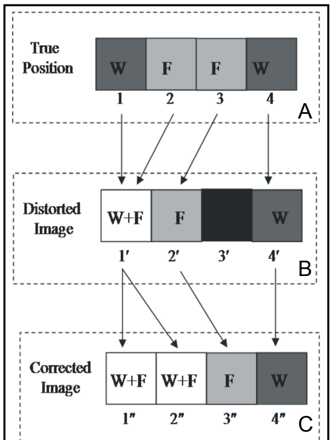

Figure 1

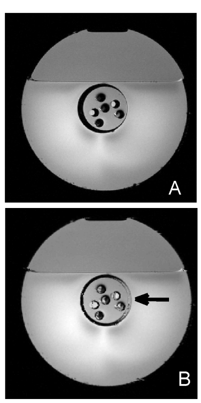

Figure 2

Conclusions: We describe a method of pre-processing clinical treatment planning images which corrects the residual fat shift artifact resulting from chemical-shift related discontinuities in the distortion field. The technique was demonstrated on a phantom containing both water and mineral oil. Current work is being carried out to evolve and apply the method for more complex in-vivo imaging.

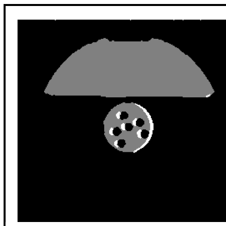

Figure 3: $M_F - M_O$ (gray); $M_F \cap M_O$ (white).

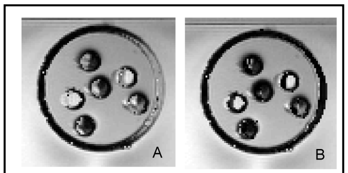

Figure 4:
(A) standard distortion correction procedure; (B) pre-processing to reduce fat-shift artifacts

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2) Jackson *et al.* Br J Radiol **80** (2007).
3) Jezzard *et al*. Mag Res Med **34** (1995)
4) Chang *et al*. IEEE Trans Med Im **11** (1992)
5) Baldwin *et al*. Med Phys **36** (2009)