On the utility of complex-averaged diffusion-weighted images

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Magnitude averaging is very common in diffusion-weighted imaging, as it avoids random phase offsets in the data from the diffusion-sensitizing gradients by simply discarding all phase information. Even when not acquiring multiple averages of the signal (aka multi-NEX), several to many magnitude images are averaged when calculating the isotropic diffusion-weighted image, necessary for the ADC, or when computing the elements of the diffusion tensor. Further, multiple receiver coil images are commonly combined using the sum-of-squares reconstruction, which is effectively a variant of magnitude averaging. Diffusion weighted images, especially the higher b-value images acquired for more advanced diffusion processing, have notoriously low SNR. It is well known that noise in magnitude MR images is no longer Gaussian, but Rician distributed [1-3]. In high SNR magnitude images, the bias of the expectation value is low. However, in low SNR magnitude images, such as diffusion images, the Rician distribution approaches a Rayleigh distribution. This introduces a severe non-zero bias of the signal expectation value and underestimates the calculated ADC [4]. The gradual deflection of the diffusion attenuation with increasing b-value can reduce the CNR but more importantly can mimic bi-exponential decay. Combining magnitude diffusion images for signal averaging, isotropic ADC, or tensor calculation does not lower this bias, whereas combining complex diffusion images with their Gaussian noise distributions in the real and imaginary channel does.

Materials and Methods: All diffusion images were acquired with an 8-channel phased array coil in a 1.5T magnet. 10 averages of a single slice with 15 diffusion directions (128x128, FOV=24cm, twice-refocused diffusion preparation, TE=90ms, TR=1s, thick=5mm) on an agar phantom were acquired with diffusion-weighted single-shot EPI. Thirteen equally spaced b-values were obtained, from 300 to 1500 s/mm^2. Both magnitude-only and complex image reconstruction was performed, and isotropic apparent diffusion coefficients (ADC) were calculated for each b-value from each reconstruction. Magnitude reconstruction used the absolute value of each image, which were combined over coils with the sum-of-squares, and averaged over NEX. The complex-preserving reconstruction estimated and removed the differential coil phase offsets, allowing complex sum-of-squares combination of coil images. The low frequency phase variation in the combined coil image was calculated and removed using the triwindowing approach [5], allowing complex averaging over interleaves, NEX, and diffusion directions. Clinical diffusion imaging was also performed, with a 3-shot R=3 EPI sequence [6], (192x192, FOV=24cm, b=1000 s/mm^2, 25 slices, 2x-refocused prep, TE=65ms, TR=4s, thickness=5mm).

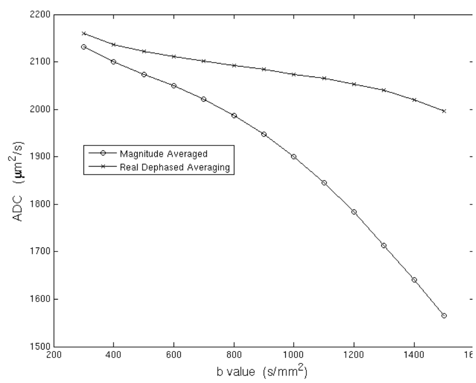

Figure 1. Variation in the ADC of a phantom is much more pronounced when using magnitude rather than complex reconstruction. 10 signal averages and 15 diffusion directions from 8 coils were combined for the ADC, in order to maximize signal.

Results: The calculated ADC for the agar phantom is plotted against b-value in Figure 1. The ADC in free water at room temperature is about 2000 μm^2/s. Although the true ADC is not known in this setup, the ADC should not vary with diffusion b-value. It is seen in the plots that the magnitude reconstruction results in approximately 30% variation in calculated ADC value for b-values ranging from 300 to 1500s/mm^2 (Fig. 1). The variation in the complex reconstruction is much smaller, varying only about 5% with b-value. 10 NEX and 15 diffusion directions were used to minimize system errors, and give maximal signal. The improvement is visible in non-quantitative diffusion imaging as well, such as in the isotropic DWI images in Figs 2 and 3. The background areas in the magnitude-only images have a non-zero mean, giving the images a "haze" that reduces CNR.

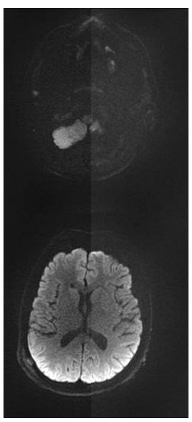

Figure 2. A volunteer DWI exam reconstructed with complex averaging for the left half of the image, but magnitude averaging for the right half.

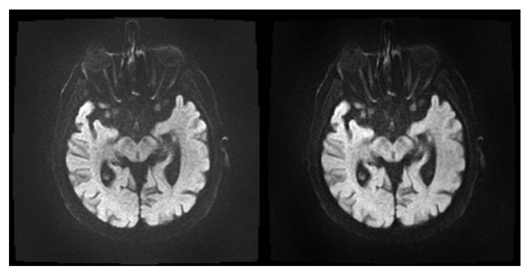

Figure 3. A clinical DWI exam reconstructed with magnitude averaging (left) versus complex averaging (right). Note the lower background signal level.

Discussion: Preserving the complex information through the reconstruction has been shown to be of benefit in diffusion-weighted imaging, which tends to suffer from low SNR. Simple methods for preserving the isochromat phase in passed-array coil image combination, as well as a well-known phase correction method for shot, NEX, and diffusion direction image combination were demonstrated. These methods have demonstrable benefits, yet are simple to implement. The influence of the noise bias in ADC and DTI processing has been noted previously; this method reduces the innate bias.

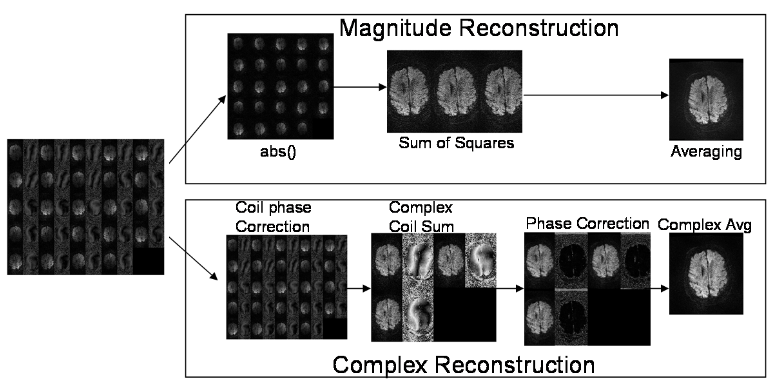

Figure 4. Simplified diagram of the commonly performed magnitude reconstruction, and the steps needed to perform a complex reconstruction. After averaging over e.g. interleaves, NEX, etc diffusion processing may be performed on either reconstruction's images.

References: 1) Gudbjartsson MRM 1995;34:910-915 2) Henkelman Med Phys 1985;12(2):232-233. 3)Miller MRI 1993;11:1051-1056 4) Dietrich MRM 2001;45:448-453. 5) Pipe JG et al. MRM 2002;47(1):42-52. 6) Skare MRM 2007;57(5):881-890

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