Effect of SNR and Thresholding on the Apparent Diffusion Coefficient in Hyperpolarized He-3 MRI

R. L. O'Halloran[1], J. H. Holmes[1], T. A. Altes[2], S. B. Fain[1]

[1]Medical Physics, University of Wisconsin, Madison, Wisconsin, United States, [2]Department of Radiology, University of Virginia, Charlottesville, Virginia, United States

Introduction: Both the mean and the standard deviation (SD) of the apparent diffusion coefficient (ADC) have been shown to be SNR dependent (1). In prior work, the mean ADC was shown to rise with SNR up to a critical threshold, after which the mean ADC was independent of SNR. Moreover, the SD was shown to depend inversely on the unweighted image SNR (SNR_l). It would be advantageous to know the SNR required for accurate measurement of the ADC and how appropriately threshold data retrospectively if regions of low SNR are included. We demonstrate in simulations and experiments that the SNR dependence shown in prior work arises from applying a threshold (typically 2.5 σ) to the diffusion weighted image. This leads to an underestimation of the mean ADC. We develop a novel approach in which the data are thresholded based directly on the SNR of the non-weighted image, either interactively or automatically. We also confirm a theoretical model for the dependence of standard deviation on SNR in a free diffusion phantom. Deviation from purely stochastic variation is demonstrated in human lungs and used as a method for extracting information about variations in lung microstructure using a SD measure that is theoretically independent of image SNR.

Methods: Numerical simulations were carried out in MATLAB (MathWorks, Natick, MA). Gaussian zero mean noise was added to images with increasing uniform signal intensity to form unweighted images. The signals were attenuated with a b value of 1.6 s/cm^2 to form weighted images and then used to calculate ADC values for each pixel. SNR was calculated for each pixel by dividing the original signal intensity by the mean of the absolute value of a uniform Gaussian noise field with the same standard deviation as the one added to the images. ADC was plotted versus SNR for each pixel both with conventional noise thresholding applied to the weighted image (1). Experiments were carried out with a 2D diffusion weighted sequence (GRE, +/-31.25 kHz, 64 × 64 matrix, 4 cm slice, TR/TE = 7msec/3.6 msec, flip ≈ 7°, and Δb = 1.6 s/cm^2). Multiple 2D images of the same slice were acquired on a 1.5 T MR scanner with broadband capabilities (Signa LX, GE Medical Systems, Milwaukee, WI). The phantoms were filled with 1 atm of pure hyperpolarized He-3. A series of images was obtained without changing the gas, thus allowing RF saturation to further degrade the SNR at each subsequent image. A chest coil tuned to the He-3 resonant frequency was used to transmit and receive.

Figure 1a:

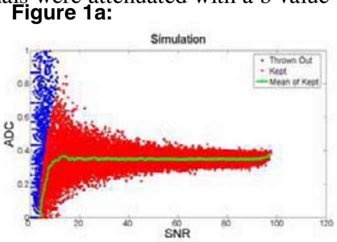


Figure 1b:

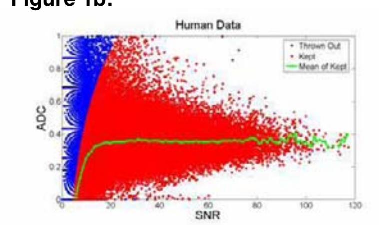
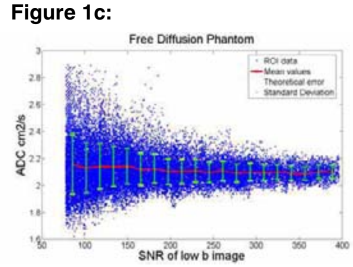


Figure 1c:



Results and Discussion: Results in the simulation are shown at right. The green line represents the mean ADC value in bins with the same SNR obtained using conventional thresholding (Figs. 1a and b; blue points are thrown out; red points are kept). Each point on the line delineates the center of each bin. Because mean ADC measurements at low SNR are biased towards lower values by conventional thresholding, the mean ADC rises with increasing SNR. The proposed technique instead applied a direct SNR threshold on the un-weighted image which keeps only unbiased data (Figs 1c and 2a). Salerno et al derived

$$SD_{ADC} = \frac{1}{\Delta b \cdot SNR_L}\sqrt{1+\exp(2\cdot \Delta b \cdot ADC)}\,. \qquad (1)$$

This stochastic dependence is plotted with green error bars in the free diffusion phantom (Fig 1c) and in the lungs of a smoker with 40 pack years (Fig 2b). The yellow error bars represent the actual error in both cases. Figure 2c shows the unthresholded data, while Figure 2d shows the data kept after thresholding (voxels within the red box in Figure 2a). Note that the results in the free diffusion phantom conform well to theory, while the human data deviates significantly from theory (Figs 1c and 2b). This residual SD, not accounted for by eq. 1 can be easily extracted and used as a potentially more sensitive metric of regional variation in lung microstructure than SD_{ADC}. An additional benefit of this method is the removal of large airways as evidenced by Fig. 2d.

Figure 2a:

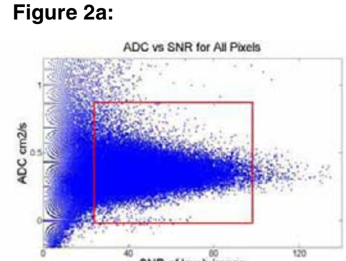


Figure 2b: Enlarged from 2a

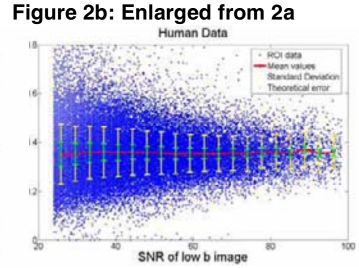


Figure 2c:

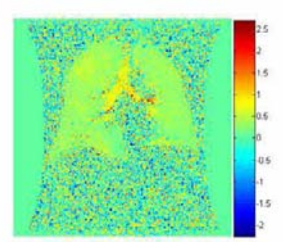
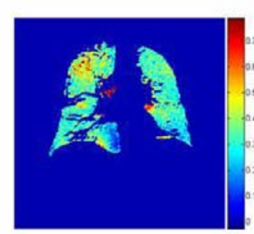


Figure 2d:



Conclusion: The application of a conventional noise threshold is shown to underestimate mean ADC in simulations and experimental data. Thresholding directly on the SNR of the unweighted image removes the SNR dependence and improves accuracy. Moreover, the theoretical dependence of the standard deviation on SNR in Eq. 1 is confirmed in a free diffusion phantom. The residual variation in the lungs of a smoker (Fig 2d) is thought to be largely due to lung microstructure and warrants further investigation as a metric of disease.

References: (1). Salerno et al Proc. Intl. Soc. Mag. Reson. Med. 11 2003