Effects of T_2-Weighting on Optimum *b*-Value vs. SNR for ADC Measurements

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Introduction: The optimization of *b*-value for two-point apparent diffusion coefficient (*ADC*) estimation schemes were previously investigated, assuming high signal-to-noise ratio (*SNR*) imaging [1-5] and also considering the effects of T_2-weighting [4-5]. Recently, the dependence of the optimum *b*-value on the *SNR* of the imaging scheme has been shown, ignoring the T_2 relaxation effects [6]. Here, we incorporate the effects of the T_2 decay, in addition to the *SNR* of the imaging scheme, to provide a more accurate optimum *b*-value for *ADC* estimation methods. The results of this work are especially important for high-resolution diffusion-weighted (DW) imaging, which intrinsically suffers from low *SNR*. We apply our method to DW imaging of the cervical spinal cord at low *SNR* values to demonstrate the improvement in the resulting DW images and *ADC* maps.

Theory: *ADC* measurements generally consist of two-point estimation schemes, where DW images are acquired at two different *b*-values, b_1 and b_2. Instead of directly calculating the optimal *b*-values, the optimization of the diffusion measurements are carried over two parameters: $D\Delta b$ product and the ratio of the number of images acquired at b_2 and b_1 ($r_{21}=N_2/N_1$). When the imaging scheme has high *SNR*, it has been shown that the optimum $D\Delta b$ value is $(D\Delta b)^*=1.28$, with optimum $r_{21}^* = e^{(D\Delta b)^*} \approx 3.59$ [1]. For low *SNR* cases, however, the noise in the *ADC* no longer has a Gaussian distribution. For these cases, the optimum $D\Delta b$ is as demonstrated with the green dash-dot curve for $T_2=\infty$ in Figure 1.b, which converges to the asymptotic value of 1.28, as previously shown in [6]. The optimum r_{21} ratio is still given by $r_{21}^*=e^{(D\Delta b)^*}$.

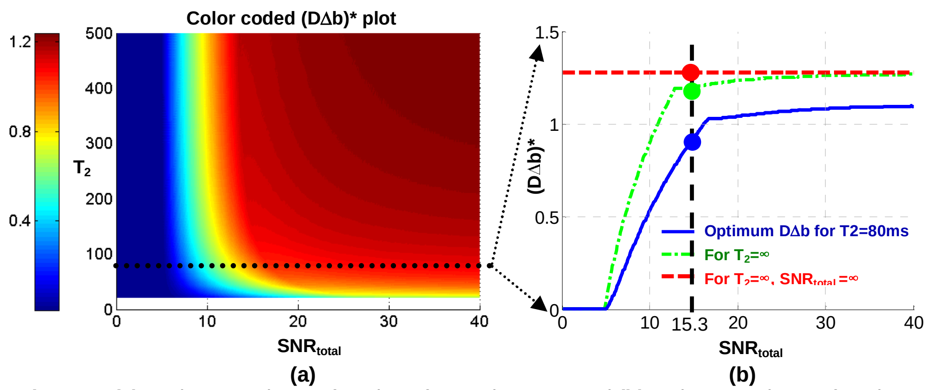

Figure 1. ***(a)*** *Optimum $D\Delta b$ as a function of T_2 and SNR_{total} and* ***(b)*** *optimum $D\Delta b$ as a function of SNR_{total} for T_2 = 80 ms (for white matter). The optimal ratio is $r_{21}^*=e^{(D\Delta b)^*}$ for all cases.*

Calculations in both [1] and [6] were carried ignoring the effects of T_2-weighting on optimal *ADC* estimation. In practice, larger *b*-values require longer echo times (TE), which result in more T_2 relaxation. This further reduces the *SNR* of the DW images as well as the non-DW images that are acquired with the same TE. The maximum achievable *b*-value for a given TE can be expressed as a cubic polynomial in TE, where the coefficients of the polynomial depend on the timing parameters of the imaging sequence. By solving the cubic equation, a closed form expression of TE as a function of the *b*-value can be obtained [5].

Figure 1.a shows the result of incorporating the effects of T_2-weighting by expressing TE as a function of the *b*-value. Here, SNR_{total} is defined as $SNR_{total} = SNR_0\sqrt{N_{total}}$, where SNR_0 is the *SNR* of the $b = 0$ case with the shortest possible TE value that the imaging sequence allows, and $N_{total}=N_1+N_2$. Figure 1.b shows the optimum $D\Delta b$ as a function of SNR_{total} for T_2 = 80 ms, which is the typical value for healthy white matter. For both Figure 1.a. and 1.b, the optimal ratio r_{21} is $r_{21}^*=e^{(D\Delta b)^*}$. It can be shown that the knee point in Figure 1.b corresponds to the SNR_{total} point below which there is no local optimum $D\Delta b$ [6]. Therefore, $(D\Delta b)^*$ for these very low *SNR* regions is chosen such that no bias is introduced in the estimation of *ADC* due to high noise levels. To achieve this, a lower threshold of $SNR_{DW}>3.43$ is set on the DW images. This threshold also ensures that the optimum $D\Delta b$ is an increasing function of SNR_{total}.

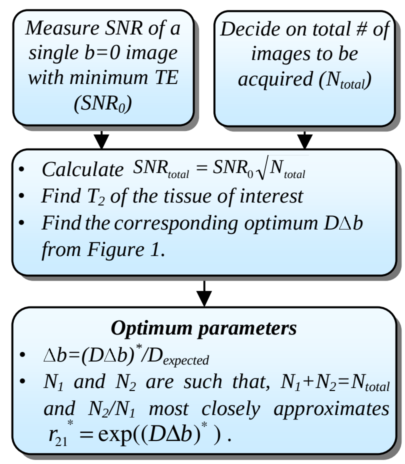

Figure 2. *Flow chart summarizing the optimum b-value selection.*

Results: A summary of the proposed optimum *b*-value selection method is given in Figure 2. To demonstrate the improvement achieved with this method, high-resolution (0.94×0.94 mm^2 in-plane resolution) single-shot EPI DW imaging of the cervical spinal cord of a healthy volunteer was performed on a 1.5T GE Excite scanner. For SNR_0=5.1, a total of 9 images were acquired, i.e., $SNR_{total}\approx 15.3$. From Figure 1.b, the optimum $D\Delta b$ for this SNR_{total} is $(D\Delta b)^*\approx 0.9$ ($r_{21}^*\approx 2.46$, N_1=3, N_2=6, TE=62 ms). These parameters were compared against the $T_2=\infty$ case (green dash-dot curve) of $D\Delta b\approx 1.2$ ($r_{21}\approx 3.31$, N_1=2, N_2=7, TE=66 ms), and the asymptotic solution for $SNR=\infty$ & $T_2=\infty$ (red dashed line) of $D\Delta b\approx 1.28$ ($r_{21}\approx 3.59$, N_1=2, N_2=7, TE=67 ms). The results of DW spinal cord imaging are shown in Figure 3. Note that both the DW image and the *ADC* map has improved *SNR* for $D\Delta b^*\approx 0.9$, corresponding to b = 500 s/mm^2, which is the optimum solution suggested for this specific case.

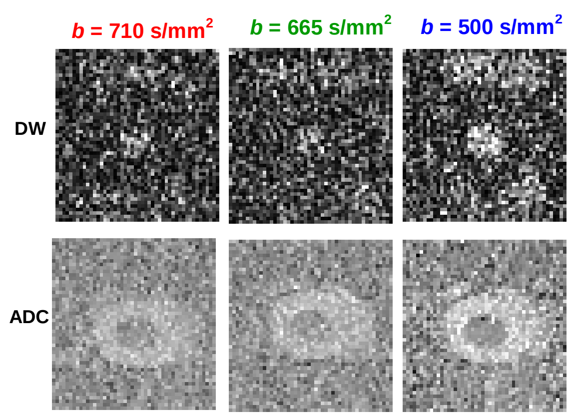

Figure 3. *Comparison at low SNR level of $SNR_{total}\approx 15.3$, as marked in Figure 1.b. DW images of cervical spinal cord at b=710s/mm^2 ($D\Delta b\approx 1.28$), b=665s/mm^2 ($D\Delta b\approx 1.2$) and b=500s/mm^2 ($D\Delta b^*\approx 0.9$), and the corresponding ADC maps. Note that, as predicted, b = 500s/mm^2 results in DW image and ADC map with higher SNR.*

Conclusion: It is shown that the optimum $D\Delta b$ depends on both the *SNR* of the imaging scheme and the T_2 of the tissue of interest, as given in Figure 1. The results presented in this work become especially important for high-resolution DW imaging, which intrinsically suffers from low *SNR*.

References:
1. Bito et al., Proc ISMRM #913, 1995.
2. Xing et al.,MRI 15:771-784, 1997.
3. Brihuega-Moreno et al., MRM 50:1069-1076, 2003.
4. Kingsley et al., MRM 51:996-1001, 2004.
5. Jones et al., MRM 42:515:525, 1999.
6. Saritas et al., Proc ISMRM #1508, 2007.