Optimization of DTI Acquisition Parameters

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Purpose

To calculate the optimum parameters (high *b* factor, and hi/lo = ratio of acquisitions at the high *b* factor to those at *b*=0) for DTI measurement of ADC, diffusion anisotropy (RA), and eigenvectors, and to confirm these predictions with simulations.

Introduction

Because DTI is very sensitive to noise, it is important to optimize data acquisition [1,2]. The optimum gradient directions are spaced uniformly, such as icosahedral vertices, faces, and edges [3,4]. The only apparent published recommendations for optimizing *b* and hi/lo suggest using bD = 1.09 and hi/lo = 11.3 for all DTI measurements, including ADC, anisotropy (sRA = RA scaled 0-1, or FA), and eigenvectors, with a slightly lower bD when T_2 effects are considered [1]. However, such recommendations 1) were based on incorrect application of propagation-of-error formulas, 2) were calculated only for isotropic diffusion, 3) did not recognize that ADC, sRA, and eigenvectors have different optimum parameters, and 4) did not provide a range of useful values that provide near-optimum results. Different groups often use very different measurement parameters, apparently with good results. The purposes of this work are 1) to derive propagation-of-error formulas to calculate noise in DTI measurements of ADC and sRA with any anisotropy level and tensor orientation and reasonably spaced gradients, 2) to confirm these formulas with simulations, 3) to optimize the parameters for eigenvector calculations by simulations, and 4) to determine the optimum range of bD and hi/lo for ADC, sRA, and eigenvectors.

Methods

With M icosahedral gradient directions, ADC and sRA can be calculated directly from the individual signal intensities (S_0 for b=0, S_i for b>0) or measured ADCs (D_i) without calculating the tensor [3,4]. For these cases the variance in ADC or sRA can be calculated by applying the standard propagation-of-error formula, resulting in

$$\sigma^2 = \left(\frac{K}{SNR_0 b}\right)^2 \left(\frac{1}{n_1} + \frac{1}{M(N-n_1)}\sum_{i=1}^{M} Q \exp(2bD_i)\right) \quad [1]$$

where $K = Q = 1$ for ADC, $K = \mathrm{sRA}/D_{av}$ and $Q = [(\langle D_i^2\rangle - D_i D_{av})/(\langle D_i^2\rangle - D_{av}^2)]^2$ for sRA, D_{av} is the mean diffusivity (trace/3), N total acquisitions, n_1 acquisitions at b=0, and SNR_0 is the SNR with b=0. The optimum b and n_1 are those that minimize σ^2. For ADC with isotropic diffusion, Eq. [1] simplifies to the published formula [2]. All calculations and simulations assumed cylindrical symmetry with M = 31 (6 vertices + 10 faces + 15 edges) or 6 icosahedral gradient directions [3,4], or 6 (cube edges)[3,4], 7 (cube, 3 faces + 4 vertices)[4], or 12 (all possible sets with ±1, 0.5, 0) non-icosahedral directions, and 10000 repetitions with $SNR_0 \geq 100$ to improve the reproducibility of the results. For eigenvectors, the mean angular error, the SD of the angle distribution, and the 95% cone of uncertainty yielded nearly the same optimum bD for each sRA level.

Results and Discussion

The calculated SDs agreed well with simulations for ADC and sRA over the range $0.1<bD<1.9$ and $0.05<\mathrm{sRA}<0.95$, even for three non-icosahedral gradient schemes with 6, 7, and 12 directions. The optimum bD and hi/lo for measuring ADC, sRA, and the orientation (angle) of the principal eigenvector with M = 31 icosahedral gradient directions are shown in Table 1. The results were generally within 10% of the optimum for bD within ~30% of the optimum bD, for up to a 2.8-fold change in hi/lo, and for hi/lo ≥ 4.8 for sRA at all anisotropy levels. For eigenvector angles, the use of hi/lo ≥ 4.8 corresponds to <10% increase in SD, since SD is proportional to $1/(N-n_1)^{1/2}$. The optimum bD decreases with anisotropy, and is 10-25% higher for ADC than for sRA or eigenvectors. When T_2 effects are considered, the optimum values for ADC decrease 10-20% for bD [1,5] and for hi/lo [1]. Thus, the use of bD = 0.7–0.9 ($b \approx 1000$ for human brain) and hi/lo = 5-8 should yield nearly optimum results for most applications. This bD is lower than the suggested bD =1.09 [1], while the suggested hi/lo = 11.3 [1] is good for sRA and eigenvectors, but slightly high for ADC.

Table 1. Optimum bD and hi/lo for ADC, sRA, and eigenvector angle, with M=31 gradient directions and sRA = 0, 0.4, and 0.7.

sRA	ADC: *bD*	ADC: hi/lo	sRA: *bD*	sRA: hi/lo	angle: *bD*	angle: hi/lo			opt *bD* (10% range)	opt hi/lo
0	1.28	3.6	1.00	>100	1.0	∞		ADC	0.95 (0.88-1.05)	3 (1.3-8)
0.4	1.02	3.2	0.83	7.8	0.8	∞		sRA	0.8 (0.63-0.96)	8 (4.8-13.6)
0.7	0.80	2.9	0.73	4.4	0.7	∞		angle	0.8 (0.7-0.9)	∞ (>4.8)

Note: The optimum values of bD and hi/lo decrease 10-20% when T_2 effects are considered.

Conclusion

The use of bD = 0.7–0.9 ($b \approx 1000$ for human brain) and hi/lo = 5-8 (higher for eigenvectors) should yield nearly optimum results for most applications. Optimum hi/lo is ~3 for ADC and 5-12 for sRA. The bD should decrease with anisotropy, increase for ADC.

References

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