Optimal b-values distribution for biexponential DWI of prostate

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Authors: J. Jarvinen, I. Jambor, M. Pesola, H. Aronen; Turku/FI
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Purpose

Diffusion weighted imaging (DWI) is a promising tool in detection and management of prostate cancer which remains the most common cancer among men in developed countries [1]. Apparent diffusion coefficient (ADC), calculated from DWI data assuming monoexponential decay, increases accuracy of prostate cancer detection and correlate with Gleason score [2, 3]. However, the signal decay curve obtained using stronger motion probing gradients (b-values up to 3000 s/mm$^2$) is better described by biexponential fit in the healthy prostate [4] and prostate cancer [5].

Acquisition protocol for DWI, particularly number and distribution of b-values, has varied greatly among researchers [eg. 2, 3, 6]. Optimization of data collection and robust estimation of diffusion properties is crucial for achieving the best diagnostic performance of DWI.

The aim of this study was to find optimal b-value distribution for biexponential DWI of prostate, including fast and slow components of DWI.
Methods and Materials

In all simulations, signal intensity decay curves of prostate were calculated according to biexponential decay function (eq.1):

\[ \frac{S(b)}{S(0)} = (1-f) \cdot \exp(-b \cdot Ds) + f \cdot \exp(-b \cdot Df), \] (eq.1)

where \( f \) is fraction of fast diffusion, \( Ds \) is slow component of diffusion and \( Df \) is fast component of diffusion. Literature values [4] , \( f = 0.74 \), \( Df = 0.00252 \), \( Ds = 0.00023 \), were used to simulate signal intensity decay curves of biexponential DWI of normal prostate tissue. To create a noise model, two components of Gaussian noise with the same standard deviation (STD) were added to the signal to simulate a Rician distribution (eq. 2):

\[ r(b) = \sqrt{\left( s(b) + n_1(b) \right)^2 + n_2(b)^2}, \] (eq.2)

where \( r \) is the total signal value, \( b \) is the b-value and \( n_1 \) and \( n_2 \) are the two noise STDs. In all simulations, the two noise STDs were assumed to be the same.

After adding the noise, all signal values were normalized by the first signal value \( S(0) \). The parameters \( f \), \( Df \) and \( Ds \) were fitted to the noisy signal curve using non-linear least square curve fitting with constraints. The constraints (\( f = 0.6 \) to 0.9, \( Ds = 0 \) to 0.004 and \( Df = 0 \) to 0.01) were set based on the literature values to improve convergence of total error (\( E_{tot} \)) calculated by summing the relative errors of the three fitted parameters.

To define convergence, the standard deviation of last 100 total errors was calculated. When this standard deviation became lower than defined limit, referred as convergence criterion, the calculation was considered to have converged. All simulations were performed using MATLAB (Mathworks Inc.,Natick,MA,USA).

The following three methods were used to generate optimal b-values distribution:

1. B-values were added consequently to the initial three b-values. To increase the amount of b-values all possible new combinations were examined and calculations were carried out until the convergence of the total error was reached. The combination with the smallest converged total error was chosen as the new optimal distribution.

2. Starting with 41 b-values, the number of b-values was consequently decreased. Similarly to 1st method, each possible new combination was examined. The combination which increased the total error the least was chosen as the next optimal combination.
3. Iteratively moving the found optimal b-values stepwise. The iterative algorithm consists of following steps:

1. Calculate the total error of initial distribution found by 1st method.
2. A stepwise change of 50 was attempted for each b-value starting with the lowest b-values. Values above 2000 were not accepted and minimum distance of 50 was applied.
3. If the new total error is smaller than the initial one, assume the new distribution as the best distribution and continue changing the b-value in the same direction.
4. If the position of the b-value is more favourable than that of its neighbours, move to the next b-value.
5. After all b-values are tested, the algorithm is reset to 2nd step but this time beginning with the highest b-value.
6. If no b-values are changed, the algorithm returns to the initial attempt in 2nd step, but the direction of the change is reversed and the magnitude of the step is increased by 50.
7. The algorithm stops when no b-value can be changed by the amount of the changing step.

The following conditions were kept the same for all methods: the first three b-values were 0, 50 and 100 s/mm$^2$ and the optimal distribution of 13 additional b-values was calculated. The highest b-value was 2000 s/mm$^2$ and minimum distance between b-values was 50. The minimum distance also defined the minimum step used for the iterative method.

To assess signal to noise ratio (SNR) dependence of the optimal b-value distribution, four different levels of Rician noise with standard deviation of 0.1, 0.02, 0.01 and 0.001 were applied to signal intensities. Initial values for the iterative method were chosen based on the results from 1st method. Total errors were compared using One-way ANOVA with Bonferroni Multiple Comparisons [7]. P-values below 0.05 were considered statistically significant.
Results

Histograms of the optimal b-value distribution obtained using all three methods for 16 b-values are shown in Figure 1. The optimization process was repeated at least 10 times. All of the applied optimization methods resulted in b-value distributions forming three separate clusters (Figure 1). Optimal b-value distribution depended on STD of noise applied to simulated signal. Lower STD of noise added to the simulated signal resulted in more b-values in the upper range of b-values. Moreover, the middle cluster moved toward the higher b-values.

Fig. 1: Histograms of optimal b-value distributions for 1st, 2nd and 3rd method. Applied noise standard deviations were 0.1, 0.02, 0.01 and 0.001. The histograms contain at least 10 measurements. The parameters used in optimization process were f = 0.74, Df = 0.00252, Ds = 0.00023.

References: Department of radiology, VSSHP/SAPA/VSKK - Turku/FI

Figure 2 shows box and whisker diagrams for mean $E_{tot}$ with P-values. Table 1 summarizes mean $E_{tot}$ at all noise levels for both parameter sets. As can be seen in Figure 2, mean $E_{tot}$ was the lowest for 1st method at lower SNR while distributions obtained by 3rd method outperformed the other methods at higher SNR’s with p-values of less than 0.05.
Fig. 2: Box and whisker diagrams for the mean $E_{tot}$ at noise standard deviations of a) 0.1, b) 0.02, c) 0.01 and d) 0.001. The boxes show median, upper and lower quadrants for the total error $E_{tot}$. The lines from the boxes show 95% confidence intervals for the total error. One-way ANOVA with Bonferroni multiple comparison was used to calculate the p-values.

References: Department of radiology, VSSHP/SAPA/VSKK - Turku/FI
Table 1: Mean total errors for all methods and parameter sets at noise level standard deviations of 0.1, 0.02, 0.01 and 0.001.

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Conclusion

We simulated optimal b-value distributions for biexponential DWI of prostate and demonstrated the effect of SNR on the optimal b-value distribution, which was shown to be the clustered distribution with values concentrated in the low, mid and high ranges.
References
