# Evaluating Effects of Diffusion Weighting Choice on Accuracy of Diffusion Tensor MRI of Fixed Mouse Spinal Cord

D. H. Laidlaw, Brown University Computer Science, Providence, RI, USA.
K. L. Cook, Y. M. Goldfeld, Caltech Biological Imaging Center, Pasadena, CA, USA.

**Introduction** A Diffusion Tensor Image (DTI) is calculated from a set of Diffusion Weighted Images (DWI's). Our goal was to find a set of DWI's that could be acquired with the lowest signal-to-noise ratio (SNR) possible while still bounding the error in a resulting DTI. We simulated DWI acquisitions and present estimates of the accuracy of DTI calculations for several possible sets of DWI's. One set, newly reported, achieves better results than others tested.

For each set of DWI's we evaluated the SNR necessary to keep tensor measurements accurate to within 5%, 10%, or 20%. We are interested in imaging fixed neural tissue, and so we estimated error in the calculated principal diffusion rates for three materials:

| Principal Diffusion Rates ($10^{-6}\mathrm{mm}^2/\mathrm{s}$) | | | |
|---|---|---|---|
| water | 2000 | 2000 | 2000 |
| gray matter | 230 | 230 | 230 |
| white matter | 560 | 120 | 120 |

The water rates are approximate. The tissue rates are measured in fixed samples of mouse spinal cord at $8^\circ$ C [1]. Errors in the calculated DTI's were estimated relative to the average diffusion rate for each material.

**Methods** For each candidate set of DWI's, we simulated images of the three materials at different noise levels. We found the noise level at which the error in the calculated DTI was less than 5%, 10%, and 20% for all three materials. The diffusion weighting in each of our simulated images came from a matched pair of square gradient pulses 2.5 ms in duration and 8 ms apart (start to start). As an example, a 10 G/cm magnitude pair of pulses produces a diffusion weighting (so called b-matrix value [2]) of 737 $\mathrm{s/mm^2}$[3, 4]. The magnitude of each pulse, a 3D vector, varied for each DWI. For simplicity, we ignored diffusion effects of imaging gradients, although our software can easily incorporate them. The imaging parameters (gradient durations, spacing, and magnitude) were chosen for our 11.7 T imaging system. For other imaging regimes parameters leading to essentially identical diffusion weighting can be calculated and will produce identical simulated error results.

Our initial candidate set of DWI's was chosen with maximum b-matrix diffusion-weighting elements on the order of 2000 $\mathrm{s/mm^2}$ [1]. We arranged our other approaches around this value by varying the maximum diffusion weighting and the distribution of diffusion weightings. Each of our candidate sets of DWI's has 28 members defined by 28 3D vectors. With a constant number of images acquired, each candidate set of DWI's requires identical imaging time and results can be easily compared. A vector represents the diffusion weighting as described above. The first candidate set consists of the 7 vectors $(1, 0, 0)$, $(0, 1, 0)$, $(0, 0, 1)$, $(1, 1, 1)$, $(-1, -1, 1)$, $(1, -1, -1)$, and $(-1, 1, -1)$ each scaled by 2.5 G/cm, 5 G/cm, 7.5 G/cm and 10 G/cm. We name this set "septa-10" for the seven directions and the maximum 10 G/cm gradient strength. Set "septa-20" has the same 28 elements but a maximum gradient strength of 20 G/cm. Similarly, "septa-30," "septa-40," and "septa-50" have maximum gradient strengths of 30 G/cm, 40 G/cm, and 50 G/cm, respectively. "septa-40-low" uses the same directions, but changes the spacing of the gradient strengths to cluster closer to 0: 5 G/cm, 10 G/cm, 20 G/cm, and 40 G/cm. "septa-40-high" again uses the same directions, but changes the spacing of the gradient strengths to cluster closer to the maximum value: 20 G/cm, 30 G/cm, 35 G/cm, and 40 G/cm.

Another candidate set of DWI's was also tested. The points were chosen randomly to be approximately uniformly distributed on the 2-sphere and distributed radially from 0-30 G/cm as follows. First, a nearly-uniform radial distribution is found. All radii are then squared to cluster the values nearer 0. This distribution is named "sph-30-2." The vectors are: $(0.6265, -14.6624, -8.6531)$, $(8.2561, -11.1706, -0.2143)$, $(-17.2854, 6.2301, -9.2034)$, $(-3.7998, 4.1036, 10.9711)$, $(-4.6618, -6.0758, -12.6152)$, $(-0.1316, -8.3505, -0.7308)$, $(-16.0012, 1.0531, 9.2667)$, $(-11.6077, -11.2239, 22.2324)$, $(-1.7741, -0.2991, 0.3998)$, $(-3.5474, 4.2673, -4.3507)$, $(1.0486, -2.7996, 1.2936)$, $(0.0858, 0.0488, -2.6339)$, $(21.4388, 14.3474, 0.5298)$, $(-3.9190, 2.0213, 3.7151)$, $(-3.4427, -9.6250, 5.0479)$, $(-3.2879, -2.6234, -1.8800)$, $(0.3218, -0.2476, 0.0919)$, $(-7.7384, -3.4836, 4.7320)$, $(5.0112, -7.3550, 21.9010)$, $(2.8439, 0.2325, 4.2236)$, $(-1.8289, 1.1295, 0.3989)$, $(-0.3094, -0.5254, 0.0217)$, $(10.5116, -0.5686, 1.0100)$, $(-0.5879, -0.0551, 0.6892)$, $(0.0220, 0.1537, -0.1661)$, $(1.5739, -3.1228, -2.1412)$, $(0.7332, -0.3235, 0.8582)$, $(0.6492, 1.0699, 0.9240)$,

**Results** For each set of DWI's we estimated the noise level necessary to calculate diffusion rates with error smaller than a specific value. We converted noise to SNR based on the signal for water in a non-diffusion-weighted image. The SNR will be lower images with diffusion weighting.

| | SNR for | | |
|---|---|---|---|
| DWI set | $<$ 5% error | $<$ 10% error | $<$ 20% error |
| septa-10 | 546 | 266 | 134 |
| septa-20 | 312 | 163 | 87 |
| septa-30 | 320 | 163 | 86 |
| septa-40 | 601 | 288 | 149 |
| septa-50 | 1913 | 968 | 410 |
| septa-40-high | >3000 | >3000 | >3000 |
| septa-40-low | 306 | 136 | 69 |
| sph-30-2 | 249 | 127 | 67 |

The SNR levels are unachievably high in many cases, particularly for *in vivo* application. However, the results appear consistent for different choices of error level, suggesting that the relative ranking of candidate sets of DWI's may be valid more broadly.

**Conclusions** Accuracy of DTI's is dependent on the choice of DWI's. For the 7-direction "septa" cases we evaluated, a maximum gradient strength of 20-30 G/cm (corresponding to b-matrix values of 2900-6600 $\mathrm{s/mm^2}$) produces the most accurate DTI's for fixed neural tissues and water at $8^\circ$ C. Geometrically distributing the gradient values closer to 0 also increases the accuracy of the resulting DTI's. For eacherror level, the best results balance the error levels for the different materials. For example, smaller maximum gradient strengths work better for water and larger maximum gradient strengths work better for neural tissue, and so a range of weightings appropriate for all materials is important. Finally, the "sph-30-2" set of DWI's performed better than any of the "septa" cases, particularly for the lower-error cases.

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**References**

[1] E. T. Ahrens, D. H. Laidlaw, C. Readhead, C. F. Brosnan, S. E. Fraser, and R. E. Jacobs, *Magn. Res. in Med.*, 40(1), 119–132, 1998.

[2] D. L. Bihan, *Diffusion and Perfusion Magnetic Resonance Imaging – Application to Functional MRI*, 1968.

[3] P. J. Basser, J. Mattiello, and D. Lebihan, *J. Magn. Res. B*, 103, 247–254, 1994.

[4] J. Mattiello, P. J. Basser, and D. LeBihan, *J. of Magn. Res. A*, 108, 131–141, 1994.

# References

[1] E. T. Ahrens, D. H. Laidlaw, C. Readhead, C. F. Brosnan, S. E. Fraser, and R. E. Jacobs, "MR microscopy of transgenic mice that spontaneously acquire experimental allergic encephalomyelitis," *Magnetic Resonance in Medicine*, vol. 40, no. 1, pp. 119–132, 1998.

[2] D. L. Bihan, *Diffusion and Perfusion Magnetic Resonance Imaging – Application to Functional MRI*. New York: Raven Press, 1968.

[3] P. J. Basser, J. Mattiello, and D. Lebihan, "Estimation of the effective self-diffusion tensor from the NMR spin-echo," *J. Magnetic Resonance B*, vol. 103, pp. 247–254, Mar. 1994.

[4] J. Mattiello, P. J. Basser, and D. LeBihan, "Analytical expressions for the b matrix in NMR diffusion imaging and spectroscopy," *Journal of Magnetic Resonance, Series A*, vol. 108, pp. 131–141, 1994.