ROBUST MAXIMUM LIKELIHOOD ESTIMATION IN *Q*-SPACE MRI

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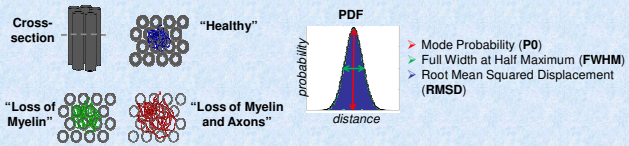
ABSTRACT

Q-space imaging is an emerging diffusion weighted MR imaging technique to estimate molecular diffusion probability density functions (PDFs) without the need to assume a Gaussian distribution. We present a robust M-estimator, Q-space Estimation by Maximizing Rician Likelihood (QEMRL), for diffusion PDF's based on maximum likelihood. PDFs are modeled by constrained Gaussian mixtures. In QEMRL, robust likelihood measures mitigate the impacts of imaging artifacts. In simulation and in vivo human spinal cord, the method improves reliability of estimated PDF's and increases tissue contrast. QEMRL enables more detailed exploration of the PDF properties than prior approaches and may allow acquisitions at higher spatial resolution.

Q-SPACE MRI

- The Brownian motion of water within a voxel is noninvasively inferred from signal attenuations observed in the presence of sensitization gradients.
- The degree of attenuation (and motion) reflects the intra-voxel cyto-architecture.



- Rather than assuming a Gaussian distribution for the water diffusion probability density function (PDF) as in diffusion tensor imaging (DTI), q-space analyses experimentally determine non-parametric PDFs for single diffusion directions.
- The PDF represents the probability that a spin (i.e., water hydrogen) diffuses a particular distance from its initial position during the DW time.

"Long-time Limit":

- With impermeable membranes and infinite diffusion time, the propagator becomes the autocorrelation of the restriction geometry (zero phase).

In practice for the CNS:

- Exchange is slow relative (100-600 ms) to diffusion time
- Diffusion characteristic distances (~10 μm) are greater than the spacing of cellular membranes (1-5 μm)

MRI ACQUISITION

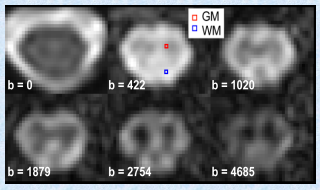
Attenuation Equation

$$S(q,\Delta) = S_0 \left| \int \mathbf{P}(\mathbf{r}-\mathbf{r}_0, \overbrace{\Delta}^{\text{Time}})^{\overbrace{\text{Motion}}} e^{j2\pi q r} dr \right| \approx \mathcal{F}^{-1}(P(r-r_0,\Delta))$$

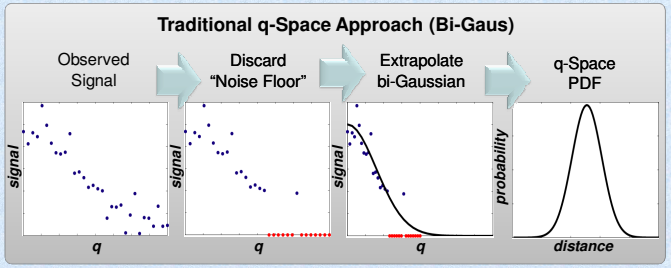
Observed · Reference · Propagator · Phase

- Axial diffusion weighted images acquired with SS-EPI, 1.3x1.3x3.0 mm, SENSE=1.8, TR/TE=7000/106 ms.
- Two orthogonal directions perpendicular to the spinal cord with 32 linearly spaced q-values (0 to 414 cm^{-1})
- Total acquisition time was 10 minutes

Representative Images

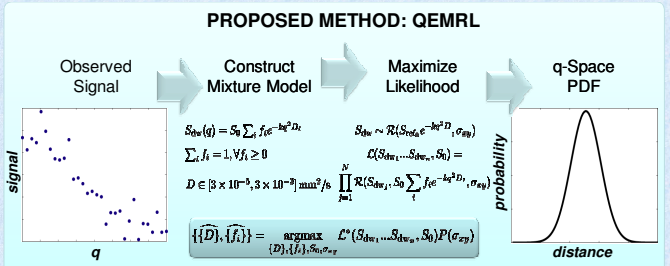


METHOD



Challenges with Traditional Approaches

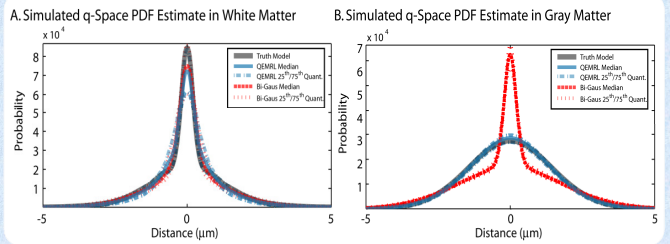
- Ad hoc "Noise Floor" Criteria
- Strict Model Fitting
- Rician distributed observations
- Bias at low SNR
- Inability to image *in vivo* at high q
- Susceptibility to artifacts



- Use truncated likelihood to reduce the impact of imaging artifacts
- Use L-curve criterion to adaptively select the number of mixture components

SIMULATIONS

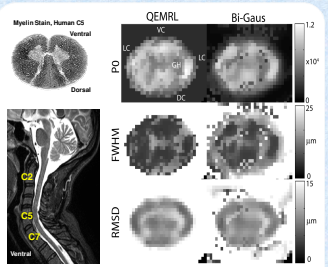
- Simulations were performed with two-component exponential mixtures (with diffusivities drawn at random from 3x10^{-5} to 3x10^{-3} mm^2/s).
- Each simulation consisted of two repetitions of 32 data points that linearly spanned the signal decay curve from q=0 to 400 cm-1 at an SNR of 7:1 on the q=0 images.
- Overall, QEMRL reduced the median MSE on the estimated PDF by 95%.
- In simulated white matter, QEMRL offered less of an improvement (21%) (Panel A).
- In simulated gray matter, QEMRL resulted in an improvement (98%) (Panel B).



IN VIVO SPINAL CORD

Validation

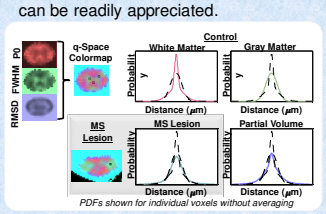
- Four repetitions of a standard q-space sequence were acquired for a healthy volunteer on a 3T Philips MR scanner (covering C2 to C6).
- QEMRL reduced the mean variability of estimated PDF's by 30% over the traditional (Bi-Gaus) method.
- The adaptive model order selection procedure identified 3:6±1:1 mixture compartments per voxel.
- QEMRL more clearly revealed GM/WM contrast in the cervical spinal cord in the P0, FWHM, and RMSD contrasts.



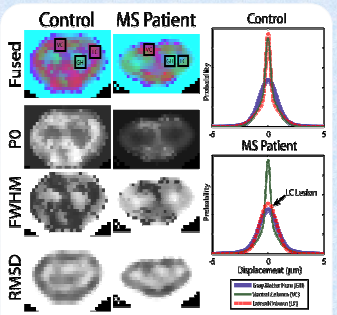
QEMRL increases contrast between the gray matter horns (GH) and the spinal cord white matter, include the lateral (LC), dorsal (DC), and ventral (VC) columns.

Multiple Sclerosis (MS)

- Results for a representative slice for the healthy control show that PDFs in WM are tall and narrow, whereas PDF's in GM are low and broad.
- MS lesions show abnormal height and shape of PDFs; however, quantitative analysis of the PDFs is complicated by the high dimensionality.
- Differences between narrow and wide PDF's and the presence of heavy tails can be readily appreciated.



PDFs shown for individual voxels without averaging



Slices at the level of C4 are shown for a control (left) and a MS patient with a LC lesion (center). Mean PDFs within the indicated regions are presented at right.

DISCUSSION

- **QEMRL improves the accuracy and reliability of PDFs derived from q-space by accounting for the Rician noise properties in magnitude images.**
- **Furthermore, QEMRL estimates a projection of PDFs onto a finite basis set, which has a physical interpretation as the mixture of diffusion compartments and may be useful as a biomarker for micro-structural changes**

ACKNOWLEDGEMENTS / REFERENCES

This work was supported by NIH/NCRR P41RR15241; National MS Society CA-1029-A-2; TR-3760-A-3, Nancy Davis Center without Walls, NIH R01 NS056307, and DOD/ONR NDSEGF.

References: Y. Cohen and Y. Assaf, NMR Biomed 15:516 (2002). H. Gudbjartsson and S. Patz, Magn Reson Med 34:910 (1995). J. Sijbers and A. J. den Dekker, Magn Reson Med 51:586 (2004). B. Landman, P-L. Bazin, and J. L. Prince, MMBIA (2007). T. Niendorf, et. al., Magn Reson Med 36:847 (1996). J.A. Farrell, et al., ISMRM, 270 (2007). P. J. Rousseeuw and C. Croux, J. Amer. Statistical Assoc. 88:1273 (1993)