Model-based Bootstrap Resampling Methods for HARDI: Quantitation of ODF Uncertainty without Multiple Acquisitions

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Introduction:

Measurement noise in diffusion MR causes uncertainty in quantitative characterizations of white matter microstructure. These errors have been shown to have consequences for both region of interest based tensor metrics and diffusion tractography. Bootstrap analysis is a non-parametric statistical method of data resampling to generate many data sets from a limited number of real data acquisitions. Prior studies have examined the accuracy of repetition bootstrap resampling and residual model-based resampling methods in determining uncertainties in DTI parameters [1,2]. This work extends these methods to the problem of assessing uncertainty in q-ball reconstruction from high angular resolution diffusion imaging (HARDI) data [3,4]. Residual model-based resampling methods, which only require one image set acquisition, are of particular interest, as the acquisition of multiple HARDI data sets is too time consuming to be feasible for routine scientific and clinical applications. In this study, repetition resampling and residual model-based resampling estimates for uncertainty are compared with a gold-standard through Monte Carlo simulation.

Methods:

Simulated Data: A two-fiber population noiseless signal S(**q**) was simulated with two diffusion tensors with fractional anisotropy of 0.8, $\mathbf{D}_1$ and $\mathbf{D}_2$, separated by 90 degrees: $S(\mathbf{q}) = S_0 e^{(-b\mathbf{q}\mathbf{D}_1\mathbf{q}^{\mathrm{T}})} + S_0 e^{(-b\mathbf{q}\mathbf{D}_2\mathbf{q}^{\mathrm{T}})}$, with b=3000 s/mm^2, and **q** covering 55 gradient directions derived from electrostatic repulsion. Rician noise is added to generate a noisy signal with SNR=10. The orientation distribution function (ODF) and generalized fractional anisotropy (GFA) were calculated using the q-ball method and a spherical harmonic basis truncated at order 4 [3,4]. ODFs were constructed on 642 directions from an order 3 icosahedral tessellation of the sphere. The uncertainty of each ODF element, ODF(i), i=[1:642], and the GFA was measured. The standard deviations of these ODF parameters were calculated from ODFs constructed from 500 resamples. The simulation was run 100 times to determine the distribution of standard deviations for each resampling method. For a gold-standard experiment, 10000 noisy data sets were constructed and the standard deviations calculated directly from 10000 ODFs. To compare repetition resampling methods to residual model-based methods, three repetitions were used for all simulations.

Repetition Methods: The repetition bootknife and repetition bootstrap methods require 2 or more HARDI acquisitions. Repetition bootknife randomly omits one of n repetitions and randomly selects n from the n-1 samples remaining to comprise a resampled data set. Repetition bootstrap does not omit any repetitions.

Residual Methods: The residual bootstrap [1] and wild bootstrap [5] methods are based on a single HARDI acquisition. The noisy data are fit to a fourth order SH model. Residuals are calculated as the difference between the raw noisy data and the fitted model. Uncertainty is introduced in the wild bootstrap by randomly multiplying the residual for each gradient direction by the two-point Rademacher distribution and adding the result to the fitted data. For residual bootstrap, resampled data sets are created by randomly choosing a residual with replacement from the set of all signal residuals and adding the chosen residual to the signal.

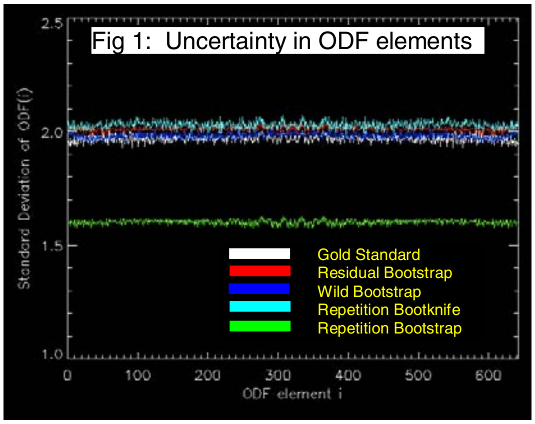


Fig 1: Uncertainty in ODF elements

Results:

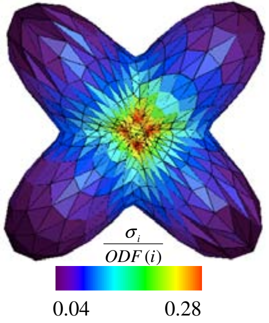
The table shows the bias of each resampling method's estimate of the GFA uncertainty. Both residual methods (residual bootstrap and wild bootstrap) and the repetition bootknife provide uncertainties within 3% of the gold-standard uncertainty. The repetition bootstrap underestimates the uncertainty of the GFA by 20.8%. Figure 1 shows that the repetition bootstrap also underestimates the uncertainty of the individual ODF elements. Figure 2 shows the radial distribution of uncertainty in ODF elements normalized by the magnitude of ODF(i) as predicted by the residual bootstrap method. The ODF peaks which indicate the fiber population orientation have the lowest percent uncertainty.

Discussion/Conclusion:

Model-based residual bootstrap methods can adequately estimate the uncertainty of the q-ball ODF. The repetition bootstrap method is downward biased in its estimate of uncertainty as has been previously shown for DTI [1]. Model-based resampling methods can be applied to single HARDI acquisitions and used for probabilistic fiber tracking applications.

Bias of Uncertainty in GFA as compared to the Gold Standard	
Residual Bootstrap	-0.05% ± 8.5%
Wild Bootstrap	-3.0% ± 8.6%
Repetition Bootknife	+1.5% ± 13.3%
Repetition Bootstrap	-20.8% ± 7.3%

Fig. 2: ODF Uncertainty



References:

1) Chung, S., et. al. Neuroimage. Nov 2006, 33(2):531-41.
2) Jones, DK. MRM 49: 7-12, 2003
3) Hess, C P., et. al. MRM. Jul 2006, 56(1):104-17.
4) Tuch, DS. MRM. 2004, 52:1358-1372.
5) Whitcher, B. ISMRM, Miami Beach, 2005. pg. 1333.