Introduction to Diffusion Tensor Imaging

http://csci.ucsd.edu/courses/cogs260w2018/

Prof Larry Frank
lfrank@ucsd.edu
Lecture 1
Introduction and Class Outline
Exploring the Brain

The Three Pillars of MR Neuroimaging

Anatomical  Diffusion  Functional
Lecture Summary

1. Why are you here?
2. Class Objectives
3. Course outline
4. Lab Lectures (AFNI & QUEST)
5. Term Project
6. Grading
7. Readings
Frontal circuitry degradation marks healthy adult aging: Evidence from diffusion tensor imaging

Adolf Pfefferbaum, Elfar Adalsteinsson and Edith V. Sullivan

*Neuroscience Program, SRI International, USA
†Department of Psychiatry and Behavioral Sciences, Stanford University School of Medicine, 401 Quarry Road, Stanford, CA 94305, USA
‡Department of Electrical Engineering and Computer Science, MIT, Cambridge, MA 02139, USA
§Harvard-MIT Division of Health Sciences and Technology, MIT, Cambridge, MA 02139, USA

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The Problem

**MRI and DTI acquisition protocol**

The DTI-structural acquisition and analysis incorporated correction of spatial distortion due to main field \((B_0)\) inhomogeneity. MRI data were acquired on a 3-T General Electric (Milwaukee, WI) Signa human MRI scanner (gradient strength = 40 mT/m; slew rate = 150 T/m/s; software version VH3). The following four sequences were collected:

(a) Structural fast spin echo (FSE; FOV = 24 cm, TR = 10,000 ms TE = 14/98 ms, thick = 2.5 mm, skip = 0, slice locations = 62);

(b) Inversion Recovery Prepared Spoiled Gradient Recalled echo (IRPrepSPGR; FOV = 24 cm, TI = 300 ms, TR/TE = 6.5/1.54 ms, thick = 1.25 mm, slices = 124);

(c) Diffusion Tensor Images (DTI; FOV = 24 cm, TR = 11,000 ms TE = 97.6 ms, thick = 2.5 mm, skip = 0, slice locations = 62, 0 (8 NEX) + 6 non-collinear diffusion directions (4 NEX, gradient orientations \(+x \ +y \ +z, +x \ +z, -x \ +y, -y \ +z, +x \ -z\) with a repeat of these six orientations with opposite gradient polarity, 1.45 Gauss/cm with 32 ms duration and 38 ms separation, resulting in a \(b\) value of 860 s/mm\(^2\), x-dim = 96, y-dim = 96, 3472 total images);

(d) Fieldmap (FOV = 24 cm, multislice, dual echo, single-shot spiral acquisition, x-dim = 128, y-dim = 128).

The SPGR data were aligned such that two 1.25-mm slices subtended each 2.5 mm thick FSE and DTI slice with custom scanner prescription software, which computed precise slice locations. The data from the spiral acquisition for each echo were gridded and Fourier transformed, and a fieldmap was estimated from a complex difference image between the two echoes (Pfeuffer et al., 2002).
DTI analysis

DTI quantification was preceded by eddy current correction using a template made from an average image created across all gradient directions and a 2-D, 6-parameter affine warp on a slice-by-slice basis (Woods et al., 1998). Using the field maps, $B_0$-field inhomogeneity-induced geometric distortion in the eddy current-corrected images was corrected with FUGUE (FMRI’s Utility for Geometrically Unwarping EPIs) (Jenkinson, 2003). Next, the $b = 0$ images were warped to the late echo FSE images in 3-D, first with a 12-parameter affine, followed by stepwise 2nd and 3rd order polynomial functions. This transformation was then applied to all $B_0$ field-corrected and eddy current-corrected averaged images (Fig. 1). Finally, using the corrected images, $b = 0$ and $b = 860 \text{ s/mm}^2$, 6 maps of the apparent diffusion coefficient (ADC) were calculated.

Solving 6 simultaneous equations with respect to ADCxx, ADCxy, etc. yielded the elements of the diffusion tensor. The diffusion tensor was then diagonalized, yielding eigenvalues $\lambda_1$, $\lambda_2$, $\lambda_3$, as well as eigenvectors that define the predominant diffusion orientation. Based on the eigenvalues, the fractional anisotropy (FA) and bulk mean diffusivity (the mean of the eigenvalues, $<D>$) were calculated on a voxel-by-voxel basis (Basser and Jones, 2002; Basser and Pierpaoli, 1998; Pierpaoli and Basser, 1996).
The Problem

Fiber tract mapping and extensions of DTI

In fact, diffusion tensor imaging (DTI), as is used by our diffusion-based tracking method, is unable to truly resolve the crossing of multiple axon directions within a single voxel [11], [39]–[41]. Despite the fact that the information captured from DTI is limited by the second-order tensor model it applies, which assumes water molecules follow Gaussian diffusion in biological tissues, the tensor formalism is well accepted and its attributes can be obtained in a straightforward way. Furthermore, the macroscopic theory of Gaussian diffusion is modeled by Fick’s first law (see (1)), which makes simulating the diffusion process by solving the diffusion equation (2) a natural fit-in to obtain information of the underlying fiber structure and connectivity. For those reasons, the tracking algorithm based on diffusion simulations is implemented to use the DTI data, which needs to be fed into the corresponding diffusion equation (2). Essentially, most existing tracking techniques are banking on the diffusion tensor framework. However, it has been suggested to get around the inadequacy presented in DTI by using newly developed imaging approaches, like high angular resolution diffusion imaging (HARDI) [39]–[42], q-space imaging (QSI) [43], [44], or generalized diffusion tensor imaging (GDTI) [45], [46]. An outstanding feature of the fiber reconstruction method using diffusion simulations is that it can be seamlessly adapted to a platform established by the new imaging techniques.
The Goal

Understand the basic “standard method” and its limitations
Tractography

Standard DTI
The Goal

By end of class, have a *working* knowledge of the state-of-the-art method
Course Logic

- Preliminary Mathematics
- Diffusion
- MRI
- MRI diffusion sensitivity
- Diffusion weighted imaging (DWI)
- DWI analysis
Course Logic

Preliminary Mathematics

Basic structures
Scalors, Vectors
Matrices, Tensors
Complex Numbers

Transformations
Rotations
Fourier Transforms

Linear Algebra
Least squares
Eigensystems
Course Logic

Diffusion

Classical Diffusion

Flux, concentration, continuity diffusion equation

Probability theory

Random walk diffusion equation
Course Logic

MRI

NMR

signal creation and detection

Spatial localization

Gradients
Fourier reconstruction

Image formation (MRI)

Pulse sequences
Fourier reconstruction
Course Logic

MRI diffusion sensitivity

diffusion in gradients

DTI

diffusion weighting, sampling

signal loss
Course Logic

- DWI analysis
  - DWI pre-processing
  - Standard DTI
  - Heterogeneous voxel DWI (State-of-the-art)
  - distortion correction
  - image registration
  - diffusion tensor
  - anisotropy
  - tractography
  - DWI-ESP
  - anisotropy
  - tractography
By the time we get to standard Diffusion Tensor Imaging, it will seem obvious, ... an assemblage of parts you already know
Our ultimate goal, however, is to learn

**DWI-ESP**

A new method
More complicated, but worth it!
The Goal

anisotropy

tractography
CFMRI Autism Study

in collaboration with the lab of Dr Axel Mueller
Lab Lectures

The two lab lectures will focus on getting practical experience with the QUEST platform.

Requirement

AFNI and the QUEST Plugin must be working onto your computer prior to these lectures. Thomas will assist people who need help with this.
Lab Lectures

https://afni.nimh.nih.gov
Lab Lectures
The Three Pillars of Neuro-MRI

Morphology

Connectivity

Function

SWD

DTI-ESP

FMRI-ESP
Term Project

Write a review paper on an application of DTI relevant to your interests

• Importance of your application
• Why DTI is useful for your application
• Review and critique of 5 (min) related papers
• Summary of current status of field
Grading

40% attendance
30% homework
30% final project
Office Hours

Wed 12-2
La Jolla Village Professional Center
(behind Rock Bottom Brewery)
Suite B227

My contact in: lfrank@ucsd.edu