3D Brain Mapping for Neurosurgery

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National Alliance for Medical Imaging,
Neuroimage Analysis Center
Clinical Case
Clinical Case

- A 47-year old patient with previous surgery for low grade glioma
- Gradual radiographic recurrence of his tumor
- Professional golfer
T1 and T2 anatomical scans
Pre-operative Planning

- Gliosis
- Tumor
- Motor cortex
Neurosurgery Challenges

- Lack of visible landmarks that would indicate safe passage to deep structures
- Abundance of eloquent areas and major blood vessels
- Rigidity of the skull and dura

Image courtesy of Arya Nabavi, MD
Neurosurgical Planning

Goal: Help Maximize the extent of the tumor resection while preserving eloquent white matter tracts involved in motor, vision and language function.
Structural MR data

T1 and T2 imaging

3D location and shape of the tumor
What does the clinician want to see?

• Where are the eloquent white matter tracts?
• Are they normal?
• Are they symmetric?
• Is anything missing?
• Are they functional?

Dr. Alexandra Golby, BWH
dMRI pre-operative

Diffusion MR scan
31 gradient direction
1 baseline
(GE Excite 3T Scanner)
Diffusion MR tractography

Diffusion imaging

3D location and shape of trajectory of major fiber bundles
Diffusion MRI Tractography
White Matter Exploration

White matter appears homogeneous on T1 and T2 MR Imaging
Diffusion MR Imaging Data

• First non-invasive window on the organization of the brain white matter pathways
• Measurement of the diffusion of water molecules along axons
Diffusion MR Tensor Imaging

\[ S_i = S_0 e^{-b\hat{g}_i^T D \hat{g}_i} \]

Stejskal-Tanner (1965)

\[
D = \begin{bmatrix}
D_{xx} & D_{xy} & D_{xz} \\
D_{yx} & D_{yy} & D_{yz} \\
D_{zx} & D_{zy} & D_{zz}
\end{bmatrix}
\]
Diffusion Tensor

- The diffusion tensor $\mathbf{D}$ in the voxel $(I,J,K)$ can be visualized as an ellipsoid, with the eigenvectors indicating the directions of the principal axes, and the square root of the eigenvalues defining the ellipsoidal radii.

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$
Diffusion Tensor Shape

\[ \lambda_1 = \lambda_2 = \lambda_3 \]

\[ \lambda_1 \gg \lambda_2, \lambda_3 \]

\[ \lambda_1 \sim \lambda_2 \gg \lambda_3 \]

Isotropic media (CSF, gray matter)

Anisotropic media (white matter)
DT-MRI Tractography
Tract Tracing
Tract Tracing
DTI Tractography
DTI as a Neuroimaging marker

- Visualization of *in-vivo* normal and pathological anatomy
- Insights into white matter abnormalities which may include changes in direction, radial displacement or diameter of white matter fiber bundles
Tractography findings

- Spatial relationship between the tract and the tumor
- Demonstration of tract displacement
- Assessment of tumor infiltration
Clinical Case

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DTI Tractography

Corticospinal Tract (CST)
Current Limitations

• DTI tracts provide a mathematical representation of the underlying white matter anatomy.

• Each voxel contains hundreds of thousands of axon fibers: voxel ~ 1-5 mm vs axon ~ 0.1-10 μm

→ A DTI tract is not equivalent to a real fiber.
Challenges in clinical transfer of Diffusion MRI:

Validation of DTI Tractography
A wide variety of tractography techniques has been developed over the past decade (streamline, stochastic, volumetric, two-tensors...)

 Courtesy of J De Siebenthal & CF Westin

 Courtesy of A. Areza & CF Westin

 Courtesy of T.Fletcher & R. Whitaker

 Courtesy of A. Tannenbaum
How to choose?

Neurosurgeons face the challenge of selecting the appropriate tractography method and tract selection strategy.

Need for validation of DTI tractography.
Sources of variability

\[
\ln p(X | \pi, \mu, \Sigma) = \sum_{k=1}^{N} \ln \left( \sum_{i=1}^{K} \pi_i N(x_n | \mu_i, \Sigma_i) \right)
\]
Validation Approaches

- Mathematical Phantoms
- Physical Phantoms
- Histological Studies
- Real Subject Data
Mathematical Phantoms

- Known absolute ground truth
- Freedom of shape design
Mathematical Phantoms

- Known absolute ground truth
- Freedom of shape design
- Freedom of parameter selection

Performance evaluation
Physical Phantom

- Simple/complex tract configurations
- Real MR images
- Variations in voxel size, B-value and SNR

Courtesy of C.Poupon and P.Fillard, LNAO
Animal studies

- Real anatomical structures
- Real physiological conditions
- Correlation histology/DTI findings
- Not applicable to humans

Dauguet et al, MICCAI 2006
Complementary approaches
Our approach

Qualitative and quantitative evaluation of multiple existing tractography methods in the absence of ground truth
How to compare?

Challenge 1: many degrees of variability (patient, MR sequence, tumor location, etc..)
How to compare?

Challenge 2: absence of ground truth
NA-MIC pilot initiative

- Exploratory work initiated by the National Alliance for Medical Image Computing

- Cross-comparison of tractography algorithms on major white matter fascicles on human subject data
Early Implementation: Healthy Subjects

Fiber Tracking
SCI, Utah

GTRACT
Iowa University

Streamline
BWH, Harvard

Volumetric Connectivity
SCI, Utah

Pujol et al. ISMRM 2009
The DTI Tractography Challenge for Neurosurgical Planning
Neurosurgical Case

- A 47-year old patient with previous surgery for low grade glioma
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- Professional golfer
Neurosurgical case

- T1, T2, DWI, DTI
- Pre-segmented tumor regions
- 3D White Matter Surface
DTI Challenge

International initiative to tackle the problem of white matter mapping for neurosurgery

- **Standardized evaluation** of white matter tracts identified through post-processing of Diffusion MR images
- **Real clinical cases** operated on in the AMIGO suite at BWH
- 12 international **tractography teams** and 5 leading **neurosurgeons** participating in MICCAI 2011-2012 DTI Challenge workshop
DTI Challenge Working Group

- Neurosurgeons, neuroradiologists and scientists
- Short-term objective: Standardization effort:
  - Anatomical definitions
  - Diffusion Data
  - Tractography Evaluation
- Long-term goal: Validation of DTI Tractography for neurosurgery
- International teams (USA, Canada, France, Italy, Germany, Turkey, Spain, China)
Neurosurgeons

- **Dr. Alexandra Golby**, Brigham and Women's Hospital, Harvard Medical School, Boston, USA
- **Dr. Arya Nabavi**, University Hospital Schleswig-Holstein, Kiel, Germany
- **Dr. Sandrine De Ribaupierre**, Western University, London, Ontario, Canada
- **Dr. David Fortin**, Sherbrooke University, Sherbrooke, Canada
- **Dr. Francesco Cardinale**, Epilepsy and Parkinson Surgery Centre "Claudio Munari", Milan, Italy
- **Dr. Xiaolei Chen**, PLA General Hospital, Beijing
MICCAI 2011 DTI Challenge, 1st Edition

14th International Conference on Medical Image Computing and Computer Assisted Intervention

DTI Tractography for Neurosurgical Planning: A Grand Challenge

MICCAI 2011 Workshop
Sunday September 18, 9am-6pm
Westin Harbour Castle
Toronto, Canada

Workshop Faculty
Sonia Pujo, PhD, Surgical Planning Laboratory, Harvard Medical School
Ron Kikinis, MD, Surgical Planning Laboratory, Harvard Medical School
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William Wells, PhD, Surgical Planning Laboratory, Harvard Medical School
Carl-Fredrik Westin, PhD, Laboratory of Mathematics in Imaging, Harvard Medical School
Sylvain Gouttard, MSc, The Scientific Computing and Imaging Institute, University of Utah


National Alliance for Medical Image Computing
MICCAI 2011 Workshop

A MICCAI community effort:

- 8 international DTI teams
- 25 participants
- 352 corticospinal tracts generated

http://dti-challenge.org
Welcome to the 2nd edition of the MICCAI DTI Tractography Challenge. The workshop will be held on Monday October 1st, 2012 as part of the 15th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2012).

The 15th International Conference on Medical Image Computing and Computer Assisted Intervention
1-5 October 2012 - Acropolis Convention Center - Nice, France

http://dti-challenge.org
MICCAI 2012 DTI Challenge

- 10 tractography teams
- 5 practising neurosurgeons
- 36 international participants
Patients

- Patient 1: Recurrent/residual anaplastic astrocytoma Grade III
- Patient 2: Oligodendroglioma grade II
- Patient 3: Oligodendroglioma Grade II
- Patient 4: Anaplastic astrocytoma Grade III
DTI Challenge Evaluation

• Quantitative assessment of variability among methods

• Qualitative evaluation by a panel of clinicians and DTI experts using standardized review criteria
### MICCAI DTI Challenge Results

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<th>Team 1</th>
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Workshops findings

- Large intra- and inter-algorithm variability
- Improved results for some of teams from year 1 to year 2

Tractography needs to be used with caution
Bridging the Gap

Two-way bridge between the scientists who create the tractography tools, and the neurosurgeons who will use the tools in the clinics.
The two editions of the DTI Challenge gathered an international group representing 16 leading organizations from USA, Canada, France, Spain, Turkey, Germany, Italy.
Diffusion MR tractography

- DTI Tractography can provide useful information for the pre-operative assessment peritumoral white matter
- Technology needs to be used with caution
- Validation and standardization effort
DTI Tractography for brain tumor treatment planning

Stereotactic Radiotherapy planning

DTI tractography has the potential to help optimize treatment margins by predicting the pattern of microscopic tumor spread

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