fMRI and Tractography in Preoperative Neurosurgical Planning

Ronald L. Wolf, M.D., Ph.D.
University of Pennsylvania Medical Center
Acknowledgements/Disclosures

• Radiology
  • Ragini Verma
  • Birkan Tunc
  • Sumei Wang
  • Paolo Nucifora
  • Elias Melhem

• Neurosurgery
  • Steve Brem, Tim Lucas, Luke Macyszyn, Isaac Chen

• CHOP
  • Jeff Berman

• Funding: NIH R01 NS096606 (PI Verma, R)
• Disclosures: No relevant financial disclosures
Presurgical Mapping

- **Tools**
  - Diagnosis: MRI ± DWI, PWI, MRS
  - Cortical mapping: fMRI, MEG
  - Subcortical mapping: DTI and fiber tracking

- **Practical presurgical mapping**
  - Combined assessment: clinical, MRI, fMRI and DTI, intraoperative mapping
  - Integration into workflow
  - Other problems, pitfalls
Cortical Mapping

BOLD fMRI

MEG

MEG courtesy Erin Simon Schwartz (CHOP)
Deterministic:
Fiber Assignment by
Continuous Tracking
(FACT)
Considerations for Clinical fMRI, DTI

• **fMRI**
  - Activation critical or non-activating region not critical?
  - Reorganization or pseudo-reorganization?
  - Task performance altered by pathologic function like aphasia – better task or functional connectivity?

• **DTI**
  - Interruption potentially more devastating
  - Are all “fibers” tracked eloquent (and those not tracked)?
  - Performance not an issue (except for motion)

• **Pathophysiology alters performance of both**
  - Cells, necrosis, hemosiderin, edema, metal, motion
  - Altered hemodynamic response, diffusion, signal, noise
Presurgical Mapping

**Tools**
- *Diagnosis*: MRI ± DWI, PWI, MRS
- *Cortical mapping*: fMRI, MEG
- *Subcortical mapping*: DTI and fiber tracking

**Practical presurgical mapping**
- Combined assessment: clinical, MRI, fMRI and DTI, intraoperative mapping
- Integration into workflow
- Other problems, pitfalls
Presurgical Planning
Combined assessment

- Clinical evaluation
- Neuroanatomy on MRI
- Presurgical mapping (fMRI, DTI, MEG, Wada, etc.)
- Intraoperative mapping and functional testing

- Each of these is imperfect
Functional Mapping

- Primary targets
  - Motor
  - Language
  - Vision
  - Memory
- Cortical – BOLD fMRI
- Subcortical – DTI fiber tracking

Wernicke-Geschwind model

http://thebrain.mcgill.ca
Cortical Motor
RUE/RLE seizures ("heaviness", contractions), normal interictal
Language Mapping

“Just show me Broca’s and Wernicke’s areas”
GB, post Chemoradiation

Right handed, word finding difficulty
## Selected Tracts and Deficits

<table>
<thead>
<tr>
<th>TRACT</th>
<th>DEFICIT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Projection</strong></td>
<td>Left (Dominant)</td>
</tr>
<tr>
<td>CST</td>
<td>Weakness</td>
</tr>
<tr>
<td>OR</td>
<td>Field cut</td>
</tr>
<tr>
<td><strong>Association</strong></td>
<td></td>
</tr>
<tr>
<td>SLF (AF)</td>
<td>Conduction aphasia</td>
</tr>
<tr>
<td></td>
<td>Ideational apraxia</td>
</tr>
<tr>
<td></td>
<td>Left hemispatial neglect</td>
</tr>
<tr>
<td>ILF</td>
<td>Alexia</td>
</tr>
<tr>
<td></td>
<td>Tactile object recognition</td>
</tr>
<tr>
<td></td>
<td>Face recognition</td>
</tr>
<tr>
<td></td>
<td>Visual hypoemotion</td>
</tr>
<tr>
<td></td>
<td>Object recognition</td>
</tr>
<tr>
<td></td>
<td>Memory</td>
</tr>
<tr>
<td>IFOF</td>
<td>Visual agnosia</td>
</tr>
<tr>
<td></td>
<td>Semantic paraphasia</td>
</tr>
<tr>
<td></td>
<td>Visual agnosia</td>
</tr>
<tr>
<td></td>
<td>Optic ataxia</td>
</tr>
<tr>
<td></td>
<td>Impaired simultaneous perception</td>
</tr>
<tr>
<td></td>
<td>Impaired spatial perception</td>
</tr>
<tr>
<td>UF</td>
<td>Disturbance in concept, fact memory retrieval</td>
</tr>
<tr>
<td></td>
<td>Disturbance in personal experience memory retrieval</td>
</tr>
</tbody>
</table>
Color FA vs. Tractography
Corticospinal Tract (CST)
Corticospinal Tract, Motor fMRI
Presurgical Mapping

• **Tools**
  - Diagnosis: MRI ± DWI, PWI, MRS
  - Cortical mapping: fMRI, MEG
  - Subcortical mapping: DTI and fiber tracking

• **Practical presurgical mapping**
  - Combined assessment: clinical, MRI, fMRI and DTI, intraoperative mapping
  - Integration into workflow
  - Other problems, pitfalls
Intraoperative Navigation

Registered source data, DTI FT, fMRI, etc

Registered volumes in navigation space

Upload to OR computer
Validation

• **DTI-FT**
  - Co-localization at about 5-10mm
  - Deficits increase with proximity

• **fMRI**
  - Preop / postop deficits increase with activation closer to lesion
    - Håberg et al, Neurosurgery 2004; 54: 902
    - Wood et al, AJNR 2011; 32: 1420 (figure, University of Wisconsin)

• **Impact**
  - Treatment plans altered, often more aggressive plan
  - Reduced surgical time, seizure rate
    - Petrella et al, Radiology 2006; 240: 793
  - Less postop deficit, better 6mo Karnofsky
    - Wu et al, Neurosurgery 2007
Manual Tractography

- Inter- and intra-user variability
- Variability between DTI-FT acquisitions and post-processing
- Time-consuming

Fig. from Marenco et al, PNAS 2007; 104: 15117
Automated Tract Clustering

NIH R01 NS096606

Individualized Map of White Matter Pathways: Connectivity-Based Paradigm for Neurosurgical Planning

**BACKGROUND:** Advances in white matter tractography enhance neurosurgical planning and glioma resection, but white matter tractography is limited by biological variables such as edema, mass effect, and tract infiltration or selection biases related to regions of interest or fractional anisotropy values.

**OBJECTIVE:** To provide an automated tract identification paradigm that corrects for artifacts created by tumor edema and infiltration and provides a consistent, accurate method of fiber tractography.

**METHODS:** An automated tract identification paradigm was developed and evaluated for glioma surgery. A fiber bundle atlas was generated from 6 healthy participants. Fibers of a test set (including 3 healthy participants and 10 patients with brain tumors) were clustered adaptively with this atlas. Reliability of the identified tracts in both groups was assessed by comparison with 2 experts with the Cohen k used to quantify concurrence. We evaluated 6 major fiber bundles: cingulum bundle, fornix, uncinate fasciculus, arcuate fasciculus, inferior fronto-occipital fasciculus, and inferior longitudinal fasciculus, the last 3 tracts mediating language function.

**RESULTS:** The automated paradigm demonstrated a reliable and practical method to identify white matter tracts, despite mass effect, edema, and tract infiltration. When the tumor demonstrated significant mass effect or shift, the automated approach was useful for providing an initialization to guide the expert with identification of the specific tract of interest.

**CONCLUSION:** We report a reliable paradigm for the automated identification of white matter pathways in patients with gliomas. This approach should enhance the neurosurgical objective of maximal safe resections.

**KEY WORDS:** Arcuate fasciculus, Diffusion tensor imaging, Fractional anisotropy, Glioma, Surgical planning, Tractography

Birkan Tunc et al, Neurosurgery 2015
Presurgical Mapping

• **Tools**
  - *Diagnosis: MRI ± DWI, PWI, MRS*
  - *Cortical mapping: fMRI, MEG*
  - *Subcortical mapping: DTI and fiber tracking*

• **Practical presurgical mapping**
  - *Combined assessment: clinical, MRI, fMRI and DTI, intraoperative mapping*
  - *Integration into workflow*
  - *Other problems, pitfalls*
Pseudo-Reorganization

Right handed: anaplastic astrocytoma (WHO III)

February 2008 – initial preop

December 2010 - progression
Partially Successful Mapping

Min FA = 0.1
Max turning angle = 24 °
Failed fMRI
Navigation Issues: DTI

Preop distortion and misregistration, intraoperative shift

Eddy current distortion, misregistration (Mukherjee, AJNR 2008)

Skull base, air interface distortion

Distortion from programmable shunt

Shift on Intraoperative MRI (Nimsky Radiology 2005)
Pathology Altering FA, Tracking

Edematous

Deviated

Interrupted

Infiltrated

Deviated

Infiltrated
Risk vs. Control

Grade II oligoastrocytoma

Glioblastoma
Other Problems

- DTI assumes Gaussian diffusion
- DTI fails to resolve crossing fibers
Solution: Non-DTI Approach

- **HARDI** (64 direction, b=3000)
- **DTI** (30 direction, b=1000)
- **HARDI**
- **Q Ball**

Berman J, Magn Reson Imaging Clin N Am, 2009
Connectomics Meets Neuro-oncology

Mapping the brain for treatment planning
NIH R01 NS096606 (Verma, Brem)

Fig. 8: CST created using (left) clinical planning software overlaid with functional activation (green blob); (center, right) views showing clinical tract (yellow) and our tracts (blue), overlaid with STIM points (red: negative, green: positive).
HARDI, DTI, Cortical and Subcortical Stimulation

Red: DTI
Blue: HARDI

Jeffrey Berman (CHOP), Tim Lucas (HUP), Isaac Chen (HUP)
Conclusion

Preoperative Mapping: Combined assessment

- Clinical evaluation
- Neuroanatomy on MRI
- Presurgical mapping (fMRI, DTI, MEG, Wada, etc.)
- Intraoperative mapping and functional testing

*Each of these is imperfect*
Acknowledgements/Disclosures

- Radiology
  - Ragini Verma
  - Birkan Tunc
  - Sumei Wang
  - Paolo Nucifora
  - Elias Melhem
- Neurosurgery
  - Steve Brem, Tim Lucas, Luke Macyszyn, Isaac Chen
- CHOP
  - Jeff Berman
- Funding: NIH R01 NS096606 (PI Verma, R)
- Disclosures: No relevant financial disclosures