MRI Features of Spinal Cord Injury

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Jefferson

1

Value Add – MRI in SCI

- MRI has changed the clinical and research landscape for SCI.
- First imaging technique that provided non-invasive reliable information about:
  - The integrity of spinal cord
  - Intrinsic pathologic state
  - Extent and location of injury
  - External influences – compression, vascular
- Physiologic techniques provide inference about function
  - Diffusion
  - Functional
  - Perfusion
  - Spectro
  - Myelin water fraction
  - Axonal density
  - And more….!

2

Morphology of SCI

- Penetrating injuries
- Mechanical Transection
- Blunt Injury
  - Simple contusion (edema)
  - Hemorrhagic contusion

3

Cord Transection

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Cord Transection

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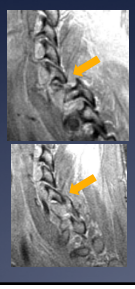
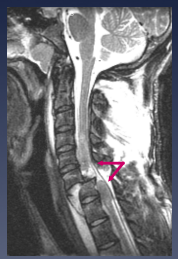
BID & Cord Transection





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Cord Transection

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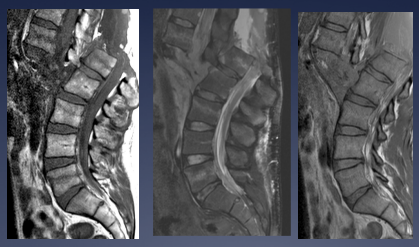
T/L Spondylopsis



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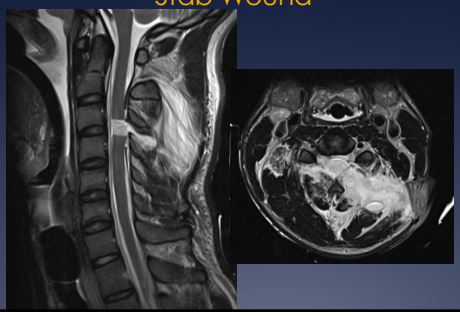
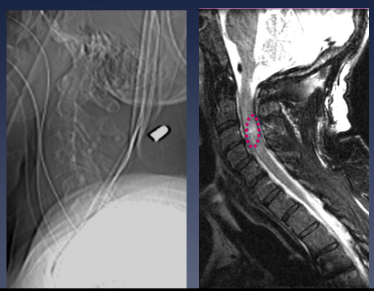
Stab Wound



9

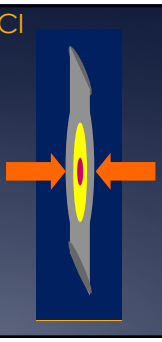
GSW – Concussive Injury



10

MRI Features of Blunt SCI

- More common.
- Portions of architecture are salvageable.
- Type is of therapeutic interest.
- Features of SCI on MRI include:
  - Spinal Cord Swelling
  - Spinal Cord Edema
  - Spinal Cord Hemorrhage
- Edema length prop to neurologic deficit and prognosis.
- Heme associated with most severe injuries and predicts poor neurologic recovery.
- Heme location correlates with NLI.



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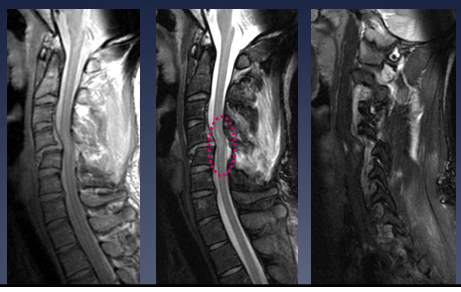
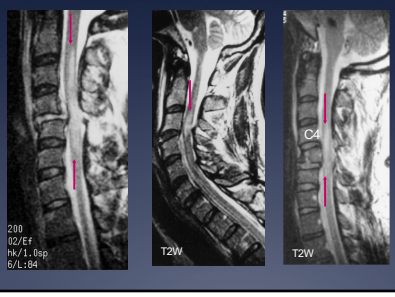
UID & SCI



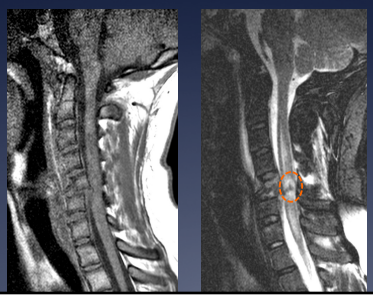
12

Spinal Cord Edema



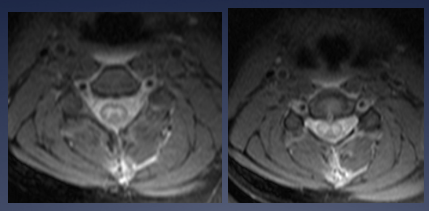
13

Flexion Teardrop & SCI



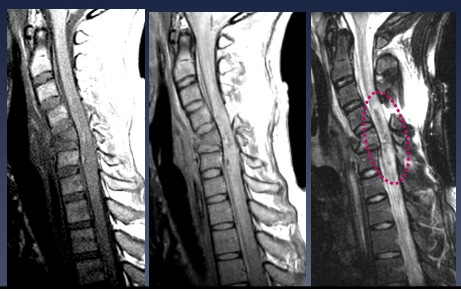
14

Flexion Teardrop & SCI



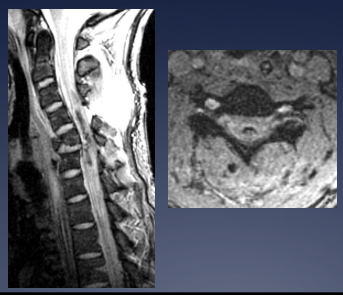
15

Flexion Teardrop & Hemorrhagic SCI



16

Flexion Teardrop & SCI

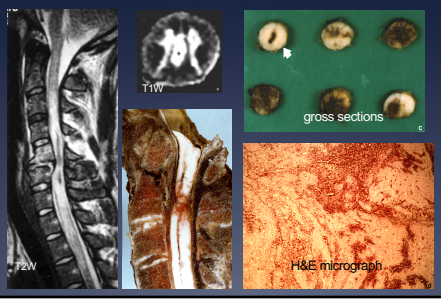


17

T8/9 Hyperflexion Dislocation

18

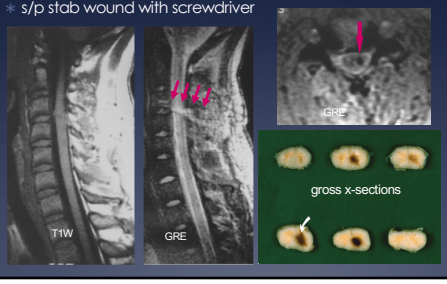
Hemorrhagic Cord Injury



19

Penetrating Injury

* s/p stab wound with screwdriver

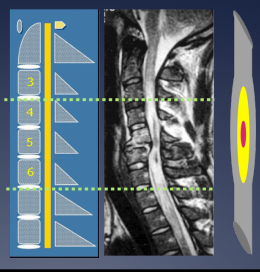


20

CDE Key SCI Features

Acute SCI features

- Edema top
- Heme top
- Center
- Heme bottom
- Edema bottom
- Edema length *(derived)*
- Heme length *(derived)*
- Cord transection (y/n)



21

BASIC Score

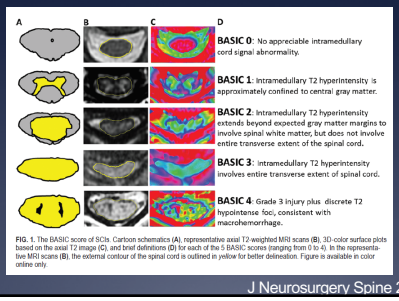
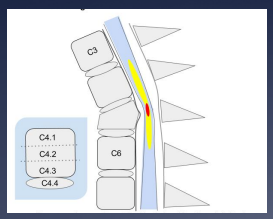


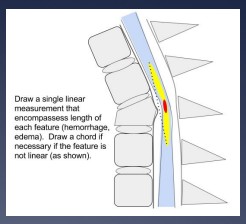
FIG. 1. The BASIC score of SCIs. Cartoon schematics (**A**), representative axial T2-weighted MRI scans (**B**), 3D color surface plots based on the axial T2 image (**C**), and brief definitions (**D**) for each of the 5 BASIC scores (ranging from 0 to 4). In the representative MRI scans (**B**), the external contour of the spinal cord is outlined in yellow for better delineation. Figure is available in color online only.

J Neurosurgery Spine 2015;23:495

22

Continuous and Categorical CDE Features Related to SCI





23

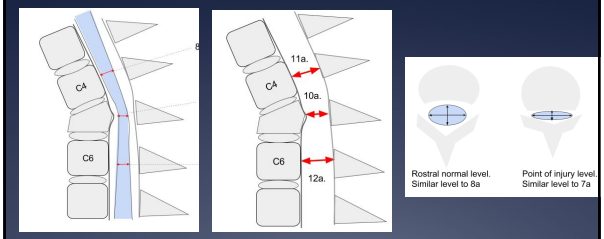
CDE Canal/Cord Continuous Measures

Canal/Cord Measurements

- Sagittal canal diameter rostral to injury
- Sagittal canal diameter at injury
- Sagittal canal diameter caudal to injury
- Sagittal Cord diameter rostral to injury
- Sagittal Cord diameter at injury
- Sagittal Cord diameter caudal to injury
- Axial A-P Cord diameter at level of injury
- Axial Transverse Cord diameter at level of injury
- Axial A-P Cord diameter rostral to injury
- Axial Transverse Cord diameter rostral to injury

24

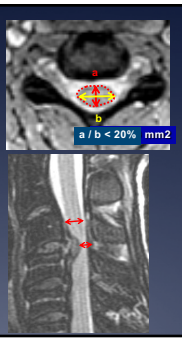
Ordinal Features Related to Canal/Cord Measurements



25

Compression Ratios

- Spondylosis Index (Edwards & LaRocca)
  - Difference between *developmental sagittal diameter* & *spondylotic sagittal diameter.*
- Sometimes expressed as a ratio
  - Stenosis / canal
- Compression ratio (a/b)
- CTM and MRI evidence that symptoms of myelopathy occur at a threshold of cord compression.
  - Compression ratio < 20%



26

Connect With Us

Assessments and Examinations

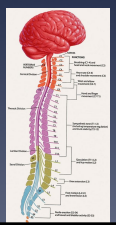
Spinal Imaging/Spinal Cord Imaging

CRF Module/Guidance	CDEs
Spinal Cord Injury CDE Imaging Guidelines	N/A
Imaging	CDE Details
Magnetic Resonance Imaging	CDE Details
Diffusion Tensor Imaging	CDE Details
Spinal Cord Imaging Modules-Diffusion Tensor Imaging	N/A
Imaging Protocol Table Sequencing 1.5T	N/A
Imaging Protocol Table Sequencing for 3T	N/A

SCI Start-Up Resource Listing: All Core and Supplemental-Highly Recommended CDEs recommended for SCI study start-up.
SCI Highlight Summary: Overview of all SCI-specific CDE recommendations as they appear on the website.
Click **Expand All** to view the CDEs associated with the CRF modules, organized by domain and subdomain.

27

Correlating MR Parameters with Neurologic Deficit in SCI



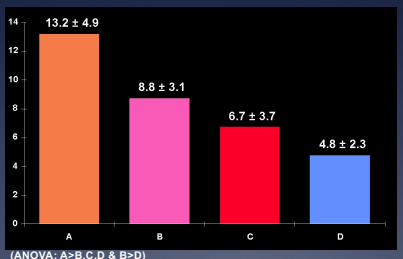
28

Relationship of MR Findings to Initial Neurologic Deficit

- Frank hemorrhage associated with complete neurologic injuries.
  - Petechial heme visualized in incomplete injuries.
- Longer lesions associated with complete injuries.
- Edema alone correlates with incomplete injuries.
- No abnormality on MRI ; high correlation with normal examination.

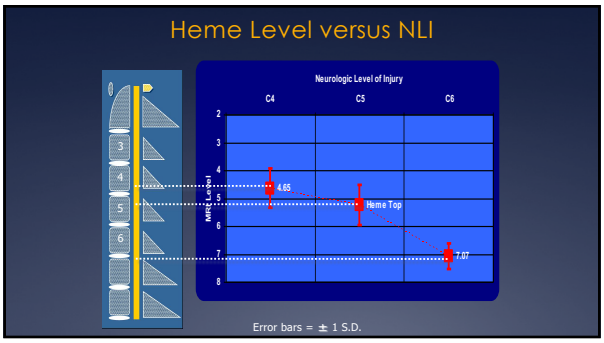
29

Mean Edema Length (units) by ASIA Grade



(ANOVA: A>B,C,D & B>D)

30



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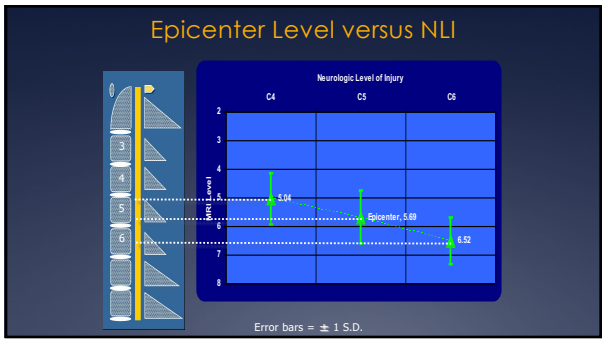

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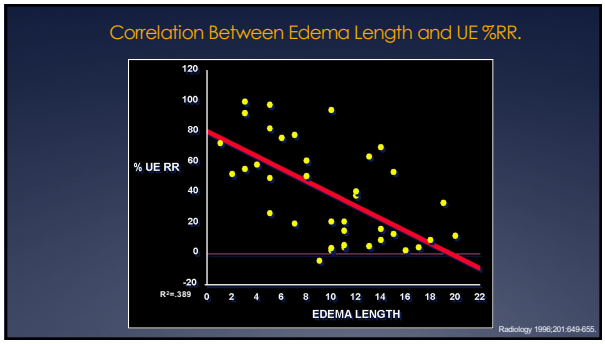

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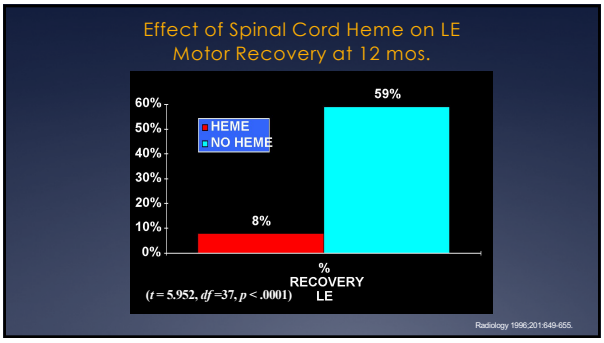

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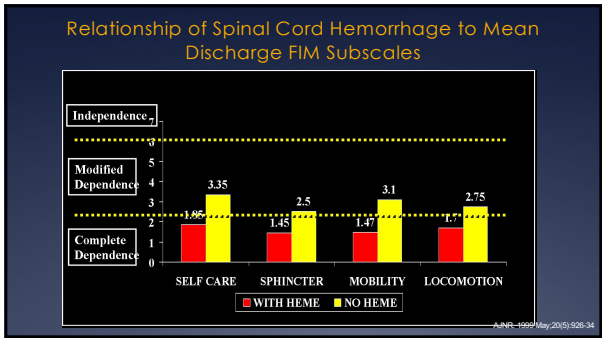

36

Improvement in Statistical Power in Predicting Recovery

- Incorporation of MRI SCI parameters to a clinical statistical (multiple stepwise regression) model (using MIS, ASIA, NLI) *increased statistical power of model*
- UE MIS – Prediction at one year
  - MIS; stat power *improved* **27%.**
  - # useful muscles (> 3); stat power *improved* **34%.**
- LE MIS – Prediction at one year
  - MIS; stat power *improved* **16%.**
    - +/- heme, lesion length & initial MIS were independent predictors of final MIS.
  - # of useful muscles (>3); stat power *improved* **22%.**

Radiology 1996;201:649-655.

37

Predicting Neurologic Recovery in Cervical Spinal Cord Injury With Postoperative MR Imaging

Boldin et al. *Spine* 2005;31:554-559.

- Performed quantitative measure of SCI lesions on MRI prospectively in 29 pts. compared to changes in ASIA score.
- Hemorrhagic lesions ~ Complete injury.
  - Odds ratio 2.33, 95% C.I., 1.42-3.82
- Complete injuries
  - Median hematoma length ~ 10.5 mm.
  - Median edema length ~ 66.5 mm.
- Incomplete injuries
  - Median hematoma length ~ 4 mm.
- *Heme < 4 mm ~ better prognosis.*
- Small cohort, no control for follow up or time to imaging.

38

Acute Cervical Traumatic Spinal Cord Injury: MR Imaging Findings Correlated with Neurologic Outcome – Prospective Study with 100 Consecutive Patients.

- 100 patients (79 male; 21 female)
- Compared admission and follow-up ASIA grade to features of canal compromise, cord compression, lesion length, SC heme, SC swelling, disc herniation, canal stenosis.
- Complete injuries associated with greater canal and cord compromise, and longer SC lesions than incomplete.
- Complete SCI's associated with heme, edema, swelling & stenosis.
- *Conclusion: Spinal cord compression, heme and swelling are associated with poor prognosis.*

Radiology 2007 v243 p820

39

Impact of Admission Imaging Findings on Neurological Outcomes in Acute Cervical Traumatic Spinal Cord Injury

- 99 consecutive cervical SCI patients.
- Clinical and radiologic factors in predicting recovery at one year after injury.
- (AIS) grade, presence of a spinal fracture and central cord syndrome were predictive of AIS conversion at 1-year.
- Both BASIC and IML were stronger predictors of AIS conversion as compared to MCC and MSCC (P=0.0002 and P=0.04).
- BASIC score demonstrated the highest overall predictive value for AIS conversion at 1-year (AUC 0.94).
- Admission intrinsic cord signal findings are predictive markers of neurologic recovery after cervical SCI.
- BASIC score is the single best acute predictor of the likelihood of AIS conversion.

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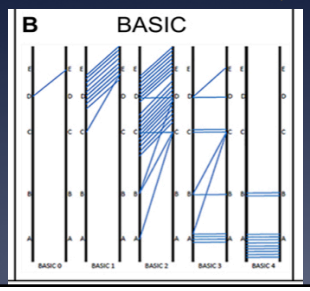
40

Impact of Admission Imaging Findings on Neurological Outcomes in Acute Cervical Traumatic Spinal Cord Injury



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41

Chronic MRI Changes From SCI

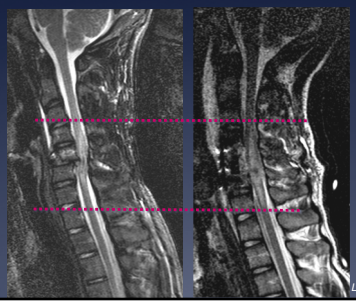
42

Subacute/Chronic Changes of SCI

- "Normal" enlargement
- SPAM – subacute progressive ascending myelopathy.
- PTPM (post-traumatic progressive myelopathy).
  - Progression in neuro status after period of stability.
  - Morphologic changes associated:
    - Syringomyelia
    - Myelomalacia
    - Cord tethering
    - Atrophy

43

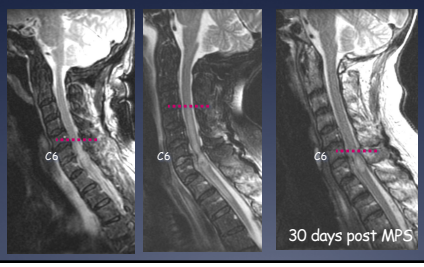
3 Day - Lesion Enlargement



44

SPAM - Monitoring Dynamic Changes

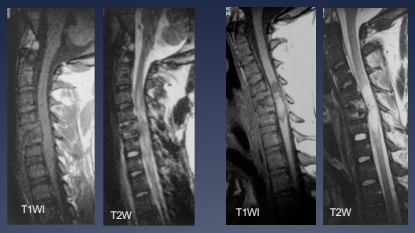
- C5 level ascending to C3 – day 10



45

Evolution of Spinal Cord Injury

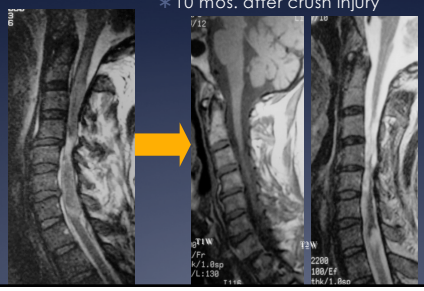
- 18 y/o C5 ASIA A



46

Atrophy & Myelomalacia

- 10 mos. after crush injury

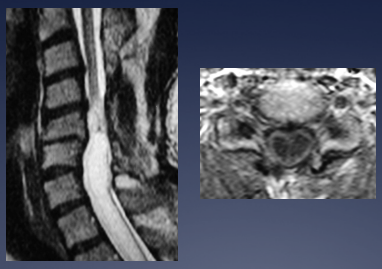


47

Chronic Changes following SCI

48

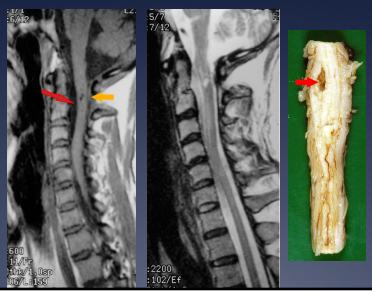
Post Traumatic Syringomyelia



Images courtesy of Steve Falcone, MD

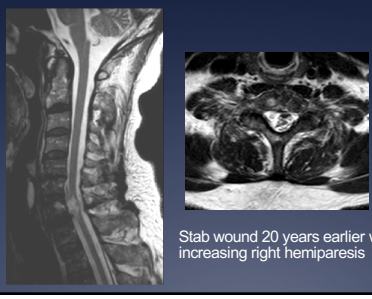
49

Chronic Cord Tethering & Cyst



50

Chronic Changes From SCI

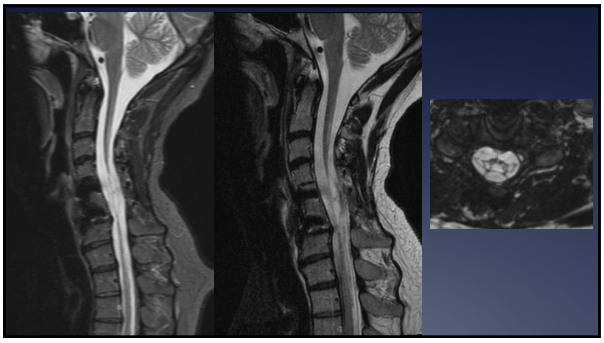


Stab wound 20 years earlier with increasing right hemiparesis

51

Challenges Assessing Chronic SCI for Clinical Trials

52



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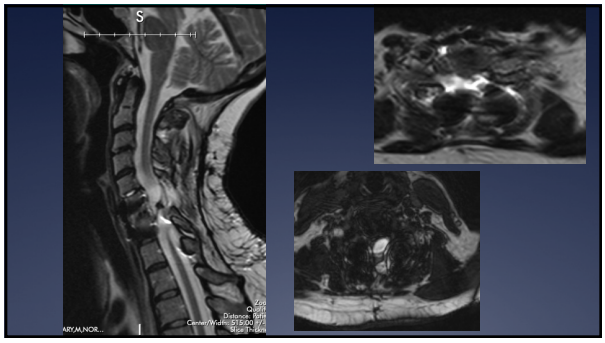


54

Spinal Cord Diffusion

55

Spinal Cord Diffusion

- Linear organization of the spinal cord fibers suited for this evaluation.
- Technically challenging
- Feasible that diffusion parameters correlate with functionality of WM.
- Biomarker for recovery and neuroplasticity.

$$FA = \frac{\sqrt{3}}{\sqrt{2}} \frac{\sqrt{(\lambda_1 - \lambda)^2 + (\lambda_2 - \lambda)^2 + (\lambda_3 - \lambda)^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

56

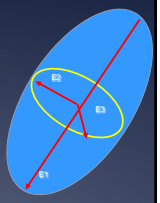
DWI & DTI Spinal Cord Techniques

- Navigated pulsed-gradient spin-echo
- Single shot echo planar
- Interleaved Multi-shot echo planar
- FSE/TSE propeller DTI
- SE navigated spiral DTI
- Line Scan Spin Echo DTI
- Sense/Parallel Imaging
- Small FOV Imaging
- DKI – Diffusion Kurtosis Imaging
- NODDI (Neurite Orientation Dispersion and Density Imaging)

57

DTI in Spinal Cord Injury

- Changes correlate to function.
- In experimental SCI:
  - Increase in *transverse* diffusivity (RD).
  - Decrease in *longitudinal* diffusivity (AD).
  - Loss of anisotropy around injury (FA)
  - Similar to chronic injuries
- More accurate biomarker for assessing white matter tract function.



Schwartz AJNR 2005;26:7-18.

58

DWI & SCI

- 51 y/o male s/p fall; C2 fx.
- Neurologic status: C3 Brown-Sequard.
- MRI 2 hour after injury:
  - C2 fx
  - Vague signal changes on T2
  - Focus of restricted diffusion.
- No follow-up

Sagiuchi et al. JCAT 2002;26:654

59

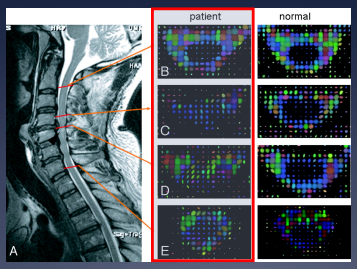
DTI & Cervical Spine Trauma

- DTI performed on 20 cx SCI patients and 8 volunteers at 1.5T using parallel single-shot EPI in 6 directions (1000 s/mm^2.)
- ADC values sig lower for all pts.
  - Particularly heme lesions & quadriplegic.
- Volume ratio significantly increased.
- Trend towards FA reduction.
- Most FA & RA reduction at injury site.
- ADC was the most sensitive marker of cord injury.
- ***Diffusion characteristics are a sensitive biomarker for SCI in humans.***

Shanmuganathan et al. AJNR 2008 v 29

60

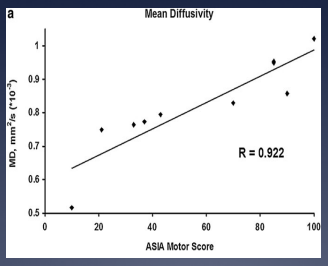
DTI & Cervical Spine Trauma



Shanmuganathan et al. AJNR 2008 v 29

61

DTI & Spinal Cord Injury

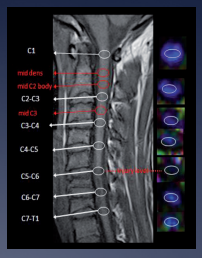


J Neurotrauma 2011

62

DTI in Pediatric SCI

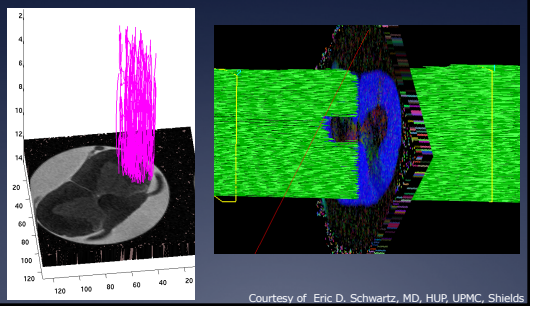
- Assessed 10 youths with DTI correlated to ISNCSCI clinical parameters – repeated once.
- Moderate-to-strong reliability (ICC=0.75-0.95) for MD, AD, RD at all spinal levels.
- Diffusivity moderate-good relationship with 4 ISNCSCI values.
- DTI had a stronger correlation with clinical parameters than MRI alone.



Mulcahey et al Spine 2012

63

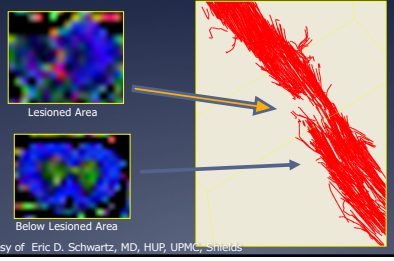
DTI and Spinal Cord Fiber Tracking in Normal Rat at 9.4T



Courtesy of Eric D. Schwartz, MD, HUP, UPMC, Shields

64

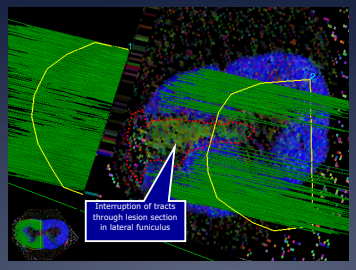
DTI Fiber Tracking in Rat Spinal Cord Following Hemisection In Vivo at 4.7T



Courtesy of Eric D. Schwartz, MD, HUP, UPMC, Shields

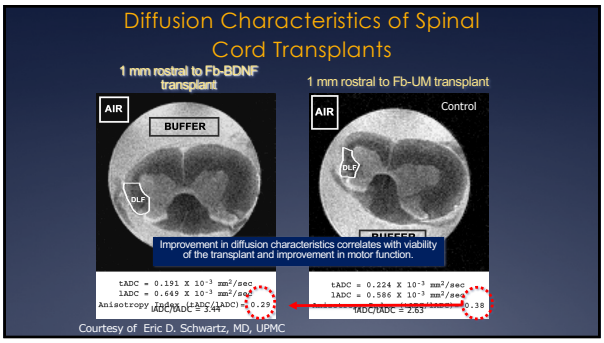
65

DTI and Spinal Cord Fiber Tracking at 9.4T in Lesioned Cord

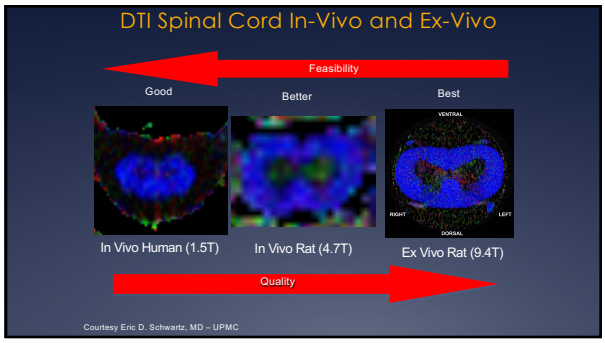


Courtesy of Eric D. Schwartz, MD, HUP, UPMC, Shields

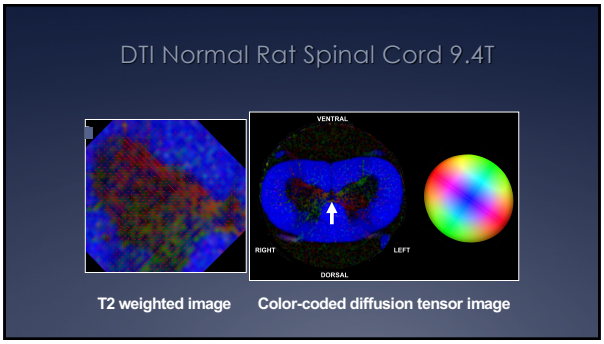
66



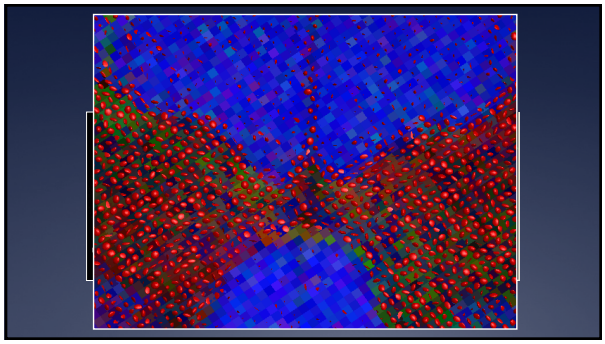
67



68



69



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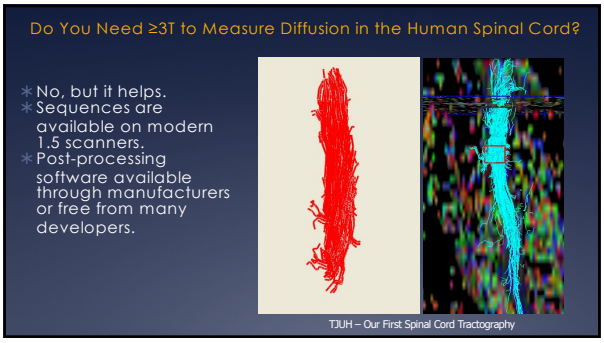
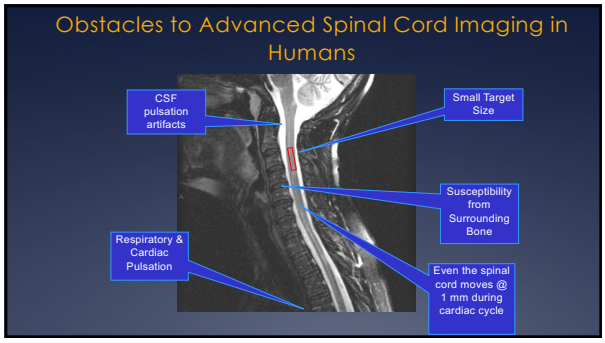
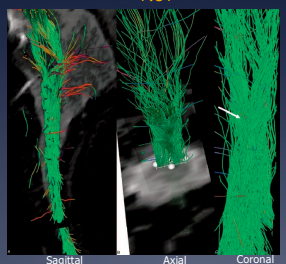


71



72

Cervical Spinal Cord Tractography at 1.5T

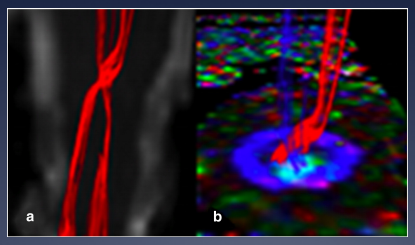


Note: decussation of fibers in coronal view (arrow)

Ducreux AJNR 2006;27:214

73

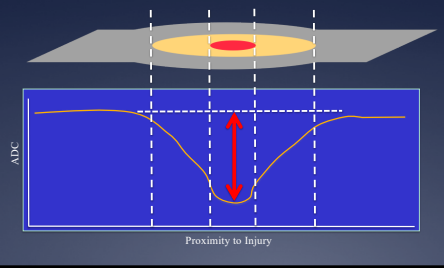
Decussation of CST with DTI



Neuroimage 2013

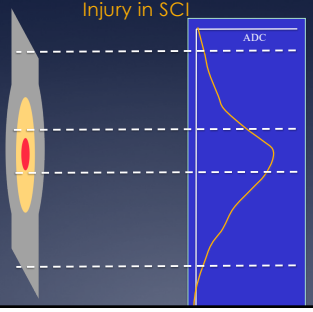
74

Theoretical Representation of Relationship of DTI Values & Proximity to Injury



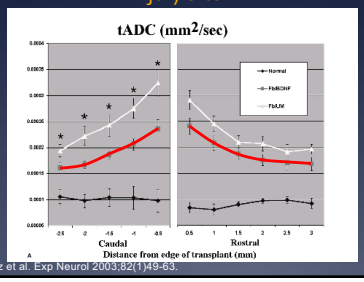
75

Diffusion "Envelope" Around Anatomic Injury in SCI



76

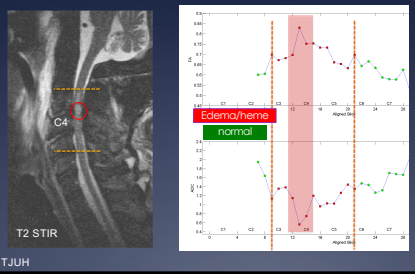
Relationship of tADC to Proximity of Injury Site



Schwartz et al. Exp Neurol 2003;82(1):49-63.

77

Result: Patient Example – C3 AIS A



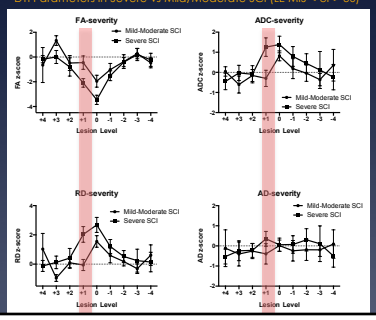
TJUH

78

Funded in part by DoD Grant Proposal No. SC090288, Award No. W81XWH-10-1-0935, HRPO Log No. A-16324

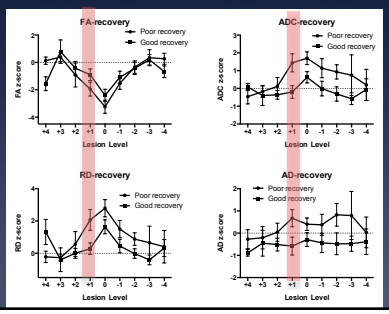
79

DTI Parameters in Severe vs Mild/Moderate SCI (LE MIS < or > 30)

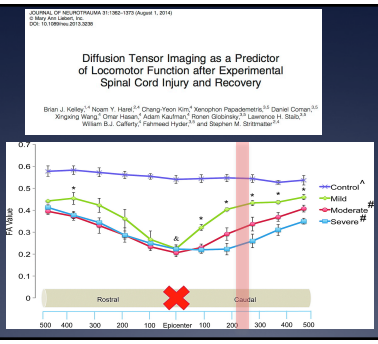


80

DTI in Good vs. Poor Recovery at 6 mos. (RR< or >0.5)



82



FA values adjacent to the lesion, but not at the lesion itself, are able to discern mild from moderate/severe injury

84

Summary – DTI & Recovery

- FA, ADC, and RD values obtained at the time of injury may be useful in discriminating recovery rates from acute spinal cord injury.
- DTI indices measured *immediately cranial to the actual lesion* epicenter exhibit strong correlations in predicting neurologic recovery than indices measured at the lesion center.

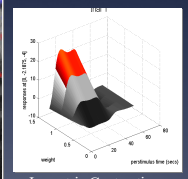
86

Current Limitations of DTI in Clinical Trials

- Spinal instrumentation can limit repeat evaluation of the spinal cord.
- Normalization of DTI values is problematic across instruments and sites.
- Even low ferromagnetic property hardware can create distortion with DTI parameters.
- Many other methods and parameters – e.g. myelin water fraction, MRS that are not readily available.

87

Spinal fMRI During UE Movement



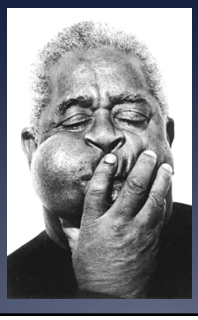
Isometric Contractions

Courtesy S. Madi, PhD.

88

fMRI Signal Generated by Biceps Contraction

89



90

Summary

- MRI is the only non-invasive method to evaluate the spinal cord architecture.
  - Harbors prognostic information.
  - Has value in chronic injury states.
- Signal changes in spinal cord have clinical and prognostic value.
- DTI spinal cord is becoming more mainstream; may harbor additional clinical information – surrogate for neuro exam.

91

92