Diagnosis and Imaging of TBI

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Traumatic Brain Injury
- Clinically heterogeneous population
- Etiology and Pathophysiology Diverse
  - Closed Injury
    - Concussive
    - Blast wave
  - Penetrating Injury
- Pathoanatomic Assessment is Complex
- Temporal Evolution of Lesions
  - Changes over time

Epidemiology of TBI
- During 2002, the Centers for Disease Control and Prevention (CDC) estimated that more than 50,000 Americans die each year from traumatic brain injury (TBI) – approximately one-third from motor vehicle accidents, 10% from falls, and 40% [20k] from penetrating wounds caused by firearms.

Classification of TBI
- Clinical (intake) Criteria – GCS or ?
- Pathoanatomic Classification
  - Imaging and Pathology
- Physical Mechanism
  - Impact, Acceleration/Deceleration
  - Overpressure (Primary Blast Injury)
- Pathophysiology
  - Primary Damage
  - Secondary Insult (↓BP, ↓O2, ↑pCO2, ↑BP)
- Prognostic Modeling

Problems with GCS
- GCS 3 – comatose to GCS 15 – awake
- NOT a good predictor of cognitive sequelae
- >80% of mTBI or Concussion have GCS 13-15
- GCS is a poor discriminator ≥13
- GCS is a poor discriminator ≤4

Six Patients w/ GCS < 6

Pathoanatomic TBI

SAH

Diffuse Axonal Injury

Contusion

Hematoma

Ball Bearing from IED

IED: Penetrating Injury

Scalp hematoma, skull fracture, cortical contusion, surface fragment

Intracranial air, blood and metal fragments along wound track.

IED Penetrating Injury – Brain Swelling
What is Blast TBI (bTBI)?

- LOC, PTA, GCS probably NOT useful in bTBI
- Unknown how they relate to bTBI
- Most of these bTBI have associated Cx spine injuries.

Case, after Case, after Case

- Normally, that would be a series ...
- Often, it literally means three cases
- In consideration of Primary Blast Injury
  - It is the same case being shown by everyone, and shown everywhere

Underdiagnosis of Blast TBI

- Civilian blast underdiagnosed
- Causes
  - Private dwelling(31), Industrial pressure(20), Industrial gas(16), Military Training(15), Home explosive(8), Fireworks(1)
- Types of bTBI
  - Cerebral Contusion(13), SDH(8), DAI(4), SAH(3),ICH(3),EDH(3),IVH(2)

Robust Imaging Portfolio

- CT - Computed Tomography
- MRI – Magnetic Resonance Imaging
  - DTI and Tractography
  - MRS
  - fMRI – attention, memory, PTSD
- NM - Nuclear Medicine
  - FDG PET
  - SPECT, New labeling agents
- Pathology
  - Gross brain examination
  - Histology
Five Easy Pieces

- Who Needs Imaging?
- Skull, Scalp, and Epidural
  - Lucid Interval, Drain or not
- Subdural
  - Variable Presentation
  - Variable Appearance
- Contusion
  - Coup vs. Contrecoup
- Shearing Injury
  - Deep Lesions
  - Coma

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Shearing Injury

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Traumatic Brain Injury

- Motor deficits
- Seizure
- Sensory deficit
- Coordination
- Memory
- Personality
- Executive functioning

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Executive Functions

- Define a Goal
- Make a Plan
- Measure progress toward the Goal
- Example
  - Renew your driver’s license
  - Bring flowers for Mother’s Day

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Clinical Diagnosis of Head Trauma

- Rising Blood Pressure
- Slowing Pulse
- Slowing Respirations
- Coma
  - Unconscious
  - Unresponsive
- Fundoscopic Examination
  - Dilated Pupil(s)
  - EOM’s?

Rising Blood Pressure

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CNS TRAUMA

- Impact
  - CONTACT INJURY
    - Scalp/skull Abnormal

- Inertial
  - NON-CONTACT INJURY
    - Acceleration/deceleration
    - Scalp/skull Normal

Impact

- CONTACT INJURY
  - Scalp/skull Abnormal

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  - Scalp/skull Normal

Inertial

- NON-CONTACT INJURY
  - Acceleration/deceleration
  - Scalp/skull Normal

Types of Injury

- Primary Brain Lesions
  - Immediate Neurological Effects
  - Contusions
  - Shearing Injury

- Secondary Brain Lesions
  - Variable Delay in Symptoms and Signs
  - Epidural, Subdural, Subarachnoid Hemorrhage
  - Mass Effect, Increased ICP, Brain Herniation
  - Vasospasm, Hyperemic Swelling, Brain Infarction

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Causes of Head Trauma

- Motor Vehicle Accidents – 50%
- Falls from a height – 20%
- Accidental
- Non-accidental (e.g. Child Abuse)
- Workplace
- Recreational
- Combat

TBI Educational Objectives

- Who needs brain imaging?
- What type of imaging is needed?
- Intraaxial Lesions » Primary Lesions
  - Contusion, Shearing Injury
  - Immediate Neurological Effects
- Extraaxial Lesions » Secondary Lesions
  - Epidural, Subdural, Subarachnoid
  - Delayed Neurological Effects

Indications for Imaging

- Acute Neurologic Deficit
- Observed L. O. C.
- Persistent HA
- Severe Trauma
- Obvious Injury

Hydroplaning Accident

- 9 passenger van
- All belted in
- 180 direction turn
- 2-1/2 turn barrel rollover
- No one blacked out
- Everyone walked away

Should we have been scanned?

Minor Head Trauma: with Normal GCS

“CT can be safely limited to those who have ...”
- Headache
- Seizures
- Vomiting
- Age > 60 yrs
- Drug or EtOH intoxication
- Physical trauma above clavicles

NEJM 2000;34: 100-1005

Dx Sensitivity/Specificity

- mTBI or Concussion may not be imaged
- Most patients have only screening CT – 85% “Normal” - Insensitive test for mTBI
- “Mild TBI or concussion with a normal GCS ... CT ... lesions in less than 15% ...”
Minor Head Trauma: with Normal GCS

“CT can be safely limited to those who have:

- Headache
- Seizures
- Vomiting
- Age > 60 yrs
- Drug or EtOH intoxication
- Physical trauma above clavicles

We would like to add:

- Post-traumatic amnesia > 30min
- Anosmia
- Ruptured Tympanic Membrane

NEJM 2000;34: 100-1005

Weber Coaster Headache

- Roller Coasters can create 2.5 – 3.5 G’s
- Grandpa rides with Granddaughter
  - She’s screaming with excitement
  - He’s subdued by a Subdural Hematoma

Reference:

TBI Educational Objectives

- Who needs brain imaging?
- What type of imaging is needed?
- Intraaxial Lesions » Primary Lesions
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- Extraaxial Lesions » Secondary Lesions
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Traumatic Brain Injury

NINDS “Classification of TBI for Targeted Therapies” – Oct 2007

- Clinical (intake) Criteria – GCS or ??
- Pathoanatomic Classification
  - Imaging and Pathology
- Physical Mechanism
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  - Overpressure (Primary Blast Injury)
- Pathophysiology
  - Primary Damage
  - Secondary Insult (BP, O2, pCO2, 1BP)
- Prognostic Modeling

History of Imaging TBI

- Autopsy
- Skull series plain films
- Angiography
  - Gross mass lesions (EDH, SDH)
- Computed Tomography
  - EDH, SDH, Contusion, some DAI
- Conventional Spin Echo MRI
  - More of the above
- GRE/MSI, DTI, MRS, fMRI
  - Even more

1970s Pre-CT

- Clinical Evaluation
  - Clinical Examination of CNN 2-12
  - Pupils evaluated for signs of herniation
- Skull X-ray Series
- Angiography
  - “Exploratory Burr Holes”
Little bit of history …

1980s
- All Level 1 Trauma Centers must have 25X7 CT available
- How do you triage patients?
- Who gets “advanced” neuroimaging?
  - Obvious Injuries

Times Have Changed
- In 1980 CT replaced Skull Series
- In 2000 MRI complemented CT
  - But did not replace CT as screening exam
- In 2008 ...
  - MRI w/ DWI, GRE/SWI, DTI, MRS
  - fMRI w/ New paradigms
  - PET/SPECT, Biomarker Imaging

Imaging of Head Trauma
- Autopsy
- Plain Radiographs
- Angiography
- Computed Tomography
- Spin Echo MRI
- FLAIR, DWI, ADC maps
- Susceptibility Imaging - SWI
- Diffusion Tensor Imaging - DTI

Relative Sensitivity
- MR Spectroscopy (global decreased NAA)
- Diffusion Tensor Imaging – (anisotropy)
- Magnetic Susceptibility (SWI or GRE)
- Apparent Diffusion Coefficient
- Diffusion Weighted Imaging
- FLAIR
- Conventional SE MR (T2W > T1W)
- CT (ECT > NCT)
- Skull Radiogram
3 Reasons for Getting an MR
- CT fails to explain Pt’s Condition
- CT fails to explain Pt’s Condition
- CT fails to explain Pt’s Condition

Hospitalized patients need further evaluation with MR

Imaging of Head Trauma
- Autopsy
- Plain Radiographs
- Angiography
- Computed Tomography
- Spin Echo MRI
- FLAIR, DWI, ADC maps
- Susceptibility Imaging - SWI
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MRI Techniques Vary
- T2
- DWI
- SWI

History
- 26 y/o man transferred by air-evac after a helicopter crash. Upon arrival, patient was intubated and sedated. CT of the head was performed as part of trauma evaluation.

Causes of Coma
- Physiologic/metabolic conditions:
  - Hypoxia
  - Hypotension
  - Hypoglycemia
  - Drugs and Intoxicants
- Structural/anatomic lesions:
  - Cerebral Hemispheres
  - Thalamus
  - Reticular Activating System (brainstem)
Causes of Coma

- Expressive Cortex
- Associative Cortex
- Receptive Cortex
- Internal Reference Cortex
- Thalamus
- Reticular Activating System

Arousal
Responsiveness

Coma: Lesions and Locations

Shearing Lesions are small (<15mm) and deep (subcortical, WM, Corpus callosum, Thalamus, Brain stem)
- Subcortical – many needed
- White Matter – many needed
- Thalamus – few needed
- Reticular Activating System
  - Dorsal Brainstem
  - Only one needed

26 y.o. man in Coma

Deep Lesions ... including thalamus ... “shearing injury” ... causing coma

Findings

- No Midline shift
- No explanation for GCS of 6
- Possible small hemorrhage left occipital horn
  - Torn subependymal veins?
  - Shearing Injury?
- MR with a “blood sensitive” sequence
  - Left occipital horn blood
  - Right thalamic bleed
  - Central corpus callosum bleed

Differential Diagnosis

- Shearing Injury
- Diffuse Axonal Injury
- Diffuse White Matter Injury

Traumatic Hemorrhage

- Subgaleal
- Cephalohematoma
  - Subperiosteal Outer Table
- Epidural (Extradural)
  - Subperiosteal Inner Table
- Subdural
  - “Epi-arachnoid”
- Subarachnoid
- Parenchymal Hemorrhage
- Intra-ventricular
TBI Educational Objectives

- Who needs brain imaging?
- What type of imaging is needed?

**Extraaxial Lesions » Secondary Lesions**
- Epidural, Subdural, Subarachnoid
- Delayed Neurological Effects

**Intraaxial Lesions » Primary Lesions**
- Contusion, Shearing Injury
- Immediate Neurological Effects

CENTRIPETAL APPROACH (outside to inside)
- Scalp
- Calvarium
- Epidural
- Subdural
- Subarachnoid
- Intra-parenchymal
- Intra-ventricular

CNS TRAUMA -- SUBGALEAL

- Between periosteum of OUTER table and the GALEA (under scalp fat)
- In CHILD, significant blood loss
- Spontaneous decompression of intracranial (Epidural) hematoma

**CENTRIPETAL APPROACH (outside to inside)**
- Scalp
  - Calvarium
  - Epidural
  - Subdural
  - Subarachnoid
  - Intra-parenchymal
  - Intra-ventricular

Subgaleal Hematoma

Skull Fractures

- Linear
- Stellate
- Depressed
- Basilar
- Eggshell
Basilar Skull Fracture:

- RHINORRHEA (CSF)
- OTORRHEA (CSF / Hemotympanum)
- PNEUMOCEPHALUS
  - air in sulci
  - air and fluid/levels in sinuses
- RACCOON EYES
  - periorbital ecchymoses
- BATTLE’S SIGN
  - Retro-auricular ecchymoses

BASILAR SKULL Fx:

- CSF LEAK
  - Infection
  - Pneumocephalus
- CNN. INJURY
  - Deficit Acute or Delayed
- VASCULAR TRAUMA
  - Laceration or dissection
  - Occlusion & infarction
  - FISTULAE (Carotid-Cavernous)

Traumatic Hemorrhage:

- Subgaleal
  - Subperiosteal Outer Table
    - Cephalohematoma
  - Subperiosteal Inner Table
    - Epi-arachnoid
- Subdural
  - ‘Epi-arachnoid’
- Subarachnoid ***
- Parenchymal Hemorrhage
- Intra-ventricular

Membrane Hematomas:

- Cephalohematoma
  - Sub-periosteal, Outer Table Skull
- Epidural hematoma
  - Sub-periosteal, Inner Table Skull
- Subdural hematoma
  - Epi-arachnoid
Epidural Space

2 y.o. with dilated pupil

CNS TRAUMA EPIDURAL HEMATOMA
- Young Men (20-40's)
  - Head Trauma frequent
  - Also, dura (periosteum) more adherent in older people
- Acute presentation
- Skull fracture (90%)
- Bi-convex, hyperdense- limited by sutures

EPIDURAL HEMATOMA
- Source of Bleeding
  - MENINGEAL VESSELS
    - Arterial (high pressure)
      - Venous (low pressure)
  - DURAL SINUS
    - High flow, low pressure
  - OTHER
    - Diploic veins (Fx)
    - Marrow sinusoids

EPIDURAL HEMATOMA
- Significant trauma
- Fracture & concussion (l.o.c.)

- Lucid Interval
  - pc Wakes Up
  - 40% pts.
- Delayed neurologic Sx (hrs. Later)
- Herniation, coma and death

EPIDURAL HEMATOMA
Trauma -> fracture & concussion
Tearing/stripping of both layers from inner table
Laceration of outer periosteal layer
Laceration of meningeal vessels
Inner (meningeal dura) intact
Blood between naked bone and dura
NORMAL arterial pressure continues to dissect periosteum from bone
Brain Herniation Syndromes

Epidural Hematoma - Treatment
- Craniotomy
- Drain clot
- Repair the Artery!

Small EDH – Conservative Tx

Smile of the Quadrigeminal Cistern
Progressive EDH

10 AM  8 PM

SUBPERIOSTEAL HEMATOMA
- CEPHALOHEMATOMA
  - (Birth trauma)
  - (outer table, sub-periosteal)
- EPIDURAL HEMATOMA
  - (Inner table, "sub-periosteal")

Cephalohematoma
Birth Trauma

Membrane Hematoma
- Epidural
  - Acute
  - Biconvex
  - Unilateral
  - Skull fracture
  - Limited by sutures
- Subdural
  - Acute to Chronic
  - Concave layer
  - Bilateral
  - Fracture +/-
  - Cross sutures

Cephalohematoma - Calcified

Traumatic Hemorrhage:
- Subgaleal
- Cephalohematoma
  - Subperiosteal Outer Table
- Epidural (Extradural)
  - Subperiosteal Inner Table
  - "Epi-arachnoid"
- Subarachnoid
- Parenchymal Hemorrhage
- Intra-ventricular
Subdural Hematoma

- Scalp & Skull
- Dura
- Arachnoid
- Pia and Brain
- Ventricle and CSF

Complex Subdural Hematoma: Adult

1cm pineal shift, 3cm Right-to-Left shift and Subfalcial Herniation

Herniation: Subfical and Transtentorial

Left to Right Shift ... Subfical herniation ... Downward Transtentorial

SUBDURAL HEMATOMA

- Extremes of age
  - Infants/elderly
- Subacute presentation
  - Days or weeks after trauma
- Fracture not needed
- Crescentic
  - Not hyperdense
  - Crosses sutures commonly
  - Interhemispheric fissure (kids)
- Epi - Arachnoid

SUBDURAL HEMATOMA - Source of Blood

- Laceration Of Cortical Aa. and Vv.
  - Direct: Penetrating Injury
- Large Contusions
  - Direct/indirect: "Pulped Brain"
- Torn Bridging (Cortical) Veins
  - Indirect
  - Acceleration-deceleration

SUBDURAL HEMATOMA

- Acceleration-deceleration
- Sagittal Plane
  - Causes Oscillation Of Brain
  - Brain LAGS Behind Skull
- Bridging Veins Stretch & Tear
  - Venous Bleeding (Slow)
  - Multiple and Bilateral Veins
- Dissection Of Subdural Space
  - Under Dura => Over Arachnoid
  - Spreads around convexity
  - Into the interhemispheric fissure (child)
Bridging Veins

Dural Baffles: Falx and Tentorium

SDH → Brain Herniation

SDH → Brain Herniation

PCA Infarct Tentorial Herniation

Courtesy Mauricio Castillo, M.D. UNC
Acute Subdural Hematoma: Child, High Attenuation

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute</td>
<td>&lt; 3 days</td>
</tr>
<tr>
<td>Subacute</td>
<td>3d – 2 wks</td>
</tr>
<tr>
<td>Chronic</td>
<td>&gt; 2 wks</td>
</tr>
</tbody>
</table>

Hyperdense ➣ Isodense to Brain ➣ Hypodense

Complex Subdural Hematoma

Mixed Subacute-acute Subdural Hematoma
- Acute blood-bright
- Alternating bands
  - rebleeding
- Mass effect
  - Subfalcial herniation
  - "Trapped" ventricle
Child Abuse?

The "Multiple Sclerosis" of trauma:
- Lesions separated in space
- Lesions separated in time

Ophthalmoscope Exam Required
- Retinal hemorrhage highly correlated with non-accidental trauma

Skeletal survey?

Arachnoid Membrane

SUBDURAL HEMATOMA
Source of Re-bleeding
- NEO-MEMBRANES
  - fragile capillaries
- BRIDGING VEINS
  - stretching across SDH
  - constant tension

SUBDURAL HEMATOMA
- 2-3 wks. to develop fully
- develop from outer (dural) margin
- not from arachnoid side
  - inner (arachnoid) border intact
- fibroblasts, and new immature capillaries that are fragile

Membrane Hematoma
- Epidural
  - Acute
  - Biconvex
  - Unilateral
  - Skull fracture
  - Limited by sutures
- Subdural
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CEREBRAL CONTUSION

- Traumatic/mechanical disruption of small (capillary) vessels
- Extravasation of whole blood, plasma (edema) and RBC's
- Admixture of blood mixed with native tissue (petechial hemorrhage)
- Mottled / speckled density ("salt and pepper" on CT)

CEREBRAL CONTUSION

- MECHANICAL INJURY TO VESSELS
  - Extravasation of whole blood
- PETECHIAL / PERIVASCULAR HEMORRHAGE
  - Admixture of tissue and blood
  - Average density may NOT be high
- SWELLING/MASS EFFECT
- MAY PROGRESS TO HEMATOMA
  - If larger vessels are damaged
  - Large confluent mass of blood

Massive Contusions

Courtesy of Alice B. Smith, UCSF

CEREBRAL CONTUSION

naming conventions

- COUP
  - SAME SIDE AS IMPACT
  - w/fractures, small area of impact

- INTERMEDIATE (CENTRAL)
  - DAI/Shearing Injury

- CONTRE - COUP
  - OPPOSITE IMPACT
  - w/falls, broad surface of impact

Coup vs. Contrecoup

Courtesy of Alice B. Smith, UCSF
Coup vs. Contrecoup

- Cranial nerves 2-12 intact... but the patient smells badly, not bad, but badly... Anosmia
Cerebral Cortical Contusion

- Crowns of Gyri
- Linear or flame shape
- NOT in depths of Sulci

Cerebral Fx Contusion

Acute vs. Chronic Contusion

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SHEARING INJURIES

- **Deep lesions**
  - High Velocity (MVA) Trauma
  - Acceleration/Deceleration
    - Especially **CORONAL angular momentum**
    - Side Impact (Running a Red Light)
  - Do not require an impact or Fx.
- **“SHEARING OF AXONS”**
  - Breaks connections
  - Actual force may be tension & excito-toxicity
- **“SHEARING” of Small WM VESSELS**
  - Small (petechial) hemorrhages

Coma: Lesions and Locations

Shearing Lesions are small (<15mm) and deep (subcortical, WM, Corpus callosum, Thalamus, Brain stem)

- **Coronal Angular Acceleration**
- Subcortical – many needed
- White Matter – many needed
- Thalamus – few needed
- Reticular Activating System
  - Dorsal Brainstem
  - Only one needed
Deep Lesions - Terminology
- Intermediate Contusions
- Shearing Injury
- Diffuse White-matter Injury (DWI)
- **Diffuse Axonal Injury (DAI)**

5 MPH for Pedestrian-Auto
- Auto weighs 2500 – 4000 lbs
- One auto hits another auto
  - Significant acceleration at 35 mph
- Auto hits a Pedestrian (60-260 lbs)
  - Significant acceleration at 5 mph

DWI/DAI = Deep Lesions
- **<15mm diameter** and BELOW cortex
- Subcortical and Hemispheric WM
- **Corpus Callosum**
  - posterior body
  - splenium
- **Brain stem**
  - Dorsolateral Quadrant of Upper BS
  - Deep BS
  - Ventral BS

DIFFUSE AXONAL INJURY
- **Neurologic Sx Begin at Impact**
  - Some have Immediate L.O.C.
  - Some have Persistent Vegetative State
- Pathology:
  - foci of hemorrhage in callosum, brainstem, etc.
  - axon retraction balls (ARB)
- Long-Term Survivors:
  - microglial clusters
  - foci of demyelination

Deep Lesions – Coronal Forces
Angular momentum in the coronal plane:
- Running a Red Light ... T-Bone the cars

WM – Axonal Transection
Axon Retraction Balls – Cytoplasm leaking from transected axons and disrupted axolemma.

DTE - Diffusion Tensor Imaging:
Detects loss of anisotropy in areas where axons are disrupted and disconnected.
**DAI or DWI**

- Non limited to White Matter
  - Basal Ganglia and Thalamus
- Some patients in “Coma”
  - Different types of “Coma”
    - Global lesions
    - Small focal lesions (e.g. Reticular formation)
- Some patients have only subtle changes on specialized psychometric tests

**Experimental Model:**
Requires Hemisphere >> Brainstem

- Mouse – no
- Rat – no
- Cat – no
- Monkey – no
- Chimpanzee – no
- Great Ape – yes
- Politician - no

University of Wisconsin and Michigan State Comparative Mammalian Brain Collections

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**Dorsolateral Brainstem**

**Corpus Callosum**

Dense, compact, white matter, bundles of axons

**Corpus Callosum -> Ventricle**

**Corpus Callosum and BG**
Let’s Catch-up with our Pt …

- 26 y/o man transferred by air-evac after a helicopter crash. Upon arrival, patient was intubated and sedated. CT of the head was performed as part of trauma evaluation.

26 y.o. man in Coma

CT Scan  
MR Scan w/“blood sensitive” technique

Deep Lesions ... including thalamus ... "shearing injury" ... causing coma

Corpus Callosum

T2W  SWI

Diffuse Axonal Injury - SWI

Diffuse White-Matter Injury

Shearing Injury vs. Contusion

Contusions are surface lesions