CRUSH INJURY

Body Trauma: An Unrecognized Impact

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Dr. Uzma Samadani

Intellectual Property related to:
• concussion and brain injury assessment
• assessment of dementia after brain injury
• treatment of intracranial hemorrhage

Grant funding, salary/employment, consulting fee, honorarium or equity
• Abbott Diagnostic Laboratories
• Continuing Legal Education in MN, NY
• Hennepin County Medical Center
• Hennepin Health Foundation
• Integra Corporation
• Islamic Medical Association of North America
• Medtronic Corporation
• Minnesota Brain Injury Alliance
• National Football League
• National Neurotrauma Society
• North American Brain Injury Society
• Oculogica Inc.
• Steven and Alexandra Cohen Foundation for Veteran Post Traumatic Stress and Traumatic Brain Injury
• Texas, Minnesota, and Wisconsin High School Coaches Associations
• United States Veterans Administration and Office of Research and Development
• USA Football
UZMA SAMADANI, MD, PhD

- **Education:**
  - Undergraduate: University of Wisconsin
  - Graduate and Medical School: University of Illinois
  - Residency: Hospital University of Pennsylvania
  - Fellowship: Georg-August-Universität Göttingen, Germany

- **Accomplishments and Titles:**
  - Rockswold Kaplan Endowed Chair for TBI Research
  - American Board of Neurological Surgeons Board-Certified
  - Fellow of the American Association of Neurological Surgeons (FAANS)
  - Fellow of the American College of Surgeons (FACS)
  - Congress of Neurological Surgeons Executive Committee for Trauma and Critical Care
  - Executive Board of Women in Neurosurgery
The Brain Injury Research Lab was founded by Dr. Samadani in August of 2015 at Hennepin County Medical Center.

This was a joint venture between HCMC Neurosurgery and the Minneapolis Medical Research Foundation (MMRF)

- 16 employees
- 37 volunteers

GOAL: “to better classify brain injuries by analyzing blood-based biomarkers, eye tracking, and imaging.”

http://www.samadanilab.com/
This eye tracking technology was developed by Dr. Samadani to prognose the severity of brain injury based on the patient’s ability to track the movements of images on a video for 220 seconds.

This technology allows for us to track each eye separately and collect ~ 90 different metrics to test for cranial nerve palsies and other ocular dysmotilities indicative of TBI.

- **CRUSH**: Do thoraco/abdominal crush injuries increase ICP more than extremity crush?
- **Integra Study**: What is the physiological impact of changes in ICP vs CPP and Bt02
- **Outcome Measure**: Can eye tracking be used to assess recovery from ICH?
- **Concussion**: does eye tracking correlate with concussion symptoms in patients with trauma?
The birth of Eye Tracking

How does it work?
The Basics
The video makes 5 clockwise rotations around the screen

Each pupil’s movements are tracked and plotted

All five of the plots are then combined and averaged

Conjugacy is assessed by delta X and delta Y graphs
Traumatic Brain Injuries (TBIs) are associated with some degree of fluctuation in Intracranial Pressure (ICP) which are proportional to the primary severity and resultant secondary pathology.

- Ranging from the most mild concussion to the most severe, catastrophic intracranial event.
- However, we did not have a reliable or appropriate tool with which we can measure these changes in patients who do not warrant invasive ICP monitoring devices until now.
- As such, these ICP changes in mild to moderate TBI have gone undiagnosed and unmeasured.
- Elevated ICP can result from TBI due to vascular swelling or obstruction of cerebral edema and cerebrospinal fluid (CSF) flow (2).

TBI and ELEVATED ICP

![Diagram of brain showing ICP changes due to edema and hemorrhage](image-url)
Elevated ICP may eventually lead to intracranial hypertension (ICH) which is clinically defined as an **ICP > 20 mmHg** (3).

- This is often the case in patients who suffered a severe TBI

Two current main methods of routine ICP monitoring:

- **Intraventricular catheter** → difficulties in catheter placement and risk of ventriculitis (4)
- **Intraparenchymal microsensor** → potential misrepresentation of global ICP value due to intraparenchymal pressure gradients (4)

**Indications** for ICP Monitoring Device:

- Severe TBI with sustained ICP > 20 mmHg (5)
- GCS < 8 (5)
- Post-craniotomy (5)
The intracranial contents, including the Cranial Nerves which exit at the base of the brain, are susceptible to changes in intracranial pressure (ICP) that result from Traumatic Brain Injury (1).

- In particular CN III, IV, and VI are injured by the elevation of ICP.
- These nerves are often injured due to their long course and can be affected even in mild TBI's where there is an increase in ICP.
  - CN III: Oculomotor
  - CN IV: Trochlear nerve
  - CN VI: Abducens

Eye tracking has been shown to pick up on these cranial nerve palsies.
### CRANIAL NERVE

<table>
<thead>
<tr>
<th>CRANIAL NERVE</th>
<th>MUSCLE INNERVATION</th>
<th>FUNCTION</th>
</tr>
</thead>
</table>
| Oculomotor Nerve (CN III) | Superior Rectus  
Inferior Rectus  
Medial Rectus  
Inferior Oblique  
Levator Palpebrae Superioris | Adduction  
Depression  
Elevation  
External Rotation |
| Trochlear Nerve (CN IV) | Superior Oblique | Abduction  
Internal Rotation  
Depression while adducting |
| Abducens Nerve (CN VI) | Lateral Rectus | Abduction |
CRANIAL NERVE MUSCLE INNERVATION

Oculomotor Nerve (CN III)
- Superior Rectus
- Inferior Rectus
- Medial Rectus
- Inferior Oblique
- Levator Palpebrae Superioris
  - Adduction
  - Depression
  - Elevation
  - External Rotation

Trochlear Nerve (CN IV)
- Superior Oblique
  - Abduction
  - Internal Rotation
  - Depression while adducting

Abducens Nerve (CN VI)
- Lateral Rectus
  - Abduction

OCULAR DYSMOTILITY [continued]

Preoperative
Left Eye
Aspect Ratio 0.81
Right Eye
1.34

Postoperative Day 2
Left Eye
Aspect Ratio 1.04
Right Eye
1.00
## Cranial Nerve Innervation and Function

<table>
<thead>
<tr>
<th>Cranial Nerve</th>
<th>Muscle Innervation</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oculomotor Nerve (CN III)</td>
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<td>Adduction, Depression, Elevation, External Rotation</td>
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<td>Superior Oblique</td>
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<td>Abducens Nerve (CN VI)</td>
<td>Lateral Rectus</td>
<td>Abduction</td>
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### Ocular Dysmotility (continued)
CRANIAL NERVE MUSCLE INNERVATION

**Oculomotor Nerve (CN III)**
- Superior Rectus
- Inferior Rectus
- Medial Rectus
- Inferior Oblique
- Levator Palpebrae Superioris

**Adduction**
- Depression
- Elevation
- External Rotation

**Trochlear Nerve (CN IV)**
- Superior Oblique

**Abduction**
- Internal Rotation
- Depression while adducting

**Abducens Nerve (CN VI)**
- Lateral Rectus

**OCULAR DYSMOTILITY**

[continued]
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CRANIAL NERVE MUSCLE INNERVATION

**Oculomotor Nerve (CN III)**
- Superior Rectus
- Inferior Rectus
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- Levator Palpebrae Superioris

- **Function**
  - Adduction
  - Depression
  - Elevation
  - External Rotation

**Trochlear Nerve (CN IV)**
- Superior Oblique

- **Function**
  - Abduction
  - Internal Rotation
  - Depression while adducting

**Abducens Nerve (CN VI)**
- Lateral Rectus

- **Function**
  - Abduction

Ocular Dysmotility [continued]
It has been previously shown that elevated ICP correlates with increasingly abnormal eye tracking results (1).
EYE TRACKING AND ICP

- Elevated ICP also corresponds with decreasing box areas, and thus abnormal eye tracking, for the left and right eyes.¹
  - CN III Palsy → assessed by measuring *vertical* distance moved by pupil¹
  - CN VI Palsy → assessed by measuring *horizontal* distance moved by pupil¹

*FIG. 1. Charts showing that as the ICP increases, the area of the box plot decreases, suggesting impaired ocular motility at higher ICPs. The area of the eye-tracking scatterplot (box plot) is charted against the ICP in 23 patients undergoing 55 eye-tracking sessions. Each symbol represents an individual patient, with lines connecting the occasions on which each patient was tracked at a different ICP. Patients who were only tracked once do not have lines. Panel A represents the mean area in the left eye, and panel B is of the mean area in the right eye. Figure is available in color online only.*
Fitting the Pieces

TRACKING CRUSH INJURY
**Crush Injury:** Compression of extremities or different parts of the body that lead to muscle swelling and/or neurological disturbances in various areas of the body

**Common Traumatic Pathology:**

<table>
<thead>
<tr>
<th>Extremity</th>
<th>Abdominal</th>
<th>Thoracic</th>
<th>Systemic ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft tissue injuries</td>
<td>Abdominal perforation</td>
<td>Penetrating chest injury</td>
<td>Hypotension</td>
</tr>
<tr>
<td>Femur fracture</td>
<td>Abdominal hemorrhage</td>
<td>Rib/Sternal fracture</td>
<td>Rhabdomyolysis</td>
</tr>
<tr>
<td>Humerus fracture</td>
<td>Splenic laceration</td>
<td>Vertebral fracture</td>
<td></td>
</tr>
<tr>
<td>Tibia fractures</td>
<td>Lumbar fractures</td>
<td>Spinal cord Injury</td>
<td></td>
</tr>
<tr>
<td>Radial fractures</td>
<td>Sacral fractures</td>
<td>Palmar contusion/hemorrhage</td>
<td></td>
</tr>
<tr>
<td>Ulnar fractures</td>
<td>Pelvic fractures</td>
<td>Cardiac contusion</td>
<td></td>
</tr>
<tr>
<td>Compartment Syndrome</td>
<td>Bowel contusion</td>
<td>Aortic Injury</td>
<td></td>
</tr>
<tr>
<td>Crushed Limb Syndrome</td>
<td>Liver laceration</td>
<td>Pneumothorax/hemothorax</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abdominal Compartment Syndrome (ACS)</td>
<td>Chest asphyxia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acute Renal Injury</td>
<td>Esophageal/ Bronchial perforation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bronchial perforation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diaphragmatic Injury</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post-traumatic pneumonia</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulmonary Embolism</td>
<td></td>
</tr>
</tbody>
</table>
WHAT DOES THE LITERATURE SAY?
THE CASE OF ERIK BEDEAUX

CLASSIFY TBI
Case Report published in August, 2012 focused on a 44-year-old male who suffered from chest asphyxia after a crush injury to his chest and torso (1).

Patient was crushed by heavy vehicle parts and “developed traumatic asphyxia with severe thoracic injury and mild brain edema…” (1).
Increased intra-abdominal pressure (IAP) and intrathoracic pressure (ITP) can affect vital systems outside the thoracoabdominal region, including nervous, cardiovascular, pulmonary, and gastrointestinal. This results due to diminished blood flow to these areas (cite R1).
**Multiple Proposed Mechanisms:**

- IAP decreases lumbar venous plexus blood flow and CSF absorption in the lumbar cisterna → elevated ICP
- Thoracic crush trauma → increased ITP → increased jugular venous pressure, decreases cerebral blood flow (low cerebral perfusion pressure), and increased intracranial blood volume → elevated ICP
- Chest trauma → increased ITP → increased superior vena cava pressure → decreased cerebral blood flow → elevated ICP
- Acute IAP causes increase in intracranial pressure due to increase in pleural pressure (cerebral perfusion pressure decreases due to functional obstruction of cerebral venous outflow) (2,3)
- Abdominal and thoracic cavities linked via diaphragm → transmission of IAP to the intrathoracic pressure has been noted in previous studies (2)
- Increased ICP is correlated with TBI (4)
Sparked by the case of Erik Bedeaux

○ Patient initially enrolled as body control, but we noticed abnormal eye tracking
○ Abnormal eye tracking → cranial nerve palsy → elevated ICP → neurologically similar consequences to TBI

Raised the question: Do patients in different categories of crush injury experience similar neurologic symptoms as patients who suffered TBI?

○ Prompted us to compare thoracoabdominal crush-injured patients to extremity crush-injured patients

We expected to see elevated ICP more-so in thoracoabdominal crush patients than in extremity crush patients

○ Proposed mechanism: Thoracoabdominal crush → elevates ITP and/or IAP → decreases venous return → decreases CPP/elevates ICP
Objectives:

1.) To evaluate if certain crush injuries without a clear cranial impact have neurologic consequences similar to those of typical traumatic brain injuries.

2.) To present preliminary data suggesting that thoracoabdominal crush injury causes an increase in ICP leading to cranial nerve palsies that can be detected by noninvasive eye tracking technology.

3.) To further assess the utility and validity of eye tracking technology in detecting ICP elevations in patients whose injuries would not typically warrant conventional ICP monitoring devices.

4.) To evaluate whether or not extremity crush injury has an effect on the intracranial compartment.
We examined **four groups** of crush-injured patients:

1. **Isolated** abdominal/thoracic crush injury - 6 subjects
   a. Crush injury to abdomen/thorax with *no* clear head trauma
2. **Isolated** extremity crush injury - 4 subjects
   a. Crush injury to an extremity with *no* clear head trauma
3. **Head injury** + thoracic crush injury - 2 subjects
   a. Crush injury to thoracic region with associated head trauma
4. **Head injury** + extremity crush injury - 4 subjects
   a. Crush injury to extremity and with associated head trauma
Crushed by Amusement Ride

- 41 M was working on the Power Tower Ride at Valleyfair when part of the ride landed on his right upper chest. No blunt trauma to the head.

- In the ED:
  - Physical Exam - x
  - Physical Exam - x
  - Physical Exam - x
  - Physical Exam - x

- He was admitted etc
ISOLATED THORACIC CRUSH

→ 2 week time-point eye tracking data

- Disconjugate movements of the left and right vertical and horizontal planes
ISOLATED
THORACIC CRUSH

2 week

6 month

12 month
Auto vs Pedestrian

- 36 M who presented to the ED after their right lower extremity was crushed between two vehicles at approximately 10 mph. There was no blunt trauma to the abdomen, thorax, or head.

- In the ED:
  - Physical Exam - atraumatic outside of tenderness and ecchymosis of the right femur, CMS intact
  - FAST Exam - negative
  - Right Femur XR - negative
  - Pelvic XR - negative

- Discharged from the ED with Occupational Medicine follow up

- Discharge Diagnoses: RLE contusion
ISOLATED EXTREMITY CRUSH

NORMAL EYE TRACKING

PATIENT’S EYE TRACKING
Crushed by Tree Limb

- 52 M who presented to the ED after a tree limb fell hitting him in the head and right leg. He was found to have a + LOC and obvious open RLE fracture. Flown in via helicopter.

- In the ED:
  - Physical Exam - GCS 15, scalp hematoma and abrasion, open deformity of the right midshaft tibia/fibula with CMS intact distally
  - FAST Exam - negative
  - CT Cervical Spine - C7 posterior arch fracture
  - Right Tib/Fib XR - displaced fractures of both distal diaphysis

- Patient was admitted underwent surgery for the RLE fractures

- Discharge Diagnoses: Tib/Fib fx, C7 posterior arch fx, TBI
HEAD INJURY + EXTREMITY CRUSH

PATIENT'S EYE TRACKING

AR: 0.9247
AR: 1.0171
AR: 1.0096
AR: 1.007
AR: 1.026

AR: 0.9004
AR: 1.0618
AR: 1.0776
AR: 1.1463
AR: 1.1492

AR: 0.9604
AR: 0.9605

Delta X(Y, Z)
- 48 yo male, involved in motor vehicle collision, ejected, and pinned under vehicle

- Among several other injuries, sustained traumatic subarachnoid hematoma, closed fractures of multiple ribs, multiple foot fractures, and pneumonia

- Patient admitted on 1/9/2017, discharged 1 month later to a skilled nursing facility

- Discharged with 20 medications, surgical follow-up 2 weeks post-discharge and TBI follow-up in 1 month

- Left hospital with 17 discharge diagnoses
HEAD INJURY + ABD/THORACIC CRUSH

- In Hospital Time-Point eye-tracking data
HEAD INJURY + ABD/THORACIC CRUSH

In Hosp

left.AR=0.959

right.AR=0.960

12 mo

left.AR=1.132

right.AR=0.965
DATA

BOX SCORE

- Insert definition
- Insert P values
DATA

LEFT AREA MEDIAN

- Insert definition
- Insert P values
DATA

RIGHT AREA MEDIAN

- Insert definition
- Insert P values
DATA

RIGHT SKEW TOP

- Insert definition
- Insert P values
Eye tracking can be performed as a means of noninvasive detection and long-term monitoring of elevated ICP (1)

- Evaluating slight cranial nerve palsies that can be detected by abnormal eye tracking metrics
- Slight abnormalities in specific metrics might be indicative of a TBI

Can be performed on anyone who suffered a TBI, whether mild, moderate, or severe

Does not require a trained examiner, pupil dilation, imaging studies, or invasive procedures (1)

Data obtained from eye tracking suggests that elevated ICP may have effects at levels lower than those currently considered pathological (1)


SPECIAL THANKS TO

Daniel Rafter, M.D.