ABSTRACT
Traumatic brain injuries (TBI) and its complications are a leading cause of morbidity, mortality, disability and socioeconomic losses in India and other developing countries. Especially in children it poses a significant global public healthcare concern from the time of insult until many years later when long-term sequelae may manifest. The rapid surge in urbanization, motorization and lifestyle changes are leading to an increased risk for TBI. The exact statistics from India is not available. It is the prevention of worsening of the secondary injury that is often targeted during the medical management. Due to the fact that pediatric brain is still developing and has not completely matured, proper understanding is required for adequate management of pediatric patients with TBI.

Keywords: Traumatic Brain Injury, ICP, CPP, ICP monitoring, Raised ICP

Table 1: Classification of TBI [8] (GCS- Glasgow Coma Scale)

<table>
<thead>
<tr>
<th>Classification</th>
<th>GCS</th>
<th>Loss of Consciousness</th>
<th>Post Traumatic Amnesia</th>
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<tbody>
<tr>
<td>Mild</td>
<td>13-15</td>
<td>0-30 minutes</td>
<td>&lt;1 day</td>
</tr>
<tr>
<td>Moderate</td>
<td>9-12</td>
<td>30 minutes-24 hours</td>
<td>1-7 days</td>
</tr>
<tr>
<td>Severe</td>
<td>3-8</td>
<td>&gt;24 hours</td>
<td>&gt;7 days</td>
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Primary injuries are due to trauma per se and include direct injury to the brain such as diffuse axonal shear and rupture, contusion, fractures of the skull. Meanwhile, secondary injuries occur after the initial injury due to failure of autoregulation and biochemical changes, and vary from local inflammation to global ischemia. This is dependent on the presence of increased intracranial pressure (ICP) and this is directed in the management-ICP and CPP directed therapy. 

Poor prognosis is noticeable in age group <4 years with better outcomes in the age group of 5–15 years.

Pathophysiology
The intracranial vault is a rigid container comprised of three constituents: Brain (80%), cerebrospinal fluid (CSF) (10%), and cerebral blood volume (CBV) (10%). The Monro–Kellie doctrine states that any...
individual component of the intra-cranial vault may undergo alterations but the total volume within skull remains fixed. Therefore, any increase in one of these components will either cause an equivalent decrease in the other two or increase in pressure within the box. The brain has normal compensatory mechanisms in place to maintain the normal ICP. Once these compensatory mechanisms are exhausted a small increase in volume will result in a large rise in ICP and herniation may occur. This relationship between ICP and intracranial volume is best described by the volume-pressure curve in Fig 1.

The etiology of increase in ICP in severe TBI is multifactorial. It may be due to traumatic mass lesion, vascular engorgement and/or cerebral edema. Hyperemia occurs early after trauma and persists for few days. Compensatory vasodilatation to maintain optimal cerebral blood flow may lead to increase in CBV. Studies have shown that it is the brain edema, and not increased CBV which is the major culprit for brain swelling after TBI. Both vasogenic and cytotoxic cerebral edema occur in TBI, however incidence and onset depends on the nature of the injury.

Cerebral perfusion and Autoregulation
Cerebral blood flow (CBF) is higher in children as compared with adults, matching their higher cerebral metabolism. The CPP is the main determinant of cerebral blood flow (CBF). Normally CBF is coupled to metabolic demand of tissue, with normal flow greater than 50ml/100 g/min. Less than 20 ml/100 g/min is considered the ischemic threshold. The process of cerebral autoregulation maintains CBF between CPP ranges of approximately 50 - 150 mmHg in adults. This autoregulation is because of the ability of cerebral vessels to change diameter in response to changing physiological conditions. Outside these ranges CBF becomes pressure-dependent. As shown in Fig 2, when CPP is less than the lower threshold for autoregulatory compensation, CBF progressively decreases with CPP, resulting in ischemia.

The physiological response of blood vessels to partial pressure of carbon dioxide (PaCO2) is the rationale for the use of brief hyperventilation as useful tool in the acute management of increased ICP. As PaO2 (Partial Pressure of Oxygen) declines it causes vasodilatation and increase in CBF which in presence of disrupted blood brain barrier promote the formation of vasogenic edema. Avoiding hypoxia is therefore important in the acute management of TBI.

Emergency Room Management of TBI
In any child with trauma, a quick primary and secondary survey must be done with prompt attention to airway, breathing and circulation. Immediate assessment and early initiation of neuroprotective measures mark the cornerstone of management in TBI. The primary purpose is to provide adequate

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Figure 1: Intracranial Pressure-Volume curve. The curve has 3 parts: A flat part representing good compensatory reserve (A-B), an exponential part representing reduced compensatory reserve (B-C) and a final flat part representing terminal derangement of cerebrovascular responses at high ICP (C-D).

Figure 2: Cerebral autoregulation curve in adults. In the normal relationship (solid line), with CBF held constant across a wide range of CPP (50±150 mmHg). In disease states (e.g. Vasospasm, ischemia, intracranial mass lesion), cerebral blood flow may become pressure passive (dotted line).
oxygenation and maintain the cerebral perfusion pressure (CPP).
If the child is in a metropolitan area, he/she should be immediately shifted to a pediatric trauma center. ABC's should be assessed along with cervical spine stabilization. Airway should be established and if required supplemental oxygen should be provided.
In case of hypotension volume repletion should be initiated with isotonic fluids like normal saline. Hypertonic saline can be used there is a suspicion of intracranial bleed in view of its beneficial effects on intracranial hypertension.
Assess the level of sensorium using Modified Glasgow coma scale and assess brain stem function for features of herniation. If modified Glasgow coma score is less than 8 or there is evidence of herniation, intubate and ventilate. If modified Glasgow coma score is between 12 and 14, or intubation is not possible immediately and there is evidence of progressive uncal or central herniation give mannitol 0.25 g/kg. Rapid Sequence Intubation should be done in these patients. The criteria for intubation include hypoxemia, hypercarbia (PaCO2 >45 mm Hg), hypocapnia (hyperventilation causing PaCO2 <25 mm Hg), GCS <9, a drop in GCS >3 irrespective of initial GCS, anisocoria >1 mm, abnormal breathing due to cervical spine injury, chest wall dysfunction and loss of protective airway reflexes. Medications like lidocaine, thiopentone, etomidate and propofol decrease cerebral metabolic rate and can be used during RSI. However, propofol should be avoided in presence of hypotension. Recent studies suggest use of Ketamine in the presence of hypotension, as it has not shown to increase ICP if patient already has raised ICP. Similarly, it is better to avoid usage of depolarizing muscle relaxant drugs like succinyl choline as it can cause acute surge in ICP.

Role of Imaging
Neuroimaging after traumatic brain injury (TBI) helps in identifying acute and chronic sequelae of injury, such as intracranial hematomas, brain contusions, and posttraumatic complications including hydrocephalus and infections. Computed tomography (CT) is ideal for acute imaging of children who suffered TBI. Advanced neuroimaging techniques, including MR imaging, Diffusion Tensor Imaging (DTI), blood oxygen level–dependent functional Magnetic Resonance Imaging (fMRI), MR spectroscopy, perfusion imaging, PET (Positron emission tomography) or SPECT (Single Photon Emission Computed Tomography), and magnetoencephalography, are of particular interest in identifying further injury in patients with traumatic brain injury when conventional Non Contrast CT and MR imaging findings are normal, as well as for prognostication in patients with persistent symptoms.

ICU Management
After the initial resuscitation, management should be aimed at preventing secondary brain injury such as hypoxemia, hypercapnia, hyponatremia, hyperthermia, seizures and hypo/hyperglycemia and increase in ICP.

Ventilatory and Hemodynamic Objectives
Hypotension and hypoxia are the most common contributors to secondary brain injury and poor outcome. Hypotension in the first 6 hours is particularly deleterious, emphasizing the need for early monitoring of blood pressure. Hypoxia should be prevented and normocapnia should be maintained (PaCO2 36-45 mmHg). As end tidal CO2 reflects the PaCO2, it should be monitored regularly. Maintaining age-appropriate systolic blood pressure great or equal to the 75th percentile may also be associated with better outcome.

Intracranial Hypertension
Intracranial hypertension is a key variable associated with secondary brain injury after severe TBI. Intracranial hypertension is associated with a poor neurological outcome and death in children. Measures should be taken to avoid rise in intracranial tension and maintain cerebral perfusion pressure. Intracranial hypertension is defined as ICP >20 mmHg for >5 minutes.

Neuro-Monitoring
Monitoring of a neurologically injured child is categorized as below
a. Neurological examination - Pupils, reflexes, muscle tone, new focal deficits
b. General systemic monitoring - Arterial blood pressure, heart rate, respiratory rate, body temperature, arterial blood gases, laboratory tests
c. Imaging monitoring modalities - Computed
tomography (CT)-scan, magnetic resonance imaging (MRI), positron emission tomography (PET) scan, cerebral angiography
d. Multimodal cerebral monitoring - Intracranial pressure (ICP)/cerebral perfusion pressure (CPP), brain tissue oxygen pressure (PbtO$_2$), jugular venous oxygen saturation (SjvO$_2$), oxygen extraction, electroencephalogram (EEG), Evoked potentials, transcranial Doppler flow, Microdialysis (lactate/pyruvate/glutamate levels) Near-infrared spectroscopy. 

ICP monitoring and EEG monitoring are the most commonly used parameters of multimodal cerebral monitoring.

**ICP monitoring**

Invasive ICP monitoring in pediatric patients first became part of the Brain Trauma Foundation guidelines for the management of severe TBI in children in 2003. 

The Level III recommendation of ICP monitoring use was based on the high incidence of intracranial hypertension among children with severe TBI and the strong association between high ICP and poor neurological outcome. Intracranial pressure monitoring (ICP) is appropriate in infants and children with severe traumatic brain injury (TBI) (Glasgow Coma [GCS] score ≤ 8). The presence of open fontanels and/or sutures in an infant with severe TBI does not preclude the development of intracranial hypertension or negate the utility of ICP monitoring.

ICP cannot be reliably estimated from any specific clinical feature or computed tomography (CT) finding and must actually be measured. Different methods of monitoring ICP have been described (Fig. 3) but two methods are commonly used in clinical practice: intraventricular catheters and intraparenchymal catheter-tip, microtransducer systems.

The “gold standard” technique for ICP monitoring is placement of ventricular catheter. The advantage is measurement of global ICP, periodic external calibration, therapeutic drainage of CSF, and administration of drugs (eg, Antibiotics). In TBI literature therapeutic target for ICP treatment is based on adult studies, with an ICP treatment threshold of 20 mmHg.

**ICP Targeted Therapy**

In ICP targeted therapy, ICP is the primary target and CPP is maintained above physiological threshold. Chambers et al have suggested age-related CPP targets (0–2 years > 40 mmHg, 2–6 years > 53 mmHg, 7–10 years > 63 mmHg, 11–15 years > 66, >16 years > 70 mmHg) for ICP targeted protocols.

**CPP Targeted Therapy**

In CPP based therapy, higher CPP is targeted as autoregulation is shifted towards right side in the injured brain. CPP based therapy is better when cerebral autoregulation is preserved. For CPP targeted therapy, CPP between 60–70 mmHg seems to provide the best outcomes. For CPP targeted therapy, we use CPP > 50 in infants and > 60 mmHg in older children.

**Management of raised ICP**

Head elevation at 30° can lower ICP without adversely affecting MAP or CPP

- Adequate sedation and analgesia as agitation can increase the cerebral metabolic demand leading to increase in CBF and ICP.
- Osmotic agents are used to decrease brain edema. Mannitol has been in use since decades. It decreases ICP by two mechanisms-by decreasing blood viscosity and creating an osmotic gradient. But it poses the risk of hypovolemia, electrolyte imbalance and acute renal failure. Mannitol in dosages of 0.5 to 1 gm/kg may be used intravenously at 6 hourly intervals or as bolus doses when there is sudden increase in ICP from baseline.
- Recently, hypertonic saline has gained significance for use in raised ICP. 3% N.S
received a stronger level II recommendation over mannitol in the 2012 pediatric TBI guidelines. It preserves intravascular status along with added benefits like restoration of normal cellular resting membrane potential and cell volume, stimulation of atrial natriuretic peptide release, inhibition of inflammation, and enhancement of cardiac output. It can be used 2-3ml/kg maintaining serum sodium in the range of 150-160 mEq/L.

- Cerebrospinal fluid drainage decreases the intracranial volume and provides an immediate, but transient, decrease in ICP.
- Hyperventilation is the fastest method to decrease ICP in children with impending herniation. It decreases ICP by vasoconstriction and thereby decreasing CBF. However, studies have found that hyperemia is uncommon after TBI and hyperventilation can further cause cerebral ischemia. The 2012 guidelines have a stronger recommendation against prophylactic hyperventilation.
- Second tier therapies include barbiturate coma, decompressive craniectomy, and therapeutic hypothermia.
- Use of steroids is not recommended.

In Centers where ICP monitoring is not available it might be safer to follow ICP targeted protocol, which aims at maintaining normotension and use of osmotherapy. Child should be observed clinically for early detection of herniation syndromes. They would need more frequent neuroimaging like CT head. CPP targeted protocol should not be implemented if ICP monitoring facilities are not available. Recently attempts have been made to measure ICP noninvasively. Optic nerve sheath diameter measurement (ONSD) [more than 5.9mm was predictive of elevated ICP], tympanic membrane displacement, and Transcranial Doppler ultrasonography.

Glycemic control
The relevance of strict glycemic control is particularly controversial in the context of neurocritical care. In the first 48 h after TBI, hyperglycemia is observed in 34% of children, even in the absence of glucose infusion. Hyperglycemia has been associated with poor outcome, explained either by a more severe TBI or by the neurotoxicity of glucose. Hyperglycemia augments oxidative stress and inflammation, while on the other hand brain metabolism depends on glucose. So an adequate control should be achieved keeping the blood glucose levels between 100-200mg/dl.

Hypothermia
Hypothermia has been found to be neuroprotective by decreasing cerebral metabolism, excitotoxicity, production of free radicals, and nitric oxide synthesis. But there are controversies regarding the effect of hypothermia considering which moderate hypothermia (core temperature 32–33°C) for ICP not controlled by conventional measures, beginning within 8 h of injury, and maintained for 48 h may be applied.

Hematologic Objectives
Coagulopathy is common after TBI and should be treated as there is clear association with severity and outcome. INR values are usually maintained between 1.2 to 1.6 to prevent surgical bleeding. Anemia is common in TBI. A recent study confirmed that red blood cell transfusion transiently improves brain oxygenation in pediatric TBI patients, especially in those with lower initial hemoglobin values.

Seizure Control
Use of prophylactic phenytoin in all head injury is not supported by clinical evidence. However, Phenytoin should be loaded in children with seizures. Status epilepticus should be treated as per protocol with care taken to prevent hypotension. In children who are muscle relaxed EEG monitoring should be done to detect non convulsive seizures and treat them to decrease cerebral oxygen consumption.

Nutrition
Early enteral feeding is recommended if there is no associated intra-abdominal injury. Once hemodynamic stability is achieved full nutritional requirements can be met.
Decompressive surgery
Both craniotomy and craniectomy are used in setting of a hematoma after trauma. Studies have been controversial regarding the benefits of decompressive surgeries in TBI.

Table 2: Indications for surgical evacuation of intracranial hematomas with respect to decline in mental status (GCS). Thickness is in regard to the maximum thickness on CT of the head. MLS- midline shift.46

<table>
<thead>
<tr>
<th>Type of hematoma</th>
<th>Without respect to decline in GCS</th>
<th>With respect to decline in GCS</th>
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<tr>
<td>Subdural</td>
<td>Thickness ≤ 10 mm or more, MLS ≤ 5 mm</td>
<td>Thickness &gt;10 mm and MLS &gt;5 mm if GCS decreased by 2 points or more since presentation</td>
</tr>
<tr>
<td>Epidural</td>
<td>Volume ≤ 30 cc or more</td>
<td>GCS ≤ 8 or less with anisocoria</td>
</tr>
<tr>
<td>Intraparenchymal</td>
<td>Elevated ICP refractory to medical management, signs of mass effect on CT, Lesion volume &gt; 30 cc or more</td>
<td>Signs of deterioration referable to the lesion, GCS ≤ 8 or &gt;20 cc of frontal or temporal contusions and MLS of 5 mm or more and/or cisternal compression</td>
</tr>
<tr>
<td>Posterior Fossa</td>
<td>Mass effect in posterior fossa (evidence of 4th ventricular distorsion, effacement of basal cisterns, hydrocephalus)</td>
<td>Any deterioration that may be attributed to the hematoma</td>
</tr>
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Key points
- Prompt resuscitative efforts in the emergency department and ongoing critical care support are aimed at the maintenance of normoxia, normocarbia, normovolemia, normoglycemia and normothermia.
- Optimal cardiorespiratory status is the cornerstone of pediatric TBI management.
- Hyperventilation should be restricted to impending herniation refractory intracranial hypertension without the evidence of brain hypoperfusion and should be accompanied by monitoring of brain oxygenation.
- CPP targeted therapy can improve outcomes and should be implemented only if ICP monitoring facilities are available and if child has intact cerebral autoregulation.
- Decompressive craniectomy should be discussed early in cases of uncontrolled intracranial hypertension without the evidence of severe irreversible brain damage.
- Conclusion
TBI in children and adolescents is a problem of enormous magnitude and carries a good outcome with prompt treatment. In India injury patterns/modes are different from the developed nations. Most of these injuries are preventable in infancy and childhood by ensuring proper vigilance, care by the parents and the caretaker, and in adolescence by pursuing safe driving with helmet and counselling for maladaptive behavioral patterns.

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References
12. Dunn LT. Raised intracranial pressure. J Neuro...


