

Critical care management of head trauma in children

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Trauma is the leading cause of both morbidity and mortality in the pediatric population, and traumatic injury causes >50% of all childhood deaths. Significant mortality rates have been reported for children with traumatic brain injury. Although children have better survival rates as compared with adults with traumatic brain injury, the long-term sequelae and consequences are often more devastating in children due to their age and developmental po-

tential. The costs involved in the care of a child with severe traumatic brain injury, extended over that child's lifetime, are significant. It is unfortunate that despite preventive measures, traumatic brain injury remains the major morbidity and mortality factor for children. (Crit Care Med 2002; 30[Suppl.]:S393-S401)

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Each year, there are over 150,000 pediatric head injuries, which result in about 7,000 deaths and 29,000 children with new, permanent disabilities (1-4). Although most of these injuries result in minor head trauma, even children who have "mild" traumatic brain injury (TBI) may develop life-long sequelae (5, 6). The most common mechanism of injury differs based on age. For example, younger children under the age of 4 yrs most often have TBI secondary to falls, motor vehicle collisions, and child abuse. For older children, TBI is most often attributed to their participation in sports or to motor vehicle collisions. TBI in the teenage population is usually associated with motor vehicle collisions. However, violent crime and assault are now the second leading cause of death in teenagers (7).

PATHOPHYSIOLOGY

Primary brain injury, or the trauma that results directly from the impact, is best prevented by aggressive injury-prevention campaigns such as those implemented by organizations such as Think First/National Injury Prevention Foundation. Seatbelts, helmets, and airbags, when used correctly, can either

help to eliminate or at least minimize the effects of the impact at the time of injury. The forces involved in both pediatric and adult TBI include contact and inertial forces. Linear force vectors, which occur when the head is struck by a moving object, are responsible for contact force generation, whereas acceleration-deceleration or angular-rotational movement of the head in space accounts for inertial forces involved in TBI. A combination of contact and inertial forces are responsible for the resultant pathologic brain injury. Because the child's head-to-torso ratio is much greater than that of the adult, angular biomechanical forces, which cause brain acceleration and deceleration, are magnified in the pediatric trauma victim. As a result, children often have more diffuse brain injury. Adult TBI more often involves focal trauma. The reasons for this difference are likely due to the unique biomechanical and tissue properties of the pediatric brain. The immature brain has a higher water content and lacks complete axonal myelination. It is also possible that the increased risk of second insults in infants and young children contributes to the diffuse nature of pediatric TBI (8, 9). In addition, postmortem studies of pediatric TBI victims often show venous congestion, edema, and diffuse axonal injury (10, 11).

Second insults differ from secondary brain injury. Second insults are events, (e.g., hypoxia, hypotension) after the primary TBI that amplify and exacerbate the severity of the secondary injury and are known to worsen prognosis. Secondary brain injury describes the events, both physiologic and biochemical, that ensue

after the primary TBI that may or may not have been complicated by a second insult. The goals of postinjury intervention are directed at reducing the secondary injury to the brain by lessening the iatrogenic second insults and lessening the effects of the secondary injury or cascade of events on the injured but viable brain. Secondary brain injury may develop acutely or subacutely after TBI and is defined as the cascade of physiologic and biochemical reactions that occur after the primary trauma. This may result in a loss of cerebral autoregulation and may incite or exacerbate the diffuse swelling and edema observed in pediatric TBI (12). Children seem to be more susceptible to hypoxia and hypotension, and their normal cerebral blood flow (CBF) and metabolism are different from that of the adult population (12). Xenon CBF studies in children have demonstrated that soon after TBI, CBF is reduced. This acute reduction of CBF may have been due to cortical hypoperfusion and ischemia and was associated with poor outcomes (12). After 24 hrs, lower CBF was not associated with poor outcome, but higher CBF was associated with good outcome (12). In addition, secondary damage may be exacerbated by the release of excitatory neurotransmitters, as shown in both *in vivo* and *in vitro* studies (13, 14). Other factors that are involved in secondary injury include elevated intracellular calcium and potassium concentrations and the formation of free radicals (15). It has also been demonstrated in experimental studies that the immature brain may be more susceptible to apoptosis or delayed cell death. These studies showed that the

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severity of neurodegeneration after trauma was highest in the youngest animal brains; this age-dependent degeneration also corresponded to an increase in intracellular proteolytic activity (16).

Since second insults such as hypoxia, hypotension, and intracranial hypertension are the leading factors associated with poor outcome, management has focused on developing better ways to improve oxygen delivery, reduce intracranial pressure (ICP), maximize cerebral perfusion pressure (CPP), and monitor for a better understanding of the biochemical response to trauma. Management in both adults and children to date has not focused on lessening secondary injury, although interventions to reduce excitotoxicity, inflammation, and other factors would fall in this category.

Specifically with regard to children, there are differences in the management and outcome of children with TBI based on the child's age at the time of injury. The initial assessment of the extent of injury based on clinical and neurologic examination may be difficult. Traditional adult trauma scores, such as the Glasgow Coma Scale (GCS), may not directly apply to children, particularly young children, and there are modified GCS scores available for pediatric trauma patients. In addition, children normally have both lower ICP and mean arterial pressure compared with adults. Whereas an ICP of 20 mm Hg may be well tolerated in an adult, an ICP of 20 mm Hg is extremely high for an infant. Lower relative mean arterial pressure is more common in pediatric trauma patients, and children will often maintain a normal systolic pressure until they enter the later stages of hypovolemic shock. The clinician taking care of the injured child needs to take into account these important issues in the assessment and management of children with TBI to minimize the potential for iatrogenic second insults. Through improved initial assessment tools, monitoring techniques, and understanding of the unique pediatric response to injury, earlier and appropriate intervention will hopefully improve outcome for children with TBI.

INITIAL ASSESSMENT

The initial assessment and management decisions made at the time of presentation are crucial to the outcome of the pediatric trauma patient. Children are often brought in directly from the scene of the trauma. In these cases, the

description of the accident and the victim by the paramedic transport team is often helpful in determining the extent and severity of injury. In other cases, the critical care team may be involved in the transfer of the patient from another facility. In such scenarios, it is crucial to establish the stability of the child, the nature of the injuries, and the available radiologic findings. In this way, necessary interventions may be started as soon as possible to stabilize the patient and facilitate the transfer.

There have been several retrospective studies that have examined the importance and significance of pediatric trauma centers. One recent study by Potoka et al. (17) looked at the number of neurosurgical procedures, morbidity, and mortality rates among pediatric trauma victims. Data were collected from the Pennsylvania Trauma Outcome Study Registry for children between 0 and 16 yrs of age who were treated at an accredited trauma facility between 1993 and 1997. There were >3000 children enrolled in the study, and the study included children with mild, moderate, and severe head injuries. For children with severe TBI, mortality was significantly lower in pediatric trauma centers and adult trauma centers with added qualifications to treat children as compared with level I and level II adult trauma centers. In addition, the overall number of neurosurgical procedures performed on children with severe TBI was significantly higher in pediatric trauma centers with lower mortality. The mortality was higher at level II adult trauma centers for children with severe TBI who required neurosurgical interventions. Clearly, however, it is always in the best interest of the trauma victim to be stabilized as soon as possible, at the closest trauma facility, and then transferred when possible to a pediatric trauma center. This transfer should be carried out as safely and expeditiously as possible.

Neurologic Exam. A brief initial neurologic examination provides crucial information about the severity of the brain injury and overall prognosis. Whereas loss of consciousness alone is a poor predictor of intracranial injury, the GCS has provided a standard guideline for the assessment function in TBI victims (18). Based on wakefulness, motor function, and verbal function, the GCS is an important component of the initial neurologic assessment of trauma patients. In a study of 653 TBI patients younger than

15 yrs of age, Levi et al. (19) demonstrated that the most important prognostic indicators were presence of associated trauma, admission GCS scores, traumatic mass lesions with increased ICP, and the presence of diffuse axonal injury. The GCS must be age modified for very young children and infants. Michaud et al. (20) reported that pupillary responsiveness and the total trauma severity scores were the most significant predictors of survival in children. Clinical signs, although helpful, do not always rule out significant TBI (21). Impact seizures, which are more common in the pediatric population, may be indicative of head trauma and can also occur in children without significant intracranial pathology (18).

Radiologic Studies. It is clear that universal imaging of all suspected pediatric head trauma would be costly and unnecessary. Any child with suspected head injury, with an altered level of consciousness, focal neurologic deficit, or physical sign of head trauma should have computed tomography (CT) of the head (18, 22). Rapid information can be gained from CT scans of the head, and studies have demonstrated that even in an intact child, CT scans have shown traumatic mass lesions requiring surgery, especially after high-risk injury (6, 22–24). Skull fractures, subdural and epidural hematomas, intraparenchymal contusions, cerebral edema, and obliteration of the basal cisterns are readily visualized. With the current-generation software applications and spiral CT scanning, CT angiography and venography are rapidly becoming available. CT angiography is able to show regions of stenosis or flow voids within the cervical and intracranial arteries. Likewise, CT venography defines areas of venous or sinus compression or occlusion. Reconstructed, three-dimensional CT views illustrate intracranial anatomy in exquisite detail and are often helpful in surgical planning. Xenon CT has proved to be an invaluable resource in providing information about the autoregulation of CBF after TBI in adults and in children. The patient's $Paco_2$ and blood pressure can be optimized to maximize cerebral perfusion. Positron emission tomography scanning recently has been used for adult TBI on a limited basis for research purposes but has not been used in children (25). Magnetic resonance imaging has not been found to add to the diagnosis of operative head injury; however, there is a significant correlation between the extent of brain injury seen in magnetic reso-

nance imaging to the cognitive outcome, especially diffusion-weighted imaging and is often indicated to evaluate the extent of brain and brainstem injury (26). Diffusion-weighted imaging can reveal nonhemorrhagic infarction hours to days before conventional CT scanning and provides an indicator of severity that is more complete than any other imaging modality.

Neuroinvasive Monitoring. Continuous ICP monitoring for patients with GCS scores of ≤ 8 are recommended by the Adult Head Trauma Guidelines (27). Although pediatric guidelines for ICP monitoring are still being developed, evidence supports the recommendations of the adult guidelines for children with TBI. Because elevated ICP and lower CPP contribute to secondary brain injury, ICP monitoring is an important component of monitoring of the child with head injury. CPP should be maintained at normal levels to support adequate oxygen delivery to the brain. In a single-center study reported in 1992, out of 51 children with severe closed head injury who underwent ICP monitoring, 94% of children with maximum ICPs of <20 mm Hg survived (28). Only 59% of those children with maximum ICPs of >20 mm Hg survived. Prolonged elevations of ICP, for >1 hr, were found to be more detrimental, and in those cases, the outcomes were worse. In most cases, we recommend insertion of an external ventricular drain (EVD), whenever possible, to allow for ICP monitoring and cerebrospinal fluid (CSF) diversion. CSF diversion is often useful for lowering ICP of patients with TBI and subsequent cerebral edema.

Electrophysiologic Monitoring. Neurophysiological monitoring is also an important adjunct method of monitoring neurologic function in TBI patients. Serial or continuous somatosensory evoked potentials and electroencephalograms are still controversial but have been used in the early detection of subtle changes in cerebral function (e.g., expanding hematomas). Somatosensory evoked potentials are relatively unaffected by cerebral suppressive medications and can be used in sedated or comatose patients. Some studies have shown that the bilateral absence of cortical peaks in the somatosensory evoked potential is one of the strongest predictors of poor functional outcome in children (29). Electroencephalographic studies have also demonstrated that mild slowing may be associated with a good outcome, but the lack of variability and

reactivity in the electroencephalogram correlates well with poor outcome (30, 31). Brainstem auditory and visually evoked potentials may also be useful in evaluating brainstem function after TBI, even in comatose children (32).

TREATMENT OF SEVERE TBI IN CHILDREN

Goals of treatment in children with severe TBI are directed at preventing second insults, which exacerbate neuronal damage and amplify secondary brain injury, and the interventions are generally aimed at lowering ICP and maximizing CPP and oxygen delivery to the brain. CPP and oxygen delivery depend on adequate ventilation, cardiac function, and systemic perfusion. Immediately after injury, stabilization and diagnosis are paramount. Hypotension and hypoxia should be avoided, with a goal that normocarbia be maintained. Hyperventilation to reduce the $Paco_2$ to <35 mm Hg may be useful in an acute setting of raised ICP or when signs and symptoms of impending brain herniation become manifest. However, reactive vasoconstriction can cause decreased CBF, cerebral hypoperfusion, decreased oxygen delivery, and ischemia. Hypercarbia may cause cerebral vasodilation and may acutely increase ICP. Hypotension, which often occurs in the pediatric trauma patient, can also cause cerebral hypoperfusion. Once volume deficits have been corrected, vasopressors should be administered for persistent hypotension in the normovolemic patient. Transfusions should not be delayed, when indicated, and hemoglobin and hematocrit should be kept at >10 mg/dL and 30%, respectively. Due to their smaller circulating volumes, children with significant blood loss have a propensity to become hypotensive rather quickly. Signs of hypoperfusion include increased heart rate, loss of peripheral pulses, decreased urine output, and prolonged capillary refill time. As stated earlier, children will often maintain systolic blood pressure despite significant blood loss until they develop severe hypovolemic shock and acute hypotension.

Either after stabilization in the emergency department or after surgical intervention, the child with a severe TBI enters into a severe TBI protocol in the intensive care unit. The following section represents one set of treatment recommendations and an algorithm for the critical care setting (Fig. 1).

Head Positioning. The child's head should be maintained in a neutral position. Elevation of the head of the bed to 30 degrees can be useful to decrease ICP while maintaining mean arterial pressure. At 30 degrees of head elevation, there is little detrimental effect on cerebral perfusion, whereas elevating the head of the bed to >30 degrees has been shown to reduce CPP in some adult patients (33). There are no pediatric TBI studies evaluating the position of the head of the bed. Jugular venous obstruction should be avoided by excessively tight endotracheal ties or tape because elevations of ICP have been associated with jugular distension. In addition, because of the size of the head relative to the body in children, a shoulder roll may be necessary to maintain a neutral head, neck, and chest position.

Treatment of Elevated ICP and CSF Diversion. Although there are insufficient data to recommend the use of one method of ICP monitoring over another, we advocate the placement of EVDs to allow for the diversion of CSF and the lowering of ICP. The Adult Guidelines for the Management of Severe Traumatic Brain Injury recommended, based on the accuracy and stability of ICP measurement, that ventricular ICP be used as the reference standard in comparing the accuracy of ICP monitoring devices placed in other intracranial compartments (34). Although intraparenchymal monitoring with fiberoptic or strain-gauge technology is possible, there is the potential for measurement drift. Subarachnoid, subdural, epidural, and external anterior fontanelle monitors have been shown to be less accurate compared with fluid-coupled ventricular drains. EVDs may be continuously clamped and transduced; alternatively, they may be kept open at or above the level of the tragus for continuous drainage. There are no studies that document a significant difference in the methodology employed for the management of external drains. Although there are no standards for the threshold for treatment of elevated ICP, treatment of elevated ICP should be initiated at ICPs of >20 mm Hg for older children and teenagers. For younger children and infants, one can initiate treatment once the ICP has risen above age-appropriate levels (e.g., for infants, ≥ 15 mm Hg; for children <8 yrs of age, ≥ 18 mm Hg). In addition, if a child with TBI has clinical evidence of rising ICP or impending herniation, aggressive interventions should

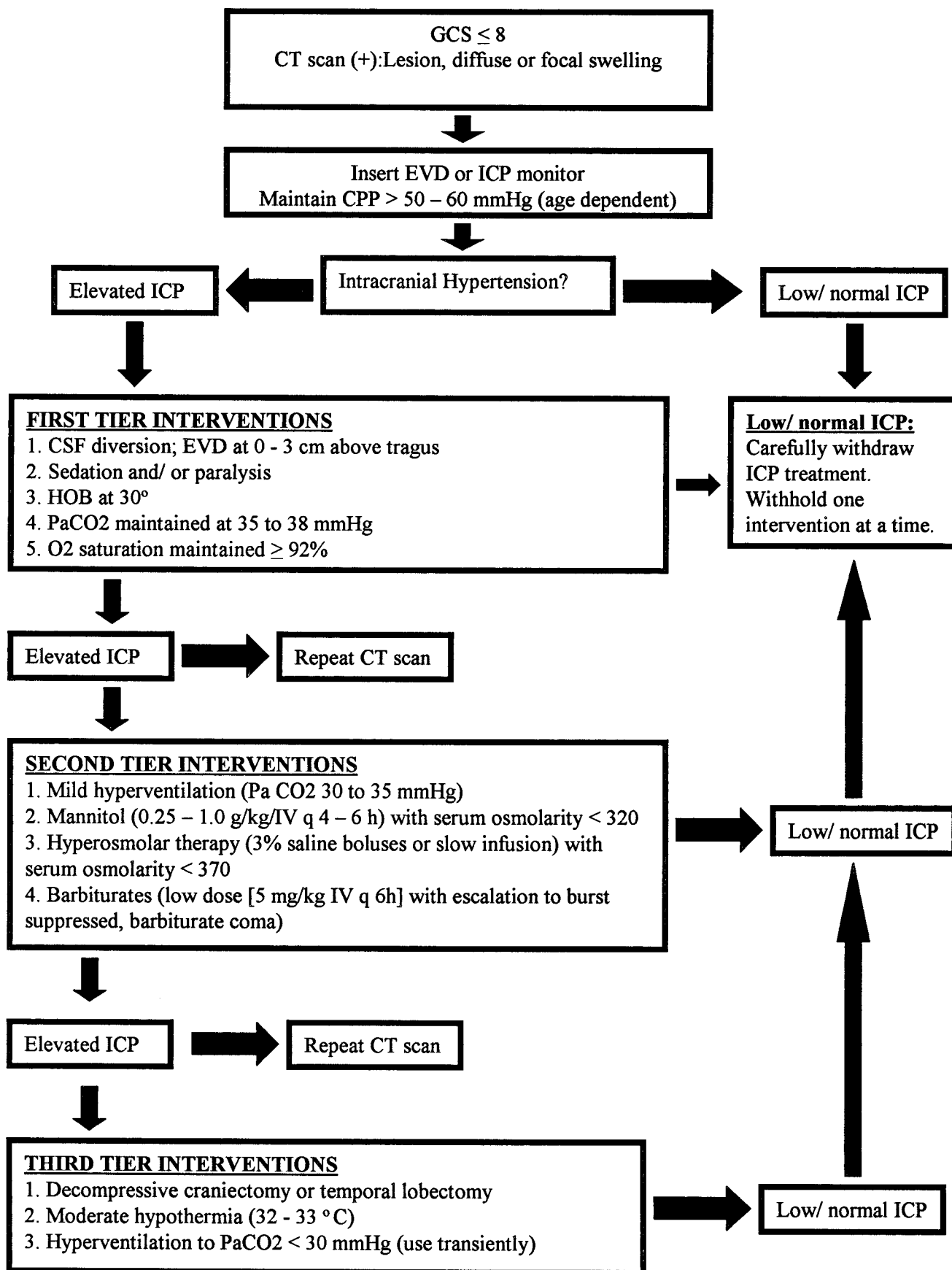


Figure 1. Algorithm for the critical care setting. *GCS*, Glasgow Coma Scale; *CT*, computed tomography; *EVD*, external ventricular drain; *ICP*, intracranial pressure; *CPP*, cerebral perfusion pressure; *CSF*, cerebrospinal fluid; *HOB*, head of bed; *IV*, intravenous; *q*, every.

be started early and aimed at lowering ICP as soon as possible. In a retrospective study in children with TBI with external CSF diversion, Shapiro and Marmarou (35) studied 22 children with EVDs placed after TBI. ICP, pressure-volume index, and mortality were measured. Diverting CSF allowed for lowering of ICP and an increased pressure-volume index. There was also decreased mortality in children with well-controlled ICP. Ventricular drains may be safely placed in the trauma bay, in the intensive care unit, or in the operating room. The neurosurgeon will choose location of placement based on preference and expediency. Studies which have investigated the infection rates of ICP monitors placed in these various settings have not found a significant difference of infection rates (36). In this study, the overall infection rate was 7%, and all of the infected catheters were infected with *Staphylococcus aureus*. We will usually start prophylactic intravenous (intravenous) antibiotics for Gram-positive bacterial coverage at the time of monitor placement using cefazolin. The ventricular drain insertion procedure usually takes approximately 10 mins, and the associated risks are minimal compared with the potential benefits. There have been no prospective, randomized, controlled trials documenting the risk for EVD placement as compared with parenchymal monitor placement in the adult or pediatric population.

CPP. Since CPP is defined as the mean arterial pressure minus the ICP, it is easy to understand how lowered mean arterial pressure or elevated ICP would affect CPP. Cerebral ischemia and decreased delivery of metabolic substrates to the brain can cause serious sequelae. Combined with cerebral edema and systemic hypotension, cerebral vasospasm can also cause regional hypoperfusion within the brain. Although there is little literature for the treatment threshold of low CPP, there is evidence from retrospective studies that seem to indicate that children with CPP of >40 mm Hg have better overall outcomes (37–39). Kaiser and Pfenninger (38) reported that in 24 children (mean age, 6.3 yrs) with severe TBI who survived their head injury, all had a minimum CPP of >50 mm Hg. Elias-Jones et al. (37) showed that in all but one survivor of pediatric TBI, the minimum CPP was >40 mm Hg and that CPP of <40 mm Hg was associated with higher mortality rates. For infants and young children with TBI, CPP should be

maintained above 40–45 mm Hg, whereas in older children and adolescents, CPP should be kept at more than 50–55 mm Hg.

Sedation and Pain Management. Sedation and pain control are controversial topics in pediatric TBI. Midazolam and morphine-based narcotics are often used in the acute setting. Long-acting sedatives are avoided because they may prolong the periods between useful neurologic examinations and thus may complicate the provision of appropriate management. Pain control is managed by fast- and short-acting morphine or fentanyl. Ketamine is avoided because it elevates ICP. Propofol has been used and studied in adults, but at this time, the prolonged use of propofol in children with TBI is not recommended due to the complication of metabolic acidosis associated with its use.

Neuromuscular Blockade. Neuromuscular blockade facilitates the management of mechanically ventilated pediatric patients with severe TBI. Used with appropriate sedation, induced paralysis may be necessary for safe intubation for airway protection and maintenance. Paralysis should be carefully monitored, and the neuromuscular blockade in awake patients should be avoided at all times. Once paralyzed, the patient requires adequate attention to all points of pressure and positioning. Deep venous thrombosis prophylaxis may be considered in older children or in children who require prolonged paralysis or high-dose barbiturate therapy. We currently recommend the use of anti-embolic stockings or devices in such situations. Once the need for induced paralysis has passed and neuromuscular blockade is terminated, adequate sedation is necessary, with airway protection, until the patient has full motor function and can be safely extubated.

Osmolar Agents and Diuretics. Osmotic agents have been extensively used for management of elevated ICP in TBI, although there is little data supporting its use in children TBI (40–43). It has been recommended that mannitol be given as bolus infusions of 0.25–1.0 g/kg body weight. Since the half-life of mannitol is 3–4 hrs, the dosing interval can range from every 2 hrs to every 8 hrs. Mannitol is believed to exert its effects in two ways: decreasing blood viscosity and reducing the extravascular volume. Through normal autoregulation, decreased blood viscosity increases CPP while reducing extravascular volume and increasing

intravascular volume and CBF. In addition, mannitol is believed to reduce extravascular volume and cerebral edema by drawing water into the intravascular space through a direct osmolar effect. This effect is thus dependent on an intact blood-brain barrier. Some have argued that in areas of focal intraparenchymal trauma mannitol may escape through “leaky” capillaries and actually exacerbate focal edema. Older studies challenged the utility of mannitol in head trauma.

Recently, there has been renewed interest in hypertonic, 3% sodium chloride after pediatric TBI (44–48). Fisher et al. (45) reported results of a double-blind, crossover study comparing 3% saline and 0.9% saline boluses in 18 children with TBI. During the trial boluses with hypertonic saline, there was decreased ICP and reduced requirements for additional interventions. In another study, hypertonic saline was titrated to a rate that maintained the ICP below 20 mm Hg, and serum sodium was measured every 6 hrs. The mean highest serum sodium concentration was 170.7 mEq/L, and the mean highest serum osmolality was 364.8 mOsm/L. These values were well tolerated, although two children with sepsis or multiple organ failure developed transient and reversible acute renal failure (46). Hypertonic, 3% saline can be given as a bolus or as a continuous infusion, with a range of 0.10–1.0 mL/kg body weight per hour. Rat head-injury models and clinical studies in children have demonstrated that both mannitol and hypertonic saline reduce ICP but that the effect of hypertonic saline may be greater and longer lasting (44).

Whether mannitol or hypertonic saline is used, euvoemia should be maintained. The goal of current therapy is euvoemia with hyperosmolality. Central venous pressure should be carefully monitored. Although previous recommendations had been to maintain serum osmolality below 320 mOsm/L with mannitol use, it has been found that much higher osmolalities are well tolerated with hypertonic saline. There is a risk of acute tubular necrosis and renal failure with mannitol administration; however, early reports of renal failure associated with osmolar therapy were based on patients with concomitant dehydration and hypovolemia. More recent literature has not reported this complication. It is not clear if this is because mannitol has a stronger diuretic effect, and that patients treated with mannitol may become hypovolemic,

or if the hypovolemia is unique to mannitol use. It is clear that serum osmolarities of 360 mOsm/L have been safely followed in children treated with hypertonic saline after TBI. Certainly, comparative studies need to be done to determine the best treatment for elevated ICP in children with head trauma.

Hyperventilation and Hypocapnia. Intubation of trauma patients for airway protection and mechanical ventilation allows the physician to maintain adequate oxygen saturation (>90%) and avoid hypercarbia (Paco₂ of >38 mm Hg). The adult trauma guidelines recommend that chronic hyperventilation and hypocarbia should be avoided in the absence of impending intracranial herniation or severely increased ICP (49). Since hypocarbia induces vasoconstriction and may lead to relative ischemia, it is a method that should be used judiciously and conservatively (50). Initial hyperventilation may be indicated at the scene of the trauma or in the emergency department if the patient with TBI demonstrates clinical signs and symptoms consistent with impending herniation. These signs may include transitory pupillary dilation, abnormal posturing, unexplainable hypertension, or bradycardia. Once stabilized, the arterial blood gases and Paco₂ should be carefully monitored, and the Paco₂ should be kept within the range of 35–38 mm Hg.

It had been thought that hypocapnia prevented or reduced hyperperfusion associated with TBI. Several, more recent studies have clearly shown that cerebral hypoperfusion, which occurs after the first 24–48 hrs postinjury, is actually more likely to be problematic in pediatric patients with TBI (12, 51). Adelson et al. (12) reported results of CBF studies in children with severe head injury and found that a significant percentage of patients had a CBF of <20 mL·100 g⁻¹·min⁻¹ at the time of admission. It is now known that hyperventilation and hypocarbia after TBI causes ischemia in both normal and traumatized brain. It is therefore recommended, in agreement with the current adult recommendations, that hyperventilation be avoided in pediatric patients with TBI.

Antiepileptic Medications. Antiepileptic prophylaxis is indicated after severe TBI if there is significant parenchymal injury seen on the initial CT scan. Likewise, if the trauma patient is having a seizure or there is severe head trauma obvious on clinical examination, then

phenytoin can be given in the emergency department. Seizures increase ICP by increasing metabolic demand, Valsalva effect, releasing neurotoxic excitatory amino acids, and by decreasing or increasing systemic blood pressure (52, 53). Adult TBI studies show that the benefit of giving 1–2 wks of prophylactic phenytoin outweighs the minimal risks associated with this medication. Infants are especially at risk for posttraumatic seizures, even after minor head trauma, occurring in upwards of 70% of children <1 yr old. In infants, phenobarbital may be given intravenously or orally for seizure prophylaxis; carbamazepine has also been used on occasion. There are no data to support the prophylactic use of antiepileptic medications beyond the first 2 wks after trauma in either children or adults, although termination of treatment should be done with care if there are documented electrophysiologic abnormalities.

Barbiturates. The use of barbiturate therapy may be useful for lowering refractory intracranial hypertension after head injury in hemodynamically stable patients. Barbiturates lower ICP by altering cerebrovascular tone and decreasing metabolic demand in the traumatized brain. In addition, ischemia is better tolerated and free-radical injury is reduced (54). Early initiation of pentobarbital and “barbiturate coma” may prevent malignant cerebral edema and secondary injury. Some data suggest that complete burst suppression on electroencephalography may not be necessary for the protective effects of pentobarbital and that lower doses (5 mg/kg intravenously every 4–6 hrs) may be given to avoid myocardial depression and resultant systemic hypotension. It is recommended that pentobarbital be started at low doses and then titrated with increasing dosage, as necessary, to treat unresponsive, elevated ICP. Starting with lower doses of pentobarbital may potentially alleviate the likelihood of coma-induced complications. However, some studies have found that the therapeutic effect of pentobarbital therapy is best monitored and measured by electroencephalographic patterns demonstrating complete burst suppression, which can be obtained with high-dosage of barbiturates (55). Care of the burst suppressed or comatose patient involves maintaining blood pressure, monitoring liver and lung functions, avoidance of potential sources of infection, and prophylaxis of deep venous thrombosis

and pressure-induced decubiti. In addition, we recommend that during periods of high-dose pentobarbital treatment, enteric feeding be avoided due to the higher prevalence of gastroparesis and ileus.

Operative Intervention. There are no current guidelines or treatment recommendations on this topic because there is insufficient data supporting such standards. After imaging, significantly depressed skull fractures should be elevated and epidural and subdural hematomas with mass effect should be evacuated. Intracranial and intraparenchymal mass lesions obviously need to be treated expeditiously. Evacuation or debridement of large, hemorrhagic contusions or infarcted brain should be done to lower ICP and maintain cerebral perfusion, particularly if medical management is failing. Other operative interventions in the head trauma patient may involve repair of cerebrovascular injury, stenting of arterial dissection, or partial lobectomy for decompression. Reconstructive or cosmetic surgeries may be delayed until any cerebral edema has safely resolved. Studies have shown that decompressive craniectomy may be appropriate for pediatric patients with severe head injury, refractory intracranial hypertension, and cerebral edema (56–58). Usually performed within the first 48 hrs after head injury, decompressive craniectomy can help to lower ICP and improve CPP. Decompressive craniectomy may be considered as part of another surgery (e.g., the evacuation of a traumatic intraparenchymal hematoma), or it may be used as a separate surgical modality.

Steroids. Since there have been no conclusive studies that show any advantage of the use of steroids in head trauma, we do not recommend that steroids be given for TBI in children. Steroid use in children is known to decrease cortisol production and may lead to increased rates of infection and gastrointestinal hemorrhage.

Antibiotics. The prophylactic use of antibiotics after TBI is not recommended in the adult head trauma guidelines or after pediatric TBI. Patients with penetrating head injury may be placed on a short course of antibiotic therapy for suspected *S. aureus* and *Staphylococcus epidermidis* infection, and we will often initiate intravenous antibiotic therapy for ICP monitor or EVD placement. First-generation cephalosporins may be used for prophylaxis against *S. aureus* and *S. epidermidis* infection. Intravenous im-

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munoglobulins have been used for prophylaxis against infection in adult trauma victims, but these studies are preliminary, and specific studies have not yet been done in children (59).

Hypothermia. As of yet, there are no contemporary data supporting the use of hypothermic treatment (core body temperature of $<35^{\circ}\text{C}$) after pediatric TBI. The induction of hypothermia for the treatment of TBI was originally reported 50 yrs ago. Studies from the 1950s showed that hypothermia may be useful for the treatment of TBI in children (60–62). Several adult studies have shown strong correlations between hypothermia and good outcome, although the most recent adult trial did not demonstrate a significant effect on outcome (63, 64). In the United States, there is an ongoing phase II prospective trial to study the safety of hypothermia in pediatric TBI and a phase III trial that was recently initiated in Canada. Hyperthermia (temperatures of $>38.5^{\circ}\text{C}$) as a second insult is known to exacerbate secondary brain injury through a multitude of mechanisms by increasing metabolic demands, inflammatory changes, lipid peroxidation, neuronal excitotoxicity, and cell death, and it may contribute to the development of seizures. Seizures, too, may be considered a second insult and may potentially worsen outcome. Measures to maintain normothermia should be un-

dertaken to prevent second insults and further cerebral injury.

Nutritional Support. Although there is currently little data recommending the extent and type of nutritional support of the pediatric TBI patient, replacement that is at least 30–60% above the weight-adjusted, basal metabolic expenditure should be considered using either intravenous alimentation or enteric feeding. It is clear that children have higher metabolic rates, especially after trauma, and have caloric and protein demands greater than that of the adult. Considering the clinical situation, the risk of central venous catheterization may be necessary in patients with gastroparesis or prolonged ileus. Patients with refractory intracranial hypertension treated with high-dose barbiturate therapy are at higher risk for developing gastrointestinal dysmotility. In these patients, intravenous hyperalimentation should be initiated and continued until ICP is well controlled and barbiturates can be safely discontinued. Lower metabolic demand with barbiturates should be considered and usually involve adjustment of intake during induced coma. It is also recommended that intravenous glucose be avoided in the first 48 hrs, unless the patient is hypoglycemic (serum glucose of $<75\text{ mg/dL}$) due to the potential of increased lactic acidosis.

MORBIDITY AND MORTALITY

Over the past 20 yrs, there has been a significant decline in the morbidity and mortality associated with pediatric TBI (1, 65). Studies have shown that children of <4 yrs of age and older adolescents have higher morbidity and mortality rates compared with their school-age counterparts (66–70). Luerssen et al. (1) reported that among children with mild to severe TBI, children younger than 15 yrs of age had lower mortality rates than those older than 15 yrs old. But infants still had the highest overall mortality. Mortality rates decreased with increasing age until age 14 and then increased until adulthood. In contrast, Levi et al. (19) found that outcomes worsened with increasing age during childhood, corresponding to increasing severity of injury. Tilford et al. (71) studied the relationship between various interventions and outcomes in different pediatric intensive care units. Admission GCS, the use of neuromuscular blockade, the use of hypothermia, and ICP monitoring were

evaluated. Despite obvious variations in the modalities of treatment, there was no significant correlation with outcome in TBI patients. Since there are so few definitive TBI studies in children, it is clear that multicenter, prospectively randomized, class I studies are needed to determine the significance of these different therapeutic interventions in the pediatric population.

CONCLUSIONS

The goals of management of pediatric patients with TBI include normalizing the ICP, optimizing CBF and CPP, preventing second insults that exacerbate secondary injury, and avoiding complications associated with the various treatment modalities employed. Although significant advances have been accomplished, in our understanding of the mechanisms of secondary injury, the long-term outcomes of infants and young children with head injury remain poor. There are studies underway that will hopefully clarify and define the optimal treatment of children at different ages of injury.

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