Review Article

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ASSESSMENT OF INTRACRANIAL PRESSURE IN PEDIATRIC TRAUMATIC BRAIN INJURY: METHODS, EVIDENCE, AND CLINICAL IMPLICATIONS

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Background: Pediatric traumatic brain injury (TBI) is one of the leading causes of disability and early mortality, constituting a global public health problem. Even mild TBI can cause neurological deterioration due to secondary brain injury, usually associated with elevated intracranial pressure (ICP) compromising cerebral perfusion. Early identification and appropriate management of intracranial hypertension are therefore fundamental in the care of this population.

Methods: A narrative review of the literature was conducted to identify and synthesize current evidence on ICP monitoring methods in children and adolescents, encompassing original articles, systematic reviews, meta-analyses, and clinical guidelines.

Results: ICPM is an essential tool for preventing secondary brain injuries, guiding therapeutic interventions, and maintaining ICP and cerebral perfusion pressure within target ranges. Invasive methods, particularly the external ventricular drain, remain the gold standard for accuracy and allow direct therapeutic intervention, but carry risks of infection and hemorrhage. Intraparenchymal sensors offer a safer alternative with comparable accuracy. Noninvasive methods, including optic nerve sheath diameter ultrasonography, transcranial Doppler, and skull surface extensometry, demonstrate reasonable ability to detect intracranial hypertension and are particularly useful for triage, screening, and follow-up, though they do not yet replace invasive monitoring in critical clinical decisions.

Conclusions: The choice of ICP monitoring method should be individualized, balancing accuracy, safety, available resources, and the patient's clinical context. In severe TBI, invasive methods remain indispensable, whereas noninvasive approaches play a complementary role, particularly when invasive access is contraindicated or unavailable. Integrating multiple monitoring strategies may optimize ICP assessment in the pediatric population..

Keywords: Intracranial hypertension, intracranial pressure, pediatrics, traumatic brain injuries.

INTRODUCTION

Traumatic brain injury (TBI) in the pediatric population is one of the leading causes of death and long-term disability. In addition to being a global public health problem, it has a significant socioeconomic impact worldwide. TBI affects children and adolescents across various age groups, primarily impacting individuals aged 0 to 2 years and those between 15 and 18 years. The numbers vary among countries, with epidemiological studies reporting between 47 and 280 cases per 100,000 children per year, with a high prevalence in emergency department visits, where TBI accounts for a significant proportion of pediatric admissions [1-3]. In Brazil, there are estimates of 29,017 annual hospitalizations for pediatric TBI, with approximately 941 deaths per year and direct costs to the public health system of around 12.3 million dollars, confirming its socioeconomic and health impact [4]. Furthermore, TBI in this population contributes to adverse outcomes following the trauma, such as cognitive deficits, behavioral disorders, psychiatric hospitalizations, low educational attainment, and early mortality in adulthood [5, 6]. Chronic neurological changes such as post-traumatic epilepsy may also occur in up to 10% of severe cases [7], while cases of mild TBI can cause neurocognitive deficits (decreased IQ, perceptual reasoning, and processing speed) [8]. In this context, TBI remains one of the leading causes of death and disability among children and young people in various epidemiological settings [1, 4, 5, 9, 10]. Although the vast majority

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of TBI cases are mild, the clinical course may present with impaired consciousness, such as coma, and focal neurological deficits. This may be related to the development of a secondary brain injury, particularly in the most severe cases. Among its main determinants, elevated intracranial pressure (ICP) stands out, a condition that can compromise cerebral perfusion, exacerbate neuronal damage, and significantly increase morbidity and mortality. Thus, early identification and appropriate management of intracranial hypertension (ICH) constitute fundamental pillars in the care of pediatric patients with severe TBI [11–13]. In this context, intracranial pressure monitoring (ICPM) emerges as an essential tool to guide decision-making and enables interventions aimed at preventing secondary injuries. Although ICPM is widely used, significant gaps and inconsistencies persist in the literature regarding the best monitoring strategies in the pediatric population. The heterogeneity of pediatric TBI and the limitations of the available evidence highlight the need for greater standardization and scientific investigation, particularly regarding indications, methods, and reference values in children and adolescents [1, 4, 13]. This study aims to update knowledge on ICPM methods, discussing their indications, options, and outcomes.

INTRACRANIAL PRESSURE

ICP results from the dynamic equilibrium between the three main components of the intracranial compartment—brain parenchyma, blood, and cerebrospinal fluid (CSF) — contained within a virtually rigid structure, the skull. The conceptual basis of ICP pathophysiology lies in the Monro–Kellie doctrine, according to which the sum of the three intracranial volumes must remain constant. Thus, an increase in one of these components must be compensated by a reduction in the others, and the loss of this balance results in elevated ICP, leading to ICH [14–16]. This classical doctrine has been revised to incorporate the concept of "intracranial dynamics." Studies have demonstrated greater implications of cerebral venous drainage in ICP regulation, related to extracranial factors (intrathoracic and intra-abdominal pressure and jugular vein compression), cerebral tissue compliance, and the glymphatic system [17]. Thus, the relationship between volume and intracranial pressure is mediated by intracranial compliance (ICC), defined as the system's capacity to accommodate volume increases with minimal pressure elevation. Initially, volume increases are compensated by mechanisms such as CSF displacement, venous collapse, and deformation of cranial structures. However, once the limit of compliance is reached, small volumetric variations result in exponential increases in ICP. Reduced compliance is associated with a higher risk of refractory intracranial hypertension and a poorer prognosis, especially in cases of severe TBI [12, 17–19]. ICP exerts a direct influence on cerebral perfusion pressure (CPP), defined as the difference between mean arterial pressure (MAP) and ICP. Elevations in ICP reduce CPP, compromising cerebral blood flow and potentially leading to ischemia. In response, cerebral autoregulatory mechanisms adjust arteriolar tone to maintain adequate flow under physiological conditions [11, 12, 15, 18]. In addition, systemic compensatory mechanisms may be activated, such as an increase in MAP to preserve cerebral perfusion in the face of elevated ICP, suggesting the existence of an integrated regulatory system between intracranial and systemic compartments [20]. In children, the pathophysiology of ICP has unique characteristics related to the anatomical and functional development of the skull and the central nervous system [21]. Cranial compliance is greater in pediatric-aged individuals, especially in the first years of life, allowing for greater accommodation of increases in intracranial volume before a significant rise in ICP. This phenomenon is directly related to the presence of open fontanelles and unfused cranial sutures, which confer greater expansion capacity to the intracranial compartment. However, this apparent advantage may delay the clinical recognition of intracranial hypertension, since classic signs may appear late. In addition, the immaturity of the nervous system affects intracranial dynamics, including variations in cerebral compliance, cerebral hemodynamics, and autoregulatory mechanisms. This leads to greater susceptibility to edema formation, cerebral perfusion disturbances, and metabolic insults. Even slight increases in intracranial pressure can reduce cerebral perfusion pressure and blood flow, causing cerebral hypoxia and ischemia. These data indicate that children may be more vulnerable to damage caused by cerebral hyperemia and intracranial hypertension [13, 22, 23].

MONITORING OF INTRACRANIAL PRESSURE

Intracranial hypertension occurs when the cerebral autoregulatory system and compliance are overwhelmed, leading to increased ICP, reduced CPP, and reduced cerebral blood flow. This can result in

ischemia, herniation, and brainstem compression, potentially leading to neurological deficits and death [11, 15, 24]. ICPM is a fundamental tool in the management of patients with severe acute brain injury, especially in cases of TBI, with the goal of detecting early changes in compliance and ICH, guiding therapeutic interventions, and maintaining ICP below 20–22 mmHg and CPP at 60 mmHg in adult patients [16, 25, 26].

Although widely used, ICP monitoring varies in clinical practice. Studies demonstrate significant differences between centers and countries regarding indications, timing of initiation, and strategies for use, even in patients with similar clinical characteristics. Additionally, available recommendations are based predominantly on observational evidence, with no robust Level guidelines. Although there is an association between adequate ICP control and reduced mortality in severe cases, the optimal strategy for treatment with monitoring remains a subject of debate [16, 24, 25, 27, 28]. In the pediatric context, these limitations are even more evident. There are significant gaps in guidelines specific to children, with a scarcity of dedicated studies and frequent extrapolation of data from adult populations. Furthermore, age-related physiological differences, such as greater cranial compliance and variations in autoregulatory mechanisms, make it difficult to define universal criteria for the indication of ICPM in this population. The primary indication for its use is based on the patient's clinical condition, typically a coma with a Glasgow Coma Scale (GCS) score below 8, associated with findings suggestive of ICH on neuroimaging. In patients with severe TBI under deep sedation, neuromuscular blockade, or mechanical ventilation, where clinical examination is limited, the use of ICPM becomes particularly relevant for guiding therapeutic management. In moderate TBI (Glasgow 9–12), monitoring may be considered in selected cases with a higher risk of deterioration, such as the presence of extensive lesions on neuroimaging or the need for deep sedation. Despite existing controversies regarding ICP monitoring and improved prognosis in patients with ICH, there is consensus regarding the need for appropriate ICP management in patients with severe TBI. In children, the Brain Trauma Foundation guideline assigns a Level III recommendation regarding improved prognosis, suggesting its use as a therapeutic option, primarily due to the risk of ICP in severe TBI in this age group [16, 24, 25, 28–30].

METHODS FOR MONITORING INTRACRANIAL PRESSURE

There is a wide variety of ICP monitoring systems, including invasive methods, which require surgical access to the intracranial space, and non-invasive methods [16, 25, 26]. ICP monitors should have a pressure range of 0 to 100 mmHg, an accuracy of ±2 mmHg in the 0–20 mmHg range, and a maximum error of 10% in the 20–100 mmHg range. The ideal system should be easy to use, accurate, reliable, reproducible, inexpensive, and associated with a minimal risk of infections and hemorrhagic complications [11, 12, 16].

Invasive ICP monitoring uses intraventricular catheters and intraparenchymal sensors and is considered one of the cornerstones of neurocritical care. It provides continuous and accurate data that aid in the management of patients with severe TBI, enabling early detection of secondary damage and guiding therapy such as the use of osmotic agents, CSF drainage, continuous sedation, and decompressive craniectomy. It has disadvantages due to its nature, such as risks of hemorrhage and infection, high cost, and the need for a specialized neurosurgical team. Furthermore, it is not available in all locations, and there is a possibility of loss of monitor calibration, resulting in inaccurate data. Noninvasive ICP monitoring methods offer the advantage of not requiring surgical access to the nervous system, thereby avoiding associated complications. They enable rapid, bedside assessment of ICP dynamics and can be used in prehospital care and for screening patients at risk of developing ICH. Although they have significant clinical utility, particularly as screening and monitoring tools, these methods do not yet achieve sufficient accuracy to replace invasive ICP measurement [11, 16, 25, 26, 31].

INVASIVE METHODS FOR MONITORING INTRACRANIAL PRESSURE

Ventricular Catheter

The use of an intraventricular catheter with external ventricular drainage is considered the gold standard for ICP measurement. The technique involves inserting a catheter into the ventricular system through a trepanation hole in the skull, connected to a multiparameter monitor via a pressure transducer. It allows for recalibration of pressure parameters when necessary, provides continuous and accurate pressure monitoring, and can also be used to manage ICH by facilitating CSF drainage. It is also useful for the administration of intrathecal medication and the drainage of intraventricular hemorrhage. The risk of hemorrhage ranges from 2% to 10%, with an impact on morbidity and mortality of 0.9% to 1.2% of cases. Infection rates vary across studies, ranging from 1 to 27% of cases, varying from surgical site skin infections, meningitis, and ventriculitis to sepsis. Other challenges with this method include the possibility of catheter tip obstruction due to debris or blood in the ventricular system, and displacement of the transducer, which must be maintained at the level of the external auditory meatus, which can lead to an incorrect ICP measurement. Difficulty in properly positioning the catheter (extraventricular, intraparenchymal position) can occur in up to 38.6% of cases; this is due to technical difficulty in accessing the ventricle, which may be collapsed due to trauma or in young patients who do not present ventricular dilatation. The use of an intraventricular catheter is a reliable option in the management of ICP, and care should be taken to avoid mechanical catheter obstructions and to minimize the risks of hemorrhage and infection [12, 16, 25, 26].

Intraparenchymal Sensors

These are microtransducers inserted into the brain parenchyma, within the white matter, typically in the cortex of the non-dominant frontal lobe. These sensors may be fiber-optic devices, tension or strain measurement devices, or pneumatic sensors. Microtransducers show good correlation with intraventricular devices [11, 12, 15, 16, 25, 26]. They are easier to manage than systems with ventricular catheters and do not show changes with changes in the patient's position. Because there is no direct contact with fluid—CSF—and surgical management for their insertion is simpler, they present a lower risk of infection and hemorrhage. On the other hand, they cannot be calibrated after insertion and may become inaccurate due to changes in baseline pressure over the course of monitoring. Fiber-optic devices, such as the Camino monitor (Integra Life Sciences, Plainsboro Township, New Jersey, USA), work by transmitting light through the fiber into brain tissue. The light is reflected toward a mirror located at the tip of the device. Changes in ICP distort the mirror, and differences in the intensity of the reflected light are translated into an ICP value. This device exhibits a daily pressure drift of 0.3 mmHg over time, with a mechanical failure rate of 4.5 to 10%, due to sensor defects, broken transducers, or catheter kinks. Hemorrhages detected by imaging occurred in 1.1 to 2.5% of patients, with 0.6% of cases being symptomatic, while infections affected between 2.1 and 4.8% (usually caused by coagulase-negative Staphylococcus). Because the transducer contains a ferromagnetic component, it is not compatible with magnetic resonance imaging. The Camino device reliably measures ICP, with fewer complications compared to the intraventricular catheter. Tension or strain measurement devices such as the Codman MicroSensor (Codman & Shurtleff, Raynham, MA, USA), the Raumedic Neurovent-P ICP sensor (Raumedic, Helmbrechts, Germany), and the Pressio sensor (Sophysa, Orsay, France) have a tip-mounted sensor that deforms in response to ICP variations. When the sensor is deformed, the resistance changes, and ICP can be calculated. The Codman device shows good correlation with the intraventricular device, with a baseline pressure deviation of 2 mmHg after 7 days of monitoring. Infection and hemorrhage rates were very low in the literature. The Raumedic Neurovent sensor showed a similar profile, with a baseline pressure deviation of 0.8 mmHg after 6 days of monitoring, with no clinically symptomatic infection and hemorrhage on radiological examinations in 2% of cases. The Codman and Raumedic sensors are magnetic resonance imaging (MRI)-compatible, unlike the Pressio sensor, which facilitates the management of patients with severe TBI who require imaging evaluation alongside ICP monitoring. The cost of these sensors is higher compared to ventricular catheters; however, they offer adequate safety, with low rates of infection, hemorrhage, and mechanical malfunctions. On the other hand, they do not allow for therapeutic CSF drainage. Devices with a pneumatic sensor, such as the Spiegelberg ICP monitor (Spiegelberg GmbH & Co. KG, Hamburg, Germany), feature a balloon at their tip that detects pressure changes. Due to its design, this sensor can be placed in the subdural space, epidural space, within the brain parenchyma, and even in the ventricle. This device allows for CSF drainage and automatic correction of baseline pressure deviation. Hemorrhagic and infectious complications are rare, with a mechanical failure rate of 3%. In general, subdural and epidural monitors are less reliable than intraparenchymal ones,

as ICP in the subdural space is lower than in the epidural space, making their use less common in medical practice [11, 12, 15, 16, 25, 26].

Other Invasive Methods

Lumbar puncture can be used to measure ICP in the absence of cerebrospinal fluid flow obstruction in the spinal canal, and its opening pressure is similar to intraventricular pressure. Lumbar drainage, performed by inserting a catheter into the lumbar region, can be used to measure ICP; however, it has low reliability and carries a risk of causing cerebral herniation in cases of ICH, particularly in severe TBI, and is therefore rarely used. The pressure measurement obtained by lumbar puncture reflects the value at the time of the procedure and can be used in the investigation of ICP in cases of ventricular dilation or idiopathic ICP [11, 25].

NONINVASIVE METHODS FOR MONITORING INTRACRANIAL PRESSURE

Transcranial Doppler

Developed by Klingelhofer in 1987, transcranial Doppler (TCD) measures blood flow velocity in the middle cerebral artery, indirectly assessing cerebral compliance and estimating ICP through secondary parameters such as peak systolic velocity, mean flow velocity, and end-diastolic velocity, which calculate the pulsatility index (PI). When cerebral autoregulation is preserved, an increase in the PI is associated with an increase in CPP. In cases where autoregulation is impaired, an increase in the PI is associated with a decrease in CPP, suggesting an increase in ICP. PI values greater than 1.3 indicate ICH. However, the accuracy of ICP measurement by TCD has limitations, with an error of up to 10 mmHg when compared to invasive methods. Studies have shown a good correlation between ICP values and TCD, particularly with ICP above 20, but there are questions regarding the utility of this method for assessing ICP in both adult and pediatric populations [16, 25, 31, 32].

Optic Nerve Sheath Diameter

The optic nerve sheath (ONS) is filled with CSF present in the subarachnoid space of the intracranial cavity. The correlation with ICP is based on the principle that increases in CSF pressure increase ONS distension, making it possible to assess ICP dynamically. This method is performed using ultrasound with a linear transducer in the 7.5–13 MHz range applied over the closed eyelid, visualizing the eyeball and the optic nerve. The diameter is measured at a distance of 3 mm from the posterior pole of the eyeball. An ONS diameter of 4.5 to 5.5 mm or greater suggests ICH. There is a significant correlation between increased ICP and ONSD, particularly at values above 20 mmHg, with a sensitivity of 90% and a specificity of 85%. There are limitations to the use of this technique, which requires specialized training, and intra-observer (0.2 mm) and inter-observer (0.3 mm) differences may exist. Local changes in the eyeball, such as traumatic optic nerve injuries in polytrauma patients, ocular inflammatory conditions, and diseases such as orbital tumors, sarcoidosis, and Graves' disease, may limit its use. Assessment of the ONS diameter by MRI is possible, but it has lower sensitivity compared to ultrasound [15, 16, 25, 32–35].

Displacement Of The Eardrum

This method correlates cochlear fluid pressure with cerebrospinal fluid (CSF) pressure in the subarachnoid space, indicating changes in ICP. When cochlear fluid pressure increases, the tympanic membrane moves due to displacement of the stapes in the oval window. Measurement of this displacement in response to an auditory stimulus forms the basis of this technique. Its limitations include the need for specialized equipment and a normal stapedial reflex (which may be absent or altered in patients with brainstem dysfunction or under deep sedation). There is considerable variability across studies regarding the effectiveness of this method in measuring ICP [11, 15, 16].

Brain4care

This noninvasive method for assessing cerebral compliance was developed by Braincare Corp (Brazil) in 2008. The device consists of a mechanical extensometer that detects nanometric variations on the surface of the skull caused by bone deformations resulting from increased ICP. This method analyzes the

morphology of ICP waves to assess intracranial compliance. ICP waves exhibit three distinct peaks. The first peak (P1, or percussion wave) results from arterial pressure transmitted from the choroid plexus to the cerebral ventricle. The second peak (P2) corresponds to the "tidal wave" and is related to intracranial compliance. The last peak (P3), the dicrotic wave, results from the closure of the aortic valve. Changes in these peaks reflect alterations in both blood pressure and cerebral blood volume. Under normal conditions, P1 is larger than the other peaks. When ICP changes, the relative amplitudes of the peaks also change. For normal ICP, the amplitudes of the peaks are such that P1 > P2 > P3. However, as intracranial compliance decreases and ICP increases, the waveform morphology changes and the amplitude of P2 increases relative to P1 and P3. Studies using this device in the pediatric population, employing the P1/P2 ratio derived from ICP waves, have noninvasively detected ICP in patients with hydrocephalus and craniosynostosis. A P2/P1 ratio between 0.86 and 1.05 was considered the normal range in neurologically normal pediatric patients [36–39].

Other Noninvasive Methods

Other methods (pupillometry, ophthalmic artery Doppler, spectroscopy, dynamic magnetic resonance imaging, optical coherence tomography, etc.) have the potential for less invasive ICP monitoring. However, their use is still limited to research settings or specific applications [11, 15].

Table 1. Comparison of methods for assessing intracranial pressure

Method type	Degree of invasiveness	Accuracy	Risks	Clinical applicability
External ventricular drain (EVD)	High	Very high (reference standard)	Infection, bleeding, technique	Severe TBI, hydrocephalus, need for treatment
Intraparenchymal sensor	High	High	Bleeding, measurement error	Severe TBI, when there is no ventricular access
Subdural / epidural	High	Moderate to low	Smaller, but less reliable	Restricted use
ONSD Ultrasound	Non-invasive	Moderate to high (screening)	Minimum	Emergency, triage, follow-up
Transcranial Doppler	Non-invasive	Moderate (trend)	Minimum	Hemodynamic monitoring, triage
BRAIN4CARE	Non-invasive	Variable / being validated	Minimum	Research, supplementary support

ONSD: Optic Nerve Sheath Diameter; TBI: Traumatic Brain Injury

CONCLUSION

The choice of ICP assessment methods lies in the balance between accuracy and safety. Invasive methods, especially the external ventricular catheter, offer greater accuracy, allow for continuous monitoring and direct therapy, and are considered the gold standard in ICP management. However, significant risks of infection, hemorrhage, and technical dependence limit their use. In contrast, non-invasive methods offer greater safety, with minimal risk and greater ease of application, including at the

bedside. Techniques such as optic nerve sheath ultrasonography and transcranial Doppler demonstrate good ability to detect intracranial hypertension, although they have limitations regarding the absolute accuracy of the measurement. The choice of the most appropriate method depends heavily on the clinical context. In patients with severe brain injury, where critical therapeutic decisions depend on precise ICP values, invasive methods remain indispensable. Conversely, in triage scenarios, during follow-up, or when there are contraindications for invasive procedures, non-invasive methods play a significant role. Finally, factors such as the patient's age, clinical condition (e.g., open fontanelle in infants), availability of resources, and staff experience directly influence the choice. Thus, the ideal approach tends to be individualized and, whenever possible, based on strategies that integrate different methods to optimize ICP assessment.

DISCLOSURES

ETHICAL APPROVAL

This study was performed in line with the principles of the Declaration of Helsinki. Ethics approval was not required from Institutional Review Board in accordance with local guidelines. Written informed consent for publication of data and images was not obtained from patients as this was a retrospective analysis.

CONFLICT OF INTEREST

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper

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ARTIFICIAL INTELLIGENCE

The authors affirm that no artificial intelligence tools were used in the writing, editing, or content generation of this manuscript.

CONTRIBUTIONS

Adriano Keijiro Maeda: Conceptualization, Data Curation, Formal Analysis, Writing – Original Draft.
Zeferino Demartini Jr: Writing – Review & Editing, Supervision.

All authors are responsible for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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