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Review Article

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Intracranial Pressure Monitoring for Acute Brain Injured Patients: When, How, What Should We Monitor

Youngbo Shim [1,*], **Jungook Kim** [2,*], **Hye Seon Kim** [3,*], **Jiwoong Oh** [4], **Seungioo Lee** [5], **and Eun Jin Ha** [6]

[1]Department of Critical Care Medicine, Kangbuk Samsung Hospital, Seoul, Korea
[2]Gachon University Gil Hospital Regional Trauma Center, Gachon, Korea
[3]Department of Neurosurgery, Incheon St. Mary's Hospital, College of Medicine, The Catholic University, Incheon, Korea
[4]Departments of Neurological Surgery and Critical Care Medicine, Severance Hospital, Yonsei University College of Medicine, Seoul, Korea
[5]Departments of Neurological Surgery and Critical Care Medicine, Asan Medical Center, University of Ulsan College of Medicine, Seoul, Korea
[6]Department of Critical Care Medicine, Seoul National University Hospital, Seoul National University College of Medicine, Seoul, Korea

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Address for correspondence:
Eun Jin Ha
Department of Critical Care Medicine, Seoul National University Hospital, Seoul National University College of Medicine, 101 Daehak-ro, Jongno-gu, Seoul 03080, Korea.
Email: 65932@snuh.org

*These authors contributed equally to this work.

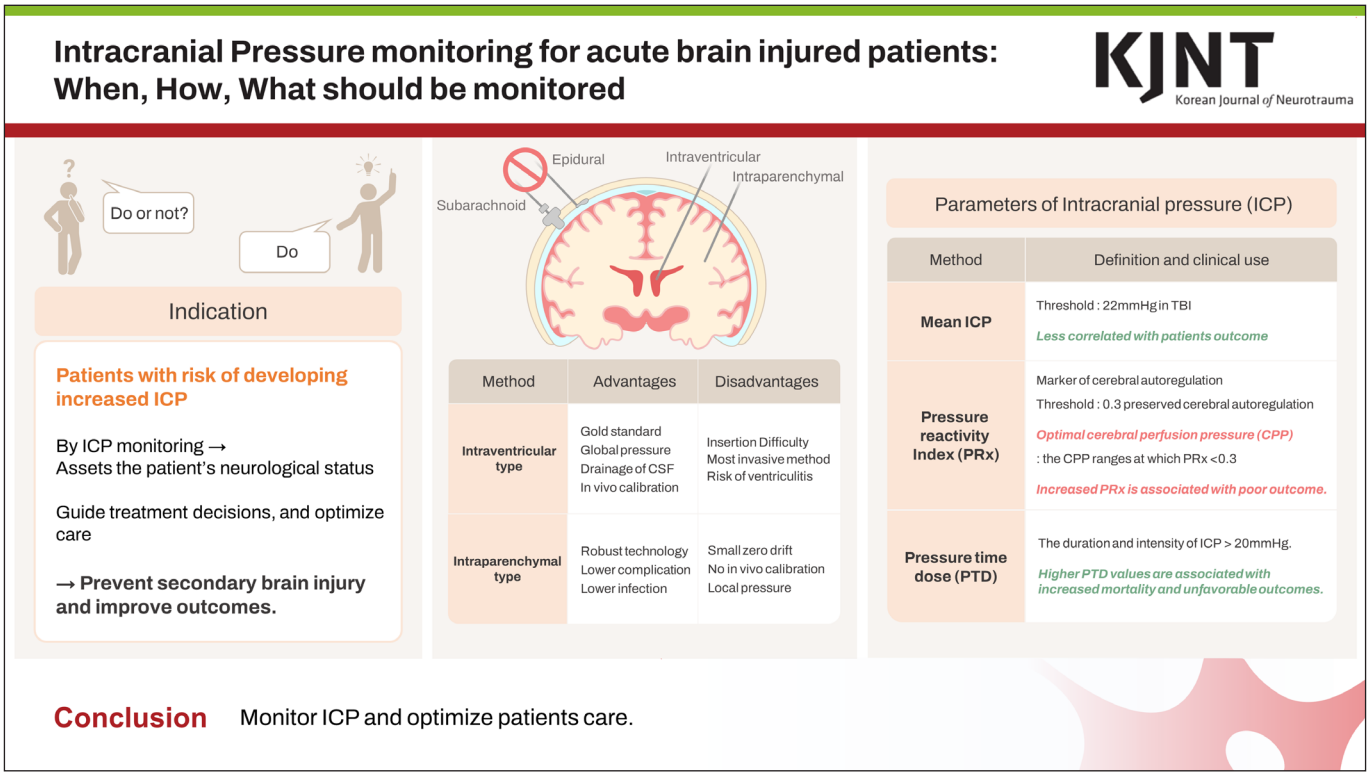
ORCID iDs
Youngbo Shim
https://orcid.org/0000-0002-3350-362X
Jungook Kim
https://orcid.org/0000-0002-6667-6447
Hye Seon Kim
https://orcid.org/0000-0002-0298-2402
Jiwoong Oh
https://orcid.org/0000-0001-6065-4821

ABSTRACT

While there is no level I recommendation for intracranial pressure (ICP) monitoring, it is typically indicated for patients with severe traumatic brain injury (TBI) with a Glasgow Coma Scale (GCS) score of 3–8 (class II). Even for moderate TBI patients with GCS 9–12, ICP monitoring should be considered for risk of increased ICP. The impact of ICP monitoring on patient outcomes is still not well-established, but recent studies reported a reduction of early mortality (class III) in TBI patients. There is no standard protocol for the application of ICP monitoring. In cases where cerebrospinal fluid drainage is required, an external ventricular drain is commonly used. In other cases, parenchymal ICP monitoring devices are generally employed. Subdural or non-invasive forms are not suitable for ICP monitoring. The mean value of ICP is the parameter recommended for observation in many guidelines. In TBI, values above 22 mmHg are associated with increased mortality. However, recent studies proposed various parameters including cumulative time with ICP above 20 mmHg (pressure-time dose), pressure reactivity index, ICP waveform characteristics (pulse amplitude of ICP, mean ICP wave amplitude), and the compensatory reserve of the brain (reserve-amplitude-pressure), which are useful in predicting patient outcomes and guiding treatment. Further research is required for validation of these parameters compared to simple ICP monitoring.

Keywords: Traumatic brain injury; Intracranial pressure; Critical care

GRAPHICAL ABSTRACT



Seungioo Lee
https://orcid.org/0000-0003-0641-3917
Eun Jin Ha
https://orcid.org/0000-0003-3278-0550

Conflict of Interest
The authors have no financial conflicts of interest.

INTRODUCTION

Based on recent research and expert consensus, it is understood that measuring and regulating intracranial pressure (ICP) is a critical process to minimizing secondary brain injury and is a key component of neurocritical care monitoring. While it is commonly accepted to monitor the response to treatment and evaluate ICP as like monitoring blood pressure, clear indications for ICP monitoring are only suggested as the guideline level for conditions such as traumatic brain injury (TBI). For other acute severe condition by brain injury, there may be conflicting recommendations or no suggestion for ICP monitoring at all. This is due to the lack of higher level evidence demonstrating ICP monitoring leads to significant improvement in outcomes, suggesting the uncertainties regarding the utility of ICP monitoring.

Furthermore, there are several issues regarding the application of ICP monitoring, such as being suitability for implementation (e.g., external ventricular drain [EVD] vs. intraparenchymal vs. other types), the decision for appropriate location of the sensor in cases of intraparenchymal monitoring (IPM), the threshold for ICP, the parameters to be observed (whether it is the mean value of ICP or other values), and the definition of normal ranges. These issues require the discussion and research in the field.

It's important to note that the field of ICP monitoring is in progress, and the current understanding and recommendations may continue to evolve as emergence of the new evidence and consensus. In this review, the indications, methods, and major indicators of ICP monitoring are summarized and discussed.

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INDICATION AND CLINICAL EFFECTIVENESS OF ICP MONITORING

TBI

According to the Brain Trauma Foundation third edition guidelines published in 2007, ICP monitoring was recommended for all viable patients with a Glasgow Coma Scale (GCS) score between 3 and 8, which exhibited abnormal computed tomography (CT) findings. It included the hematoma, contusion, swelling, herniation, and compressed basal cistern (**TABLE 1**). Even in the absence of the abnormalities, ICP monitoring was recommended for patients aged 40 or older having unilateral or bilateral abnormal postures (decerebrate or decorticate), or with the following: systolic blood pressure less than 90 mmHg.[5] However, the Brain Trauma Foundation fourth edition in 2016 removed these recommendations and simply provided the evidence for ICP monitoring reduced the mortality of in-hospital and 2-week post-injury, which evaluated as level IIB.[1]

Setting the level of evidence for ICP monitoring was based on the BEST:TRIP: A Trial of Intracranial-Pressure Monitoring in Traumatic Brain Injury[8] and 4 cohort studies.[3,15,18,45] The BEST:TRIP trial, the only randomized clinical trial (RCT) among them, reported no difference of mortality and Glasgow Outcome Scale (GOS) Extended at 6 month between the groups of pressure monitoring and the imaging-clinical examination.[8] However, these were inconsistent with the remaining good-quality cohort studies,[3,15,18,45] in which the specific patient population and medical conditions in the South American region where the trial was conducted were taken into account, there were limitations in the applicability of the results. Therefore, it was considered that subsequent RCTs could potentially reverse the results of the BEST:TRIP trial.

As there is still controversy regarding whether ICP monitoring itself improves the outcomes in TBI patients, there is consensus in need to manage ICP appropriately in TBI patients. The International Multidisciplinary Consensus Conference on Multimodality Monitoring in Neurocritical Care in 2014 strongly recommended ICP monitoring and protocol-based treatment when there is a perceived risk of ICP elevation clinically or radiologically.[26] In addition, the World Society of Emergency Surgery conference in 2019 also strongly recommended ICP monitoring in cases of intracranial hypertension, regardless of the need for surgical intervention.[34] The Seattle International Severe Traumatic Brain Injury Consensus Conference in 2019 presented the maintaining of cerebral perfusion pressure (CPP) with at least 60 mmHg as part of the basic treatment.[22] In fact, a survey of 66 centers included in the 2017 CENTER-TBI registry revealed that 58 institutions (91%) performed ICP monitoring in cases where GCS was 8 or below and abnormal CT findings were present.[9]

The BEST:TRIP trial[8] divided patients into groups based solely on the presence of ICP monitoring. The results included that the imaging-clinical examination group had more

TABLE 1. Summary of ICP indication

Key question	Recommendations
Do or not	Do: Patients are at a higher risk of developing increased ICP, which can be a critical condition requiring close monitoring and prompt intervention. By continuously monitoring ICP levels, healthcare providers can assess the patient's neurological status, guide treatment decisions, and optimize their care. ICP monitoring is an important tool in the management of TBI patients to prevent secondary brain injury and improve outcomes.
TBI	In patients with TBI who have a GCS score of 3–8 or are at risk of intracranial hypertension, ICP monitoring is recommended.
SAH	In cases of poor-grade SAH, hydrocephalus, and IVH, proactive ICP monitoring (specifically, EVD) is considered necessary.
Intracranial hemorrhage	ICP monitoring is weakly recommended in patients with intracerebral hemorrhage and a GCS score of 8 or less.

ICP: intracranial pressure, TBI: traumatic brain injury, GCS: Glasgow Coma Scale, SAH: subarachnoid hemorrhage, IVH: intraventricular hemorrhage, EVD: external ventricular drain.

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active treatments such as hypertonic saline, mannitol, and hyperventilation compared to the pressure-monitoring group. Thus, this indicates that the ICP control itself should be considered based on the research results. The four cohort studies[3,15,18,45] that formed the basis for ICP monitoring in the Brain Trauma Foundation guidelines were composed of three retrospective studies with 10,628, 2,347, and 1,304 participants, and one prospective observational study with 216 participants. Collectively, these studies reported that ICP monitoring itself significantly reduced in-hospital mortality and 2-week mortality.

Recently, with the availability of continuous ICP measurement using high-resolution ICP monitoring, the parameter known as pressure time dose (PTD) has been used to measure the burden of increased ICP (IICP). It has been reported that higher PTD values are associated with worse outcome of performance and survival rate.[48] Additionally, there is an expectation that analyzing the trend and waveform of ICP and admitting it for treatment may results in additional significant results.

In conclusion, despite the negative outcome of RCTs on ICP monitoring in severe TBI patients, there is a consensus based on the limitations of the studies and the results of good-quality cohort studies that ICP monitoring is necessary. Furthermore, it is important to analyze the impact of ICP-guided treatment on patient outcomes and to conduct research using high-resolution ICP monitoring.

Spontaneous subarachnoid hemorrhage (SAH)

In cases of SAH, there is a significant occurrence of elevated ICP, particularly in patients with higher Hunt and Hess grade or World Federation of Neurosurgical Societies grade. The 54%–81% of patients experienced episodes of ICP exceeding 20 mmHg. The severe TBI shows has the consensus in need for ICP monitoring, but SAH does not need the same level of consensus. In 2014, the Neurocritical Care Society conducted a survey on ICP monitoring in non-TBI patients. It was agreed that ICP monitoring should be considered in SAH patients with the risk of elevated ICP, especially in cases with a high likelihood of hydrocephalus, intraventricular hemorrhage (IVH), or poor-grade SAH.[33] SAH patients with poor-grade who are deeply sedated or have severe initial brain injury with decreased consciousness may have benefit from early detection of hydrocephalus or delayed cerebral ischemia by ICP monitoring as part of multimodal monitoring (**TABLE 1**).[12] However, the evidence regarding the impact of ICP monitoring on outcomes and mortality in SAH patients is limited, and further research is required. In TBI, there is a consensus on ICP monitoring in severe cases, but SAH is not as strong as TBI.

Spontaneous intracerebral hemorrhage (ICH)

Intracranial hypertension (IICP) is prevalent in ICH patients. Meta-analysis showed that 67% of patients experienced IICP events with ICP exceeding 20 mmHg, which is closely linked to mortality. The 2022 American Heart Association/American Stroke Association guidelines recommend ICP monitoring in ICH patients with a GCS score of 8 or less.[21] Consensus on the timing for necessary of ICP monitoring in ICH patients is lacking, but it is suggested that it should be considered in cases of obstructive hydrocephalus and concomitant IVH, in addition to serving the purpose of cerebrospinal fluid (CSF) drainage. Studies on clinical effectiveness have shown mixed results. Some of studies showed no significant differences in mortality or functional outcomes between ICP monitoring and non-ICP monitoring groups, but higher infection rates and increased use of aggressive treatments in the ICP monitoring group were included.[7,19,38] The MISTIE trial reported higher rates of poor functional outcomes and higher mortality in the ICP monitoring group. A recent study reported the better

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functional outcomes and lower mortality with ICP monitoring, particularly in patients with GCS scores of 9–12 (TABLE 1).[38] In conclusion, while IICP occur in ICH patients, consensus on the necessity and indications for ICP monitoring is still lacking. Further research, particularly regarding long-term outcomes is needed.

TYPE OF ICP MONITORING

The Brain Trauma Foundation's 4th edition guidelines for the management of severe TBI discussed the necessity and indications for ICP monitoring, but there is no specific recommendation regarding the type of monitoring device. The guidelines acknowledge that the choice of monitoring device should be based on the clinician's experience and judgment. This indicates that the decision on which specific monitor to use leave the discretion of the treating physician to consider the factors such as the patient's individual characteristics, clinical presentation, and available resources. It highlights the importance of clinical expertise and personalized decision-making to determine the appropriate monitoring approach for TBI patient.

Intraventricular monitor (IVM)

Lundberg[30] introduced the earliest form of ICP monitoring, which remains the gold standard for monitoring to the present day.[30] The reference point for the transducer is the Foramen of Monroe, which closely corresponds to the external auditory meatus, making it clinically convenient to use as a reference. The insertion is commonly performed through Rt. Kocher's point, but the specific approach may vary based on clinical judgment considering the brain pathology. This is cost-effective type of monitoring, but it can measure the real ICP as global CSF pressure. It allows for recalibration from external sources even after initial insertion. One advantage is the ability to control ICP through therapeutic CSF drainage, which affect the patient outcomes. Additionally, it facilitates drainage of IVH and enables the administration of therapeutic agents. However, compared to other types of ICP monitors, this method carries a higher risk of complications such as bleeding and infection. Infections have been reported in meta-analyses with rates ranging from 0.7% to 2.5%, even some studies reported the rates as high as 27% in specific cases.[23,29,39,47] Bleeding is also a major complication, but significant impact of bleeding on morbidity and mortality is low, ranging from 0.9% to 1.2%.[36] Other drawbacks of this method include misplacement, twisting, obstruction due to clots or protein, and the impact of transducer position on accuracy. Considering that ICP measurement with this technique is performed within the ventricle, the factors related to ventricular compliance should also be taken account. Therefore, accurate measurement may be challenging in pediatric patients or cases of SAH. Difficulties may arise during procedures when there is severe brain edema leading to ventricular collapse.

IPM

IPM is currently used around the world with taking various characteristics of brain injuries into consideration. It is typically inserted into the non-dominant frontal hemisphere's white matter, which assist local ICP measurement. However, as significant pressure difference between the ipsilateral and contralateral sides are present, the overall CSF pressure can be over or underestimated by IPM.[40]

The accuracy is the biggest drawback of IPM. It does not reflect the overall CSF pressure accurately, and zero drift is a possible issue in situations when recalibration is not available.

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The studies reported that IPM devices like Camino or Codman showed zero drift with less than 0.8 mmHg over 24 hours, but the difference was observed with approximately 0.6±0.99 mmHg when it was used longer time with 5 days.[10,35]

There are various types of IPM, including fiber optic (Camino), strain gauge microtransducers (Codman), pneumatic strain gauge (Spigelberg), and Neurovent-P ICP monitor. Fiber optic cables are operated by sending the light to a mini-displaceable mirror, which measures the distortion of the mirror by the changes of ICP. Compared to other IPM types, it is relatively expensive, but has a lower risk of infection and hemorrhage. However, there is still possible issues with malfunction or failure of the fiber optic component.[35]

Another ICP monitor type is the strain gauge microtransducers, which composed of two semiconductor strain gauges attached to a thin diaphragm at the tip of the catheter. This method provides relatively accurate measurements and allows CSF drainage when connected to an EVD. The small size of the catheter is suitable for applying to pediatric or various anatomical sites in the brain.[24]

The other types based on the pneumatic strain gauge technology, employing a balloon-tipped catheter system. It is cost-effective and accurate, but also simultaneous CSF drainage by a monitor tip.

Neurovent-P ICP monitor measures ICP by an electronic chip surrounded by a thin silicone membrane at the catheter tip. This method measure ICP, brain tissue oxygen partial pressure, and temperature simultaneously, but there is still a lack of clinical data.

IVM vs. IPM

IVM has a higher procedural difficulty, relatively higher risk of infection, and uncertainty in measurements caused by ventricle shape or compliance compared to IPM. One of the significant advantages of IVM is the ability to perform CSF drainage. According to Liu et al.,[27] IVM shows lower mortality, favorable 6-month GOS, and lower refractory intracranial hypertension (IICP) compared to IPM, suggesting it has a role of CSF drainage. Therefore, IVM is more commonly used in conditions of SAH or ICH which highly require for therapeutic CSF drainage compared to TBI. Robba et al.,[39] report based on the statistical analysis of 146 intensive care units in 42 countries showed that IPM was more commonly used for TBI (73%), while IVM was frequently for SAH and ICH cases (54%) (**TABLE 2**).

Other invasive monitoring type

Various attempts have been made to minimize the brain tissue damage, mainly caused by inserting catheters into different locations such as the subdural or epidural space to measure pressure. However, most of these attempts has the low accuracy. Lumbar drains by inserting a catheter into the lumbar region have been used for ICP monitoring. However, issue with the

TABLE 2. Comparison of intracranial pressure monitoring devices

Method	Advantages	Disadvantages
Intraventricular type	Gold standard	Insertion may be difficult
	Measures global pressure	Most invasive method
	Allows therapeutic drainage of cerebrospinal fluid	Risk of hematoma
	In vivo calibration possible	Risk of ventriculitis
Intraparenchymal type	Robust technology	Small zero drift over time
	Low procedure complication rate	No in vivo calibration
	Low infection risk	Measures local pressure

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low reliability and the risk of brain herniation by posing in cases of intracranial hypertension occur. It is important to note that invasive monitoring methods other than IVM and IPM are generally not suitable for monitoring ICP in patients with TBI or other conditions associated with IICP. These alternative methods lack the adequate accuracy or reliability for precise ICP measurement in such cases.[4]

Non-invasive monitor

As the invasive monitoring including IVM and IPM has the risk for bleeding and infection, non-invasive methods has been brought to attention. Several studies reported the different type of invasive method by transcranial Doppler (TCD) sonography, Near-Infrared Spectroscopy, Tympanic Membrane Displacement (TMD), and Optic Nerve Sheath Diameter (ONSD) measurements.[16,17,32,41,42,46,49]

However, there is currently no proven method for the utility in terms of accuracy and practicality.

TCD

Developed by Klingelhofer in 1987, TCD measures the blood flow velocity in the middle cerebral artery by indirectly assessing the brain compliance and ICP was estimated by secondary parameters such as peak systolic velocity, mean flow velocity, end-diastolic velocity, and pulsatility index.[41] However, the accuracy for ICP calculation by TCD has limitations with errors of up to 10 mmHg compared to invasive ICP measurements. Furthermore, it is difficult to predict intracranial hypertension in all cases by TCD, resulting in the clinical usefulness.[49]

ONSD

Since the increased ICP is transmitted to the optic nerve through the subarachnoid space's CSF pressure, measuring the ONSD can be indirect method to estimate ICP. It allows real-time assessment of intracranial compliance. Reported data demonstrated that measurement of intracranial hypertension has the 90% sensitivity and 85% specificity.[17]

TMD

Based on the principle of ICP transmitting to cochlear fluid pressure, which affects stapedial excursion, TMD allows the detection of transient changes in ICP when continuously measured. However, it has challenge to the accurate measurement of the ICP value and the limitations including the requirement for normal stapedial reflex, middle ear pressure, and cochlear aqueduct.[32,42]

Pupillometry

Pupillometry enables quantitative measurement of changes in pupillary light reflex. High ICP has been found to be related to the pupillary constriction velocity, and a 10% change in pupil size has been linked to intracranial hypertension. Continuous ICP monitoring is challenging, and the application is difficult when the measuring the patient's pupils is not feasible caused by eyeball trauma.[16,46]

PARAMETERS OF ICP

As mentioned previously, numerous studies reported that exceeding of ICP above the certain value leads to worse the patient outcomes.[25,43] Thus, a number of effort to lowering ICP

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TABLE 3. Parameters of ICP

Parameters	Definition and clinical use
Mean ICP	Threshold: 22 mmHg in TBI, but less correlated with patients outcome
PRx	Marker of cerebral autoregulation Threshold: <0.3 means preserved cerebral autoregulation Optimal CPP: the CPP ranges at which PRx <0.3 Increased PRx is associated with poor outcome
PTD	The duration and intensity of ICP exceeding 20 mmHg Higher PTD values are associated with increased mortality and unfavorable outcomes
AMP	AMP is the pulse amplitude and MWA is the average AMP over 6-second time window
MWA	AMP has shown a statistically significant association with cerebral autoregulation
RAP index	RAP is the correlation between mean ICP and the amplitude of ICP waveform
wICP	Compensatory reserve-wICP wICP=(1−RAP)×ICP wICP may be a more effective predictor of outcomes

ICP: intracranial pressure, TBI: traumatic brain injury, PRx: pressure reactivity index, CPP: cerebral perfusion pressure, PTD: pressure time dose, AMP: pulse amplitude of intracranial pressure, MWA: mean intracranial pressure wave amplitude, RAP: reserve-amplitude-pressure, wICP: weighted intracranial pressure.

below this threshold value as treatment has been made. However, it has controversy that solely measuring the mean value of ICP and striving to lowering below a single value is not comprehensive enough. Considering this, it is likely to explore the different variables that can be obtained through ICP monitoring beyond just the mean value (**TABLE 3**).

Pressure reactivity index (PRx)

The PRx is a physiological parameter used in the management of TBI to assess cerebrovascular reactivity. It quantifies the brain's ability to regulate cerebral blood flow in response to changes in ICP by analyzing the correlation between ICP and arterial blood pressure (ABP) waveforms. A positive PRx indicates impaired cerebrovascular reactivity, while a negative value suggests intact autoregulation.[13]

PRx monitoring provides real-time information about cerebral autoregulation and helps the decision to guide treatment. Elevated PRx values indicate dysfunctional autoregulation reflecting a poor prognosis, while negative or low values suggest intact autoregulation related to better outcomes.

There are studies shown PRx as the potential prognostic marker and its association with functional outcomes related to TBI severity.[28,44] Steiner et al.,[44] reported that after evaluation PRx in TBI patients high value had poor clinical outcomes and increased mortality. Liu et al.,[28] investigated the association between PRx and cerebral blood flow and found worse functional outcomes with higher PRx and impaired pressure reactivity. In summary, PRx is a valuable tool for TBI management, providing insights into cerebrovascular reactivity and helping optimize cerebral perfusion. Clinicians can use PRx to optimize CPP and prevent secondary brain injury.

PTD

The PTD is a concept employed in neurocritical care to quantify the cumulative exposure of the brain to elevated ICP over a specific duration. It is determined by assessing the duration and intensity of ICP exceeding a defined threshold, typically set a specific pressure value with 20 mmHg. The PTD provides a comprehensive measure of the brain's capacity to withstand increased ICP by considering both the pressure level and duration of exposure. A study conducted by Vik et al.,[48] in 2008 demonstrated a stronger correlation between the cumulative dose of ICP, calculated based on the duration ICP surpasses 20 mmHg, the Marshall CT score

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and clinical outcome in patients. The study proposed that the area under the curve of ICP serve as a more valuable tool in managing TBI. This discovery led to the development of the PTD concept. Subsequent research by Åkerlund et al.,[2] utilizing the CENTER-TBI dataset found a correlation between PTD and patient mortality. Similar findings have indicated that higher PTD values are associated with increased mortality and unfavorable outcomes, not only in TBI patients but also in other populations with acute brain injuries.[31] These findings suggest the potential applicability of PTD in various acute brain injury populations.

Pulse amplitude of ICP (AMP)/mean ICP wave amplitude (MWA)

AMP and MWA both involve measuring the pulse amplitude from the ICP waveform, but they have different approach. AMP is based on the amplitude of the ICP waveform, while MWA measures the pulse amplitude based on the time in the ICP waveform. However, previous studies have shown a strong correlation between AMP and MWA values (p<0.001), indicating that they can be examined together.[20]

According to a study by Radolovich et al.,[37] AMP has a statistically significant association with cerebral autoregulation in TBI patients, suggesting the beneficial effect in the treatment of TBI patients. Additionally, Eide et al.,[14] reported that the patient group with SAH treated based on mean ICP and MWA values showed significantly better functional outcomes after 12 months compared to the treated group based on mean ICP values alone.

Correlation coefficient (R) between AMP (A) and mean pressure (P) (RAP) index

RAP index is a coefficient that reflects the correlation between mean ICP and the amplitude of ICP waveform over a short period of time. The index closes to 0 indicates a state where ICP can increase while maintaining effective pressure-volume compensation. On the other hand, RAP value approaching to +1 suggests that minimal volume changes generate significant pressure differences or no pressure changes occur. As ICP continues to increase, amplitude (AMP) decreases, and in such cases, the RAP index approach a negative value close to –1.[11]

It is important to note that the RAP index is a relatively new concept and further research is required to validate its clinical utility and establish the significance in predicting patient outcomes or guiding management decisions.

Weighted ICP (wICP)

The concept of compensatory reserve-weighted ICP or wICP consider the negative correlation between ICP and volume. It is defined as wICP=(1–RAP)×ICP, where RAP is the reserve-amplitude-pressure index. The Czosnyka group conducted a study on TBI patients within a single institution, comparing the measurement of ICP and wICP and the predictive value for patient mortality. Although statistically significant was not observed, wICP predicted mortality better than ICP alone.[6]

In large-scale studies using databases, wICP has been reported to predict patient survival or mortality and better reflect patient prognosis significantly compared to ICP. These findings suggest that wICP is a more effective predictor for outcomes and provide better insights into patient prognosis than ICP alone.[50]

It is important to note that further research and validation studies are needed to fully establish the clinical utility and significance of wICP to predict patient outcomes and guide the management decisions.

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CONCLUSION

ICP monitoring is crucial for patients with acute brain injuries, including TBI, specifically there is a risk of IICP crisis. It helps for the treatment goal establishment, therapy evaluation, and guidance. The invasive IPM type of ICP monitoring is currently considered as the most suitable, accompanied with the IVM type when an extraventricular drain is needed. However, relying solely on mean ICP values has limitations. To overcome this, recently various secondary parameters were applied. Understanding and utilizing these parameters support to determine optimal CPP and maintain cerebral blood flow. This is valuable particularly in situations where multimodal monitoring options including Brain Tissue Oxygenation, cerebral blood flow, and unavailable of microdialysis application.

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