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REVIEW ARTICLE

# A Descriptive Review of Non-Invasive Techniques for Intracranial Pressure (ICP) Monitoring

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## Abstract

**Purpose:** This paper aims to thoroughly investigate non-invasive techniques employed in monitoring Intracranial Pressure (ICP) accompanied by a thorough exploration of the research endeavors in this specialized domain.

**Materials and Methods:** A thorough review of papers sourced from PubMed was conducted to explore the latest methods utilized in monitoring Intracranial Pressure (ICP). A search was carried out for review papers, systematic reviews, books and documents, and meta-analysis using the term “non-invasive AND intracranial pressure AND monitoring” yielding 82 results. The study systematically examined past and recent literature, focusing prominently on newer techniques. The gathered data from these sources was diligently incorporated into the paper, providing updated insights into ICP monitoring methods. These techniques were then analyzed and compared to highlight their advantages and disadvantages, based on their applications.

**Results:** The review focused on several key non-invasive methods for Intracranial Pressure (ICP) monitoring, notably encompassing Imaging techniques such as CT and MRI, Electroencephalogram (EEG), Near-Infrared Spectroscopy (NIRS), Optic Nerve Sheath Diameter (ONSD) measurement, and Transcranial Doppler (TCD) Ultrasound. These modalities were examined for efficacy and feasibility in non-invasively assessing and monitoring ICP and compared accordingly.

**Conclusion:** While invasive methodologies, particularly the intraventricular catheter, are commonly favored in clinical settings for Intracranial Pressure (ICP) monitoring due to their accuracy, non-invasive alternatives gain traction, especially when employing invasive techniques isn't viable. The emergence of non-invasive methods marks a significant stride in ICP monitoring. Despite their relatively lower familiarity in clinical practice, these non-invasive approaches present notable advantages, notably enhanced safety and a reduced risk of infection. Their growing significance lies in offering feasible options when invasive monitoring poses challenges, thus expanding the scope and safety of ICP monitoring beyond conventional invasive methods.

**Keywords:** Intracranial Pressure; Transcranial Doppler; Subarachnoid Hemorrhage; Traumatic Brain Injury; Lumbar Puncture; Mean Arterial Pressure.

DOI:

## 1. Introduction

Intracranial Pressure (ICP) monitoring stands as a cornerstone of neurocritical care, greatly influencing a patient’s health. ICP refers to the pressure within the skull and it should be steady, with the volume of the intracranial cavity constant under normal conditions [1].

The Brain Tissue (BT), Cerebral Blood Flow (CBF), and Cerebrospinal Fluid (CSF) make up the intracranial cavity [2, 3] and an increase in the volume of any of these three components can result in the elevation of ICP. This principle, called The Monro-Kellie doctrine, was formulated in the late 18th and early 19th centuries, and named after Scottish anatomist Alexander Monro and British physiologist George Kellie. The Monro-Kellie doctrine posits that since the cranial cavity is a non-expandable compartment containing three primary components: brain tissue, Cerebrospinal Fluid (CSF), and blood, a sudden increase in the volume of any of these three components must be compensated by a decrease in the volume of another component to thoroughly maintain a constant ICP. It can be expressed accordingly:

Intracranial Pressure (ICP) = Volume of the Brain Tissue (VBT) + Volume of Cerebrospinal Fluid (VCSF) + Volume of Blood (VBLD)

The doctrine underlines the equilibrium that must be maintained within the intracranial cavity. Disruptions to this balance, such as intracranial tumors, meningitis, hydrocephalus, and cerebral edema, can lead to elevated ICP [3]. Understanding and maintaining normal ICP levels are essential to prevent these adverse outcomes.

Normal ICP varies with a person’s age, body position, and posture, but it is found to be in the range of 5-15 mmHg in healthy adults, 3-7 mmHg in children, and 1.5-6 mmHg in infants [4]. Detailed ICP monitoring is crucial for clinical diagnosis and many methods have been developed in the past years apart from invasive methods to provide for precise assessment of ICP. These methods include non-invasive approaches such as Transcranial Doppler (TCD) ultrasound, Electroencephalogram (EEG), Optic Nerve Sheath Diameter (ONSD), Imaging (CT & MRI), Near Infrared Spectroscopy (NIRS), etc.

Invasive methods such as intraventricular catheterization, where a hole is drilled into the skull, which can accommodate a probe that can help determine the CSF pressure, are considered the gold standard of ICP monitoring [4], providing the most accurate clinical diagnosis.

However, invasive methods of ICP monitoring carry a lot of disadvantages including the risk of severe infection, bleeding, technical difficulties, and the high cost of the surgery. The reviewers have summarized the advantages and disadvantages of the four most preferred invasive ICP monitoring techniques: intraventricular catheter monitoring, intraparenchymal monitoring, subarachnoid screw/bolt monitoring, and fiber-optic sensor monitoring in Table 1 [1, 3, 4]. These techniques are evaluated on the basis of accuracy, reliability, risk of infection, extent of invasiveness, risk of tissue damage, and level of technical expertise required to operate, etc.

Clinicians are looking into non-invasive methods to prevent complications faced during invasive ICP monitoring. Current research includes examining non-invasive methods and developing technology that aids in the endeavor. This paper highlights the non-invasive methods in ICP monitoring, and the research conducted in it, and while invasive ICP monitoring remains the most preferred method [5], non-invasive methods have shown substantial progress in monitoring ICP with regard to patient safety and health

## 2. Materials and Methods

A literature search was carried out for this review on PubMed, with no particular restrictions on date, or language of publication. The search was conducted from January 1988 to December 2023 for review papers, systematic reviews, books and documents, and meta-analysis using the term “non-invasive AND intracranial pressure AND monitoring”, which yielded 82 results.

The titles and abstracts were reviewed in depth for relevance to this review, resulting in the selection of 47 publications for examination further. After thoroughly reviewing these 47 articles, 30 were

**Table 1.** Advantages and disadvantages of Invasive ICP monitoring

| Invasive ICP monitoring methods | Advantages | Disadvantages |
|---|---|---|
| **Intraventricular Catheters** | 1. Considered the most accurate ICP monitoring method (Gold Standard).<br>2. Has a comparatively lower risk of dislodgment or mispositioning since the catheter is fixed within the ventricle.<br>3. Allows for the sampling of CSF, which can be further used for analysis and diagnosis. | 1. High risk of infection.<br>2. Limited adjustability of the catheter.<br>3. Potential risk of haemorrhage.<br>Requires extreme technical expertise and precision to insert in order to avoid several complications. |
| **Intraparenchymal Monitoring** | 1. Provides accurate and reliable results in monitoring ICP.<br>2. Is less invasive compared to intraventricular catheters.<br>3. Comparatively reduced risk of infection. | 1. Potential risk of tissue damage due to the insertion of the monitor into brain tissue.<br>2. Is relatively expensive.<br>3. No provision for the sampling of CSF. |
| **Subarachnoid screw/bolt Monitoring** | 1. Is less invasive compared to intraventricular catheters.<br>2. Relatively easy to install than the intraventricular catheter.<br>3. Smaller in size and easier to handle.<br>4. Allows for the sampling of CSF, which can be further used for analysis and diagnosis.<br>5. Comparatively reduced risk of infection. | 1. Cannot be recalibrated after installation.<br>2. Comparatively less reliable.<br>3. Transducer tip can become obstructed if it comes in contact with brain parenchyma. |
| **Fiber-optic Sensor** | 1. Comparatively less invasive, since it involves a small-diameter catheter.<br>2. May cause less tissue damage compared to other catheters.<br>3. Offers great adjustability and flexibility in terms of catheter placement. | 1. Is relatively expensive.<br>2. Potential risk of dislodgment.<br>3. No provision for the sampling of CSF.<br>4. Less availability due to being a non-traditional monitoring technique.<br>5. Difficult to re-calibrate. |

deemed highly relevant and accordingly included in this review.

These publications focused on the most recent and significant studies related to non-invasive ICP monitoring.

Figure 1 demonstrates the methodology of the selection process of the papers.

## 3. Non-Invasive ICP Monitoring Methods

### 3.1. Imaging (CT & MRI)

Imaging techniques have offered valuable insights into the structural and functional aspects of the brain. Using Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), morphological changes associated with elevated ICP can be identified.

A study to assess ICP in patients with Traumatic Brain Injury (TBI) using the image-processing algorithm on CT scans demonstrated that specific morphological features of CT scans may be used to identify patients having a low risk of elevated ICP which can help eliminate any unnecessary invasive procedure. A total of 45 scans from 20 patients, with an inclusion criterion where patients with severe TBI i.e. with a GCS (Glasgow Coma Scale) of less than

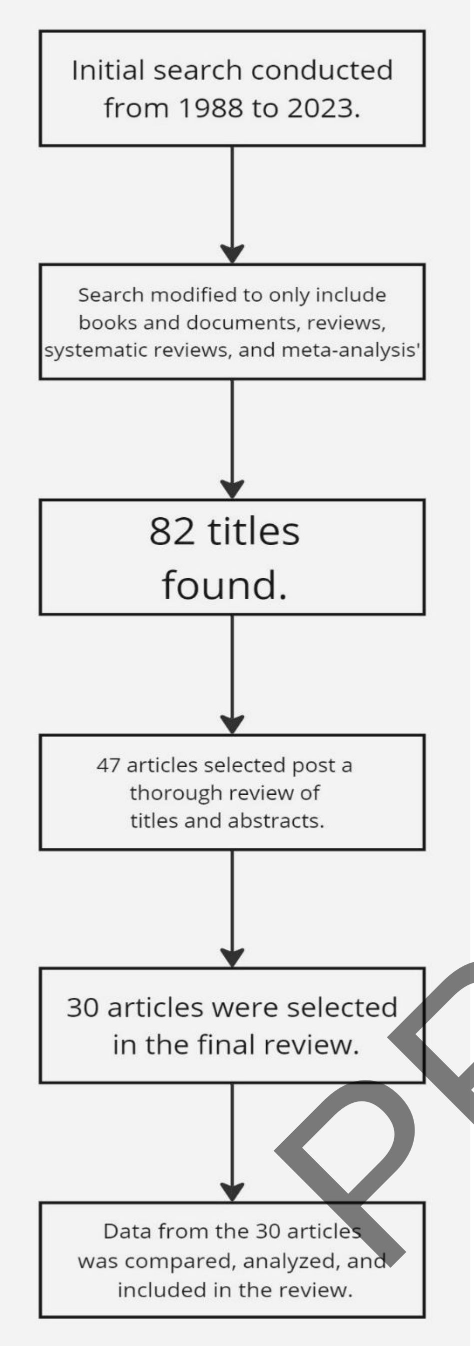

**Figure 1.** The methodology of the selection process of articles

9 were selected, was analyzed and the value of $csf_v/icv_v$ (ratio of the volume of CSF to the total intracranial volume) threshold was determined to be 0.034 with a predictive accuracy of 67 %. A ratio of $csf_v/icv_v > 0.034$ results in an ICP value of less than 20 mmHg [6]. The study has demonstrated promising results and has discussed having better results with a larger population and other techniques of image segmentation for the image processing algorithm.

In another study, where ICP was estimated using CT scans in patients with severe head injury, the researchers demonstrated that a normal-appearing CT scan indicated normal ICP and the equation for estimating ICP using the first CT findings on admission is valuable in predicting the initial ICP. Their research produced results that clarified that ICP correlated best with the narrowing of cisterns, especially basal cisterns [7]. The equation that they introduced utilizing multiple regression analysis, induced approximately 80% of predicted ICP within ±10 mmHg of the measured ICP.

These prominent results demonstrate how high-resolution CT scans allow clinicians to identify several factors associated with an elevated ICP, such as ventricular compression, ventricular enlargement, cerebral hemorrhage, and midline shift [1, 2]. While CT scans alone may not aid in detecting ICP early on, with cases where they've not helped predict ICP [8], they've still been a valuable source to help detect ICP in many other studies.

Magnetic Resonance Imaging (MRI), too has helped in the detection of ICP, despite not being used as often as CT. In a pilot study [9], the correlation between MRI-derived ICP measurements and invasive ICP measurements was compared. The study included thirteen healthy elderly patients who were community dwellers and had sustained no head injuries, traumas, or any other neurological conditions with an exclusion criterion of having motor or sensory deficits, lower literacy, or consumption of significant anticholinergic properties, and six brain trauma patients. The ICP of the thirteen patients was measured primarily using a Lumbar Puncture (LP), which is a medical procedure used to collect CSF from the spinal canal located near the lower back for measuring CSF pressure which can aid in providing information about the ICP. The ICP of the six brain trauma patients was measured using the External Ventricular Drain (EVD), which involves inserting a catheter into the brain's lateral ventricle to drain CSF to measure its pressure. Post acquiring MRI scans of the patients, with scans obtained from three healthy participants excluded due to poor image quality, a derivation of the non-invasive MR-based ICP method was utilized to determine MR-ICP values for the patients based on the linear relationship between cranial elastance and ICP from a previous study where researchers used MR imaging measurements of CSF and blood flow to calculate intracranial volume and pressure changes. They then derived an elastance index from the ratio of pressure to volume change. The measurements of the elastance index with invasive ICP measurements were then compared and found to correlate very well in the study [10]. The MRI-derived ICP measurements were then compared with the invasive ICP measurements of the patients, and a positive correlation was found, with invasive ICP measurements being higher than MR-ICP measurements by 2.2 mmHg on average. The researchers concluded that MR-ICP provides a reliable estimate of ICP, with fourteen out of sixteen data points within the clinically acceptable range.

While imaging hasn't been the most reliable of techniques to detect ICP, it has been used and accepted widely as a means of understanding the anatomic changes better in the brain since these techniques have several advantages, such as high resolution for MRI and quick scan time for CT [6], and are usually widely available compared to other methods of non-invasively measuring ICP.

### 3.2. Electroencephalogram (EEG)

Electroencephalogram (EEG) is a test used to measure the electrical activity of the brain, using electrodes that are attached to the scalp [11]. When neurons in the brain produce electrical impulses, the electrodes detect and record them, which can help clinicians recognize unfamiliar or abnormal activity present in the brain. When ICP is elevated, there are changes in the CBF and brain metabolism, which affect the electrical activity of the brain. These changes can be measured using EEG. For example, focal pressure from a hematoma can cause changes in the EEG patterns in the area near the lesion [12], or elevated ICP can sometimes cause a lack of electrical activity in the brain, also known as electrocerebral silence, which is evident in an EEG [13].

In a study published in 2012 [14], a new method of ICP monitoring was introduced utilizing EEG power spectrum analysis. The researchers recorded the EEG signals in 62 patients (34 males and 28 males) with central nervous system (CNS) disorders such as tuberculous meningitis, viral encephalitis, etc., and measured their ICP by the Lumbar Puncture test, with the patient in lateral decubitus position. The EEG power spectrum analysis involved primarily processing the EEG signals to remove any noise interferences and artifacts, and randomly selecting 20 segments of EEG signals, each lasting five seconds, for further analysis. Upon analysis, the researchers determined several important parameters from the signals, such as total power (sum of the power across all frequency components), median frequency (the frequency at which the power is divided into two halves: 50 percent of the total power is below the frequency), and the delta ratio (ratio of delta power (0-4 Hz) to the sum of alpha and beta power: Delta Power/ (Alpha Power + Beta Power)). From the experiment and analysis, it was found that 1 / (median frequency × delta ratio) had the strongest correlation with ICP and it was defined as the Pressure Index (PI). After the data was evaluated by the Spearman rank correlation analysis, the researchers derived a negative correlation between ICP and PI ($r=-0.849$ and $p < 0.01$) and concluded that analysis of specific parameters from the EEG power spectrum might reflect the ICP. The researchers discussed limitations such as the lack of electrodes used to validate their findings and stated how continuous EEG acquisition would've produced better results over one-time EEG acquisition which the researchers conducted, which could've led to unstable PI values.

Researchers affiliated with Hospital Universitario de la Princesa in Madrid [15] carried out a study in which the relation between EEG and ICP was studied in neurocritical care patients. The inclusion criteria were patients either older than eighteen years, SAH or TBI and clinical criteria for ICP monitoring. Continuous EEG-ECG was performed during ICP monitoring which was performed using an intraparenchymal sensor. The researchers then employed the Grainger Causality (GC) test to find out if any relationship existed between EEG and ICP. After analyzing 21 patients for 1055 hours, the researchers observed significant GC statistics, indicating a predictive relationship between EEG activity and ICP, during 37.88% of the monitoring period, with typical lags of 25-50 seconds between EEG and ICP signals. The researchers concluded that this useful relationship could lead to the development of a medical device to measure ICP in a non-invasive way.

Despite providing clinicians with useful data for monitoring ICP, EEG tests haven't been widely accepted as a method for non-invasively monitoring

ICP. Patterns in EEG can be susceptible to changes from different brain conditions that do not necessarily impact ICP. EEG tests also do not directly quantify the 'pressure' during elevated ICP, which doesn't make it a very suitable method for monitoring ICP. However, EEG allows for continuous and real-time monitoring of brain activity, which could provide great insights that could be crucial for timely interventions.

### 3.3. Near-Infrared Spectroscopy (NIRS)

Near-Infrared Spectroscopy (NIRS) is a technique used to monitor the changes in the oxygen levels or blood flow in the brain using the principle of light absorption and scattering. Near-infrared light sources emit light within the 'near-infrared' spectrum, with the wavelength ranging from approximately 700 nm to 2500 nm. When this light comes in contact with the brain after penetrating the skin and the skull, it either gets absorbed by the molecules in the blood, for example, hemoglobin, or gets scattered or thrown off inside the brain parenchyma. The light that gets reflected is detected by the NIRS sensor, which is further used to analyze the blood flow or oxygen level by determining how much light got absorbed and reflected. Abnormalities in the brain tissues often reflect in the amount of light absorbed and scattered and aid in understanding the state of the brain parenchyma.

As discussed in a preliminary report [16], NIRS was used for monitoring ten children with severe TBI (admission GCS $\leq 7$). After continuously monitoring their ICP, MAP, and EEG using a ventriculostomy, an arterial line, and EEG leads, NIRS was performed by placing optodes over the frontal-parietal region of the more severely affected side based on the initial CT scan. The optodes emitted light in the near-infrared range (700 nm - 900 nm), illuminating the underlying tissue, and this reflected signal was received at the optode patch, leading to the calculation of OxyHemoglobin (HbO$_2$), deoxyhemoglobin (Hb), total hemoglobin (THb), and regional cerebral oxygen index (rSO$_2$). The researchers found that high ICP (>20T) is often correlated with increased THb and HbO$_2$. They concluded that NIRS was able to detect changes in cerebral blood volume in children with increasing ICP and remarked that changes in MAP of >20T were correlative in 50% of the instances of cerebral oximetry change, and were mostly associated with ICP/CPP changes.

NIRS can also be used to help detect the development of cerebral edema but it still cannot be used as a substitute for initial CT imaging [17]. The application of NIRS is better suited to monitoring cerebral oxygenation rather than ICP since it shares a clear picture of hemodynamic changes better than imaging or EEG [16], and the implementation of NIRS can be difficult for patients with facial and scalp injuries since the presence of hematomas is known to impact the NIRS-derived rSO$_2$ readings [17], along with making it a more painful process for the patient.

### 3.4. Optic Nerve Sheath Diameter (ONSD) Measurement

The Optic nerve sheath is a membrane that encapsulates the optic nerve, which is the nerve that transmits electrical impulses from the eyes to the brain. Since the optic nerve sheath is in close proximity to the brain, any changes in ICP reflect in the diameter of the optic nerve sheath. ONSD measurements of up to 5 mm are considered normal in healthy adults and measurements greater than 5 mm are correlated with ICP above 20 mmHg [18].

An ultrasound probe is positioned at an angle that achieves an axial view of the optic nerve sheath [19], and the high-frequency sound waves emitted by the ultrasound bounce off the tissues inside the eye, providing an image of the optic nerve sheath [20]. The measurement of the diameter of the optic nerve sheath is taken about 3 mm behind the globe in each eye [21], and the process is repeated over time to find accurate values of ONSD.

In an observational study [21] where ONSD was used as a marker for the evaluation and prognostication of ICP in 101 Indian adults, a control group (group A) included 41 healthy adults and a study group (group B) included 60 patients admitted with fever, headache, vomiting, and altered sensorium. After examining them in the supine position using a 10 MHz phased linear array probe on closed eyelids, the mean ONSD observed in control and study group for females was 4.627 ± 0.09 mm and 5.103 ± 0.62 mm and for males was 4.8 ± 0.10 mm and 5.081 ± 0.58 mm, respectively. The measurements were taken 3 mm behind the globe, since the researchers found this position providing consistent results, especially after confirming with previous studies. A radiological sign of raised ICP was confirmed in 35 patients (females = 11 and males = 24) with a high ONSD value. Out of 25 patients in their study who showed no signs of raised ICP, 10 showed high ONSD, with values of 4.735 mm in females and 4.907 mm in males. The researchers discussed that acute rise in ICP is tough to diagnose because of nonspecific symptoms, however, they concluded that the results of their study were encouraging as compared to imaging methods utilizing CT, for example, since a normal CT scan doesn't rule out the possibility of an elevated ICP despite appearing normal.

In another study [22] where ONSD was measured and correlated with directly measured ICP in Korean adults, with inclusion criteria of patients age greater than 18 years, having an abnormal brain CT or MRI scan, requiring EVD, and being admitted to the ED or ICU. The researchers measured the ONSD of 62 patients who had their ICP monitored with an EVD catheter simultaneously. Thirty-two patients were found to have an increased ICP (IICP), accounting for 51.6% of total patients. They found the value of ONSD higher in patients with an elevated ICP (5.80 ± 0.45 mm) than in those without an elevated ICP (5.30 ± 0.61 mm), hence deriving that an ONSD value greater than 5.6 mm pointed to an elevated ICP. The results demonstrated how increased ICP showed a more significant linear correlation with ONSD, with a p-value less than 0.01 as compared to non IICP group with a p-value of 0.02. They concluded that ONSD correlated well with increased ICP in Korean adults with brain lesions.

Both studies concluded that ONSD correlated well with ICP and could be used as a non-invasive approach to safely monitoring ICP. However, studies have also suggested that ONSD cannot be used in patients with medical conditions such as sarcoidosis, Grave's disease, tumors, inflammation, etc. [4].

In a setting where there is an unavailability of invasive ICP monitoring techniques, ONSD can be used as a potential technique to determine an elevation in ICP in a patient.

### 3.5. Transcranial Doppler (TCD) Ultrasound

Transcranial Doppler (TCD) ultrasound is a technique that assesses the Cerebral Blood Flow (CBF) velocity in the middle cerebral artery [4]. A transducer placed on the scalp emits ultrasound waves that penetrate the skull and get reflected by red blood cells within the cerebral vessels. The frequency shift between the emitted and are reflected rays is known as the 'Doppler Effect', and it is directly proportional to the blood flow velocity [23].

An elevation in ICP can lead to changes in the CBF velocity. Due to impaired cerebral perfusion from an elevated ICP, blood flow velocity is compromised [24]. The Pulsatility Index (PI) derived from CBF, which helps with the assessment of vascular resistance, can be used as an indicator of ICP. Since changes in ICP affect the cerebral hemodynamics, PI gets influenced, too [25]. Research has reported a strong correlation between PI and ICP with a mean deviation of ± 4.2 mmHg from invasively measured ICP [25], deeming the approach to be clinically acceptable. However, PI doesn't factor in other parameters except CBF [26], and if CBF isn't affected during a sudden spike in ICP, there would be no absolute indication of an elevation in ICP.

When there's an increase in Arterial Blood Pressure (ABP), the cerebral arteries are constricted which reduces the blood flow velocity. Numerous studies have incorporated ABP along with CBF velocity to provide a better understanding of monitoring ICP non-invasively. One such study proposed a simplified intracranial hemo- and hydro-dynamics model that consisted of two simple resistance circuits. The researchers constructed the simulation CBF signal using the original Ursino model [27] with real ABP. Their proposed method tracked sudden ICP changes successfully after obtaining a small root mean square error between the estimated ICP by their approach and the reference ICP derived from the original Ursino model. They concluded that their method could be used for monitoring ICP non-invasively [26].

Despite being an extremely preferred and effective method to monitor ICP non-invasively, there have been intra- and inter-observer variations noted in this technique [28]. It also requires significant prior experience and training [29], and cannot be used for patients with certain medical conditions, such as skull abnormalities since obtaining reliable TCD signals would be challenging and comparatively tougher.

## 4. Results

After a review of the literature on non-invasive methods for intracranial pressure (ICP) monitoring, Table 2 distinguishes the non-invasive monitoring techniques (Imaging (CT and MRI), Electroencephalogram (EEG), Near-Infrared Spectroscopy (NIRS), Optic Nerve Sheath Diameter (ONSD) measurement, and Transcranial Doppler (TCD) Ultrasound) based on various factors such as accuracy, real-time monitoring, portability, cost, continuous monitoring, patient comfort, operator dependency and complications.

Based on the comparison, ONSD stands out as the most advantageous technique for monitoring ICP non-invasively with several advantages such as high accuracy, offering real-time and continuous monitoring, being portable, and providing patient comfort.

The complications that arise from ONSD monitoring are quite negligible and it is a great tool to rely on in a clinical setting. TCD monitoring too offers great benefits and can be used as well to monitor ICP non-invasively and safely.

## 5. Discussion

Non-invasive approaches to monitor ICP have been preferred in settings where invasive approaches to monitor ICP are either unavailable or not advised. Current research in ICP monitoring still suggests that invasive approaches are more accurate and reliable, especially when the patient needs continuous ICP monitoring. However, due to the risks of invasive monitoring of ICP, non-invasive approaches are considered, since minimizing additional risks in critically ill patients is a topmost priority. Moreover, the ability to perform non-invasive ICP monitoring at the bedside enhances patient convenience and comfort, ensuring rapid assessment.

Cost-effectiveness is another critical consideration. While some non-invasive methods may have higher initial costs due to training requirements and equipment, they can ultimately reduce overall costs by decreasing the need for invasive procedures and shortening hospital stays. The potential for non-invasive methods to be used in a broader range of healthcare settings, including resource-limited environments, further underscores their importance.

The methods developed in non-invasive ICP monitoring and measurement however necessitate further research [30] and experimentations in order to be considered as a definite approach in clinical applicability.

Further research in ICP monitoring suggests multimodal approaches such as brain tissue oxygenation, potential biomarkers in body fluids, and implantable sensors for accurate monitoring.

Furthermore, newer non-invasive approaches hold a promise of making ICP monitoring a less painful and safer process, along with providing optimal results useful for determining the changes in ICP instantly.

## 6. Conclusion

Despite invasive ICP monitoring techniques such as intraventricular catheter monitoring being the gold standard for ICP monitoring [4], non-invasive ICP monitoring techniques offer valuable alternatives to invasive methods, with each technique demonstrating unique strengths and limitations.

Integrating these techniques into clinical practice can enhance patient care by enabling early detection and continuous monitoring of elevated ICP. Future research should focus on standardizing protocols and validating these methods across diverse patient populations to establish their routine clinical use.

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**Table 2.** Comparison of the main non-invasive ICP monitoring techniques

| | **Imaging techniques (CT & MRI)** | **EEG Monitoring** | **NIRS Monitoring** | **ONSD Monitoring** | **TCD Ultrasound Monitoring** |
|---|---|---|---|---|---|
| **Accuracy** | Moderate to High | Moderate | Moderate | High | High |
| **Real-time monitoring** | No | Yes | Yes | Yes | Yes |
| **Portability** | Low | High | High | High | High |
| **Cost** | Moderate to High | Low | Low | Low | Low to Moderate |
| **Continuous Monitoring** | No | Yes | No | No | No |
| **Patient Comfort** | Moderate | Moderate to High | High | High | High |
| **Operator Dependency** | Low | High | Low | High | High |
| **Complications** | Yes | No | No | No | No |

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