Evidence-Based Clinical Review: Intracranial Monitoring

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Introduction

Intracranial pressure (ICP) represents one part of the hemodynamic conditions reflecting homeostasis in the cranial vault.[1-3] It is a commonly assessed measurement in neurocritical care,[1-11] as increases in ICP have been associated with poor clinical outcomes (measured by a low Glasgow Coma Scale [GCS] score, decreased neurologic dysfunction, and decreased functional recovery) and increased mortality.[4,11-19] Monitoring and managing ICP has been associated with decreased morbidity and mortality.[4,11,12,15-17,20]

Despite the documented decreases in morbidity and mortality, ambiguity still exists regarding the absolute benefits of ICP monitoring and management, which has led to a lack of consensus in the nursing guidelines for ICP monitoring.[12,21-26] Published literature is fragmented and leaves much room for variations in care. In efforts to synthesize literature findings into a single cohesive document, the American Association of Neuroscience Nurses (AANN) formed a writing group to investigate indications for and troubleshooting of different intracranial monitoring modalities.

Methods

This evidence-based clinical review (EBCR) covers research literature on the care of patients with ICP monitoring via external ventricular device (EVD), intraparenchymal drain, brain tissue oxygen ($PbtO_2$) monitoring system, and bispectral index (BIS) for the most common neurologic diagnoses requiring monitoring. The topics are discussed in the population, intervention, comparison, and outcome (PICO) format, with discussion of the general pathophysiology behind the use of each monitoring modality. The process for the EBCR began with identifying the past 10 years of literature available (per academic standards) using key words from the PICO questions. The employed search engines were PubMed®, CINAHL, and Cochrane Library databases using relevant Medical Subject Headings (MeSH) terms and keywords (Appendix A). The literature search covered scientific publications from 2010 to 2020 and was performed by medical librarians at the Cleveland Clinic, University Hospitals Cleveland Medical Center, John Peter Smith Health Network, and University Colorado Health. The multicenter searches were performed to have saturation of relevant topics and yielded 3,053 articles. These citations were loaded into the DistillerSR® software to assist with removing duplicates and evaluating articles in a stepwise progression. Each step required a two-person review of each article to assure agreement on inclusion and exclusion criteria, level of rigor, and application to the PICO questions. First-line exclusion criteria comprised animal studies, studies with fewer than 20 participants, studies with participants aged 17 years or younger, and studies not published in English; exceptions were made for research that reported through the MeSH filters. Articles were filtered for inclusion or exclusion through four levels of review: title–abstract review, full-text screening, study design, and risk-of-bias assessment. The articles reviewed were sorted by PICO topic and evaluated for pertinence to each question; this yielded a total of 175 articles, which were further distilled by relevance to EBCR and PICO questions.

The volume and rigor of the available literature determined the Clinical Practice Guidelines Editorial Board's decision to report this version as an EBCR versus previous Clinical Practice Guideline iterations (2011, 2012, 2014), as the standard for evidence rigor has evolved. The heterogenous nature of the research literature limited the writing group's ability to make definitive evidence-based recommendations. The lack of specific care criteria within this EBCR document diverges from care recommendations issued by the Neurocritical Care Society (NCS) and other consensus groups. This is owing to the differing nature of consensus statements and EBCRs. EBCRs are held to a higher standard of scientific rigor than consensus statements. While both are based on evidence, consensus statements incorporate practitioner opinion in forming published recommendations. That is not within the scope of AANN Clinical Practice Guidelines publications. Nonetheless, the need for concrete bedside care management still exists. Hence, this document will be followed by an AANN quick guide for intracranial monitoring care.

Background

Patients with acute neurological conditions require ongoing assessment of neurological status in an objective manner. Regular assessment using the same methodology yields the most expedient identification of changes in the patient's condition. Nursing assessment of the neurological system should include level of consciousness (LOC), sensory and motor evaluation, cranial nerve assessment, and pupillary assessment.[27] While different tools and assessments exist, the neurological assessment should be completed in conjunction with body system monitoring[17] to determine effect on the neurological system. Understanding the neurologic feedback effect on cardiac and respiratory systems will provide additional information to alterations in the ICP, $PbtO_2$, and BIS measurements.

Intracranial Pressure

For neurologically injured patients requiring ICP monitoring, what are the signs and symptoms the nurse should be assessing for and the tools that should be used to identify changes in neurological status?

During the neurological assessment, the nurse may identify signs and symptoms that indicate the need for ICP monitoring (such as LOC, ophthalmic disturbances,[28] and changes in other sensory and motor functions).[16,17,23,29,30] It is important to understand that neurologic signs and symptoms may mimic other conditions nonneurologic in origin, and therefore a thorough medical history is important, including events that may have recently occurred (e.g., trauma, substance exposure or use).

Serial neurological exams by a specialty trained registered nurse can help identify subtle changes in the meningeal and intracranial environments. The timing of neurologic exams is generally spaced in accordance with the acuity and severity of the condition, balancing the intent to not cause worsening neurological insult by excessive stimulation with the need to identify acute changes. Some assessment tools used to identify changing neurological status include the GCS, cranial nerve assessment, Full Outline of UnResponsiveness (FOUR) Score, and the National Institutes of Health Stroke Scale (NIHSS).[3,16,17,21,31] Some tools are better fitted for different conditions. The GCS is generally used to determine a quick status for trauma patients and the NIHSS is specific to stroke, grading the severity of stroke symptoms. The FOUR Score is an adaptation of the GCS, including respiratory patterns and eye movements to assist in scaling changes in the ventilated and sedated neurologically injured patient.

For those patients requiring ICP monitoring, what are the indications and pathophysiology behind this need?

The need to monitor pressure within the cranial vault is determined by the type of injury to the head or spine. Assessment findings including reduced LOC, pupillary or vision changes, lowered GCS score, new onset seizures or headache, and vomiting in a patient with a neurological insult are some of the symptoms that may increase the need to monitor ICP.[17] These can occur from an initial insult to the brain, also called primary injury, or from secondary injuries—that is, conditions that result from post-initial injury sequelae, such as cellular breakdown, or postprimary injury, such as metabolic cascades.[32]

The space in the cranial vault is constant and finite after the skull is fully fused postinfancy, as stated by the Monro-Kellie doctrine,[33] and can be broken down as 80% brain parenchyma, 10% cerebrospinal fluid (CSF), and 10% cerebral blood flow (CBF).[3] This zero-sum game theory postulates risk for increased ICP if additional fluid or mass/volume is introduced into the cranial vault. If the skull integrity is compromised, ICP could increase due to less overall space housing the same volume. ICP can also increase if the normal drainage of blood or CSF is impaired or stopped due to obstruction (e.g., tumor, stenotic aqueduct).

Multiple medical conditions can increase ICP. The most common acute conditions that can increase ICP are hemorrhagic stroke, severe ischemic stroke, traumatic brain injury, seizures and status epilepticus, and hydrocephalus.[12,15,17] Other conditions, such as a brain tumor or infectious processes, may be slower in progression but have an acute period of increased ICP when they place pressure on existing physiology, impair CSF drainage, or affect cells that create CSF.

Hemorrhagic Stroke

In hemorrhagic stroke, high blood pressure or weakening of an artery can cause an aneurysm to form. This can cause arterial rupture into the subarachnoid or intraventricular spaces or create a balloon-like outpouching that displaces some of the normally occupied space for CSF and brain tissue. Rarely, a hemorrhagic stroke can occur concurrently with an ischemic stroke or as an aftereffect from ischemic stroke, causing two sources of increased pressure.

Patients with hemorrhagic stroke undergo treatment to manage the bleeding (e.g., craniotomy, hematoma evacuation, clipping, coiling), with treatment being location dependent. In these patients, ICP monitoring is performed to help assess the incidence of ongoing bleeding or rebleeding postoperatively. If the hemorrhage is in an area unamenable to surgical intervention, ICP monitoring may also rapidly identify malignant edema that may lead to a sharp increase in ICP.[17,26,34,35]

Ischemic Stroke

Ischemic strokes are attributed to vascular changes, whereby an artery is (or arteries are) partially or completely occluded, causing cerebral tissue death in the area where blood flow is reduced or blocked (primary injury). A cardioembolism may cause an occlusion related to atrial fibrillation and subsequent slowing and pooling of blood in the atrium of the heart, narrowing of an artery due to atherosclerosis, high blood pressure related to damaged arterial walls, or vasospasm. Damage can occur in any artery in the brain and neck, with cellular damage corresponding to the size and location of the occluding lesion. In areas of cellular death or damage, cerebral edema occurs as part of the aftermath.[16] In rare incidents, cerebral infarction can also occur when the venous system in the cranial vault is occluded; the additional pressure in the vascular system can cause cerebral damage.

Large hemispherical strokes may require the use of ICP monitoring for edema postevent. The larger the volume of tissue infarcted, the greater the likelihood for cerebral edema that may cause additional infarction, owing to cellular breakdown inducing excessive pressure in the volume-limited cranial vault (secondary injury).[16,36] ICP monitoring is generally performed when the need for assessment for subtle neurological changes outweighs the risk for placing an invasive EVD.

Traumatic Brain Injury

Traumatic brain injury (TBI) has many different etiologies, as damage to the brain and protective tissue can occur in varied ways. In most cases, the primary injury is compounded by secondary damage.[21,37,38] These injuries can involve subdural, epidural, and intracranial spaces; the vascular system; or the cranial body. Injuries causing increased edema, hematoma, or ruptured vessels in the intracranial space (e.g., penetrating injuries, diffuse axonal injury, blunt force trauma) are more likely to require ICP monitoring, whereas injuries to the epidural space from a ground-level fall may require a superficial drain. The preexisting use of anticoagulant therapies can also increase the need for an invasive drain. Depending on the mechanism of injury (e.g., penetrating injuries, diffuse axonal injury, blunt force trauma), the skull can be intact or open from physical insult. An open skull may not initially show assessment findings consistent with increased ICP due to the increased space to swell, but it may necessitate the use of ICP monitoring, as this type of trauma has a higher potential for secondary injury.[32,34,42]

Seizures

Though ICP monitoring is not routinely used for patients with isolated seizures, seizures that progress to status epilepticus can cause cerebral edema and increased ICP. The ongoing electrical activity may cause cerebral damage, which might require the monitoring of ICP. There are other neurologic conditions that precipitate seizures, thereby also warranting monitoring of ICP.[43]

Hydrocephalus

Other physiologic conditions that affect the production or absorption of CSF may warrant the need to monitor ICP. Congenital hydrocephalus refers to anatomical abnormalities present at birth that can reduce the body's ability to absorb enough CSF volume to prevent swelling within the cranial vault. Other conditions such as idiopathic hydrocephalus, stroke, head injury, and infections can also cause blockages in CSF reabsorption, thereby increasing ICP.[39] Regardless of the etiology of the excess CSF, these patients may require ICP monitoring to quantify the effects of excess CSF on the nervous system.[7,40]

Brain or Spinal Tumor

In patients with brain tumors, lesion location can obstruct the flow of CSF, requiring the need for ICP monitoring. In patients with ependymal cell tumors, increased production of CSF may warrant temporary ICP monitoring. Other brain tumors can cause increases in ICP via the introduction of additional cells within the space-limited cranial vault. This ICP elevation mechanism differs from excess CSF production and cerebral edema in that an additional physical element is directly introduced into the skull. Given the zero-sum game of the Monro-Kellie doctrine, increased volume in a fixed space will result in increased pressure for the coexisting matter.[27,33]

There are myriad other etiologies that can affect cerebral edema and consequently ICP, but they will not be discussed here.

Device Options

In patients who have ICP monitoring:

What type of monitoring would be most useful?

Several ICP monitoring systems exist, including invasive and noninvasive technologies. Noninvasive monitoring is typically used as an adjuvant assessment to invasive monitoring and will not be discussed to prioritize primary monitoring technologies. Further research is needed to demonstrate the accuracy of noninvasive monitoring methods.[41]

Invasive monitoring of ICP places a catheter into the ventricular system, potential subdural space, or parenchyma. There are two types of invasive monitoring systems discussed in this document: intraparenchymal monitor (IPM), also referred to as a bolt, which is a fiberoptic catheter that monitors ICP without allowing diversion of CSF and EVD, which is an intraventricular catheter that can both monitor ICP and divert CSF.[11] Selection of the type of monitor is determined by the provider and is based on clinical need and risk. Criteria for selection of the type of ICP monitor in patients with TBI may include poor GCS score, need for ICP treatment, or need for CSF drainage, such as in the setting of hydrocephalus.[14-17,42,44] There are more reported incidents of EVD over IPM usage in subarachnoid hemorrhage (SAH) due to incidence of acute hydrocephalus[17,18,45-48]; this may be a result of needing to drain CSF and monitor ICP as well as rezero throughout the duration of ICP monitoring. While EVDs offer the ability to both monitor and drain fluid, they technically are more difficult to place.[49,50] While lumbar drains (LDs) are another method to reduce increased ICP, there are limited data to support the use of LDs to monitor ICP.[51]

The data are inconclusive regarding the outcome of patients with different types of ICP monitoring. One study (N = 122) demonstrated improved outcomes (refractory intracranial hypertension IPM vs. EVD: 51.7% vs. 21%, $p < 0.001$; 1-month survival: 90.3% vs. 76.7%, $p = 0.04$; 6-month mortality: 68.3% vs. 88.7%, $p = 0.006$) in patients with an EVD.[52] Two studies associated improved outcomes with an IPM (N = 224, Glasgow Outcome Scale [GOS]: 3.8 ± 2.2 vs. 4.9 ± 2.2, $p = 0.002$; mortality: 23% vs. 10%, $p = 0.014$)[53] (N = 268, device-related complications: 10.7% vs. 32.8%, $p < 0.01$).[54] The same device complications study also found that 6-month mortality was slightly higher with an EVD (OR = 0.67, 95% CI: 0.43–0.95, $p = 0.06$) but not statistically significant.[54] These studies showed no significant differences in the demographic and severity indices in the different treatment group.[52-54] Disease comorbidities were not reported. One retrospective TBI study (N = 2,562) stated no difference in unadjusted mortality; however, the study did not report the adjusted rate and only reported the unadjusted rate, which was significant (30-day mortality: EVD = 29% vs. IPM = 25.5%, $p = 0.046$).[55] Complications were higher in the IPM group (40.2% vs. 34.4%, $p = 0.003$). More important to note is that there were significant differences in confounding variables (age, mechanism of TBI, comorbidities, admission severity, and complications) that could affect the interpretation of the findings, and the statistical write-up did not clearly account for the confounders. A study out of Massachusetts General (N = 377) found that use of EVDs was associated with increased intensive care unit (ICU) length of stay (LOS) (7.6 ± 5.6 days vs. 9.5 ± 6.2 days, $p = 0.004$) and device-related complications (31.1% vs. 11.2%, $p < 0.001$).[42] However, the intervention groups were not randomized, and indication for IPM versus EVD placement was based on differing clinical presentations. While it may be clinically appropriate, this methodology can skew findings from the outset.

Complications including infection, brain hemorrhage, and catheter occlusion or breakage occur with both EVD and IPM monitors. Several studies report that the occurrence of infection is higher in patients with an EVD compared to IPM.[54,56-58] Factors that may increase the risk for infection in EVD use include depressed skull fracture, systemic infection, catheter type, insertion technique, duration of placement, frequency of open access of device, use of multiple devices, severity index score, and the development of a CSF leak. However, there is limited evidence available to demonstrate that these factors significantly increase infection risk.[59,60] Furthermore, the technique for insertion and ongoing maintenance of the EVD may contribute to variable infection rates. Limited data demonstrate that patients with an EVD managed with an open (i.e., continuously draining) technique have a greater rate of complications compared to closed (i.e., intermittently draining) methods.[47,61] It is important to consider how additional factors impact infection such as preprocedure antibiotic administration, prophylactic antibiotics, or antibiotics used to treat other systemic infections. How catheter-associated infection and ventriculitis are defined is also variable and affects reported rates.

What type of catheter should be used?

Catheters used with EVDs include standard (also referred to as plain or no impregnation), antibiotic-impregnated (AI), and silver-impregnated (SI). One randomized clini-

cal trial (RCT) (N = 434) demonstrated a low infection rate with use of an AI-EVD catheter (2.3%). However, it was not statistically significant in comparison to the standard EVD group (2.8%, p = 1.0).[62] Three systematic reviews with meta-analyses demonstrated AI-EVD superiority for the prevention of catheter-related infection when compared to plain EVDs (p < 0.00001, p = 0.02, p < 0.05).[63-65] SI catheters similarly have demonstrated statistically significant infection reduction in comparison to plain catheters. In an RCT comparing SI-EVD to plain EVD catheters, the primary endpoint infection risk was statistically significant (p = 0.0427), favoring SI-EVD.[66] In a meta-analysis comparing SI-EVD to plain EVD catheters, the RCT subgroup analysis demonstrated a statistically significant difference between the catheter groups (p = 0.05), supporting SI-EVD.[63] In the same meta-analysis, the pooled data from four observational studies also demonstrated a statistically significant difference, supporting SI-EVD over plain EVD catheters (p = 0.04). Another systematic review with meta-analysis reported a lower rate of infection when SI-EVD was used compared to plain EVD, but the difference was not statistically significant (OR = 0.33, 95% CI: 0.07–1.69, p = 0.18).[65] AI versus SI catheters demonstrated similar reduction in catheter-related infection.[63] Other studies found when AI-EVD was used in conjunction with infection control protocol, infection rates were statistically significantly decreased (p = 0.02, p = 0.046, p < 0.0001, p = 0.0008).[67-70]

How long should the catheter be left in place?

There is no consensus regarding the length of time the catheter should remain in place.[17] Recommendations from one study versus another include keeping the catheter in place as long as clinically indicated.[17,71,72] One small study's (N = 32) protocol reported EVD usage "48–72 hours [postoperatively] till the patients were weaned off from ventilator and the ICP had returned to within normal range."[73] Two reviews suggested clamping an EVD for 12 to 24 hours, during which time the patient's neurologic assessment is closely monitored; if there is no worsening in the exam, the EVD is removed.[72,74] One review suggested that if an EVD is nonfunctioning, it should be removed.[74]

In discussions of the placement duration of any invasive device, infection control must be considered. Studies report different incidences of infection at varying days after device insertion. One center reported a higher "incidence of infections between days 5 and 11."[56] Other studies reported infection rates increasing with monitor days.[66,75-77] In contrast, one meta-analysis reported "EVD treatment of less than 7 days had a pooled VAI [ventriculostomy associated infection] rate of 19.6 per 1000 catheter-days, those with mean duration of 7–10 days had VAI rate of 12.8 per 1000 catheter-days and those with mean duration greater than 10 days had VAI rates of 8 per 1000 catheter-days."[78] This meta-analysis did note that there was significant heterogeneity within the pooled research studies and that higher-quality studies had different rates of infection from lower-quality studies (using the Newcastle-Ottawa Scale), which could account for the contrary findings.[78]

There is inadequate data to support the practice of catheter exchange as well as the optimal time frame if replacement is performed.[69,70,76,78,79] An NCS consensus statement strongly recommends against routinely changing catheter sites due to lack of supporting evidence.[71]

Placement and Care

For patients with ICP monitoring:

How should the catheter be placed (i.e., tunneled versus not)?

Tunneling an EVD catheter is the descriptor for the subcutaneous passage of the catheter away from the primary incision for the purposes of minimizing infection. Tunneling distances are reported in the literature, though few studies research optimal length. Distances of 2 to 5 cm are reported in the literature.[50,66,67,80,81] One study out of the Netherlands reported tunneling > 5 cm as part of their organizational infection control protocol.[82]

An alternative approach to catheter insertion is through a bolt. One retrospective review (N = 147) out of Copenhagen reported an 11.9% (p = 0.006) reduction in additional procedures due to use of a bolt technique compared to a tunnelled approach.[80] Another retrospective study (N = 579) found secondary outcome infection rates were similar for tunneled versus bolt placement (p = 0.20) and documented a "maximal length of EVD catheter of 6 cm from the cortical surface."[83]

Where should the catheter be placed (i.e., anatomical location)?

There is a lack of strong evidence to guide placement of monitoring devices. In the absence of intraventricular hemorrhage (IVH), the EVD is commonly placed in the right lateral ventricle.[73,74,80] Placement of the EVD in the lateral ventricle technically can be difficult if the ventricle is compressed due to mass effect or collapsed.[84] One prospective trial (N = 100) reported a greater percentage of events with ICP > 20 mm Hg and > 30 mm Hg in the ipsilateral group (IG) EVD placement.[19] Another small prospective trial (N = 45) studied outcomes of IVH patients

with IG versus contralateral group (CG) EVD placement and urokinase administration. There was no significant difference in mortality rate or functional outcome at 30 days after stroke between IG and CG despite faster clot clearance in IG.[85]

Placement of an IPM is also dependent upon the diagnosis and location of injury. In diffuse brain injury, the monitor is commonly placed in the frontal lobe of the nondominant hemisphere.[49,50] In a patient with focal injury, there is no agreement about the location of the IPM. There is concern that placement of the IPM in the hemisphere contralateral to the focal injury may underestimate ICP.[72]

In one small retrospective severe TBI study (N = 43), IPMs were placed in the nondominant frontal lobe in 72.1% of patients. In patients with dominant frontal lobe IPM placement, 75% were placed contralateral to a craniectomy, unstable skull fracture, or inoperative subdural hematoma. The majority of devices (60.5%) were placed in the injured frontal lobe.[86]

What is the care for ICP monitoring (i.e., infection control)?

There is a lack of high-quality data to support any single approach to care and maintenance of an ICP monitor. Catheter exit-site maintenance is variable regarding method for cleaning, type, and frequency of dressing change. There is agreement that a bundle approach to catheter insertion and care may reduce the incidence of EVD-related infection.[68-71,76,87] It is difficult to identify if any one component of a bundle is more effective at preventing infection, as multiple interventions are often introduced at one time. In the consensus summary on multimodal monitoring, NCS and the European Society of Intensive Care Medicine (ESICM) recommend use of insertion and maintenance protocols to safely manage patients with ICP monitoring devices.[14,44] Specifics on protocols were not documented. EVD insertion and maintenance protocols were evaluated in a systematic review and meta-analysis.[70] The mean infection rates were 16.11 + 9.09% before the institution of a protocol and 4.67 + 4.70% after institution of a protocol (p = 0.0008). However, the quality of data was not high, owing to small sample sizes and lack of randomization and varied protocol components. The Infectious Diseases Society of America also recommends the use of an infection control protocol when employing intraventricular devices.[79]

Studies reported protocols that included cleaning the exit site followed by applying benzoin tincture to the skin and covering with sterile transparent dressing.[67,69,87,88] The use of antimicrobial-impregnated discs at the exit site was not reported. The frequency of reported dressing changes varies, including every 48 hours, 72 hours to weekly, or only as needed if soiled or nonocclusive.[69,87,89,90] One retrospective review investigated the use of 2-octyl cyanoacrylate (Dermabond) at the EVD exit site and the primary incision to reduce the occurrence of EVD-related ventriculitis. Patients in the Dermabond group developed a lower rate of *S. epidermis* infections.[91] Another common bundle component is staff education regarding infection prevention. This strategy can be useful in reducing the overall rate of catheter-related infection.[76,92]

CSF sampling frequency for EVDs is also inconclusive. Some studies have found that limiting EVD manipulation frequency and sampling to only when clinically indicated reduces the occurrence of EVD-related infection.[67,70,76,81,82] One meta-analysis found no difference in the infection rate related to sampling frequency or decreased rate of infection with daily sampling.[78] A detailed sterile process when accessing the EVD catheter as a component of a bundled approach has been mentioned as a means to reduce EVD-related infection.[67]

Troubleshooting

After an ICP monitoring device is placed:

How should the nurse level and zero the EVD transducer?

The patient's neurologic injury is considered when determining the height of the EVD system. The lower the drainage system in comparison to head position, the more quickly CSF will be drained. Many external anatomical reference points may be used to align the transducer of the EVD indicating the zero level. These reference points include the outer canthus of the eye, midway between the outer canthus of the eye and the tip of the ear, the tip of the ear, the external auditory meatus, and the tragus.[3,14] Determining an external reference point that aligns with the foramen of Monro is challenging, especially when the patient's head is turned.[93] There is no definitive zero-level point documented in the literature, nor is there evidence documenting how to zero. The consensus statement for multimodal monitoring from NCS does not recommend a definitive zero level.[17]

However, in its consensus statement for ICP monitoring in TBI, NCS does state that EVDs and blood pressure transducers should be zeroed leveled to the tragus.[14] Other review articles recount the foramen of Monro as the zeroing reference, but they do not study the clinical accuracy of any given anatomical landmark.[8,11,60,94] Owing to the lack of literature on zeroing, it is best to follow manufacturer recommendations regarding zeroing frequency and technique. Available zeroing research

literature includes a survey of providers and nurses that demonstrates wide variability in the zero reference point used to level the EVD transducer.[95] Other zeroing research literature documenting LDs for ICP monitoring and CSF drainage (although this practice is less common) was not found. One study found that LDs can effectively be used to measure ICP in patients with posthemorrhagic communicating hydrocephalus. In the study, researchers zeroed both EVD and LD at the foramen of Monro.[96]

Practice variations exist regarding the placement of the arterial blood pressure (ABP) transducer at the tragus or at the phlebostatic axis along the midaxillary line.[97] These two different techniques can lead to variable mean arterial pressure (MAP) results, impacting patient management strategies to achieve a prescribed cerebral perfusion pressure (CPP) goal.[98,99] Future CPP studies should investigate the ABP reference point to establish and standardize care. ICP in conjunction with MAP reflects how well the brain is being perfused (i.e., CPP): CPP = MAP – ICP[3]. ICP treatment thresholds are often set with CPP target ranges in consideration. Variations in the measurement of MAP can affect ICP valuation and consequent CPP, thus affecting treatment implementation.

How should the nurse assess the waveform?

The ICP waveform of an EVD monitor has three notches: P1 (percussion wave, which originates from arterial and choroid plexus pulsations), P2 (tidal wave), and P3 (dicrotic wave, which occurs in successive decreasing height).[3,100] As ICP increases, the wave amplitude also increases and P2 becomes greater than P1, indicating loss of intracranial compensation and compliance.[11,100] ICP waveform analysis can aid in assessing the effects of patient activities, surroundings, and treatment on ICP.[3,14,17,44,60]

In patients with EVDs, two methods are used for draining and monitoring ICP.[101] Both methods offer advantages in different circumstances.[102] In the intermittent method, the EVD remains clamped with continuous ICP monitoring. The EVD is opened if ICP exceeds a predetermined value. In the continuous method, the EVD is open and continuously draining CSF. At a set time interval (e.g., every 15 minutes, every hour) the drain is clamped to obtain an ICP reading and waveform. This practice varies among nurses and providers.[95] Following drain clamping, it may take time for the ICP reading to equilibrate, as there is variability in the ICP following clamping.[103] There were very limited data on duration of EVD clamping. Primary investigations focused on intermittent versus continuous methodologies rather than the effects of the duration of clamping. Three studies stated protocols where EVDs remained clamped between 5 and 15 minutes,[103-105] with one study revealing that 65.9% of EVDs were clamped for less than one minute.[104] A larger randomized trial is needed to assess ideal clamping time before the ICP value is documented.

When using the open, continuously draining method, ICP readings are only obtained at set intervals. Because intrahourly ICPs are not assessed, alternate strategies to monitor ICP during continuous drainage have been proposed; however, these methods of monitoring ICP produce a wide range of measurements that have been found to be inconsistent when compared to an IPM concurrently in situ.[103] Though the open monitor method trends in ICP monitoring, the clamped method is recommended for a more accurate ICP reading and waveform analysis.[106] Additional studies are needed to further evaluate the accuracy of the open monitor method.

How should the nurse troubleshoot ICP?

Intraparenchymal monitors may be calibrated prior to insertion; after insertion, there is no zeroing capability.[3] Zero drift occurs when there is movement from the baseline (0 mm Hg) from the time of monitor insertion to removal. Data are variable regarding degree of zero drift and may depend on the type and brand of monitor as well as placement location.[14,50] The literature did not indicate a specific time when drift occurs. Rather, the consensus is that drift increases as duration of monitor placement increases.[14,107,108]

EVDs are zeroed throughout the duration of insertion. This practice is used when troubleshooting waveforms or erroneous ICP values. There were no research publications on EVD or LD zeroing methodology. In the absence of research literature, it is best practice to follow manufacturer recommendations.

If the waveform is dampened or there is absence of CSF in the burette, the patient and the drainage system should be assessed. Waveforms typically take 30 minutes to stabilize.[60] The air filter on the drainage system burette may have become wet if the system was positioned horizontally. Allowing the filter to dry should allow for CSF drainage to resume; alternatively, the drainage system may require changing. The catheter may become occluded with clots or other particulates, thereby obstructing CSF outflow. The drainage system may be temporarily lowered to check for CSF drainage.[60] The absence of CSF drainage may indicate the need for the tubing to be flushed. The clinician responsible for this procedure is specified by individual institutions. The nurse also should consider checking stopcocks for occlusion and dislodgement. A dampened waveform also might be from a small ventricular system obstruction.

How should the nurse change the EVD system?

The literature recommends minimizing manipulation of the drainage system.[69,71] Minimal data exist regarding the practice of changing the drainage system. In the setting of mechanical failure of the drainage system, the system should be changed, with the catheter remaining in place and manipulated by the provider only.[60,74]

Numerous citations support the thesis that ICP monitoring alone does not provide sufficient insight into underlying pathophysiological processes related to the degree of injury, delayed ischemic sequelae, and potential for recovery.[29,34,109-113] Accordingly, it is important to investigate monitoring and management techniques that provide a more comprehensive clinical picture. One such technique is $PbtO_2$ monitoring.

Brain Tissue Oxygenation

Background

Brain tissue oxygenation reflects the interaction between oxygen delivery, extraction, and tissue demands. It is measured with an invasive probe using a Clark electrode,[48] whereby oxygen diffuses into the probe and is reduced by a cathode. This creates a measurable electric current that enumerates oxygen concentration, allowing for trend and standardized measurement. Brain oxygen should be monitored in all patients with or at risk for cerebral ischemia and hypoxia,[17] including any patients with acute, severe neurologic injury and those at risk for secondary injury.[44,114] Where tissue oxygenation probes are placed, information on oxygen supply and consumption is obtained and can be used in two ways: assessment of adequate cerebral oxygenation delivery (supply and absorption) and discovery of nonperfusion-related brain hypoxia when CPP is at the target range.[17,109] The goal of monitoring $PbtO_2$ is to minimize and mitigate decreased brain oxygenation episodes in efforts to improve patient outcomes.[29,109,114,115]

For patients who have been assessed for cerebral oxygenation monitoring, what are the indications and pathophysiology behind this need?

An analogy can be drawn between the use of blood oxygenation monitoring in conjunction with routine vital signs assessments and the use of $PbtO_2$ monitoring in conjunction with ICP and CPP assessments. Vitals signs without the context of blood oxygenation reflect an incomplete picture of overall hemodynamic status and ignore potential warnings of impending metabolic crisis. Oxygenation levels are linked to ischemic changes within the body, and this also can be seen in brain tissue when oxygen levels decline locally or globally; cerebral hypoxia can occur in the presence of ICP and CPP management and can foreshadow hemodynamic crisis. Consequently, $PbtO_2$ monitoring is essential for a comprehensive understanding of cerebral homeostasis and to minimize ensuing cellular damage in cases of brain injury.[116]

The inclusion of $PbtO_2$, along with "traditional brain vital signs," creates a more complete picture of the cranial vault environment.[117] Adding this data is supported by research that shows cerebral hypoxia monitoring and management employed conjointly with ICP monitoring and management has been associated with lower mortality and more favorable outcomes than ICP treatment alone.[34,111,118] Research that predates this EBCR's literature search parameters is referenced by several reviews and consensus panels to support $PbtO_2$ monitoring, noting that ICP and $PbtO_2$ monitoring decreases mortality and demonstrates improved outcomes compared to ICP monitoring alone.[29,44,114] One small TBI study (N = 32) found that changes in $PbtO_2$ can occur independent of ICP, CPP, and ABP. This independent phenomenon makes monitoring brain oxygenation relevant.[119] Pathological conditions that may benefit from $PbtO_2$ monitoring include those that also may benefit from IPC monitoring as well as those with a focal oxygen metabolism alteration; these conditions are discussed in more detail below.

Aneurysmal Subarachnoid Hemorrhage and Traumatic Brain Injury

Aneurysmal subarachnoid hemorrhage (aSAH) and TBI were frequently reported conjointly in literature due to similar diffusion injury and delayed ischemic sequelae. This document follows the conjoined reporting pattern.

As all cells require oxygen, it is easy to understand that conditions in which cells do not receive sufficient oxygen can result in cellular damage or death. Cellular damage and death impair body system functions at a fundamental level. This relationship is supported by severe TBI research (N = 103) at a Level 1 trauma center, where brain hypoxia (independent of ICP, CPP, and severity of injury) was associated with poor short-term outcomes (favorable GOS 4–5: $p < 0.01$).[120] Another trauma center also found

that treatment response rate to compromised $PbtO_2$ (< 25 mm Hg) was positively associated with mortality, (survivors: 71% vs. nonsurvivors: 44%, $p = 0.01$).[121] Researchers out of the University of Texas Southwestern found that poor outcomes were associated with the number, duration, and intensity of decreased $PbtO_2$ episodes and that hypoxic episodes were common after TBI and could occur in the absence of ICP elevations.[122] Concurrently, two smaller studies of TBI patients ($N = 74$, $N = 30$)[123,124] found no statistically significant benefit of $PbtO_2$ therapy (mortality: $p = 0.34$, $p = 0.17$, respectively) (mean GOS: $p = 0.93$, 6-months Glasgow Outcome Scale Extended [GOS-E]: $p = 0.17$). Owing to oppositional findings and gaps in the literature, $PbtO_2$ monitoring in the TBI population warrants further research.

In aSAH and TBI, $PbtO_2$ is used as a target for CPP-driven therapy and has been associated with improved long-term outcomes.[44,109,115,125,126] One study that evaluated $PbtO_2$-guided CPP management in conjunction with mild hypothermia found favorable outcomes (GOS ≥ 3–4) compared to ICP/CPP management alone ($p = 0.0395$, $p = 0.0201$).[127] The effects of mild hypothermia were not parsed. Two review publications noted that an increase in the number of hypoxic episodes correlates with mortality and therefore warrants monitoring.[29,115] Other publications noted that poor outcomes are associated with the number, duration, and intensity of decreased $PbtO_2$ episodes.[111,114,120,122,128] As the vascular system is directly, physically compromised in aSAH, it is important to assess this subpopulation's $PbtO_2$ in order to detect early and mitigate further tissue ischemia, similar to TBI.[35,114] One observational cohort study ($N = 100$) found that hypoxia was common in poor-grade SAH patients despite protocolized therapies.[129] This study used oxygenation as its dependent variable and did not investigate the impact of hypoxia on outcomes. What it did highlight is the fact that hypoxia is a real issue in aSAH that can be monitored and treated. Note that the international consensus on cerebral tissue oxygenation monitoring underscored the importance of placing $PbtO_2$ monitors in the area of vasospasm.[114] Another study noted that, given the effectiveness of $PbtO_2$ monitoring in detecting cerebral vasospasms, it is a monitoring technique to consider.[130]

Ischemic Stroke

There is a gap in the literature regarding indications for $PbtO_2$ monitoring for patients with acute ischemic stroke. No articles were found within the search terms. More research is needed.

Seizures and Tumors

There is a gap in the literature regarding indications for $PbtO_2$ monitoring for patients with seizures and tumors. No articles were found within the search terms. Current recommendations are institution dependent, as there are not enough data to support placement and use of $PbtO_2$ monitors in these patient populations.

Other Conditions

In elevated ICP, hyperventilation for extended periods of time should be used with caution when brain tissue hypoxia is of concern.[110] The resulting hypocapnia causes vasoconstriction and a decrease in CBF, leading to a reduced oxygen supply to the brain tissue, which may outweigh the potential benefits of hyperventilation.

Acute lung injury is common after TBI and may cause significant reduction of systemic oxygenation, which is an independent risk factor for brain hypoxia in TBI.[131] Lung-protective strategies should be implemented to prevent brain hypoxia, as they may help decrease secondary brain injury. Attention also should be paid to over oxygenation because it can lead to lung damage.[131]

Obesity also is an independent predictor of compromised $PbtO_2$, but the exact reason remains unclear. Obesity in patients with severe brain injuries is highly predictive of prolonged periods of decreased cerebral hypoxia.[132]

Brain tissue monitoring can also assist in brain death testing as a value of zero; no $PbtO_2$ is associated with a brain death diagnosis.[126] It is important to follow individual state and institutional criteria for employing $PbtO_2$ values in the declaration of brain death.

Placement and Care

For patients requiring $PbtO_2$ monitoring:

Where and how should the catheter be placed (i.e., anatomic location and insertion practices)?

Optimal anatomic placement of $PbtO_2$ probes is not relegated to an isolated location. Research literature discusses monitor placement within the context of provider preference in research protocols rather than as primary predictor variable. Several review publications cite that monitor placement be governed by neurologic diagnosis and location of lesion or injury.[48,109,114,115,133] Recommendations from NCS and ESICM echo reviews, stating that the placement of monitors in patients at risk for ischemia and the insertion site should be selected by diagnosis and lesion location.[17,44] A review on $PbtO_2$ monitoring cites that, in TBI patients, monitors are placed in normal-appearing brain tissue and "when there is diffuse injury, the monitor is usually placed in the non-dominant sphere."[115] This recommendation was echoed by the international consensus

on the monitoring of cerebral oxygen tissue pressure in neurocritical patients.[114] DeGeorgia further states that for SAH, "the monitor is usually placed on the side of the ruptured aneurysm or the side where the hemorrhage is thickest, the area most at risk of vasospasm."[115] This was also recommended by the international consensus panel, owing to the fact that "hypoxia-ischaemia secondary to vasospasm in patients with subarachnoid haemorrhage can only be detected if the probe is inserted in the territory of the spasm."[114] This same consensus panel also recommended avoiding placement of monitors in eloquent areas in the cranial vault.[114]

Placement catheter length of $PbtO_2$ devices is comparably underresearched. If it is documented at all, it often is listed as a parameter in reviews or as part of insertion protocols in studies investigating other primary outcomes. DeGeorgia's review stated that the probe is inserted into the brain parenchyma approximately "3.5 cm below the dura," with the active tip "2.5 to 3 cm below the dura in the frontal white matter."[115] In the BOOST II trial (N = 119), a single-blinded, prospective, randomized, controlled multicenter study, "probes were inserted into brain parenchyma approximately 2 cm from the cortical surface."[34] One small, randomized TBI trial in Taiwan (N = 45)[127] had an insertion protocol of 22 to 27 mm into the normal tissue adjacent to the brain injury. In a retrospective review of SAH patients (N = 100), the authors reported insertion depth protocols of "20–30 mm below the dura mater."[134]

The area of brain tissue assessable for oxygenation enumeration by a probe is varied in the literature. Two citations state that the precalibrated probes allow for brain tissue to be monitored around the catheter tip (15 mm Hg),[48,111] whereas another review noted that brain oxygenation is measured in a 13-mm tissue cylinder.[115] The international consensus on brain oxygen monitoring stated larger oxygenation assessment areas of 18 mm^2 and 22 mm^2, device dependent.[114]

There is no clear consensus on depth of probe placement. There is a gap in the literature regarding the depth of $PbtO_2$ monitor placement. Research focusing on BIS monitor waveforms, suppression ratio (SR), and signal quality index was not found. Manufacturer recommendations or organizational policies should be followed until additional research is available.

What is the care for the $PbtO_2$ monitor (i.e., infection control)?

There is a gap in the literature regarding site maintenance. The literature states that catheter and monitoring devices are safe and can provide accurate data for up to 7 to 10 days postinsertion.[17,44,114] This same literature also discussed removing monitoring devices 48 hours after $PbtO_2$ values normalize.

What assessments are completed postplacement?

Nurses should continuously monitor and assess cerebral oxygenation values. When $PbtO_2$ deviates from the predetermined acceptable range, the provider should be notified. Routine care activities have the potential to significantly impact cerebral hemodynamics. Patient positioning is one such activity, and it has been shown to impact cerebral oxygenation values. One quasi-experimental, prospective study (N = 33) evaluated 12 different body positions for their effect on neurologic and hemodynamic parameters.[125] No single body position was found to be optimal, but the left lateral position with the head of the bed at 30 degrees was shown to decrease $PbtO_2$ (p = 0.046) while concurrently decreasing CPP (p = 0.044); hence, this position should be used with caution.

Another common patient care aspect is diagnostic imaging, which can take place either on (portable) or off the unit. One retrospective study showed that performing portable head CT scans on neuro ICU patients (57 scans on 34 patients) did not have a critical effect on $PbtO_2$ values (mean $PbtO_2$ p = 0.60, min $PbtO_2$ p = 0.73, max $PbtO_2$ p = 0.60), but transport off the unit (100 scans on 45 patients) had a slight negative impact (p = 0.07) on mean $PbtO_2$.[135] Its sister study (100 scans of 45 neuro ICU TBI and SAH patients) reported that mean, minimum, and maximum $PbtO_2$ dropped significantly (p = 0.0001, p = 0.007, p = 0.02, respectively) after transport for off-unit diagnostic imaging.[136] Additionally, this study found that after transport, compromised $PbtO_2$ could persist for up to 3 hours. The risk of transport should be weighed against the benefits of off-unit care. No other studies were found that assessed the impact of nursing care or activities of daily living on $PbtO_2$ for neurologic patients.

Nursing should also assess for postinsertion complications. Two citations report bleeding risk postinsertion as less than 3%, with little to no clinical consequences.[114,126] The BOOST II trial found zero cases of monitor-insertion-related hemorrhage and infections.[34] These low-to-zero numbers do not underlie the fact that nursing should assess for device complication following any invasive procedure.

Troubleshooting

Troubleshooting and managing a $PbtO_2$ monitor requires understanding normal $PbtO_2$ values. The literature varies widely as to what constitutes normal range. Normal $PbtO_2$ ranges have been cited as 20 to 35 mm Hg.[34,109,115,133]

However, several of these citations reference publications from the 1990s and 2000s for their derivation of $PbtO_2$ norms. The more recent BOOST II trial documented normal limits of 23 ± 7,[34] with other recent citations documenting $PbtO_2$ normal limits as ranging from 30 to 50 mm Hg.[137,138] These valuations have not been well researched, and reports exist that deviate from cited ranges. One small retrospective TBI study (N = 32) found that mortality increased ($p < 0.001$) if $PbtO_2$ remained less than 29 mm Hg within the first 72 hours of monitoring,[112] contrasting the most prevalently documented normal range. Since $PbtO_2$ values can be affected by probe placement location[114,126] and a variety of hemodynamic parameters—CBF, CPP, MAP, partial pressure of carbon dioxide ($PaCO_2$), partial pressure of oxygen (PaO_2), fraction of inspired oxygen (FiO_2), temperature, and oxygen consumption and delivery—it is important to keep these relationships in mind when interpreting values.[44]

Current guidelines[139] recommend maintaining a PaO_2 of 60 mm Hg in brain-injured patients, but one study showed the minimal requirement to be 94 mm Hg and suggests that a higher PaO_2 should be targeted in the first few days after injury.[140] Further research is needed to determine the optimal range.

After a $PbtO_2$ monitoring device is placed:

How should the nurse level and zero the transducer?

Zeroing occurs when a catheter is placed. There is a gap in the literature exploring indications for additional zeroing needs. No articles were found within the search terms.

How should the nurse manage increased $PbtO_2$?

There is no clear interpretation of $PbtO_2$ values greater than 45 mm Hg.[114]

How should the nurse manage decreased $PbtO_2$?

On the opposite end of the $PbtO_2$ valuation spectrum lies the question of exact point of cellular death. This threshold remains unclear. The author of a 2015 review reported that positron emission tomography–validated studies have found ischemia at values between 10 and 15 mm Hg and cell death at values less than 5 mm Hg.[115] Researchers at the University of Southern California and Columbia University reported that $PbtO_2$ values < 15 mm Hg have been linked to increased risk of brain ischemia, poor outcomes, and mortality.[110,130] The international consensus on the monitoring of cerebral oxygen tissue pressure in neurocritical patients also cited 15 mm Hg as the cerebral hypoxia threshold indicative of poor outcomes.[114] NCS, ESICM, the international consensus on cerebral oxygen monitoring in neurocritical patients, and the International Multidisciplinary Consensus Conference on Multimodal Monitoring in Neurocritical Care recommend treating at < 20 mm Hg based on low quality of evidence.[17,44,114,125] In several studies, this threshold is cited as the treatment threshold for brain hypoxia.[34,109,129,132,141,142] Another study reported using a 5-minute self-limiting threshold in its criteria to treat.[142] Presently, the research literature regarding $PbtO_2$ treatment thresholds is inconclusive.

Decreased $PbtO_2$ depends on several factors (e.g., carbon dioxide, oxygen, hypermetabolic states) and is not dependent on perfusion alone. Values can be improved by increasing FiO_2/PaO_2 and end-tidal carbon dioxide titration to modify oxygen concentrations; augmenting CPP; limiting metabolic utilization; and initiating or increasing sedation or barbiturates, red blood cell transfusion, intra-arterial interventions or volume infusions, and inotropic cardiac medications.[29,44,110,115,118,126,133] Two studies found increasing FiO_2 to be the most effective therapy;[118,126] younger patients tend to respond better to therapy, and those who responded favorably had lower mortality.[121] Using an algorithm to guide brain oxygenation parameters decreases the duration of cerebral hypoxia.[124]

How should the nurse monitor increased ICP?

In one study (325 rapid $PbtO_2$ change events in 23 patients), changes in $PbtO_2$ were found following changes in ABP or ICP.[117] Note, this finding does not preclude circumstances where $PbtO_2$ precedes ABP or ICP changes. Further research is needed to make recommendations regarding ICP waveforms and values to be interpreted.

For patients who have been assessed as needing BIS monitoring, what are the indications or pathophysiology?

Sedation Level Assessment

Four studies assessed the use of BIS monitoring for sedation level compared to sedation-level assessment scales. Due to its stated effectiveness in monitoring the depth of sedation during anesthesia in the OR, areas outside of the OR have evaluated the effectiveness of monitoring the depth of sedation compared to standard clinical assessments of sedation depth. Sedation scales such as the Riker Sedation-Agitation Scale (SAS) and the Richmond Agitation Sedation Scale (RASS) have been used clinically to assess sedation level. Two prospective studies compared the use of clinical assessment tools to BIS values.[151,152] In the first study ($N = 74$), the sample population was parsed into two subgroups to differentiate possible effects of different sedation pharmacotherapies (midazolam and dexmedetomidine).[151] Both subpopulations showed moderate to high correlations between BIS and RASS scores during sedation monitoring at 5-, 10-, 15-, and 20-minute assessment intervals ($p < 0.05$ for all intervals), although the midazolam group had higher correlation coefficients.[151] In the other study ($N = 28$), comparison of BIS to SAS scores was not the primary outcome but a secondary finding in the efficacy and safety comparison of midazolam versus dexmedetomidine.[152] This study also found that BIS monitoring scores correlated to SAS and that correlation improved as the sedation increased regardless of the sedative agent. In one prospective observational study on adults with severe TBI ($N = 35$), BIS monitoring was used in addition to RASS to assess sedation level and ICP management.[153] The BIS groups showed significant early reduction in ICP compared to the RASS group ($p < 0.05$) and significant lesser score variability than RASS ($p < 0.05$). One study with neurocritically ill adult patients on mechanical ventilation ($N = 67$) reported that, when BIS monitoring was added to the Ramsay Sedation Scale score during assessment, there were lower rates of propofol infusion (14.6 mcg/kg/minute vs. 27.9 mcg/kg/min, $p = 0.003$) and lower volumes of total propofol usage (93.5 ml vs. 157.8 ml, $p < 0.015$).[154] Additionally, the BIS-monitored group woke up more quickly than the control group (1.2 min vs. 7.5 min, $p < 0.0001$).

In contrast to the preceding studies, two systematic reviews offered different findings. One systematic review (16 trials, 2,138 participants) compared standard monitoring to BIS monitoring for procedural sedation (propofol infusion) and found no significant clinical benefits in relation to patient safety or sedation efficacy.[149] The second systematic review (4 trials, 256 participants) found no statistically significant differences in patient outcomes.[147] BIS monitoring was compared to clinical assessment in the ICU environment for improvement in the primary outcome of ICU LOS and secondary outcomes of ventilator days, mortality, ventilator-assisted pneumonia, hospital LOS, quantity of sedatives used, cost, long-term functional outcomes, and quality of life. The authors identified that there was insufficient evidence to support the use of BIS monitoring of mechanically ventilated patients for sedation management or resource allocation. Both reviews found no positive effect of BIS monitoring.

A third systematic review with meta-analysis identified that adult patients who had undergone anesthesia experienced less postoperative delirium and less postoperative cognitive dysfunction than those not undergoing BIS monitoring.[144] The variations in findings could be attributed to search parameters, including year of search and low Grading of Recommendations, Assessment, Development, and Evaluation scores for the research included.

Neuromuscular Blocking Agents and Sedation Monitoring

For patients receiving neuromuscular blocking agents (NMBAs), appropriate depth of sedation is required to prevent the patient's awareness of paralysis. Monitoring the depth of sedation during administration of NMBAs using standard clinical assessment tools (e.g., RASS, SAS) is not sufficiently effective. Using the BIS value, practitioners can titrate sedation medications to achieve the desired depth of sedation to prevent undersedation by targeting a goal BIS value range. Small retrospective studies evaluated the impact of BIS monitoring on sedation management with patients receiving NMBAs. One small retrospective study ($N = 31$) evaluated adult ICU patients receiving NMBAs and monitored with BIS and found that one in 10 patients could be undersedated.[156] It additionally found that BIS values less than 60 were 100% sensitive for predicting deep sedation levels (95% CI: 0–100). The study observed no correlation between BIS and RASS at the time of emergence from NMBA paralysis ($r = 0.27$, $p = 0.14$).[156] A second retrospective study assessing the effect of clinical management based on the BIS value found that there was no difference in sedation and analgesia between patients cared for using BIS monitoring and patients cared for not using BIS monitoring for titration of sedation medications ($p = 0.64$, $p = 0.18$,

respectively).[157] Additionally, these researchers found no difference in clinical outcomes when BIS monitoring was used.[157]

Brain Injury Management

The clinical assessment of sedation level and LOC in the neurologically injured patient adds additional challenges. Small studies have evaluated the use of BIS monitoring on patients with neurological injury or conditions to evaluate LOC, manage ICP, predict neurological outcome, and confirm brain death.[100,146,153,158-168] While evaluating adults with brain injury, two studies found that BIS values significantly correlated with LOC and GCS, indicating that brain-injured patients' LOC may accurately be assessed using BIS monitoring.[158,159] One of the two studies further found that mean BIS values were significantly correlated with levels (mild, moderate, and severe) of head injury severity (96.2 ± 3.2, 45.5 ± 1.2, and 31.3 ± 2.08, respectively; $p < 0.05$, $N = 61$).[159]

The effects of differing brain injury pathologies on BIS values also warrant consideration. In one study, BIS values in adult patients with elective resection of frontal intracranial tumor were compared to BIS values of patients "without intracranial pathology."[160] Interhemispheric BIS values were similar when compared between the two groups. Another study on adult patients with unilateral or diffuse TBI under barbiturate therapy in France ($N = 24$, 288 paired data points) found BIS values to be asymmetrical in both unilateral frontal and diffuse injuries.[161] However, the asymmetry did not equilibrate to significant clinical consequence, supporting the idea that asymmetrical BIS monitoring may be sufficient to manage and monitor barbiturate therapy. BIS monitoring in brain injury was demonstrated to be more reliable than RASS for maintaining stable sedation status and ICP values ($p < 0.05$).[154] This research also demonstrated that deeper sedation levels measured via BIS monitoring provide quicker ICP decreases and lower ICP variability ($p < 0.05$).

Outcome Predictions

Prediction of neurological outcome and recovery is challenging. BIS monitoring as a tool to predict recovery and outcome in different neurological conditions is worthy of investigation, especially in light of other more invasive monitoring methodologies. In postcardiac arrest, BIS can be used to evaluate brain injury due to potential arrest-related anoxia. One study in patients who experienced an out-of-hospital cardiac arrest found that a mean BIS value less than 25 at 12 hours postarrest demonstrated 49% sensitivity and 97% specificity for predicting poor neurological outcome (area under the curve (AUC) $p = 0.006$).[147] This study also found the SR measured in BIS monitoring that is greater than or equal to 3 at hour 23 predicted poor neurological outcome with a sensitivity of 74% (95% CI: 56%–87%) and specificity of 92% (95% CI: 78%–98%) (AUC: 0.836 (0.717–0.955); $p < 0.001$).[147] One study assessed the application of BIS monitoring during cardiopulmonary resuscitation (CPR) in the ICU and the prehospital field setting.[162] It found that patients who experienced poor neurological outcomes after cardiac arrest had significantly lower median BIS values and higher SRs (a secondary index in BIS monitoring) in the first 4 hours after CPR was initiated. SRs are isoelectric percentage values that are linearly inverse to BIS values. Median BIS values and SRs for patients who experienced poor neurological outcomes were 25 and 56, compared to 61 and 7 in patients without poor neurological outcomes. Additionally, the study found that a BIS value less than 40 had a sensitivity of 85.7% and a specificity of 89.5% in predicting an unfavorable neurological outcome.[162]

Another study found that the mean BIS value from the first 12.5 hours of ICU admission after cardiac arrest could be used to predict the 6-month neurological outcome of patients ($p < 0.001$).[163] An additional study evaluated the use of BIS monitoring after return of spontaneous circulation and during therapeutic hypothermia after cardiac arrest. It found that the mean BIS values at 24 hours were significantly different between the individuals considered to have a good outcome (survival to discharge with a cerebral performance category 1–2) versus a poor outcome (cerebral performance category 3–5) ($p < 0.001$).[164] This study also reported that a BIS value of 0 at any point during hospitalization correlated with poor outcomes and that BIS values at 24 hours post-resuscitation correlated with neurological outcomes.[164] These two studies (sample populations of 62 and 96, respectively) suggest that the quantitative values from BIS monitoring may assist in predicting poor neurological outcome in patients who experience cardiac arrest.[163,164]

Critically ill, unconscious patients with ischemic-hypoxic brain injury undergoing emergent surgery were also studied to evaluate BIS monitoring's ability to predict patient recovery. Researchers reported that when BIS is compared to clinical judgment and routine laboratory testing (biochemistry, hematology, and arterial blood gas), BIS may better identify patients' chances of recovery after an ischemic-hypoxic brain injury. One small prospective study ($N = 25$) found that abnormal tracings seen during BIS monitoring were strongly associated with poor neurological outcome ($p < 0.02$).[165] This same study also revealed that BIS values were significantly different in patients with poor outcome versus patients without poor outcome. Researchers were able to derive that "BIS ($p < 0.0005$) but not clinical judgment ($p < 0.16$) could identify a group of patients more likely to avoid a poor neurologic outcome."[165] A postoperative severe TBI study that

assessed combining ICP and BIS monitoring to evaluate short-term prognosis found that BIS values positively correlated with the degree of coma postoperatively and negatively with ICP ($p < 0.05$ and $p < 0.05$, respectively).[166]

One observational study in adult reperfusion patients with acute anterior ischemic stroke evaluated the impact of BIS monitoring on assessing "either delayed or ineffective recanalization or that the brain is temporarily and reversibly stunned by the ischemic insult."[167] Researchers assessed clinical course, size of infarct, and long-term outcomes and found an inverse correlation between BIS value and NIHSS score at 24 hours and discharge ($r = -0.390$, $p = 0.004$ and $r = -0.292$, $p < 0.001$, respectively) and BIS value and infarct volume at 24 hours ($r = -0.430$, $p = 0.031$). Additionally, they found that a final BIS value of 81 or greater was associated with significant clinical improvement (reflected by the NIHSS score $p = 0.028$) at discharge.[167]

BIS monitoring has also been studied in the postanesthesia care unit (PACU) to evaluate adult patients who underwent elective neurosurgery.[146] Neurological assessment scales and BIS values were compared, together and separately, for early detection of postoperative neurological complications for craniotomy and noncraniotomy groups (NCGs). This study found that neurological assessment scales (Ramsay Sedation Scale and Canadian Neurological Scale) and BIS were more sensitive than pupil assessment and GCS (94% and 50%) at identifying neurologic changes (31.4% vs. 20%, $p < 0.001$) and more precisely identified neurological complication during time in the PACU (*OR* = 7.15, 95% CI: 2.1–24.7, $p = 0.02$ vs. *OR*= 9.5, 95% CI: 2.3–39.4, $p = 0.02$) in the craniotomy group.[146] In the NCG, neurological assessment scales and BIS revealed greater sensitivity to neurologic changes than pupil assessment and GCS (39.1% vs. 2.2%, $p < 0.01$). There were no complications in the PACU for the NCG.

Brain Death

One study applied BIS monitoring to gather cerebral activity readings of patients who had met brain death criteria. This study found that in patients determined to be clinically brain dead, 34.3% of patients had a BIS value of 0 continuously and 65.7% of patients had periods of time with a BIS value that would exceed 30 for more than 30 minutes.[168] Another study focused on using BIS for early detection of brain death. While evaluating sedated patients following refractory out-of-hospital cardiac arrest and on extracorporeal cardiopulmonary resuscitation, researchers found that BIS value on admission was a predictor of brain death, even during mild hypothermia. BIS values under 30 were found to be 96% sensitive and 82% sensitive for identifying brain death occurrence during the ICU stay.[148] Further research is needed to determine the utility of BIS monitoring in the assessment of brain death.

Placement and Care

For patients needing BIS monitoring:

Where and how should the electrodes be placed (i.e., anatomic location and application practices)?

Three prospective observational studies evaluated standard and alternative electrode placement. One study ($N = 40$) found that the presence of a frontal brain tumor need not influence the placement of unilateral BIS electrodes, as it did not impact the BIS value at loss of consciousness or at return of consciousness when measured on the ipsilateral side. It also found that frontal brain tumor location did not impact titrating anesthetic administration whether or not BIS monitoring was used.[160] The second study, with 28 participants, compared the overall difference in score between standard BIS montage and alternate nasal bridge BIS sticker placement and found the score averaged 2.0 greater than the standard BIS montage score ($p < 0.0001$).[169] This study found that the alternative nasal bridge placement demonstrated more variability in values, but this was not clinically significant. The third study, with 58 participants, compared the standard frontal BIS sensor position to the alternative position across the mandible. It found significant correlation between frontal and mandibular position BIS values ($p = 0.000$) during the anesthesia maintenance period. The mandibular position was found to be reliable when the standard frontal position was not available due to surgical field requirements.[170]

How should the nurse monitor BIS?

BIS monitoring is traditionally used to monitor depth of anesthesia in the operating room (OR), but the scope of usage has extended beyond the sterile suite. BIS values range from 0 to 100. Zero indicates an absence of brain activity, and a value of 100 is equal to an awake patient.[8] The literature supports using BIS monitoring to guide titration of anesthesia gas and sedation medications. BIS also is employed to prevent intraoperative awareness events.[143] BIS monitoring technology collects raw electroencephalography (EEG) data, which is filtered, analyzed, and processed to provide a BIS value. This index value is purported to correlate with the patient's level of sedation.[144] Outside of the OR environment, the utility of BIS monitoring is being evaluated in critical care units, procedural environments, postanesthesia care units, pre-

hospital and emergency room settings, and palliative and hospice care centers.[145-150]

How should the nurse care for the BIS monitor (i.e., infection control)?

There was no literature available on frequency of lead replacement or skin cleansing. Organizational policy and manufacturer recommendations should be used until further research is available.

What are the signs and symptoms the nurse is assessing for?

BIS is a noninvasive monitoring tool; therefore, risk of bleeding and infection are not present as with invasive monitoring. In the absence of available literature on nursing assessment of BIS monitoring, organizational policy and manufacturer recommendations should be used until further research is available. Given that BIS monitoring involves EEG electrode placement, it is not unreasonable to follow standard EEG protocol guidelines.

Troubleshooting

For patients needing BIS monitoring:

How do you troubleshoot and analyze the number or waveform, EEG suppression ratio, and signal quality index?

There is a gap in the literature regarding the troubleshooting and analysis of the BIS monitor. Research focusing on BIS monitor waveforms, SR, and signal quality index were not found. Manufacturer recommendations or organizational policies should be followed until additional research is available.

Conclusion

This review of the literature for ICP, $PbtO_2$, and BIS monitoring represented the available data at the time of the search and identified multiple areas of research opportunity. Direct care of the patient with a neurological insult requiring invasive and noninvasive monitoring techniques as mentioned above will be an ongoing challenge with continued advances. Nurses and advanced practice providers have an opportunity to add to this body of literature to ensure the rigor of care evolves for patient populations with acute neurological conditions.

Future iterations of this EBCR should consider including additional monitoring techniques, such as brain tissue temperature monitoring and ICP sampling, and differences in the advanced practice nurse's role with these treatments versus the registered nurse's role.

References

1. Harary M, Dolmans RGF, Gormley WB. Intracranial pressure monitoring—review and avenues for development. *Sensors (Basel)*. 2018;18(2):465. doi:10.3390/s18020465
2. Czosnyka M, Pickard JD, Steiner LA. Principles of intracranial pressure monitoring and treatment. *Handb Clin Neurol*. 2017;140:67-89. doi:10.1016/B978-0-444-63600-3.00005-2
3. Hickey JV, Strayer AL, eds. *The Clinical Practice of Neurological and Neurosurgical Nursing*. 8th edition. Philadelphia, PA: Wolters Kluwer; 2019.
4. Balu R, Rajagopalan S, Baghshomali S, et al. Cerebrovascular pressure reactivity and intracranial pressure are associated with neurologic outcome after hypoxic-ischemic brain injury. *Resuscitation*. 2021;164:114-121. doi:10.1016/j.resuscitation.2021.04.023
5. Leinonen V, Vanninen R, Rauramaa T. Raised intracranial pressure and brain edema. *Handb Clin Neurol*. 2017;145:25-37. doi:10.1016/B978-0-12-802395-2.00004-3
6. Esquenazi Y, Lo VP, Lee K. Critical care management of cerebral edema in brain tumors. *J Intensive Care Med*. 2017;32(1):15-24. doi:10.1177/0885066615619618
7. Eide PK, Sorteberg W. Diagnostic intracranial pressure monitoring and surgical management in idiopathic normal pressure hydrocephalus: a 6-year review of 214 patients. *Neurosurgery*. 2010;66(1):80-91. doi:10.1227/01.NEU.0000363408.69856.B8
8. Mathur S, Patel J, Goldstein S, Jain A. Bispectral index. [Updated 2021 Nov 22]. In: StatPearls [Internet]. Treasure Island, FL: StatPearls Publishing; 2022. https://www.statpearls.com/ArticleLibrary/viewarticle/18342. Updated September 19, 2022. Accessed June 17, 2022.
9. Di Ieva A, Schmitz EM, Cusimano MD. Analysis of intracranial pressure: past, present, and future. *Neuroscientist*. 2013;19(6):592-603. doi:10.1177/1073858412474845
10. Olson DM, Batjer HH, Abdulkadir K, Hall CE. Measuring and monitoring ICP in Neurocritical Care: results from a national practice survey. *Neurocrit Care*. 2014;20(1):15-20. doi:10.1007/s12028-013-9847-9
11. Kawoos U, McCarron RM, Auker CR, Chavko M. Advances in intracranial pressure monitoring and its significance in managing traumatic brain injury. *Int J Mol Sci*. 2015;16(12):28979-28997. doi:10.3390/ijms161226146
12. Alali AS, Fowler RA, Mainprize TG, et al. Intracranial pressure monitoring in severe traumatic brain injury: results from the American College of Surgeons Trauma Quality Improvement Program. *J Neurotrauma*. 2013;30(20):1737-1746. doi:10.1089/neu.2012.2802
13. Karamanos E, Teixeira PG, Sivrikoz E, et al. Intracranial pressure versus cerebral perfusion pressure as a marker of outcomes in severe head injury: a prospective evaluation. *Am J Surg*. 2014;208(3):363-371. doi:10.1016/j.amjsurg.2013.10.026
14. Chesnut R, Videtta W, Vespa P, Le Roux P; Participants in the International Multidisciplinary Consensus Conference on Multimodality Monitoring. Intracranial pressure monitoring: fundamental considerations and rationale for monitoring. *Neurocrit Care*. 2014;21 Suppl 2:S64-S84. doi:10.1007/s12028-014-0048-y
15. Talving P, Karamanos E, Teixeira PG, et al. Intracranial pressure monitoring in severe head injury: compliance with Brain Trauma Foundation guidelines and effect on outcomes: a prospective study. *J Neurosurg*. 2013;119(5):1248-1254. doi:10.3171/2013.7.JNS122255
16. Wijdicks EFM, Sheth KN, Carter BS, et al. Recommendations for the management of cerebral and cerebellar infarction with swelling: a statement for healthcare professionals from the American Heart Association/American Stroke Association. *Stroke*. 2014;45(4):1222-1238. doi:10.1161/01.str.0000441965.15164.d6
17. Le Roux P, Menon DK, Citerio G, et al. Consensus summary statement of the International Multidisciplinary Consensus Conference on Multimodality Monitoring in Neurocritical Care: a statement for healthcare professionals from the Neurocritical Care Society and the European Society of Intensive Care Medicine. *Neurocrit Care*. 2014;21 Suppl 2:S1-S26. doi:10.1007/s12028-014-0041-5
18. Zoerle T, Lombardo A, Colombo A, et al. Intracranial pressure after subarachnoid hemorrhage. *Crit Care Med*. 2015;43(1):168-176. doi:10.1097/CCM.0000000000000670
19. Ziai WC, Melnychuk E, Thompson CB, Awad I, Lane K, Hanley DF. Occurrence and impact of intracranial pressure elevation during treatment of severe intraventricular hemorrhage. *Crit Care Med*. 2012;40(5):1601-1608. doi:10.1097/CCM.0b013e318241e380
20. Gerber LM, Chiu YL, Carney N, Härtl R, Ghajar J. Marked reduction in mortality in patients with severe traumatic brain injury. *J Neurosurg*. 2013;119(6):1583-1590. doi:10.3171/2013.8.JNS13276
21. Farahvar A, Gerber LM, Chiu YL, Carney N, Härtl R, Ghajar J. Increased mortality in patients with severe traumatic brain injury treated without intracranial pressure monitoring. *J Neurosurg*. 2012;117(4):729-734. doi:10.3171/2012.7.JNS111816
22. Chesnut RM, Temkin N, Carney N, et al. A trial of intracranial-pressure monitoring in traumatic brain injury [published correction appears in *N Engl J Med*. 2013 Dec 19;369(25):2465]. *N Engl J Med*. 2012;367(26):2471-2481. doi:10.1056/NEJMoa1207363

23. Tian Y, Wang Z, Jia Y, et al. Intracranial pressure variability predicts short-term outcome after intracerebral hemorrhage: a retrospective study. *J Neurol Sci*. 2013;330(1-2):38-44. doi:10.1016/j.jns.2013.04.001

24. Su SH, Wang F, Hai J, et al. The effects of intracranial pressure monitoring in patients with traumatic brain injury. *PLoS One*. 2014;9(2):e87432. doi:10.1371/journal.pone.0087432

25. Dang Q, Simon J, Catino J, et al. More fateful than fruitful? Intracranial pressure monitoring in elderly patients with traumatic brain injury is associated with worse outcomes. *J Surg Res*. 2015;198(2):482-488. doi:10.1016/j.jss.2015.03.092

26. Zeng J, Zheng P, Tong W, Fang W. Decreased risk of secondary brain herniation with intracranial pressure monitoring in patients with haemorrhagic stroke. *BMC Anesthesiol*. 2014;14:19. doi:10.1186/1471-2253-14-19

27. Littlejohns LR, McNett, M, Olson DM. *AANN Core Curriculum for Neuroscience Nursing*. 7th ed. Chicago, IL: American Association of Neuroscience Nurses; 2022.

28. Kristiansson H, Nissborg E, Bartek J Jr, Andresen M, Reinstrup P, Romner B. Measuring elevated intracranial pressure through noninvasive methods: a review of the literature. *J Neurosurg Anesthesiol*. 2013;25(4):372-385. doi:10.1097/ANA.0b013e31829795ce

29. Miller CM. Update on multimodality monitoring. *Curr Neurol Neurosci Rep*. 2012;12(4):474-480. doi:10.1007/s11910-012-0274-7

30. Olson DM, McNett MM, Lewis LS, Riemen KE, Bautista C. Effects of nursing interventions on intracranial pressure. *Am J Crit Care*. 2013;22(5):431-438. doi:10.4037/ajcc2013751

31. Kamel H, Hemphill JC 3rd. Characteristics and sequelae of intracranial hypertension after intracerebral hemorrhage. *Neurocrit Care*. 2012;17(2):172-176. doi:10.1007/s12028-012-9744-7

32. Nyholm L, Howells T, Enblad, P. Predictive factors that may contribute to secondary insults with nursing interventions in adults with traumatic brain injury. *J Neurosci Nurs*. 2017;49(1):49-55. doi:10.1097/JNN.0000000000000260

33. Mokri B. The Monro-Kellie hypothesis: applications in CSF volume depletion. *Neurology*. 2001;56(12):1746-1748. doi:10.1212/WNL.56.12.1746

34. Okonkwo DO, Shutter LA, Moore C, et al. Brain oxygen optimization in severe traumatic brain injury Phase-II: a Phase II randomized trial. *Crit Care Med*. 2017;45(11):1907-1914. doi:10.1097/CCM.0000000000002619

35. Helbok R, Madineni RC, Schmidt MJ, et al. Intracerebral monitoring of silent infarcts after subarachnoid hemorrhage. *Neurocrit Care*. 2011;14(2):162-167. doi:10.1007/s12028-010-9472-9

36. Jeon SB, Park JC, Kwon SU, et al. Intracranial pressure soon after hemicraniectomy in malignant middle cerebral artery infarction. *J Intensive Care Med*. 2018;33(5):310-316. doi:10.1177/0885066616675598

37. Tang A, Pandit V, Fennell V, et al. Intracranial pressure monitor in patients with traumatic brain injury. *J Surg Res*. 2015;194(2):565-570. doi:10.1016/j.jss.2014.11.017

38. Dawes AJ, Sacks GD, Cryer HG, et al. Intracranial pressure monitoring and inpatient mortality in severe traumatic brain injury: a propensity score-matched analysis. *J Trauma Acute Care Surg*. 2015;78(3):492-501. doi:10.1097/TA.0000000000000559

39. National Institute of Neurological Disorders and Stroke. Hydrocephalus fact sheet. https://www.ninds.nih.gov/hydrocephalus-fact-sheet. Accessed April 20, 2022.

40. Chari A, Dasgupta D, Smedley A, et al. Intraparenchymal intracranial pressure monitoring for hydrocephalus and cerebrospinal fluid disorders. *Acta Neurochir (Wien)*. 2017;159(10):19671978. doi:10.1007/s00701-017-3281-2

41. Mahdavi Z, Pierre-Louis N, Ho TT, Figueroa SA, Olson DM. Advances in cerebral monitoring for the patient with traumatic brain injury. *Crit Care Nurs Clin North Am*. 2015;27(2):213-223. doi:10.1016/j.cnc.2015.02.002

42. Kasotakis G, Michailidou M, Bramos A, et al. Intraparenchymal vs. extracranial ventricular drain intracranial pressure monitors in traumatic brain injury: less is more? *J Am Coll Surg*. 2012;214(6):950-957. doi:10.1016/j.jamcollsurg.2012.03.004

43. Classen J, Goldstein JN. Emergency neurological life support: status epilepticus. *Neurocrit Care*. 2017;27(Suppl 1):152-158. doi:10.1007/s12028-017-0460-1

44. Le Roux P, Menon DK, Citerio G, et al. The International Multidisciplinary Consensus Conference on Multimodality Monitoring in Neurocritical Care: a list of recommendations and additional conclusions: a statement for healthcare professionals from the Neurocritical Care Society and the European Society of Intensive Care Medicine. *Neurocrit Care*. 2014;21 Suppl 2(Suppl 2):S282-S296. doi:10.1007/s12028-014-0077-6

45. Olson DM, Zomorodi M, Britz GW, Zomorodi AR, Amato A, Graffagnino C. Continuous cerebral spinal fluid drainage associated with complications in patients admitted with subarachnoid hemorrhage. *J Neurosurg*. 2013;119(4):974-980. doi:10.3171/2013.6.JNS122403

46. Cossu G, Messerer M, Stocchetti N, Levivier M, Daniel RT, Oddo M. Intracranial pressure and outcome in critically ill patients with aneurysmal subarachnoid hemorrhage: a systematic review [published online ahead of print, April 5, 2016]. *Minerva Anestesiol*. 2016;82(6):684-696.

47. Amato A, Britz GW, James ML, et al. An observational pilot study of CSF diversion in subarachnoid haemorrhage [published correction appears in *Nurs Crit Care*. 2012 Jan-Feb;17(1):56]. *Nurs Crit Care*. 2011;16(5):252-260. doi:10.1111/j.1478-5153.2010.00444.x

48. Sandsmark DK, Kumar MA, Park S, Levine JM. Multimodal monitoring in subarachnoid hemorrhage. *Stroke*. 2012;43(5):1440-1445. doi:10.1161/STROKEAHA.111.639906

49. Marshall SA, Kalanuria A, Markandaya M, Nyquist PA. Management of intracerebral pressure in the neurosciences critical care unit. *Neurosurg Clin N Am*. 2013;24(3):361-373. doi:10.1016/j.nec.2013.03.004

50. Raboel PH, Bartek J Jr, Andresen M, Bellander BM, Romner B. Intracranial pressure monitoring: invasive versus non-invasive methods—a review. *Crit Care Res Pract*. 2012;2012:950393. doi:10.1155/2012/950393

51. Speck V, Staykov D, Huttner HB, Sauer R, Schwab S, Bardutzky J. Lumbar catheter for monitoring of intracranial pressure in patients with post-hemorrhagic communicating hydrocephalus. *Neurocrit Care*. 2011;14(2):208-215. doi:10.1007/s12028-010-9459-6

52. Liu H, Wang W, Cheng F, et al. External ventricular drains versus intraparenchymal intracranial pressure monitors in traumatic brain injury: a prospective observational study. *World Neurosurg*. 2015;83(5):794-800. doi:10.1016/j.wneu.2014.12.040

53. Bales JW, Bonow RH, Buckley RT, Barber J, Temkin N, Chesnut RM. Primary external ventricular drainage catheter versus intraparenchymal ICP monitoring: outcome analysis. *Neurocrit Care*. 2019;31(1):11-21. doi:10.1007/s12028-019-00712-9

54. Li Z, Quan Z, Zhang N, Zhao J, Shen D. Comparison between intraventricular and intraparenchymal intracranial pressure monitoring in Asian patients with severe traumatic brain injury. *Neurosurg Q*. 2016;26(2):120-124. doi:10.1097/WNQ.0000000000000147

55. Aiolfi A, Khor D, Cho J, Benjamin E, Inaba K, Demetriades D. Intracranial pressure monitoring in severe blunt head trauma: does the type of monitoring device matter? *J Neurosurg*. 2018;128(3):828-833. doi:10.3171/2016.11.JNS162198

56. Dimitriou J, Levivier M, Gugliotta M. Comparison of complications in patients receiving different types of intracranial pressure monitoring: a retrospective study in a single center in Switzerland. *World Neurosurg*. 2016;89:641-646. doi:10.1016/j.wneu.2015.11.037

57. Volovici V, Huijben JA, Ercole A, et al. Ventricular drainage catheters versus intracranial parenchymal catheters for intracranial pressure monitoring-based management of traumatic brain injury: a systematic review and meta-analysis. *J Neurotrauma*. 2019;36(7):988-995. doi:10.1089/neu.2018.6086

58. Bekar A, Doğan Ş, Abaş F, et al. Risk factors and complications of intracranial pressure monitoring with a fiberoptic device. *J Clin Neurosci*. 2009;16(2):236-240. doi:10.1016/j.jocn.2008.02.008

59. Sorinola A, Buki A, Sandor J, Czeiter E. Risk factors of external ventricular drain infection: proposing a model for future studies. *Front Neurol*. 2019;10:226. doi:10.3389/fneur.2019.00226

60. Muralidharan R. External ventricular drains: management and complications. *Surg Neurol Int*. 2015;6(Suppl 6):S271-S274. doi:10.4103/2152-7806.157620

61. Kim GS, Amato A, James ML, et al. Continuous and intermittent CSF diversion after subarachnoid hemorrhage: a pilot study. *Neurocrit Care*. 2011;14(1):68-72. doi:10.1007/s12028-010-9401-y

62. Pople I, Poon W, Assaker R, et al. Comparison of infection rate with the use of antibiotic-impregnated vs. standard extraventricular drainage devices: a prospective, randomized controlled trial. *Neurosurgery*. 2012;71(1):6-13. doi:10.1227/NEU.0b013e3182544e31

63. Cui Z, Wang B, Zhong Z, et al. Impact of antibiotic- and silver-impregnated external ventricular drains on the risk of infections: a systematic review and meta-analysis. *Am J Infect Control*. 2015;43(7):e23-e32. doi:10.1016/j.ajic.2015.03.015

64. Thomas R, Lee S, Patole S, Rao S. Antibiotic-impregnated catheters for the prevention of CSF shunt infections: a systematic review and meta-analysis. *Br J Neurosurg*. 2012;26(2):175-184. doi:10.3109/02688697.2011.603856

65. Wang X, Dong Y, Qi XQ, Li YM, Huang CG, Hou LJ. Clinical review: efficacy of antimicrobial impregnated catheters in external ventricular drainage—a systematic review and meta-analysis. *Crit Care*. 2013;17(4):234. doi:10.1186/cc12608

66. Keong NC, Bulters DO, Richards HK, et al. The SILVER (Silver Impregnated Line Versus EVD Randomized trial): a double-blind, prospective, randomized, controlled trial of an intervention to reduce the rate of external ventricular drain infection. *Neurosurgery*. 2012;71(2):394-4034. doi:10.1227/NEU.0b013e318257bebb

67. Flint AC, Rao VA, Renda NC, Faigeles BS, Lasman TE, Sheridan W. A simple protocol to prevent external ventricular drain infections. *Neurosurgery*. 2013;72(6):993-999. doi:10.1227/NEU.0b013e31828e8dfd

68. Kubilay Z, Amini S, Fauerbach LL, Archibald L, Friedman WA, Layon AJ. Decreasing ventricular infections through the use of a ventriculostomy placement bundle: experience at a single institution. *J Neurosurg*. 2013;118(3):514-520. doi:10.3171/2012.11.JNS121336

69. Rahman M, Whiting JH, Fauerbach LL, Archibald L, Friedman WA. Reducing ventriculostomy-related infections to near zero: the eliminating ventriculostomy infection study. *Jt Comm J Qual Patient Saf*. 2012;38(10):459-464. doi:10.1016/s1553-7250(12)38061-6

70. Sieg EP, Schlauderaff AC, Payne RA, Glantz MJ, Simon SD. Impact of an external ventricular drain placement and handling protocol on infection rates: a meta-analysis and single institution experience. *World Neurosurg*. 2018;115:e53-e58. doi:10.1016/j.wneu.2018.03.160

71. Fried HI, Nathan BR, Rowe AS, et al. The insertion and management of external ventricular drains: an evidence-based consensus statement: a statement for healthcare professionals from the Neurocritical Care Society. *Neurocrit Care*. 2016;24(1):61-81. doi:10.1007/s12028015-0224-8

72. Lavinio A, Menon DK. Intracranial pressure: why we monitor it, how to monitor it, what to do with the number and what's the future? *Curr Opin Anaesthesiol*. 2011;24(2):117-123. doi:10.1097/ACO.0b013e32834458c5

73. Tewari MK, Tripathi M, Sharma RR, Mishra GP, Lad SD. Surgical management of moderate sized spontaneous cerebellar hematomas: role of intracranial pressure monitoring. *Turk Neurosurg*. 2015;25(5):712-720. doi:10.5137/1019-5149.JTN.11011-14.1

74. Li LM, Timofeev I, Czosnyka M, Hutchinson PJA. Review article: the surgical approach to the management of increased intracranial pressure after traumatic brain injury. *Anesth Analg*. 2010;111(3):736-748. doi:10.1213/ANE.0b013e3181e75cd1

75. Hussein K, Rabino G, Feder O, et al. Risk factors for meningitis in neurosurgical patients with cerebrospinal fluid drains: prospective observational cohort study. *Acta Neurochir (Wien)*. 2019;161(3):517-524. doi:10.1007/s00701-019-03801-y

76. Chatzi M, Karvouniaris M, Makris D, et al. Bundle of measures for external cerebral ventricular drainage-associated ventriculitis. *Crit Care Med*. 2014;42(1):66-73. doi:10.1097/CCM.0b013e31829a70a5

77. Camacho EF, Boszczowski I, Basso M, et al. Infection rate and risk factors associated with infections related to external ventricular drain. *Infection*. 2011;39(1):47-51. doi:10.1007/s15010-010-0073-5

78. Ramanan M, Lipman J, Shorr A, Shankar A. A meta-analysis of ventriculostomy-associated cerebrospinal fluid infections. *BMC Infect Dis*. 2015;15:3. doi:10.1186/s12879-014-0712-z

79. Tunkel AR, Hasbun R, Bhimraj A, et al. 2017 Infectious Diseases Society of America's clinical practice guidelines for healthcare-associated ventriculitis and meningitis. *Clin Infect Dis*. 2017;64(6):e34-e65. doi:10.1093/cid/ciw861

80. Bergdal O, Springborg JB, Holst AV, et al. Accuracy of tunnelated vs. bolt-connected external ventricular drains. *Clin Neurol Neurosurg*. 2013;115(10):1972-1975. doi: 10.1016/j.clineuro.2013.05.026

81. Ducis K, Thakrar R, Tranmer B. Ventriculostomies without dressings: low infection rates but room for quality improvement. *Trauma*. 2016;18(1):40-45. doi:10.1177/1460408615613099

82. Leverstein-van Hall MA, Hopmans TEM, van der Sprenkel JWB, et al. A bundle approach to reduce the incidence of external ventricular and lumbar drain-related infections. *J Neurosurg*. 2010;112(2):345-353. doi:10.3171/2009.6.JNS09223

83. Roach J, Gaastra B, Bulters D, Shtaya A. Safety, accuracy, and cost effectiveness of bedside bolt external ventricular drains (EVDs) in comparison with tunneled EVDs inserted in theaters. *World Neurosurg*. 2019;125:e473-e478. doi:10.1016/j.wneu.2019.01.106

84. Heck C. Invasive neuromonitoring. *Crit Care Nurs Clin North Am*. 2016;28(1):77-86. doi:10.1016/j.cnc.2015.10.001

85. Wang K, Du HG, Yin LC, He M, Hao BL, Chen L. Which side of lateral ventricles to choose during external ventricular drainage in patients with intraventricular hemorrhage: ipsilateral or contralateral? *J Surg Res*. 2013;183(2):720-725. doi:10.1016/j.jss.2013.03.003

86. Foreman B, Ngwenya LB, Stoddard E, Hinzman JM, Andaluz N, Hartings JA. Safety and reliability of bedside, single burr hole technique for intracranial multimodality monitoring in severe traumatic brain injury. *Neurocrit Care*. 2018;29(3):469-480. doi:10.1007/s12028-0180551-7

87. Hill M, Baker G, Carter D, et al. A multidisciplinary approach to end external ventricular drain infections in the neurocritical care unit. *J Neurosci Nurs*. 2012;44(4):188-193. doi:10.1097/JNN.0b013e3182527672

88. Hariri O, Farr S, Lawandy S, Zampella B, Miulli D, Siddiqi J. Will clinical parameters reliably predict external ventricular drain-associated ventriculitis: is frequent routine cerebrospinal fluid surveillance necessary? *Surg Neurol Int*. 2017;8:137. doi:10.4103/sni.sni_449_16

89. Guanci MM. Ventriculitis of the central nervous system. *Crit Care Nurs Clin North Am*. 2013;25(3):399-406. doi: 10.1016/j.ccell.2013.04.005

90. Hepburn-Smith M, Dynkevich I, Spektor M, Lord A, Czeisler B, Lewis A. Establishment of an external ventricular drain best practice guideline: the quest for a comprehensive, universal standard for external ventricular drain care. *J Neurosci Nurs*. 2016;48(1):54-65. doi:10.1097/JNN.0000000000000174

91. Bookland MJ, Sukul V, Connolly PJ. Use of a cyanoacrylate skin adhesive to reduce external ventricular drain infection rates. *J Neurosurg*. 2014;121(1):189-194. doi:10.3171/2013.12.JNS13700

92. Camacho EF, Boszczowski I, Freire MP, et al. Impact of an educational intervention implanted in a neurological intensive care unit on rates of infection related to external ventricular drains. *PLoS One*. 2013;8(2):e50708. doi:10.1371/journal.pone.0050708

93. Reinstrup P, Unnerbäck M, Marklund N, et al. Best zero level for external ICP transducer. *Acta Neurochir (Wien)*. 2019;161(4):635-642. doi:10.1007/s00701-019-03856-x

94. Bader MK. What is the recommended external reference point for zeroing an intracranial pressure monitoring system at the foramen of Monro? *Crit Care Nurse*. 1999;19(6):92-93.

95. Olson DM, Batjer HH, Abdulkadir K, Hall CE. Measuring and monitoring ICP in Neurocritical Care: results from a national practice survey. *Neurocrit Care*. 2014;20(1):15-20. doi:10.1007/s12028-013-9847-9

96. Speck V, Staykov D, Huttner HB, Sauer R, Schwab S, Bardutzky J. Lumbar catheter for monitoring of intracranial pressure in patients with post-hemorrhagic communicating hydrocephalus. *Neurocrit Care*. 2011;14(2):208-215. doi:10.1007/s12028-010-9459-6

97. Livesay SL, McNett MM, Keller M, Olson DM. Challenges of cerebral perfusion pressure measurement. *J Neurosci Nurs*. 2017;49(6):372-376. doi:10.1097/JNN.0000000000000321

98. McNett M, Livesay S, Yeager S, et al. The impact of head-of-bed positioning and transducer location on cerebral perfusion pressure measurement. *J Neurosci Nurs*. 2018;50(6):322-326. doi:10.1097/JNN.0000000000000398

99. Mitchell PH, Kirkness C, Blissitt PA. Chapter 5 cerebral perfusion pressure and intracranial pressure in traumatic brain injury. *Annu Rev Nurs Res*. 2015;33:111-183. doi:10.1891/0739-6686.33.111

100. Hawryluk GWJ, Aguilera S, Buki A, et al. A management algorithm for patients with intracranial pressure monitoring: the Seattle International Severe Traumatic Brain Injury Consensus Conference (SIBICC). *Intensive Care Med*. 2019;45(12):1783-1794. doi:10.1007/s00134-019-05805-9

101. Olson DM, Lewis LS, Bader MK, et al. Significant practice pattern variations associated with intracranial pressure monitoring. *J Neurosci Nurs*. 2013;45(4):186-193. doi:10.1097/JNN.0b013e3182986400

102. Nwachuku EL, Puccio AM, Fetzick A, et al. Intermittent versus continuous cerebrospinal fluid drainage management in adult severe traumatic brain injury: assessment of intracranial pressure burden. *Neurocrit Care*. 2014;20(1):49-53. doi:10.1007/s12028-013-9885-3

103. Hockel K, Schuhmann MU. ICP monitoring by open extraventricular drainage: common practice but not suitable for advanced neuromonitoring and prone to false negativity. *Acta Neurochir Suppl*. 2018;126:281-286. doi:10.1007/978-3-319-65798-1_55

104. Liu X, Griffith M, Jang HJ, et al. Intracranial pressure monitoring via external ventricular drain: are we waiting long enough before recording the real value? *J Neurosci Nurs*. 2020;52(1):37-42. doi:10.1097/JNN.0000000000000487

105. Rogers M, Stutzman SE, Atem FD, Sengupta S, Welch B, Olson DM. Intracranial pressure values are highly variable after cerebral spinal fluid drainage. *J Neurosci Nurs*. 2017;49(2):85-89. doi:10.1097/JNN.0000000000000257

106. Sunderland NE, Villanueva NE, Pazuchanics SJ. External ventricular catheters: is it appropriate to use an open/monitor position to adequately trend intracranial pressure in a neuroscience critical care environment? *J Neurosci Nurs*. 2016;48(5):274-277. doi:10.1097/JNN.0000000000000255

107. Zacchetti L, Magnoni S, Di Corte F, Zanier ER, Stocchetti N. Accuracy of intracranial pressure monitoring: systematic review and meta-analysis. *Crit Care*. 2015;19:420. doi:10.1186/s13054-015-1137-9

108. Chen L, Du HG, Yin LC, et al. Zero drift of intraventricular and subdural intracranial pressure monitoring systems. *Chin J Traumatol*. 2013;16(2):99-102.

109. Roh D, Park S. Brain multimodality monitoring: updated perspectives. *Curr Neurol Neurosci Rep*. 2016;16(6):56. doi:10.1007/s11910-016-0659-0

110. Carrera E, Schmidt JM, Fernandez L, et al. Spontaneous hyperventilation and brain tissue hypoxia in patients with severe brain injury. *J Neurol Neurosurg Psychiatry*. 2010;81(7):793-797. doi:10.1136/jnnp.2009.174425

111. Lubillo ST, Parrilla DM, Blanco J, et al. Prognostic value of changes in brain tissue oxygen pressure before and after decompressive craniectomy following severe traumatic brain injury. *J Neurosurg*. 2018;128(5):1538-1546. doi:10.3171/2017.1.JNS161840

112. Eriksson EA, Barletta JF, Figueroa BE, et al. The first 72 hours of brain tissue oxygenation predicts patient survival with traumatic brain injury. *J Trauma Acute Care Surg*. 2012;72(5):1345-1349. doi:10.1097/TA.0b013e318249a0f4

113. Ngwenya LB, Burke JF, Manley GT. Brain tissue oxygen monitoring and the intersection of brain and lung: a comprehensive review. *Respir Care*. 2016;61(9):1232-1244. doi:10.4187/respcare.04962

114. Domínguez-Roldán JM, Lubillo S, Videtta W, et al. International consensus on the monitoring of cerebral oxygen tissue pressure in neurocritical patients. Consenso internacional sobre la monitorización de la presión tisular cerebral de oxígeno en pacientes neurocríticos. *Neurocirugia (Astur: Engl Ed)*. 2020;31(1):24-36. doi:10.1016/j.neucir.2019.08.003

115. De Georgia MA. Brain tissue oxygen monitoring in neurocritical care. *J Intensive Care Med*. 2015;30(8):473-483. doi:10.1177/0885066614529254

116. Martin DS, Grocott MPW. Oxygen therapy in critical illness: precise control of arterial oxygenation and permissive hypoxemia. *Crit Care Med*. 2013;41(2):423-432. doi:10.1097/CCM.0b013e31826a44f6.

117. Radolovich DK, Czosnyka M, Timofeev I, et al. Transient changes in brain tissue oxygen in response to modifications of cerebral perfusion pressure: an observational study. *Anesth Analg*. 2010;110(1):165-173. doi:10.1213/ANE.0b013e3181c0722f

118. Kirkman MA, Smith M. Supratentorial intracerebral hemorrhage: a review of the underlying pathophysiology and its relevance for multimodality neuromonitoring in neurointensive care. *J Neurosurg Anesthesiol*. 2013;25(3):228-239. doi:10.1097/ANA.0b013e3182836059

119. Radolovich DK, Czosnyka M, Timofeev I, et al. Reactivity of brain tissue oxygen to change in cerebral perfusion pressure in head injured patients. *Neurocrit Care*. 2009;10(3):274-279. doi:10.1007/s12028-009-9190-3

120. Oddo M, Levine JM, Mackenzie L, et al. Brain hypoxia is associated with short-term outcome after severe traumatic brain injury independently of intracranial hypertension and low cerebral perfusion pressure. *Neurosurgery*. 2011;69(5):1037-1045. doi:10.1227/NEU.0b013e3182287ca7

121. Bohman LE, Heuer GG, Macyszyn L, et al. Medical management of compromised brain oxygen in patients with severe traumatic brain injury. *Neurocrit Care*. 2011;14(3):361-369. doi:10.1007/s12028-011-9526-7

122. Chang JJJ, Youn TS, Benson D, et al. Physiologic and functional outcome correlates of brain tissue hypoxia in traumatic brain injury. *Crit Care Med*. 2009;37(1):283-290. doi:10.1097/CCM.0b013e318192fbd7

123. Green JA, Pellegrini DC, Vanderkolk WE, Figueroa BE, Eriksson EA. Goal directed brain tissue oxygen monitoring versus conventional management in traumatic brain injury: an analysis of in hospital recovery. *Neurocrit Care*. 2013;18(1):20-25. doi:10.1007/s12028-012-9797-7

124. Adamides AA, Cooper DJ, Rosenfeldt FL, et al. Focal cerebral oxygenation and neurological outcome with or without brain tissue oxygen-guided therapy in patients with traumatic brain injury. *Acta Neurochir (Wien)*. 2009;151(11):1399-1409. doi:10.1007/s00701-009-0398-y

125. Ledwith MB, Bloom S, Maloney-Wilensky E, Coyle B, Polomano RC, Le Roux PD. Effect of body position on cerebral oxygenation and physiologic parameters in patients with acute neurological conditions. *J Neurosci Nurs*. 2010;42(5):280-287. doi:10.1097/jnn.0b013e3181ecafd4

126. Oddo M, Bösel J; Participants in the International Multidisciplinary Consensus Conference on Multimodality Monitoring. Monitoring of brain and systemic oxygenation in neurocritical care patients. *Neurocrit Care*. 2014;21 Suppl 2:S103-S120. doi:10.1007/s12028-014-0024-6

127. Lee HC, Chuang HC, Cho DY, Cheng KF, Lin PH, Chen CC. Applying cerebral hypothermia and brain oxygen monitoring in treating severe traumatic brain injury. *World Neurosurg*. 2010;74(6):654-660. doi:10.1016/j.wneu.2010.06.019

128. Swanson EW, Mascitelli J, Stiefel M, et al. Patient transport and brain oxygen in comatose patients. *Neurosurgery*. 2010;66(5):925-931. doi:10.1227/01.NEU.0000368543.59446.A4

129. Rass V, Solari D, Ianosi B, et al. Protocolized brain oxygen optimization in subarachnoid hemorrhage. *Neurocrit Care*. 2019;31(2):263-272. doi:10.1007/s12028-019-00753-0

130. Arshi B, Mack WJ, Emanuel B. Invasive and noninvasive multimodal bedside monitoring in subarachnoid hemorrhage: a review of techniques and available data. *Neurol Res Int*. 2013;2013:987934. doi:10.1155/2013/987934

131. Oddo M, Nduom E, Frangos S, et al. Acute lung injury is an independent risk factor for brain hypoxia after severe traumatic brain injury. *Neurosurgery*. 2010;67(2):338-344. doi:10.1227/01.NEU.0000371979.48809.D9

132. Kumar MA, Chanderraj R, Gant R, et al. Obesity is associated with reduced brain tissue oxygen tension after severe brain injury. *Neurocrit Care*. 2012;16(2):286-293. doi:10.1007/s12028-011-9576-x

133. McCarthy MC, Moncrief H, Sands JM, et al. Neurologic outcomes with cerebral oxygen monitoring in traumatic brain injury. *Surgery*. 2009;146(4):585-591. doi:10.1016/j.surg.2009.06.059

134. Ulrich CT, Fung C, Vatter H, et al. Occurrence of vasospasm and infarction in relation to a focal monitoring sensor in patients after SAH: placing a bet when placing a probe? *PLoS One*. 2013;8(5):e62754. doi:10.1371/journal.pone.0062754

135. Peace K, Maloney-Wilensky E, Frangos S, et al. Portable head CT scan and its effect on intracranial pressure, cerebral perfusion pressure, and brain oxygen. *J Neurosurg*. 2011;114(5):1479-1484. doi:10.3171/2010.11.JNS091148

136. Swanson EW, Mascitelli J, Stiefel M, et al. Patient transport and brain oxygen in comatose patients. *Neurosurgery*. 2010;66(5):925-931. doi:10.1227/01.NEU.0000368543.59446.A4

137. Sacco TL, Davis JG. Management of intracranial pressure part II: nonpharmacologic interventions. *Dimens Crit Care Nurs*. 2019;38(2):61-69. doi:10.1097/DCC.0000000000000341

138. Francoeur CL, Pain M, Mayer SA. Multimodality monitoring: illuminating the comatose human brain. *Semin Neurol*. 2016;36(6):560-569. doi:10.1055/s-0036-1592171

139. Hawryluk GWJ, Rubiano AM, Totten AM, et al. Guidelines for the management of severe traumatic brain injury: 2020 update of the decompressive craniectomy recommendations. *Neurosurgery*. 2020;87(3):427-434. doi:10.1093/neuros/nyaa278

140. Dellazizzo L, Demers SP, Charbonney E, et al. Minimal PaO2 threshold after traumatic brain injury and clinical utility of a novel brain oxygenation ratio [published online ahead of print, November 2, 2018]. *J Neurosurg*. 2018;1-9. doi:10.3171/2018.5.JNS18651

141. Pascual JL, Georgoff P, Maloney-Wilensky E, et al. Reduced brain tissue oxygen in traumatic brain injury: are most commonly used interventions successful? *J Trauma*. 2011;70(3):535-546. doi:10.1097/TA.0b013e31820b59de

142. Spiotta AM, Stiefel MF, Gracias VH, et al. Brain tissue oxygen-directed management and outcome in patients with severe traumatic brain injury. *J Neurosurg*. 2010;113(3):571-580. doi:10.3171/2010.1.JNS09506

143. National Institute for Health and Care Excellence. Depth of anaesthesia monitoring—bispectral index (BIS), E-entropy and narcotrend-compact M. https://www.nice.org.uk/guidance/dg6. Published November 21, 2012. Accessed May 22, 2022.

144. Bocskai T, Kovács M, Szakács Z, et al. Is the bispectral index monitoring protective against postoperative cognitive decline? A systematic review with meta-analysis. *PLoS One*. 2020;15(2):e0229018. doi:10.1371/journal.pone.0229018

145. Herrero S, Carrero E, Valero R, Rios J, Fábregas N. Postoperative surveillance in neurosurgical patients—usefulness of neurological assessment scores and bispectral index. *Braz J Anesthesiol*. 2017;67(2):153-165. doi:10.1016/j.bjane.2015.09.003

146. Eertmans W, Genbrugge C, Vander Laenen M, et al. The prognostic value of bispectral index and suppression ratio monitoring after out-of-hospital cardiac arrest: a prospective observational study. *Ann Intensive Care*. 2018;8(1):34. doi:10.1186/s13613-018-0380-z

147. Shetty RM, Bellini A, Wijayatilake DS, et al. BIS monitoring versus clinical assessment for sedation in mechanically ventilated adults in the intensive care unit and its impact on clinical outcomes and resource utilization. *Cochrane Database Syst Rev*. 2018;2(2):CD011240. doi:10.1002/14651858.CD011240.pub2

148. Jouffroy R, Lamhaut L, Guyard A, et al. Early detection of brain death using the bispectral index (BIS) in patients treated by extracorporeal cardiopulmonary resuscitation (E-CPR) for refractory cardiac arrest. *Resuscitation*. 2017;120:8-13. doi:10.1016/j.resuscitation.2017.08.217

149. Conway A, Sutherland J. Depth of anaesthesia monitoring during procedural sedation and analgesia: a systematic review protocol. *Syst Rev*. 2015;4:70. doi:10.1186/s13643-015-0061-z

150. Masman AD, van Dijk M, van Rosmalen J, et al. Bispectral index monitoring in terminally ill patients: a validation study. *J Pain Symptom Manage*. 2016;52(2):212-220.e3. doi:10.1016/j.jpainsymman.2016.01.011

151. Zheng J, Gao Y, Xu X, et al. Correlation of bispectral index and Richmond agitation sedation scale for evaluating sedation depth: a retrospective study. *J Thorac Dis*. 2018;10(1):190-195. doi:10.21037/jtd.2017.11.129

152. Tripathi M, Kumar V, Kalashetty MB, Malviya D, Bais PS, Sanjeev OP. Comparison of dexmedetomidine and midazolam for sedation in mechanically ventilated patients guided by bispectral index and sedation-agitation scale. *Anesth Essays Res*. 2017;11(4):828-833. doi:10.4103/aer.AER_48_17

153. Yan K, Pang L, Gao H, et al. The influence of sedation level guided by bispectral index on therapeutic effects for patients with severe traumatic brain injury. *World Neurosurg*. 2018;110:e671-e683. doi:10.1016/j.wneu.2017.11.079

154. Olson DM, Thoyre SM, Peterson ED, Graffagnino C. A randomized evaluation of bispectral index-augmented sedation assessment in neurological patients. *Neurocrit Care*. 2009;11(1):20-27. doi:10.1007/s12028-008-9184-6

155. Medtronic. Using the bispectral index™ (BIS™) monitoring system for critical care. https://www.medtronic.com/content/dam/covidien/library/us/en/product/brainmonitoring/bis-monitoring-system-use-in-critical-care-reference-guide.pdf. Published 2017. Accessed April 5, 2022.

156. Tasaka CL, Duby JJ, Pandya K, Wilson MD, Hardin KA. Inadequate sedation during therapeutic paralysis: use of bispectral index in critically ill patients. *Drugs Real World Outcomes*. 2016;3(2):201-208. doi:10.1007/s40801-016-0076-3

157. Bass S, Vance ML, Reddy A, et al. Bispectral index for titrating sedation in ARDS patients during neuromuscular blockade. *Am J Crit Care*. 2019;28(5):377-384. doi:10.4037/ajcc2019917

158. Jung JY, Cho CB, Min BM. Bispectral index monitoring correlates with the level of consciousness in brain injured patients. *Korean J Anesthesiol*. 2013;64(3):246-250. doi:10.4097/kjae.2013.64.3.246

159. Ebtehaj M, Yaqubi S, Seddighi AS, Seddighi A, Yazdi Z. Correlation between BIS and GCS in patients suffering from head injury. *Ir J Med Sci*. 2012;181(1):77-80. doi:10.1007/s11845-011-0768-3

160. Sahinovic MM, Beese U, Heeremans EH, et al. Bispectral index values and propofol concentrations at loss and return of consciousness in patients with frontal brain tumours and control patients. *Br J Anaesth*. 2014;112(1):110-117. doi:10.1093/bja/aet342

161. Cottenceau V, Masson F, Soulard A, et al. Asymmetry of bispectral index (BIS) in severe brain-injured patients treated by barbiturates with unilateral or diffuse brain injury. *Ann Fr Anesth Reanim*. 2012;31(12):e275-e281. doi:10.1016/j.annfar.2012.09.007

162. Selig C, Riegger C, Dirks B, Pawlik M, Seyfried T, Klingler W. Bispectral index (BIS) and suppression ratio (SR) as an early predictor of unfavourable neurological outcome after cardiac arrest. *Resuscitation*. 2014;85(2):221-226. doi:10.1016/j.resuscitation.2013.11.008

163. Stammet P, Collignon O, Werer C, Sertznig C, Devaux Y. Bispectral index to predict neurological outcome early after cardiac arrest. *Resuscitation*. 2014;85(12):1674-1680. doi:10.1016/j.resuscitation.2014.09.009

164. Leary M, Fried DA, Gaieski DF, et al. Neurologic prognostication and bispectral index monitoring after resuscitation from cardiac arrest. *Resuscitation*. 2010;81(9):1133-1137. doi:10.1016/j.resuscitation.2010.04.021

165. Myles PS, Daly D, Silvers A, Cairo S. Prediction of neurological outcome using bispectral index monitoring in patients with severe ischemic-hypoxic brain injury undergoing

emergency surgery. *Anesthesiology*. 2009;110(5):1106-1115. doi:10.1097/ALN.0b013e31819daef6

166. Dong L, Chen L, Shi T, et al. Combined monitoring of intracranial pressure and bispectral index in patients with severe craniocerebral trauma post-operatively. *Clin Neurol Neurosurg*. 2016;148:42-44. doi:10.1016/j.clineuro.2016.06.004

167. Flores A, Ribó M, Rubiera M, et al. Monitoring of cortical activity postreperfusion. A powerful tool for predicting clinical response immediately after recanalization. *J Neuroimaging*. 2015;25(2):257-262. doi:10.1111/jon.12113

168. Fyntanidou B, Grosomanidis V, Aidoni Z, et al. Bispectral index scale variations in patients diagnosed with brain death. *Transplant Proc*. 2012;44(9):2702-2705. doi:10.1016/j.transproceed.2012.09.012

169. Nelson P, Nelson JA, Chen AJ, Kofke WA. An alternative position for the BIS-vista montage in frontal approach neurosurgical cases. *J Neurosurg Anesthesiol*. 2013;25(2):135-142. doi:10.1097/ANA.0b013e31826ca3a0

170. Lee SY, Kim YS, Lim BG, Kim H, Kong MH, Lee IO. Comparison of bispectral index scores from the standard frontal sensor position with those from an alternative mandibular position. *Korean J Anesthesiol*. 2014;66(4):267-273. doi:10.4097/kjae.2014.66.4.267

Appendices

Appendix A: MeSH Search Terms

1. ICP: intracranial pressure monitoring device, intracranial pressure waveform, external ventricular drain, lumbar drain, lumbar puncture, ventriculostomy, cerebrospinal fluid, monitoring devices, nursing, neuromonitoring, invasive monitoring, noninvasive monitoring, traumatic brain injury, multimodal monitoring, intraparenchymal monitors, intraventricular monitors, ventricular catheters, ICP, intracranial hypertension, catheter placement, tunneled versus bolted, increased intracranial pressure, external ventriculostomy, external ventricular drain complications, severe head injury, traumatic brain injury, fiberoptic catheter, cerebral perfusion pressure
2. Brain oxygenation monitoring ($PbtO_2$): brain tissue oxygenation, multimodal monitoring, cerebral oximetry, delayed cerebral ischemia, cerebral hypoxia, cerebral oxygenation, brain tissue oxygen tension, cerebral oxygen monitoring
3. Bispectral index monitoring: bispectral index monitoring, BIS, clinical sedation assessment, nursing, brain injury, neuro, ICU, intensive care unit, critical care, muscle artifact, burst suppression, EEG, intraoperative monitoring

Appendix B: Evidence Tables

Intracranial Pressure Monitoring

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Speck V, Staykov D, Huttner HB, Sauer R, Schwab S, Bardutzky J, 2011	Prospective	43 patients, 1,806 measurements	Intracerebral hemorrhage (ICH)/ SAH/IVH with hydrocephalus	To determine the accuracy of ICP obtained by LD	LD-ICP R^2: 0.95-0.99 EVD-ICP R^2: 0.96-1.01 LD-ICP > 20 mm Hg Sensitivity: 81% Specificity: 100%
Liu H, Wang W, Cheng F, et al., 2014	Prospective	122	TBI ≥ 13 years of age	To determine if ICP monitoring device type affects patient outcomes in TBI	IPM vs. EVD refractory intracranial hypertension: 51.7% vs. 21%, $p < 0.001$ IPM vs. EVD 1 month survival: 90.3% vs. 76.7%, $p = 0.04$ IPM vs. EVD 6 months survival: 68.3% vs. 88.7%, $p = 0.006$ 0 difference in complications, $p = 0.448$
Bales JW, Bonow RH, Buckley RT, Barber J, Temkin N, Chesnut RM, 2019	Retrospective	244	TBI	To determine if ICP monitoring device type affects patient outcomes in TBI	EVD vs. IPM 180-day GOS-E: 3.8 ± 2.2 vs. 4.9 ± 2.2, $p = 0.002$ Mortality 23% vs. 10%, $p = 0.014$ 0 statistically significant differences in demographics, arrival GCS, or midline shift in EVD vs. IPM groups
Li Z, Quan Z, Zhang, N, Zhao J, Shen D, 2016	Prospective observational study	268	Severe TBI	To compare if ICP monitoring device type affects patient outcomes in TBI	IPM vs. EVD Monitor days: 4.1 ± 3.6 vs. 7.6 ± 5.8, $p < 0.01$ Complications: 10.7% vs. 32.8%, $p < 0.01$ IPM vs. EVD ICU LOS: $p = 0.15$ Independent predictors for mortality and unfavorable survival: age, initial GCS, and midline shift size
Aiolfi A, Khor D, Cho J, Benjamin E, Inaba K, Demetriades D, et al., 2018	Retrospective	2,562	American College of Surgeons Trauma Quality Improvement Program database	To compare outcomes between IPM and EVD in TBI	ICP monitoring device was not an independent risk factor for mortality, complications, or discharge functional outcomes Unadjusted 30-day mortality: 29% EVD vs. 25.5% IPM, $p = 0.046$ Adjusted 30-day mortality reported insignificant, but quantitative findings not included
Kasotakis G, Michailidou M, Bramos A, et al., 2012	Retrospective	377	Adult TBI, with ICP monitoring	To compare if ICP monitoring device type affects patient outcomes in TBI	IPM vs. EVD Complications: 11.9% vs. 31.1%, $p < 0.001$ Monitoring duration: 3.8 ± 2.6 days vs. 7.3 ± 5.6 days, $p < 0.001$ ICU LOS: 7.6 ± 5.6 days vs. 9.5 ± 6.2 days, $p = 0.004$ 0 difference in GOS (2.7 ± 1.3 vs. 2.5 ± 1.3, $p = 0.45$), mortality (30.9% vs. 32.2%, $p = 0.82$), and LOS (15.6 ± 12.4 days vs. 16.4 ± 10.7 days, $p = 0.57$)
Dimitriou J, Levivier M, Gugliotta M, 2016	Retrospective	288	Patients with ICP monitoring	To compare complications and risk factors between IPM and EVD	EVD vs. IPM Complications: 13.9% vs. 2.4%, $p < 0.01$ Infection: 9.2% vs. 0.8%, $p < 0.01$

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Volovici V, Huijben JA, Ercole A, et al., 2019	Systematic review and meta-analysis	3,968	Patients with TBI and ICP monitoring	To compare effectiveness and complications rates between IPM and EVD to treat increased ICP	EVD vs. IPM Mortality: risk ratio [RR] = 0.90, 95% CI: 0.60–1.36, $p = 0.41$ Functional outcomes mean difference: 0.23, 95% CI: 0.67–1.13, $p = 0.61$ Complications (mainly infectious): RR = 2.56, $p = 0.02$
Bekar A, Dogan S, Abas F, et al., 2009	Prospective observational	631	Patients with intraparenchymal ICP monitors	To compare complications and risk factors between IPM and EVD to treat increased ICP	EVD vs. IPM Infection: 7.9% vs. 2.1%, p not reported EVDs 9-day <: 5.11 times infection risk, $p < 0.001$ OR vs. ICU device placement infection: 5.34% vs. 4.28%, $p > 0.05$ Complications of transducer disconnection/broken, hematoma, contusion, defective probes reported in single value percentages without p values
Amato A, Britz GW, James ML, et al., 2011	Observational	60	SAH patients with EVD placement	To determine superiority of continuous vs. intermittent CSF drainage for reducing cerebral vasospasms	Continuous vs. intermittent drainage Complications: 52.9% vs. 23.1%, $p = 0.022$; reported to data safety board, study was terminated Vasospasms: OR 0.44, 95% CI: 0.13–1.45, $p = 0.177$
Kim GS, Amato A, James ML, et al., 2011	Prospective observational pilot	37	SAH patients with EVD	To determine if there is cause for a randomized study comparing monitor first/intermittent vs. drain first/continuous CSF drainage for prespecified ICP threshold for vasospasm management	Drain first vs. monitor first Vasospasms: 66.7% vs. 53.9%, $p = 0.442$ Ventriculitis: 13% vs. 0%, $p = 0.1844$
Pople I, Poon W, Assaker R, et al., 2012	Randomized controlled trial (RCT)	434	Patients with EVD	To evaluate infection rates of AI vs. standard EVD catheters	AI vs. standard catheter infections: 2.3% vs. 2.8%, $p = 1.0$ AI catheters did not show superiority.
Cui Z, Wang B, Zhong Z, et al., 2015	Systematic review with meta-analysis	4,399	Patients with EVDs	To compare efficacy of AI, SI, and plain EVD catheters	AI vs. plain: RR = 0.38; 95% CI: 0.25-0.58, $p < 0.00001$ SI vs. plain: RR = 0.57; 95% CI: 0.33-0.99, $p = 0.05$ AI vs. SI: RR = 0.73; 95% CI: 0.29-1.83, $p = 0.51$
Thomas R, Lee S, Patole S, Rao S, 2012	Systematic review with meta-analysis	Observational $N = 3,149$ RCT $N = 472$	Neonatal EVD patients; inclusion of adult and pediatric populations due to insufficient neonatal data	To compare efficacy of AI and plain EVD catheters	Adult only AI vs. plain: RR 0.14, 95% CI: 0.02-0.74, $p = 0.02$ Adult, pediatrics, and neonate: RR 0.37, 95% CI: 0.23-0.60, $p < 0.0001$
Wang X, Dong Y, Qi XQ, Li YM, Huang CG, Hou LJ, 2013	Systematic review with meta-analysis	3,038	All published research related to antimicrobial-impregnated EVD catheters until 2012	To assess for differences in catheter-related infections among AI, SI, and plain EVD catheters	AI vs. plain infection: OR = 0.25, 95% CI: 0.12-0.52, $p < 0.05$ AI vs. plain 20-day infection rate: Hazard ratio = 0.52, 95% CI: 0.29-0.95, $p < 0.05$ AI vs. SI infection: OR = 0.33, 95% CI: 0.07-1.69, $p = 0.18$
Keong NC, Bulters DO, Richards HK, et al., 2012	RTC	278	Patients with EVD	To assess efficacy of SI catheter against CSF infection	SI vs. plain infection risk: 12.3% vs. 21.4%, $p = 0.0427$ Difference in risk in favor of SI: OR = 1.94, 95% CI: 1.015-3.713, $p = 0.0427$
Flint AC, Rao VA, Renda NC, Faigeles BS, Lasman TE, Sheridan W, 2013	Retrospective	262	Patients with EVD	To study the impact of an EVD infection control protocol on EVD infection rates	+CSF cultures pre- vs. post-IC protocol: 9.8% vs. 0.8%, $p = 0.001$ Ventriculitis pre- vs. post-IC protocol: 6.3% vs. 0.8%, $p = 0.02$ +CSF culture per 1000 catheter days pre vs. post: 11.43 to 0.79 Mortality pre vs. post: 33.6% vs. 31.9%, $p = 0.44$
Kubilay Z, Amini S, Fauerbach LL, Archibald L, Friedman WA, Layon AJ, 2013	Quality Improvement	2,928	Patients with EVD	To determine if a ventriculostomy placement bundle would decrease the rate of VAI	VAI rates pre vs. post and post-IC protocol: 9.2% vs. 2.6% vs. 0% Overall VAI rate post-IC protocol (4 years): 0.046% Infections highest (37%) 8–14 days postinsertion Infections decreased after day 15

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Rahman M, Whiting JH, Fauerbach LL, Archibald L, Friedman WA, 2012	Prospective	Total = 3,128 Preprotocol *n* = 217 Postprotocol *n* = 2,911	Patients with EVDs	To decrease EVD–related infection through the use of a protocol	Infection rate pre- vs. postprotocol: 9.2% (2006) vs. 1.2% (2007), $p < 0.0001$) < 1% (2008–2010), $p < 0.0001$ 0% through 2011 second quarter, $p < 0.0001$
Sieg EP, Schlauderaff AC, Payne RA, Glantz MJ, Simon SD, 2018	Systematic review and meta-analysis	2,317	Patients with EVD	Meta-analysis of protocols on EVD care with the intent to create institutional protocol for EVD care	Infection rates pre- vs. postprotocol: 16.11 + 9.09% vs. 4.67 + 4.7%, $p = 0.0008$ Relative risk of infection in pre- and postprotocol groups demonstrated high heterogeneity and substantial risk of publication bias. Positive association between the pre- and postprotocol infection rate ($p = 0.0015$): institutional infection rate was 12.4% in the 8 months prior to protocol initiation. In the 15 months following protocol initiation, the infection rate decreased to 0%.
Tewari MK, Tripathi M, Sharma RR, Mishra GP, Lad SD, 2015	Retrospective review	32	Moderate (2.5-4.0 cm) sized acute spontaneous cerebellar hematoma (SCH)	To establish research-based literature on the care of intracranial hemodynamics in SCH	47% of SCH required surgical evacuation. Higher GCS and normal/slightly higher ICP are associated with better outcomes. EVD insertion and ICP management were both therapeutic and prognostic.
Dimitriou J, Levivier M, Gugliotta M, 2016	Retrospective review	288	Patients with ICP monitoring	To analyze complications and risk factors associated with ICP monitoring device	EVD vs. IPM infection: 9.2% vs. 0.8%, $p < 0.01$ EVD vs. IPM complications: 13.9% vs. 2.4%, $p < 0.01$ Infections were the most representative complication. Overall infection incidence was greatest between days 5 and 11.
Hussein K, Rabino G, Feder O, et al., 2019	Prospective observational	232	Patients with EVDs, LDs, or ICP monitors	To determine risk factors for CNS infections in patients with various types of ICP monitors/drains To examine an infection prevention and control (IC) protocol to improve drain management	Patient risk factors: Diabetes mellitus, $p = 0.017$ CSF leak, $p = 0.032$ Drain opening, $p = 0.027$ Duration of the drain in days, $p = 0.035$ Catheter risk factors: Drain opening, $p < 0.001$ Drain days, $p = 0.001$ Pre- and post-infection control protocol, $p = 0.037$ EVD-only infection analysis: Drain days, $p = 0.001$
Chatzi M, Karvouniaris M, Makris D, et al., 2014	Prospective case study	139	Patients with an EVD	To study ventriculitis, outcomes and disability related to brain hemorrhage, and trauma before and after implementation of an EVD infection control bundle	Ventriculitis pre- vs. post-IC bundle: 28% vs. 10.5%, $p = 0.02$ Drain-associated infection rate: 18% vs. 7.1%, $p = 0.0001$ ICU LOS ventriculitis vs. ICU LOS no ventriculitis: 44.4 days vs. 20 days, $p < 0.001$ ICU LOS was associated with length of drainage, $p = 0.0001$. 6-months GOS was not associated with external cerebral ventricular drainage-associated ventriculitis, $p = 0.5$.
Camacho EF, Boszczowski I, Basso M, et al., 2011	Prospective	2,119	Patients with EVDs	To describe the incidence rates, mortality, and risk factors associated with EVD-related infections	Incidence of infection: 18.3% The infection rate was procedural infection rate: 16.9%. Drain-associated infection rate: 22.4/1000 catheter days Infection rate increased with increased hospital LOS. The duration of catheter placement was associated with infection, $p = 0.036$ (increased risk with increased duration).

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Ramanan M, Lipman J, Shorr A, Shankar A, 2015	Systematic review and meta-analysis	6,681	Patients with EVDs	To determine the incidence of VAI Secondary aims: to understand how other factors (length of catheter dwell time, CSF sampling frequency) were associated with the rate of VAI	Pooled VAI rate: 11.4/1000 catheter days There was significant heterogeneity. Studies with mean duration EVD dwell time < 7 days: pooled VAI rate 19.6/1000 catheter days Studies with mean duration of 7–10 days: pooled VAI rate 12.8/1000 catheter days Studies with mean duration > 10 days: pooled VAI rate 8/1000 catheter days Studies using AI: pooled VAI rate 7.2/1000 catheter days Studies using plain catheters: pooled VAI rate 12.1/1000 catheter days
Bergdal O, Springborg JB, Holst AV, et al., 2013	Retrospective review	147	Patients with EVDs	To investigate accuracy and complications of bolt-connected EVDs compared to tunneled EVDs	Higher accuracy in the bolt group vs. tunneled group, $p = 0.023$ Reduction in reoperations due to poor placement: bolt-group reduction: 11.9%, $p = 0.006$
Ducis K, Thakrar R, Tranmer B, 2016	Retrospective review	199	Patients with EVDs	To demonstrate that minimal techniques of EVD maintenance are equal in VAI compared to other published methods	Patients who developed ventriculitis had a ventriculostomy in place longer than those patients without infection ($p < 0.05$). Rate of infection was 5.1% compared to published national average of 8.8% Study limits: Retrospective nature prevents analysis of IC interventions; definition of ventriculitis not standardized in the literature; confounding comparisons not equal
Leverstein-van Hall MA, Hopmans TEM, van der Sprenkel JWB, et al., 2010	Quality improvement	467	Patients with EVDs and LDs	To study the effects of an IC protocol on patients with EVDs and LDs	VAI pre-IC, post-IC (2005), post-IC (2006) protocol: 16.2% vs. 8.9 vs. 11.3% Infections per 100 LD pre-IC, post-IC (2005), post-IC (2006) protocol: 2.4 vs. 0.6 vs. 0.8 Infections per 100 EVD pre-IC, post-IC (2005), post-IC (2006) protocol: 1.7 vs. 1.0 vs. 1.2 No correlation between the reduction in infection rates and the specific interventions could be identified, as there was insufficient data regarding compliance with interventions.
Roach J, Gaastra B, Bulters D, Shtaya A, 2019	Retrospective cohort study	579	Patients (pediatrics and adults) with ICP monitoring	To evaluate EVD placement via bolt vs. the standard tunneled technique	Tip placement accuracy bolt vs. tunneled: 66.4% vs. 61%, $p = 0.33$ VAI bolt vs. tunneled: 10% vs. 14.2%, $p = 0.20$ % cases bolt vs. tunneled placement: 26% vs. 74% Cost for placement bolt vs. tunneled: £216 vs. £1316 (largely owing to OR theatre-related costs)
Ziai WC, Melnychuk E, Thompson CB, Awad I, Lane K, Hanley DF, 2012	Prospective randomized	$N = 100$ Intraventricular recombinant tissue plasminogen activator treatment $n = 78$, placebo $n = 22$	Patients with obstructive IVH	To investigate factors contributing to increased ICP in patients with EVDs and to assess patient tolerance of EVD closure for intraventricular study medication administration To explore the impact of ICP on mortality and outcomes	ICP > 20 mm Hg placebo vs. treatment: $p = 0.03$ ICP > 20 mm Hg associated with initial IVH volume, $p = 0.002$ ICP > 20 mm Hg associated with ipsilateral EVD placement, $p = 0.001$ ICP > 20 mm Hg associated with thrombolytic Rx, $p = 0.05$ Mortality associations: ICP > 30 mm Hg, $p = 0.003$ Intracerebral hemorrhage volume, $p = 0.03$ IVH volume, $p < 0.001$ rtPA Rx, $p = 0.29$ 30-day poor Modified Rankin Scale score associations: % events ICP > 30 mm Hg, $p = 0.01$ % events ICP > 20 mm Hg, $p = 0.08$ Intracerebral hemorrhage volume, $p < 0.001$ IVH volume, $p < 0.003$ Pulse pressure, $p = 0.04$ rtPA Rx, $p = 0.52$

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Wang K, Du HG, Yin LC, He M, Hao BL, Chen L, 2013	Prospective randomized	45	Patients with IVH	To determine if patients with IVH have improved clinical outcome with EVD and intraventricular fibrinolysis placement on the ipsilateral or contralateral side of the lateral ventricle	IG: 28 patients (62.2%), CG: 17 patients (37.8%), $p < 0.05$ IG blood clot clearance of the third/fourth ventricle vs. CG: 3.3 ± 1.0 days vs. 3.9 ± 0.8 days, $p = 0.042$ ICP 20 mm Hg IG vs. CG: 18% vs. 10.9%, $p < 0.001$ ICP 30 mm Hg IG vs. CG: 6.9% vs. 3.9%, $p = 0.004$ IG vs. CG: 0 significant difference in length of time the EVD remained in place, ICU LOS, complications incidence, 30-day poststroke GOS, mortality, and 30-day functional
Foreman B, Ngwenya LB, Stoddard E, Hinzman JM, Andaluz N, Hartings JA, 2018	Prospective	43	Patients with severe TBI and multimodal monitoring	To describe the safety and reliability of using of a single, four-lumen bolt through which multiple catheters are passed into the frontal lobe for the purpose of multimodal monitoring	Multimodal monitoring means: Placement from time of injury: 12.5 hours (IQR 9.0-21.4 hours) ICU LOS: 10.4 ± 6.5 days LOS: 14.8 ± 11.3 days Monitoring hours: 97.1 (IQR 46.9–124) Modalities monitored: ICP/$PbtO_2$: 100% Regional cerebral blood flow/intracranial temperature: 95.3% Intracranial electroencephalography: 90.7% Off-unit %: 66.6% Off-unit duration mean: 50 ± 17.5 min Number of off-unit occurrences positively associated with device discontinuances, $p = 0.03$ Device placement: Nondominant frontal lobe: 72.1% Injured frontal lobe: 60.5% Clinically asymptomatic minor hemorrhage, pneumocephalus, or small bone chips within the path of devices observed in 40.5%
Hill M, Baker G, Carter D, et al., 2012	Quality improvement		Patients with EVD	To report the findings of an IC intervention	EVD care was standardized: sterile insertion, sterile dressings, sterile gloves and masking on aseptic dressing changes, MD- or advanced nurse practitioner-only EVD irrigation or CSF sampling with aseptic technique, and documentation of EVD indications and insertion procedure note. EVD infections per 1,000 catheter days in April 2008–June 2008, July 2008–June 2009, Oct. 2009–Sept. 2011: 16, 4.5, 1.3, respectively
Hariri O, Farr S, Lawandy S, Zampella B, Miulli D, Siddiqi J, 2017	Observational retrospective study	123	Patients with EVDs	To assess if changes in CSF serum or clinical features correlated with early identification of ventriculitis and if the protocol for frequency of sampling was indicated	Variables associated with VAI: CSF glucose: serum < 0.5, $p = 0.0298$ 2-point GCS decline, $p = 0.74$ White blood cell (WBC) > 11,000 2 days prior to CSF collection, $p = 0.29$ WBC > 11,000 1 day prior to CSF collection, $p = 1.0$ WBC > 11,000 day-of CSF collection, $p = 1.0$ Temp > 100.4ϒF 2 days prior to CSF collection, $p = 1.0$ Temp > 100.4ϒF 1 day prior to CSF collection, $p = 0.60$ Temp > 100.4ϒF day-of CSF collection, $p = 0.64$
Camacho EF, Boszczowski I, Freire MP, et al., 2013	Quasi-experimental	178 patients, 194 procedures	Patients with EVDs	To assess the impact of an educational intervention on EVD-related infections	Interventions: hand hygiene (chlorhexidine gluconate soap [2%] and ETOH gel), clipper hair removal, pre-EVD insertion chlorhexidine skin prep, antibiotic prophylaxis, daily dressing changes performed by resident MDs, aseptic EVD handling, nonobstruction of EVD, discontinuation of EVD if integrity is compromised, distal reservoir point CSF wasting 30-day EVD-related infection pre- vs. postintervention: 71.4% vs. 60%, $p = 0.06$ Infection per catheter days: 14.0 vs. 6.9, $p = 0.027$ Mortality pre vs. post: 42% vs. 35%, $p < 0.0001$

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Reinstrup P, Unnerback M, Marklund N, et al., 2019	Observational	20	MRIs of patients with general complaints (e.g., headache)	To investigate commonly used external zero-reference point for ICP monitor in relation to the brain center and foramen of Monro	Measurements from the skin to brain center and skin to foramen of Monro were variable when patient positions were adjusted from supine, supine with head elevated 45 degrees, upright, and lateral with head turned 45 degrees.
Olson DM, Batjer HH, Abdulkadir K, Hall CE, 2014	Survey/qualitative	241	NCS members	To describe ICP monitoring and ICP management practices among professionals in neurocritical care	Three main topics were investigated related to ICP monitoring: What is the practice for CSF drainage (continuous vs. PRN)? Where is the EVD transducer leveled? How is ICP recorded? Survey results indicate a high degree of variability in ICP monitoring and management.
McNett M, Livesay S, Yeager S, et al., 2018	Secondary analysis, prospective nonrandomized observational trial	136	Patients with SAH or IVH	To determine if ABP transducer location and head-of-bed (HOB) elevation impact ABP and CPP values	Values when the transducer was level at the tragus were lower than those from the phlebostatic axis location for all values (systolic blood pressure, diastolic blood pressure, MAP, and CPP), regardless of HOB positioning (greater than or less than 30 degrees). All differences were statistically significant based on transducer location ($p < .001$). HOB positioning does not affect readings for CPP; however, arterial transducer location does.
Olson DM, Lewis LS, Bader, MK, et al., 2013	Observational	28 RN-patient dyads	16 hospitals across the United States	To describe nursing practice for care of the patient with ICP monitoring	Prevalent differences in ICP patient care, both prescriber and nursing in origin Prescription and nursing interventions were not often supported by evidence.
Nwachuku EL, Puccio AM, Fetzick A, et al., 2014	Retrospective	62	Severe adult TBI	To evaluate the impact of open vs. closed EVD approach on ICP in the management of severe TBI	Mean ICP mm HG closed (higher) vs. open, $p < 0.0001$ ICP burden (≥ 20 mm Hg) closed (higher) vs. open, $p = 0.0002$
Liu X, Griffith M, Jang HJ, et al., 2020	Retrospective	107	SAH patients with EVD	To determine when accurate ICP values are demonstrated after temporarily closing the EVD when using a drain-first protocol	65.9% of intermittent closures were less than 1 minute. Only 22.9% met the definition to achieve equilibration before reopening the EVD.
Rogers M, Stutzman SE, Atem FD, Sengupta S, Welch B, Olson DM, 2017	Prospective non-randomized clinical trial	30	Patients with an EVD	To determine the time needed to observe the ICP after clamping the EVD to reflect an accurate ICP value	The probability that ICP max will occur within the first 1 minute ($p = 0.0046$), 3 minutes ($p = 0.0124$), 5 minutes ($p = 0.0181$), and 10 minutes ($p = 0.0402$) Based on the data, the authors concluded that ICP should be observed for at least 5 minutes after EVD clamping before observing and documenting an ICP.
Hockel K, Schuhmann MU, 2018	Retrospective review	20	Patients with SAH or IVH	To compare monitoring of ICP, ICP amplitude, and pressure reactivity index by an EVD in open and closed position with an intraparenchymal probe measurement by using a combined EVD with an air-pouch-based integrated probe	During open EVD period, ICP-EVD did not recognize 51 episodes of ICP-probe values > 20 mm Hg. There were 101 episodes of the absolute difference between ICP-EVD and ICP-probe > 10 mm Hg. In 85% of these episodes, ICP-probe was higher than ICP-EVD. When the EVD was closed, mean ICP amplitude did not vary significantly between ICP-EVD and ICP-probe.
Sunderland NE, Villanueva NE, Pazuchanics SJ, 2016	Retrospective review	50 patients, 1,053 sets of data	Patients with an EVD	To determine if the null position on the EVD provides accurate ICP readings	When comparing the open/monitor method vs. the closed method, results demonstrated agreement that ICP was within 3 mm Hg 97.6% of the time.

Intracranial Pressure Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Zacchetti L, Magnoni S, Di Corte F, Zanier ER, Stocchetti N, 2015	Systematic review and meta-analysis	64 studies	Patients with ICP monitoring	To conduct a literature review to evaluate the accuracy of ICP values over time	Two groups: Group 1: ventricular catheter and external transducer with another type of monitor Group 2: catheters other than ventricular Mean difference (fixed effects model) between all probes in Group 1 was 0.9 mm Hg; mean in Group 2 was 1.8. Mean difference (random effects) in Group 1 was 1.2 mm Hg and in Group 2 was 2.3 mm Hg. 17 of 37 articles reported adequate data on zero drift. The mean drift over the observation period was 0.75 mm Hg. 11 papers addressed the degree of drift related to the duration of use. 10 articles found no correlation, while 1 reported a positive correlation.
Chen L, Du HG, Yin LC, et al., 2013	Prospective observational study	49	Patients with ICP monitor	To study and compare zero drift between intraventricular and subdural ICP monitor	No significant difference in zero drift between intraventricular and subdural monitors. The Codman® monitor does exhibit zero drift in both intraventricular and subdural monitors. There is positive correlation with drift over time.

Brain Tissue Oxygenation Monitoring

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Okonkwo DO, Shutter LA, Moore C, et al., 2017	Two-arm, single-blind, prospective, randomized, controlled multicenter phase II trial	119	Severe TBI	To assess if a protocol can improve $PbtO_2$ levels in severe TBI patients	% time brain tissue hypoxia (BTH) ICP control vs. treatment: 0.44 vs. 0.15, $p < 0.0000147$ Trial stopped due to positive primary outcomes demonstrated with smaller than originally proposed sample size High 6-month GOS-E (8), ICP control vs. treatment: 6% vs. 13%, *p* not listed/not significant 6-month favorable outcomes GOS-E (5-8) ($n = 106$), treatment vs. control: 11% greater than control, *p* not listed/not significant Mortality, ICP control vs. treatment: 34% vs. 25%, *p* not listed/not significant
Carrera E, Schmidt JM, Fernandez L, et al., 2010	Prospective observational cohort	21	SAH, ICH, and TBI patients with continuous $PbtO_2$, ICP, CPP, and end-tidal carbon dioxide ($EtCO_2$) monitoring	To determine if reduction in $EtCO_2$ was associated with increases in BTH ($PbtO_2 < 15$ mm Hg)	BTH oxygenation, normal $EtCO_2$ vs. decreased $EtCO_2$: 15.7% vs. 33.9%, $p < 0.001$ $EtCO_2$ was predictive of BTH. OR = 0.94, 95% CI: 0.90–0.97; $p < 0.001$ CPP was predictive of BTH. OR = 0.98, 95% CI: 0.97–0.99, $p < 0.004$
Lubillo ST, Parrilla DM, Blanco J, et al., 2018	Retrospective observational	42	Patients between 16 and 64 years of age, with refractory intracranial hypertension due to isolated TBI (as defined according to an Injury Severity Score [ISS] < 182) who underwent decompressive craniotomy (DC)	To investigate whether changes in $PbtO_2$ after DC can be used as an independent prognostic factor for 6-month GOS	ICU admit $PbtO_2$ and % time pre-DC $PbtO_2 < 15$ mm HG, favorable outcomes (GOS 4-5) vs. unfavorable outcomes (GOS 1-3): 19 ± 4.5 mm Hg and 18.25% ± 21.9% vs. 12.8 ± 5.2 mm Hg and 59.58% ± 38.8%, $p < 0.001$ $PbtO_2$ 24 hours after DC, favorable outcomes (GOS 4-5) vs. unfavorable outcomes (GOS 1-3): 28.6 ± 8.5 mm Hg vs. 17.2 ± 5.9 mm Hg, $p < 0.0001$
Eriksson EA, Barletta JF, Figueroa BE, et al., 2012	Retrospective review	32 patients 8,759 time-indexed data points	Severe TBI with $PbtO_2$ monitors	To determine if $PbtO_2$ values over the first 72 hours are predictive of mortality	Higher $PbtO_2$ values alive vs. not: $F = 12.898$, $p < 0.001$ ICP alive vs. not: $F = 1.69$, $p = 0.204$ CPP alive vs. not: $F = 0.764$, $p = 0.389$ Mortality: $PbtO_2 \geq 29$ mm Hg hours; 53.3 ± 20.1 vs. 26.8 ± 16.1, $p = 0.001$
McCarthy MC, Moncrief H, Sands JM, et al., 2009	Retrospective review from a prospective observational database	145	TBI and GCS < 8	To compare outcomes of patients with two types of monitors (ICP monitor or cerebral oxygen/pressure monitor)	3 months moderate GOS, cerebral oxygen/pressure monitor or fiberoptic ICP monitor: 79% vs. 61%, $p = 0.09$ (underpowered due to sample size) Difference in 6 months + outcomes, cerebral oxygen/pressure monitor or fiberoptic ICP monitor, $p = 0.08$ Difference in 12 months + outcomes, cerebral oxygen/pressure monitor or fiberoptic ICP monitor, $p = 0.04$ Pneumonia, cerebral oxygen/pressure monitor or fiberoptic ICP monitor: 53% vs. 61%, $p = 0.43$ ICU LOS, cerebral oxygen/pressure monitor or fiberoptic ICP monitor: 12.4 ± 7.7 days vs. 12.8 ± 9.9, $p = 0.79$ Mortality, cerebral oxygen/pressure monitor or fiberoptic ICP monitor: 31% vs. 36%, $p = 0.52$

Brain Tissue Oxygenation Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Oddo M, Levine JM, Mackenzie L, et al., 2011	Retrospective review from a prospective observational database	103	Nonpenetrating TBI and $PbtO_2$ and ICP monitors	To evaluate the relationship between $PbtO_2$, ICP, and CPP and determine if brain hypoxia correlates with worse outcomes, regardless of ICP and CPP	GOS unfavorable (1-3) vs. favorable outcomes (4-5) Brain hypoxia hours: 8.3 ± 15.9 vs. 1.7 ± 3.7, $p < 0.01$ ICP > 20 mm Hg duration hours: 21.6 ± 29.6 vs. 11.5 ± 16.5, $p = 0.03$ CPP < 60 mm Hg + $PbtO_2$ < 15 mm Hg duration hours: 3.3 ± 7.4 vs. 0.8 ± 2.3, $p = 0.02$ ICP > 20 mm Hg, brain hypoxia vs. no hypoxia: 20/43 vs. 25/31, $p < 0.01$ CPP < 60 mm Hg, brain hypoxia vs. no hypoxia: 18/46 vs. 24/29, $p < 0.01$
Bohman LE, Heuer GG, Macyszyn L, et al., 2011	Retrospective review from a prospective observational database	49 patients 564 episodes of compromised $PbtO_2$	Severe TBI with at least one episode of compromised brain oxygen ($PbtO_2$ < 25 mm Hg)	To examine which therapies restore $PbtO_2$ to normal in TBI patients	Survivors vs. nonsurvivors: Daily episodes of compromised brain oxygen: 0.5 ± 0.6 vs. 1 ± 0.8, $p = 0.03$ Duration of brain hypoxia: 264 ± 494.8 vs. 461.8 ± 584.7 min, $p = 0.03$ Hypoxia interventions: 83.5 vs. 4.9, $p = 0.06$ Age ≤ 40 years was significantly associated with response to hypoxia intervention: $p = 0.04$ Increasing FiO_2 restored $PbtO_2$ 80% of the time. CPP augmentation restored $PbtO_2$ 73% of the time. Sedation restored $PbtO_2$ 66% of the time.
Green JA, Pellegrini DC, Vanderkolk WE, Figueroa BE, Eriksson EA, 2013	Prospective observational	74	All patients with a diagnosis of severe TBI (GCS B 8)	To evaluate goal-directed $PbtO_2$ monitoring compared to ICP/CPP only on mortality	ICP/CPP only vs. ICP/CPP and $PbtO_2$ Mortality: 64.9% vs. 54.1%, $p = 0.34$ Median LOS: 14 vs. 19 days, $p = 0.02$ Median ICU LOS: 10 vs. 19 days, $p < 0.01$ Baseline differences in admit ISS (30 vs. 26, $p = 0.03$) and chest Abbreviated Injury Scale severity score (2 vs. 0, $p = 0.02$)
Adamides AA, Cooper DJ, Rosenfeldt FL, et al., 2009	Prospective: before and after and case-control study design	30 100 matched	TBI patients with brain oxygen monitoring 10 Group 1: $PbtO_2$ monitored, not treated 20 Group 2: $PbtO_2$ monitored and treated 100 Group 3: not monitored, matched to Group 2 postintervention	To assess the efficacy of brain oxygen-guided therapy in improving cerebral oxygenation and neurological outcome in severe TBI patients	Duration (minutes) of hypoxia ($PbtO_2$ < 15 mm Hg) Group 1 vs. Group 2: 106 vs. 34, $p = 0.01$ Mean ISS Group 1 vs. Group 2: 33.7 vs. 24.2, $p = 0.04$ 6 months GOS-E Group 2 vs. Group 3: 3.39 vs. 2.61, $p = 0.17$ Mortality Group 2 vs. Group 3: 22% vs. 24.2, $p = 0.26$
Chang JJJ, Youn TS, Benson D, et al., 2009	Retrospective review	27	Sever TBI with ICP monitoring	To assess BTH in patients with severe TBI and to characterize the relationship between BTH and functional outcome	Relative risk of hypoxia, MAP < 80 mm Hg: 2.28, $p < 0.0001$ ICP > 20 cm H_2O: 1.79, $p < 0.0001$ CPP < 60 mm Hg: 3.01, $p < 0.0001$ FiO_2 < 0.6: 0.24, $p < 0.0001$ 20% of the time, hypoxic was associated with poorer GOS-E (1-4), $p = 0.046$

Brain Tissue Oxygenation Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Ledwith MB, Bloom S, Maloney-Wilensky E, Coyle B, Polomano RC, Le Roux PD, 2010	Quasi-experimental prospective repeated measures	33	TBI, SAH, and craniotomy for tumor	Examine effects of 12 different body positions on neuro and hemodynamic outcomes	$PbtO_2$ change Supine with HOB 30ϒ: $PbtO_2$ decreased 3.25 ± 9.0, $p = 0.006$, 0 Δ in ICP/CPP Supine with HOB 45ϒ: $PbtO_2$ decreased 3.94 ± 7.7, $p = 0.004$; ICP decreased 7.48 ± 5.8, $p = 0.002$, 0 Δ in CPP Left lateral with HOB 30ϒ: $PbtO_2$ decreased 2.89 ± 8.4, $p = 0.046$, 0 Δ in ICP, CPP decreased, $p = 0.044$ Right lateral with HOB 30ϒ: $PbtO_2$ decreased 1.9 ± 4.1, $p = 0.0428$, 0 Δ in ICP/CPP
Lee HC, Chuang HC, Cho DY, Cheng KF, Lin PH, Chen CC, 2010	RTC	45	Severe TBI after craniotomy	To evaluate the effect of hypothermia therapy among groups Group A: ICP/CPP management only Group B: ICP/CPP with mild hypothermia Group C: mild hypothermia with $PbtO_2$ and CPP management	Favorable outcome (GOS ≥ 4) %: Group A (50) vs. Group B (60) vs. Group C (71.4), $p = 0.0395$ Favorable outcome (GOS ≥ 3) %: Group A (31.4) vs. Group B (34.2) vs. Group C (34.2), $p = 0.02$ Mortality %: Group A (12.5) vs. Group B (6.7) vs. Group C (7.1), $p = 0.818$
Helbok R, Madineni RC, Schmidt MJ, et al., 2011	Retrospective review	32	Poor-grade SAH patients with multimodal monitoring	To investigate if neuromonitoring changes occur before clinically silent ischemia	$PbtO_2$ was lower preceding new ipsilateral frontal infarcts, $p = 0.08$
Rass V, Solari D, Ianosi B, et al., 2019	Bicentric observational cohort study	100 patients 5,841 $PbtO_2$ matched blood samples	Poor-grade SAH patients with multimodal monitoring	To quantify the BTH burden present under protocolized treatment and to identify pathologic values potentially amenable to treatment Protocol Rxs: CPP ≥ 70 mm Hg with vasopressors, euvolemia, transfusions for anemia, normocapnia ($PaCO_2$ ≥ 80 mm Hg), analgesia titration, and sedation	BTH ($PbtO_2$ < 20 mm Hg for > 10 min) $PbtO_2$ day 1 vs. $PbtO_2$ day 8: 25 ± 0.6 mm Hg vs. 28 ± 0.5 mm Hg, $p = 0.1$ Highest incidence of hypoxia day 1 vs. lowest incidence of hypoxia day 8: 31% vs. 20% $p = 0.047$ Vasospasm: hypoxia greatest on days 2-6, $p < 0.001$ Delayed cerebral ischemia: hypoxia greatest on days 3-6, $p < 0.01$ $PbtO_2$ and poor functional outcomes at 3 and 6 months: adjusted OR = 0.98 mm Hg, 95% CI: 0.94-1.02, $p = 0.32$
Oddo M, Nduom E, Frangos S, et al., 2010	Retrospective review from a prospective observational database	78	Severe, nonpenetrating TBI with continuous $PbtO_2$ and ICP monitoring	To examine the relationship between lung function and $PbtO_2$	$PbtO_2$ and PF ratio, adjusted $p < 0.01$; PaO_2, adjusted $p < 0.01$; and arterial oxygen saturation, adjusted $p = 0.03$ PF ratio < 300 was an independent risk factor of compromised $PbtO_2$: adjusted OR = 2.13, 95% CI: 1.21-3.77, $p = 0.009$ $PbtO_2$ correlated strongly with PaO_2 and PF ratio: $p < 0.05$, independent of $PaCO_2$, brain temperature, CPP, and hemoglobin
Kumar MA, Chanderraj R, Gant R, et al., 2012	Retrospective review from prospective single-center database	69	Patients with severe brain injury (GCS score ≤ 8) with continuous $PbtO_2$ monitoring	To assess if obesity is associated with compromised $PbtO_2$ after severe brain injury	$PbtO_2$ obese vs. nonobese: 25.8 (9.6) mm Hg vs. 31.8 (12.3) mm Hg, $p = 0.03$ Univariate predictors of compromised $PbtO_2$ ($PbtO_2$ < 20 mm Hg): Elevated body mass index, $p = 0.02$ Acute respiratory distress, $p < 0.01$ Mean PaO_2, $p < 0.01$ Maximum FiO_2, $p < 0.01$ Mean PaO_2/FiO_2, $p < 0.01$ Mean central venous pressure (CVP), $p < 0.01$ Multivariate predictors of compromised $PbtO_2$ ($PbtO_2$ < 20 mm Hg): mean CVP, $p = 0.02$

Brain Tissue Oxygenation Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Swanson EW, Mascitelli J, Stiefel M, et al., 2010	Retrospective review of prospective observational	45 patients 100 off-unit computed tomography (CT) scans	TBI	To examine whether $PbtO_2$ is influenced by transport to and from a follow-up head CT scan	Mean $PbtO_2$ pre- and posttransport: 37.93 ± 19.79 vs. 33.95 ± 17.21, $p = 0.0001$ Minimum $PbtO_2$ pre- and posttransport: 30.10 ± 16.48 vs. 27.56 ± 15.73, $p = 0.007$ Maximum $PbtO_2$ pre- and posttransport: 48.31 ± 32.89 vs. 41.92 ± 22.96, $p = 0.02$ Brain hypoxia duration 46.6 ± 16.0 longer after transport than before, $p = 0.008$
Lee HC, Chuang HC, Cho DY, Cheng KF, Lin PH, Chen CC, 2010	Prospective	45	Severe TBI with GCS 4-8 Group A: ICP-/CPP-guided care Group B: ICP-/CPP-guided care and mild hypothermia Group C: hypothermia and $PbtO_2$-guided ICP/CPP care	To assess if $PbtO_2$ monitoring in conjunction with therapeutic hypothermia improved ICP management and patient outcomes in TBI	Group A vs. Group B vs. Group C Mean GOS: 3.3 ± 1.3 vs. 3.5 ± 1.2 vs. 3.9 ± 1.2, $p = 0.0426$ Mean ICP: 20.4 ± 17.7 vs. 17.7 ± 8.6 vs. 16.0 ± 4.9, $p = 0.0459$ Favorable outcome (≥ 4) %: 50 vs. 60 vs. 71.4, $p = 0.0395$ Favorable outcome (≥ 3) %: 31.4 vs. 34.2 vs. 34.2, $p = 0.0201$ Mortality %: 12.5 vs. 6.7 vs. 7.1, $p = 0.818$
Peace K, Maloney-Wilensky E, Frangos S, et al., 2011	Retrospective review from a prospective observational database	34 patients 57 head CT scans	Severe TBI	To evaluate the effects of portable head CTs (pHCT) on ICP, CPP, and $PbtO_2$	Pre- vs. post-pHCT Mean ICP: 14.3 ± 7.4 mm Hg vs. 14.1 ± 6.6 mm Hg, $p = 0.84$ Mean CPP: 78.9 ± 20.2 mm Hg vs. 81.0 ± 19.8 mm Hg, $p = 0.59$ Mean $PbtO_2$: 33.2 ± 17.0 mm Hg vs. 31.6 ± 15.9 mm Hg, $p = 0.6$
Spiotta AM, Stiefel MF, Gracias VH, et al., 2010	Retrospective review from a prospective observational database	70 12,148 hours of continuous ICP monitoring 6,816 hours of continuous $PbtO_2$ monitoring	Severe TBI with ICP and $PbtO_2$ monitor	To determine if $PbtO_2$ or ICP-/CPP- based therapy improves patient outcomes after TBI	ICP/CPP vs. $PbtO_2$ Favorable short-term outcomes: 40% vs. 64.3%, $p = 0.01$ In patients treated with $PbtO_2$ interventions, mortality was associated with: Lower mean daily $PbtO_2$, $p < 0.05$ Longer durations of compromised brain oxygen ($PbtO_2$ < 20 mm Hg), $p = 0.013$ Longer durations of brain hypoxia (PbtO2 < 15 mm Hg), $p = 0.001$ More episodes and a longer cumulative duration of compromised $PbtO_2$, $p < 0.001$ Less successful treatment of compromised $PbtO_2$, $p = 0.03$
Ulrich CT, Fung C, Vatter H, et al., 2013	Retrospective	100	SAH patients with angiographically severe vasospasms (cerebral vasospasm [CVS])	To investigate the likelihood of a focal monitoring sensor being placed in vasospasm or infarction territory on a hypothetical basis	Sensor location corresponded with CVS territory per aneurysm location: Middle cerebral artery (MCA)–93% Internal carotid artery (ICA)–87% Anterior communicating artery (ACoA) or A2CA–76% A1CA–50% Vertebrobasilar arterial (VBA)–42% The focal probe location inside the infarction territory per aneurysm location: MCA–89% ICA–95% ACoA or A2CA–78% A1CA–50% VBA–23% Probability of probe placement within the territory of CVS and infarct is variable. MCA and ICA aneurysm had higher accurate sensor and probe placements.

Brain Tissue Oxygenation Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Radolovich DK, Czosnyka M, Timofeev I, et al., 2010	Retrospective analysis and observational study	32	Sedated, paralyzed, and ventilated head-injured patients	To assess whether $PbtO_2$ changes were related to transient changes in CPP, triggered by ABP or ICP variations	Changes in $PbtO_2$ were more triggered by changes in ABP vs. ICP: 81% vs. 19%, $p < 0.0001$. $PbtO_2$ Δs generally followed the direction of CPP changes. $PbtO_2$ Δs occurred regardless of the states of ABP, ICP, and CPP. $PbtO_2$ did not correlate with outcomes, age, or severity of injury.
Pascual JL, Georgoff P, Maloney-Wilensky E, et al., 2011	Retrospective review from a prospective observational database	92 patients 625 episodes compromised $PbtO_2$ 345 treated episodes	Severe TBI with $PbtO_2$ monitors	To identify the most common interventions used in episodes of compromised $PbtO_2$ and to analyze which were effective	Most common interventions: Narcotics or sedation, pressors, repositioning, FiO_2/positive end-expiratory pressure increases, and combined sedation or narcotics plus pressors

Bispectral Index Monitoring

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Eertmans W, Genbrugge C, Vander Laenen M, et al., 2018	Prospective observational	77	Successful out-of-hospital cardiac arrest (OHCA)	To investigate the ability of BIS monitoring to predict poor neurological outcome in OHCA	BIS ≤ 25 at 12 hours predicted poor neurological outcome, a 2.3-fold higher risk of poor neurological outcome, 95% CI: 1.38–3.85, $p = 0.001$ SR ≥ 3 at 23 hours was associated with a 4.4-fold higher risk of poor neurological outcome, 95% CI: 2.09–9.30, AUC $p < 0.001$
Conway A, Sutherland J, 2015	Systematic review and meta-analysis	2,138	Patients (adults or pediatric) who received procedural sedation and analgesia during inpatient/outpatient procedure in any hospital setting (general endotracheal anesthesia [GETA] or regional anesthesia were excluded)	To determine whether using a depth-of-anesthesia monitoring device improves the safety and efficacy of sedation	BIS vs. standard monitoring: 0 difference in hypoxemia, $p = 0.06$ 0 difference in hypotension, RR = 0.96, 95% CI: 0.54–1.70 Mean dose propofol: 51 mg lower for participants randomized to depth of anesthesia monitoring, 95% CI: -88.7–-13.3 mg Recovery time difference: -0.41, 95% CI: -0.8–-0.02; $I^2 = 86\%$
Jouffroy R, Lamhaut L, Guyard A, et al., 2017	Prospective	46	Refractory cardiac arrest treated by extracorporeal CPR	To assess the usefulness of BIS monitoring at bedside for an early detection of brain death occurrence in refractory cardiac arrest patients treated by extracorporeal CPR	BIS < 30 under mild therapeutic hypothermia had a 90% positive predictive value and 93% negative predictive value for brain death. BIS < 30 under mild therapeutic hypothermia had a mortality rate of 90%.
Masman AD, van Dijk M, van Rosmalen J, et al., 2016	Prospective	58	Unconscious end-of-life patients admitted to a palliative care center	To determine the feasibility and validity of BIS monitoring in terminally ill patients	Median BIS Δ pre- and postpharmacotherapy: Midazolam: -4.5, 95% CI: -7.0–-2.0, $p < 0.001$ Morphine: -0.8, 95% CI: -6.1–4.4, $p = 0.85$ Haloperidol: -2.5, 95% CI: -7.8–2.7, $p = 0.35$
Herrero S, Carrero E, Valero R, Rios J, Fábregas N, 2017	Prospective observational study	116	Elective craniotomy group and NCG patients	To examine if the Ramsay scale, Canadian Neurological Scale, Nursing Delirium Screening Scale, and BIS along with the assessment of pupils and GCS improved early detection of post-op neurological complications	Median BIS at time baseline for craniotomy group complications vs. no complications: 94, IQR = 8 vs. 84, IQR = 10.5, $p = 0.016$ Median BIS at Time2 for craniotomy group complications vs. no complications: 93, IQR =12 vs. 82, IQR = 16, $p = 0.019$ For CG, scales-BIS vs. pupils-GCS neuro alterations at PACU: 31.4% vs. 20%, $p < 0.001$ For NCG, scales-BIS vs. pupils-GCS neuro alterations at PACU: 39.1% vs. 2.2%, $p < 0.001$ The solitary predictive effects of BIS could not be separated from other assessment tools for neurological complications. BIS was part of joint assessments predictive of postoperative complications in the elective craniotomy population.

Bispectral Index Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Shetty RM, Bellini A, Wijayatilake DS, et al., 2018	Systematic review and meta-analysis	256	Mechanically ventilated adults in the ICU	To assess BIS monitoring compared with clinical sedation assessment on: outcomes—ICU, LOS outcomes—ventilation days, any-cause mortality, risk of ventilator-associated pneumonia (VAP), risk of adverse events (e.g., self-extubation, unplanned disconnection of indwelling catheters), hospital LOS, amount of sedative agents used, cost, longer-term functional outcomes, and quality of life	BIS vs. standard assessment ICU LOS: median 12 (6, 18) vs. IQR 8 (4, 14) vs. $p = 0.20$ Vent days: -0.02 days, 95% CI: -0.13–0.09. 0 significant difference Mortality: not reported in included studies VAP: not reported in included studies Adverse events risk: 0 significant difference Hospital LOS: not reported in included studies Sedative usage: could not be pooled because of differences in pharmacotherapies Cost: not reported in included studies Long-term functional outcomes: not reported in included studies Quality of life: not reported in included studies VAP: not reported in included studies
Zheng J, Gao Y, Xu X, et al., 2018	Retrospective cohort study	74	Age ≥ 18 years, mechanically ventilated ICU patients who had a flexible fiberoptic bronchoscopy and BIS monitoring, with stable hemodynamics	To verify the correlation of BIS and RASS to explore the possibility of replacing RASS with BIS	Correlation coefficients between BIS and RASS for midazolam and dexmedetomidine at 5-, 10-, 15-, 20-minute intervals were 0.724, 0.598, 0.681, 0.600, respectively, all $p < 0.05$
Tripathi M, Kumar V, Kalashetty MB, Malviya D, Bais PS, Sanjeev OP, 2017	Prospective, observational, and comparative study	28	Between 20 and 60 years of age, mechanically ventilated ICU patients at Dr. Ram Manohar Lohia Institute of Medical Sciences Group A: 14 dexmedetomidine treated Group B: 14 midazolam treated	To compare the efficacy and safety of midazolam and dexmedetomidine in mechanically ventilated patients with the help of BIS monitoring and correlation of BIS with SAS	Group A vs. Group B Vent duration hours: 77.86 ± 5.71 hr vs. 95.64 ± 17.00, $p = 0.001$ Shorten vent duration: 42.5 to 19.9 hr, $p = 0.016$ Group A BIS/SAS correlation Sedation at 15 min, 1 hr, 4 hr, 8 hr: $R = 0.85, 0.82, 0.83, 0.87$ Group B BIS/SAS correlation Sedation at 15 min, 1 hr, 4 hr, 24 hr: $R = 0.84, 0.89, 0.85, 0.83$
Yan K, Pang L, Gao H, et al., 2018	Prospective, observational	35	Severe TBI RASS: sedation depth -2/-3 BIS1: sedation depth 40-50 BIS2: sedation depth 50-60	To investigate the influence of different sedation levels guided by BIS on the therapeutic effects for severe TBI	RASS variability was lower in BIS1 and BIS2 than in the RASS group, $p < 0.05$ ICP reduction 13.5 mm Hg in BIS1 and BIS2 than RASS, $p < 0.05$ ICP variability was higher in RASS vs. BIS1 and BIS2, $p < 0.05$ ICP variability was lower in BIS1 vs. BIS2, $p < 0.05$
Olson DM, Thoyre SM, Peterson ED, Graffagnino C, 2009	Prospective randomized controlled clinical trial	67	Mechanically ventilated adult patients receiving continuous intravenous propofol	To assess if BIS sedation monitoring, as an adjunct to clinical evaluation (Ramsay score), was associated with a reduction in sedative drug use in a 12-hour period	BIS vs. Ramsay propofol monitoring: 93.5 ml vs. 157.8 ml, $p < 0.015$ 14.6 vs. 27.9 mcg/kg/min, $p = 0.003$ Risk of exceeding manufacturer recommended dosing: 0% vs. 23%, $p = 0.0052$ Awake time: 1.2 vs. 7.5 min, $p < 0.0001$

Bispectral Index Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Bocskai T, Kovács M, Szakács Z, et al., 2020	Meta-analysis	2,138	Trials that discussed anesthesia with and without BIS monitoring, which measured post-op delirium (POD) risk and post-op cognitive dysfunction (POCD)	To investigate the effects of BIS monitoring in anesthesia	BIS vs. non-BIS: POD day 1: 16% vs. 22.8%, RR = 0.71, 95% CI: 0.59-0.85 POCD at 12 weeks: 15.8% vs. 18.8%, RR = 0.84, 95% CI 0.66–1.08
Tasaka CL, Duby JJ, Pandya K, Wilson MD, Hardin KA, 2016	Retrospective observational	31	ICU patients receiving continuous infusion NMBA and BIS monitoring	To delineate the relationship between BIS and level of sedation for critically ill patients during therapeutic paralysis	BIS vs. RASS emergence from paralysis, $r = 0.27$, $p = 0.14$ Sensitivity and positive predictive value of BIS < 60 predicting deep sedation (RASS -5 to -4): 100%, 95% CI: 0-100, 35.7% Sensitivity and positive predictive value of BIS < 60 predicting light sedation (RASS -5-2): 92.9 %, 95% CI: 83.3-100, 92.9%
Bass S, Vance ML, Reddy A, et al., 2019	Single-center, retrospective cohort study		ICU acute respiratory distress syndrome patients receiving continuous NMBA	To evaluate differences in the effectiveness and safety of monitoring sedation by using BIS or traditional methods	BIS vs. standard monitoring Sedation used: propofol, $p = 0.24$; benzodiazepine, $p = 0.12$; both, $p = 0.01$ Daily total sedative exposure during NMBA, $p = 0.64$; daily total analgesic exposure during NMBA, $p = 0.18$
Jung JY, Cho CB, Min BM, 2013	Prospective	89	TBI	To identify the correlation between BIS and LOC in brain-injured patients	BIS correlation with LOC: $r = 0.723$, $p < 0.01$ BIS correlation with GCS: $r = 0.646$, $p < 0.01$
Ebtehaj M, Yaqubi S, Seddighi AS, Seddighi A, Yazdi Z, 2012	Prospective	61	ICU TBI patients	To evaluate correlation between GCS and BIS in TBI and to see if BIS values can be used as a prognostic factor in head trauma	GCS and mean BIS, $r = 0.88$, $p < 0.05$ BIS values for mild, moderate, severe head injuries: 96.2 ± 3.2, 45.5 ± 1.2, 31.3 ± 2.08, respectively, $p < 0.05$
Sahinovic MM, Beese U, Heeremans EH, et al., 2014	Prospective cohort	40	Elective excision brain tumor (BT) patient BT: 20 Control (non-brain tumor [NBT]): 20	To determine whether BIS values recorded at loss and return of consciousness differ between patients with unilateral frontal brain tumors and control patients	0 difference in median BIS values recorded at loss of consciousness 1, return of consciousness, and loss of consciousness 2 for BT and NBT groups 0 difference in interhemispheric in BIS in BT and NBT group Presence of BT did not affect BIS values.
Cottenceau V, Masson F, Soulard A, et al., 2012	Prospective observational	24 288 paired data points	TBI	To evaluate differences in BIS between hemispheres in two groups: unilateral frontal (UFI) and diffuse injured (DI)	Mean BIS in the two hemispheres were not statistically significantly different. There were statistic and clinical differences in some values in the two groups of patients (15% of bias greater than in UFI group and 10% in DI group).
Selig C, Riegger C, Dirks B, Pawlik M, Seyfried T, Klingler W, 2014	Prospective	79	Patients with BIS and suppression ration (SR) monitoring post cardiac arrest	To assess whether monitoring of BIS and SR could serve as an early prognostic indicator of neurological outcomes after CPR	26 patients (32.9%) survived the observation period of 1 month; 7 of them (8.9%) showed an unfavorable neurological outcome. These 7 patients had significantly lower median BIS values (25 [21;37] vs. 61 [51;70]) and higher SR (56 [44;64] vs. 7 [1;22]) during the first 4 hours after the initiation of CPR. Using BIS < 40 as threshold criteria, unfavorable neurological outcome was predicted with a specificity of 89.5% and a sensitivity of 85.7%. The odds ratio for predicting an unfavorable neurological outcome was 0.921 (95% CI: 0.853–0.985). The likelihood to remain in a poor neurological condition decreased by 7.9% for each additional point of BIS, on average.

Bispectral Index Monitoring (continued)

Reference	Study Design	Sample Size	Population	Study Aims	Findings
Stammet P, Collignon O, Werer C, Sertznig C, Devaux Y, 2014	Prospective observational	46	Adult comatose patients treated by therapeutic hypothermia after cardiac arrest	To assess the value of continuous BIS monitoring to predict neurological outcome after cardiac arrest	Good outcomes group vs. poor outcomes group median 24-hour BIS: 38 ± 9 vs. 17 ± 12, $p < 0.001$ Mean BIS value (first 12.5 hours) was a predictor of neurological outcome, $p = 6E\text{-}6$.
Leary M, Fried DA, Gaieski DF, et al., 2010	Prospective observational	62	Cardiac arrest patients treated with therapeutic hypothermia	To assess whether BIS values within 24 hours post-resuscitation are correlated with neurologic outcomes (cerebral performance category [CPC]) at discharge	Good outcome (CPC 1-2) vs. poor outcome (CPC 3-5): Mean 24 hr BIS: 49 ± 13 vs. 30 ± 20, $p < 0.001$ BIS ≥ 45 exhibited a sensitivity of 63% and a specificity of 86%, with a positive likelihood ratio of 4.67.
Myles PS, Daly D, Silvers A, Cairo S, 2009	Prospective	25	Critically ill, unconscious patients with ischemic-hypoxic brain injury who had emergency surgery	To evaluate the ability of BIS to predict outcomes for ischemic-hypoxic brain injury in patients who had emergency surgery	Abnormal BIS trace was strongly associated with poor neurologic outcome (positive likelihood ratio 6.6, 95% CI: 1.7-36.4, exact test $p = 0.002$). Normal BIS was predictive of good neurologic outcome ($p < 0.0005$). Clinical judgment was not predictive of good neurologic outcome ($p = 0.16$).
Dong L, Chen L, Shi T, et al., 2016	Prospective	30	Severe traumatic brain injury coma patients Group A: GCS 3-≤5 Group B: GCS >5-≤8	To investigate the value of BIS and ICP monitoring to evaluate postoperative consciousness and short-term prognosis in patients with severe TBI	BIS positively correlated with coma severity: $r = 0.532$, $p < 0.05$ BIS negatively correlated with ICP: $r = 0.521$, $p < 0.05$ 21-day survival was significantly different between Group A and Group B ($X^2 = 9.74$, $p < 0.01$).
Flores A, Ribó M, Rubiera M, et al., 2015	Prospective	53	Acute anterior circulation ischemic stroke patients who received reperfusion therapies were monitored with BIS during the first 6 hours of admission	To evaluate the impact of BIS monitoring before and shortly after reperfusion on early and delayed clinical improvement on stroke patients	BIS at discharge correlated with NIHSS: $r = -0.538$, $p < 0.001$ BIS at 24 hours correlated with infarct volume: $r = -0.430$, $p = 0.031$ Final BIS predicted clinical improvement status: OR = 1.21, 95% CI: 1.01-1.28, $p = 0.024$ Final BIS > 81 emerged as the only independent predictor of clinical improvement: OR = 11.6, 95% CI 1.112-122.3, $p = 0.04$.
Fyntanidou B, Grosomanidis V, Aidoni Z, et al., 2012	Prospective	35	Brain dead patients: hemodynamically stable, normothermic and normocapnic, free of oxygenation disturbances, and electrolytes within normal range	To record BIS alterations in brain dead patients	BIS values were 0 for the majority of the study period in all patients. However, in 23 patients, the BIS was > 30 for > 30 minutes. This increase could not be attributed to any external stimulation.
Nelson P, Nelson JA, Chen AJ, Kofke WA, 2013	Prospective	28 2,567 minutes of data	> 18 years of age, GETA, various surgical procedures not involving the head and neck	To compare the standard BIS montage with an alternate BIS montage across the nasal dorsum for neuromonitoring In EEG, montage refers to electrode placement	Standard BIS montage vs. nasal montage: mean nasal montage score was 2.0 greater, $p = 0.0001$ Nasal montage produced greater variability, but not clinically significant
Lee SY, Kim YS, Lim BG, Kim H, Kong MH, Lee IO, 2014	Prospective	58	Patients > 18 and < 75 years of age, GETA, various surgical procedures not involving the head and neck	To compare the standard frontal BIS sensor position with an alternative position across the mandible	Standard BIS montage vs. frontal and mandible montage High correlation with BIS values: $r = 0.869$, $p = 0.000$ Poor correlation during emergence: $r = 0.253$, $p = 0.077$ The authors postulated that the large correlation difference could be owing to physiologic changes that occur during different stages of anesthesia. Therefore, alternative montage placements should not routinely be interchanged.