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Biophysiologic Monitoring for the Neurosurgical Patient

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Abstract

Biophysiologic monitoring exists as a method of collecting objective information about the neurosurgical patient throughout their treatment and recovery process. Such data is crucial for an improved understanding of the disease processes while providing the surgeon additional clarity as they decipher the next best steps in decision-making and medical recommendations. In the current review article, the authors discuss the commonly used wearable and placeable monitoring devices and the biophysiological data that can be collected to monitor, as well as, assess the neurosurgical patient. Special focus is placed on invasive and non-invasive neurologic monitoring devices, but important and commonly used monitors for the rest of the body are also discussed as they relate to the neurosurgical patient. Last, the authors review new, as well as, upcoming devices and measurements to better analyze the neurosurgical patient's bodily function and physiologic status as needed. The synthesis of methods contained herein may provide meaningful guidance for neurosurgeons in effectively monitoring and treating their patients while also helping to guide their future efforts in patient biophysiologic monitoring developments within neurosurgery.

Keywords

Biophysiologic; Monitoring; Neurosurgery; Biophysiologic monitoring

Introduction

Within the realm of medicine and healthcare, biophysiologic monitoring exists as an important method to collect as well as visualize a patient's data, to understand their current health status as well as bodily function, with important uses before, during, and after any medical intervention. Biophysiologic monitoring plays an important role in the care and recovery of a patient in a variety of settings, including immediately postoperatively

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in the intensive care unit (ICU) (*e.g.*, pressure sensors for ventilator and non-invasive blood pressure cuffs to assess stability after anesthesia), for hospitalized patients on wards in recovery (*e.g.*, electroencephalography for capturing suspected seizure activity), or on outpatient visits for extended close monitoring (*e.g.*, Holter monitors for 24-hour ECG capture). Defined as physiologic and physical variables that require specialized technical instruments and equipment for their measurement, biophysiologic measures provide objective information to help physicians in their therapeutic decision-making and medical recommendations.[1] Because specialized technical instruments and equipment generally collect these measurements, specialists trained in such are necessary to properly use, assess, and interpret any biophysiologic measures related to a patient's current health status.

Biophysiologic monitoring in neurosurgery

Among the many types of patients seen as well as cared for within the hospital setting, neurosurgical patients often comprise the most challenging and complicated to manage, care for, and treat. Any damage or surgical intervention to the central nervous system can result in a cascade of events that must be monitored closely to ensure appropriate recovery. Monitoring is particularly important in trauma settings, where traumatic brain injury (TBI) often results in cerebral edema and intracranial hypertension, quickly impacting a patient's hemodynamic stability as well as mental status. Such conditions, if poorly monitored, can rapidly lead to high morbidity and mortality risk.[2] Biophysiologic monitoring is an umbrella term that includes many different types of monitoring techniques for the body's function. Included among such is neuromonitoring, a common method in neuro ICU and intraoperative monitoring of neurosurgical patients, comprising many different instruments, as discussed below. Neuromonitoring is a type of biophysiologic monitoring that focuses on measuring key components of brain physiology, with the goal of restoring these parameters to normal.[2] However, as the central nervous system plays such a crucial role in controlling and influencing the rest of the bodily functions and outputs, knowledge, as well as, the use of general biophysiologic monitoring techniques are of great importance for the success of a neurosurgeon by influencing their patient's recovery.

Herein, the authors discuss the commonly used wearable and placeable monitoring devices including the biophysiological data that can be collected to monitor, as well as, assess the neurosurgical patient's progress toward recovery (Table 1). The authors also review new, as well as, upcoming devices and measurements to better analyze the neurosurgical patient's bodily function to assess physiologic status as needed. The authors are confident that this review article will be valuable in both current understanding and future efforts in the neurosurgical area of medicine.

Methods, techniques, and possibilities for monitoring

Cerebral blood oxygen saturation monitoring

Monitoring cerebral blood oxygen saturation is a critical component of neurosurgical care, as it provides valuable information about the oxygen supply to the brain.[3] Considering that transient inadequate oxygen delivery to the brain can lead to permanent brain damage, stroke, or death, continuous and accurate perioperative monitoring of intracranial oxygenation is essential to detect, as well as, prevent potentially devastating complications.

Jugular bulb oximetry—Jugular bulb oximetry (JBO) is one invasive method used to monitor cerebral blood oxygen saturation during neurosurgery. This technique involves inserting a catheter into the internal jugular vein in the neck and positioning it near the jugular bulb. Using optical fiber systems, JBO can measure the oxygen saturation of the blood draining from the brain.[4] With its continuous and accurate readings, JBO is considered the gold standard for monitoring cerebral oxygenation and, by extension – metabolism.[5] However, similar to other invasive methods, JBO carries a risk of infection, bleeding, or catheter dislodgement. Furthermore, the longer JBO is used, the greater the risk of thrombosis or hematoma. Additionally, JBO may be insensitive to minor perfusion abnormalities and may not detect regional ischemia.[3]

Intracerebral microdialysis—Intracerebral microdialysis is another technique to monitor cerebral metabolism and oxygenation during neurosurgery.[6] This involves inserting a thin catheter into the brain tissue and continuously perfusing it with a sterile solution.[7] The catheter has a semi-permeable membrane that allows the exchange of substances between the brain tissue and the solution, which is then collected and analyzed for metabolites such as glucose, lactate, and pyruvate.[7] The levels of these metabolites provide information about the oxygen supply and demand in brain tissue.[8] Metabolite levels are mostly studied and used in patients suffering from TBI, including subarachnoid hemorrhage, but they can be reasonably used in any patient at risk for neurologic deterioration.[9] Despite the inherent risks of bleeding or infection, intracerebral microdialysis can provide valuable information about cerebral metabolism during neurosurgery.[8] One notable disadvantage of microdialysis is with regard to its limited time resolution as analytes must be processed.[10] While techniques have refined this processing time to potentially even less than one minute, microdialysis is technically not a real-time analysis.[10]

Partial pressure of brain tissue oxygen monitoring—A third invasive approach to monitoring brain oxygenation is to measure the partial pressure of brain tissue oxygen (PbtO2). Such a technique typically uses a specialized probe inserted into the brain tissue. The probe contains a sensor that measures the amount of oxygen in the brain tissue and transmits the information to a monitor. The monitor displays the PbtO2 value in real-time, allowing neurocritical care teams to monitor changes in brain oxygenation levels and adjust treatment as needed. PbtO2 monitoring is useful because it provides more direct information about brain oxygenation levels than other monitoring techniques and allows individual customization of intracerebral pressure (ICP), as well as, cerebral perfusion pressure (CPP) to modulate brain oxygenation.[11]

Non-invasive options—Non-invasive methods for monitoring cerebral blood oxygen saturation are becoming increasingly popular in neurosurgical practice. Such methods use light to measure the oxygen saturation in the blood vessels in the brain. Cerebral near-infrared spectroscopy (NIRS) is the most commonly used non-invasive method in neurosurgery, as it provides continuous cerebral blood oxygen saturation readings in real-time.[12] The device is usually placed on the forehead of the patient, and it uses infrared light to measure the absorption of oxygen in the blood vessels in the brain.[12] Ultrasound capabilities have been integrated into NIRS devices and have shown to have enhanced utility in accurately estimating brain oxygenation.[13] While non-invasive methods carry fewer risks, they currently provide less precise or continuous measurements than invasive methods. However, it is probable that in the coming years, further iteration and development will allow non-invasive techniques to compete with current gold standards.[3] Regardless of the method used, monitoring cerebral blood oxygen saturation during neurosurgery can help clinicians detect potential complications early and intervene promptly to prevent brain damage or other adverse outcomes. In some cases, it may also help to guide the surgeon's decisions during the operation, such as deciding when to end the surgery or administer certain medications.

Intracranial pressure monitoring

ICP monitoring is a crucial tool used in neurosurgery to measure the pressure inside the skull and the brain. As ICP rises, CPP inversely decreases, which leads to serious complications such as ischemia or herniation. As mentioned before, methods used to assess ICP can be categorized as invasive vs. non-invasive.

Invasive ICP monitoring—Fluid-based systems and implantable transducers are invasive ICP monitoring techniques. Of the two, fluid-based systems, such as a lumbar puncture or external ventricular drains (EVDs) are thought to be the gold standard for measuring ICP as they allow accurate pressure analysis and simultaneous drainage of cerebrospinal fluid (CSF).[14–16] However, implantable transducers, such as strain gauge transducers, pneumatic sensors, or fiber-optic sensors are also invasive methods validated to detect elevated ICP accurately. Strain gauge devices are thin wires inserted into the brain tissue or into the fluid-filled spaces surrounding the brain to measure changes in pressure.[17] Strain gauge devices tend to be the most clinically reliable transducers.[17] Pneumatic sensors operate by using an air-filled probe that compresses a sensor in relation to surrounding elevated ICP.[18] Fiber-optic sensors use light to measure ICP and have the distinct advantage of being MRI-compatible.[19] Another long-established invasive device is the subarachnoid screw, a specialized bolt inserted into the skull and brain tissue to directly measure ICP.[20,21] Telemetric sensors may be implanted for patients who require continuous ICP monitoring for a prolonged period. These devices are inserted into the brain tissue or the cerebral ventricle and connected to a telemetry system that wirelessly transmits the ICP data to a monitoring device outside the body. They can detect changes in ICP by measuring changes in the brain's electrical signals.

Invasive methods provide accurate and continuous measurements of ICP, but they carry notable risks, such as bleeding, infection, or damage to the brain tissue. However, in many contexts, invasive methods may be the preferred choice for ICP monitoring. For example, in patients with severe head injuries or those undergoing complex neurosurgical procedures, invasive methods may be necessary to provide accurate and reliable measurements of ICP. Additionally, invasive monitoring can provide crucial information for determining the appropriate treatment course in patients with cerebral edema or hydrocephalus.

Non-invasive ICP monitoring—Non-invasive methods for ICP monitoring include transcranial Doppler, optic nerve sheath diameter, wearable headsets, and electroencephalography (EEG). Transcranial Doppler (TCD) uses ultrasound to measure blood flow velocity in the brain, which can be used to estimate ICP indirectly.[22] Optic nerve sheath diameter (ONSD) likewise uses ultrasound to measure the diameter of the optic nerve sheath, which is strongly correlated with ICP.[23] Another recently developed non-invasive approach to monitoring ICP includes wearable headsets. Such devices use electrodes or sensors placed on the scalp to measure electrical or ultrasound signals in the brain and estimate ICP.[24] The headsets have great potential due to their versatility in various settings, including in the operating room, ICU, or outpatient clinic. Taking advantage of the soft anterior fontanelle, wearable headsets may be especially useful for monitoring the ICP of infants.[24] EEG power spectrum analysis is another non-invasive method that may become useful for analyzing ICP. Designed to measure the brain's electrical activity, EEG signal changes have been shown to correlate strongly with changes in ICP.[25,26] Continued study of the physiology that couples to EEG readings may enable this technique to become more widely used as a viable alternative to invasive ICP monitoring.[27]

Non-invasive methods may be most appropriate for patients who cannot tolerate invasive methods or have a lower risk of complications. For example, in patients with mild to moderate TBI or those undergoing less complex neurosurgical procedures, non-invasive methods may be sufficient to monitor ICP. Additionally, in critically ill patients who require frequent monitoring, non-invasive methods may be preferred due to their ease of use and lower risk of complications. While invasive ICP monitoring methods are still the preferred standard, it is anticipated that coming developments of non-invasive techniques will provide clinical equipoise and thereby favor non-invasive approaches due to their significantly diminished risk of complications.[28]

Cerebral compliance and ICP waveform analysis

Monitoring cerebral compliance and ICP waveform analysis during neurosurgery can provide valuable information about the status of a patient's brain to guide the management of increased intracranial pressure.[29]

Cerebral compliance refers to the ability of the brain to accommodate changes in volume without significant changes in pressure.[30] Monitoring cerebral compliance involves measuring changes in ICP in response to changes in intrathoracic pressure (such as during positive end-expiratory pressure, or PEEP) or changes in cerebral blood volume (such as during hyperventilation).[31,32] This information can help clinicians determine the optimal level of PEEP, the need for hyperventilation, and the response to medical interventions.[32]

ICP waveform analysis involves analyzing the shape and characteristics of the ICP waveform, which can provide information about the brain's underlying physiology as well as the patient's adaptive intracranial capacity.[33] The ICP waveform is typically composed of several peaks and troughs, which can be used to calculate metrics such as the mean ICP, pulse pressure amplitude (PPA), and plateau pressure.[33] Such metrics can help clinicians identify patterns of cerebral compliance, vasospasm, or increased intracranial pressure. For example, an elevated PPA may indicate increased cerebral vascular resistance, while a decreased PPA may indicate decreased cerebral compliance.[15] While both cerebral compliance and ICP waveform analyses may be useful adjunctive measurement modalities, such techniques require specialized equipment and expertise, plus their neurosurgical usability may be limited in certain clinical situations or geographic contexts.[15]

Spinal cord perfusion monitoring

Spinal cord perfusion monitoring during and after neurosurgery is critical to prevent spinal cord ischemia, which can lead to serious neurological deficits or paralysis.[34] One method of monitoring spinal cord perfusion is through the use of pressure probes that measure the spinal cord perfusion pressure (SCPP).[35] SCPP is the difference between the mean arterial pressure (MAP) and the cerebrospinal fluid pressure (CSFP).[36] A decrease in SCPP indicates a decrease in spinal cord blood flow and may lead to spinal cord ischemia. During and after spinal surgery, pressure probes are placed on the spinal cord to monitor SCPP continuously. The goal is to maintain SCPP within a certain range, at least between 60–80 mmHg, for adequate spinal cord perfusion.[36]

Another method of monitoring spinal cord perfusion is through the use of microdialysis catheters. Such catheters can measure spinal cord tissue oxygenation, as well as, glucose levels, which are indicators of spinal cord metabolism and perfusion.[37] Decreases in oxygen and glucose levels can indicate decreased spinal cord perfusion. Microdialysis catheters are placed in the spinal cord tissue and a small amount of fluid is continuously perfused through the catheter. The collected fluid can be analyzed to determine oxygen and glucose levels permitting individual optimization.[37,38]

Using pressure probes and microdialysis catheters together can provide a more comprehensive picture of spinal cord perfusion during neurosurgery.[37] The combination of such monitoring methods can help guide clinical decision-making and allow for early intervention in case of changes in spinal cord perfusion.

Other central and peripheral nervous system monitoring

Monitoring the central and peripheral nervous systems during neurosurgery is essential to ensure patient safety and prevent complications. One of the most commonly used methods for monitoring the central nervous system (CNS) is the EEG. An EEG measures the brain’s electrical activity, and as mentioned previously, it can be used to detect changes in cerebral perfusion or oxygenation, though its primary role is to detect seizures or other abnormal brain electrical activity. During neurosurgery, EEG electrodes are placed on the scalp, and the EEG signal is continuously monitored, as well as, analyzed to guide intraoperative decision-making. For example, EEG monitoring can help identify damaged cortex, detect ischemia, or optimize the extent of resection borders.[39,40]

In addition to EEG, several other methods can be used to monitor the peripheral nervous system (PNS) during neurosurgery. These include electrooculograms (EOGs), electromyograms (EMGs), galvanic skin response (GSR), photoplethysmogram (PPG), and electrocardiogram (ECG). EOG measures the electrical activity of the muscles around the eyes that can be used to detect eye movement and monitor the depth of anesthesia.[41] EMG measures the electrical activity of muscles and can be used to detect nerve damage or compression during surgery.[42] GSR measures change in skin conductance and can be used to detect sympathetic nervous system activity.[43] PPG measures change in blood volume in the capillaries of the skin and can be used to monitor changes in blood pressure or peripheral perfusion.[44] ECG measures the heart's electrical activity and can be used to detect intraoperative arrhythmias or changes in cardiac output in response to acute blood loss or anesthesia-related complications.[45]

Intraoperatively, additional monitoring modalities exist to help guide the neurosurgeon and his team to improve surgical decision-making and reduce neurologic complications. In addition to EEG and EMG, such modalities include electrocorticography (ECoG), somatosensory evoked potentials (SSEPs), brainstem auditory evoked potentials (BAEPs), visual evoked potentials (VEPs), and motor evoked potentials (MEPs). Intraoperative ECoG is the recording of cortical potentials from the brain, which is of particular use during functional surgery and in identifying the epileptogenic focus for proper resection.[46] Evoked potentials are an option for the surgeon to objectively assess the integrity of the neural pathway in question. SSEPs are the most common evoked potential type, and when applied to peripheral nerves, motor and sensory components can be tested simultaneously. SSEPs are of particular use in a variety of spine (posterior mainly), intracranial, and neuroendovascular surgeries.[47] BAEPs utilize an acoustic stimulus in the ear canal to assess both the conduction and function of the brainstem via cranial nerve eight and are of particular importance during posterior fossa surgeries, as well as, other brainstem-related procedures.[48] VEPs utilize flash stimulation of the retina to record visual pathway data. MEPs are often obtained via transcranial electrical stimulation of the brain's surface, an important method to monitor the corticospinal tract, particularly during critical surgical maneuvers or during challenging portions of a surgery.[49]

Combining methods can provide a more comprehensive picture of the patient's nervous system function during surgery. For example, EEG can be combined with EOG to detect changes in brain activity during eye movement or with EMG to detect changes in muscle activity during seizure activity. GSR and PPG can be used together to monitor changes in peripheral perfusion and autonomic nervous system activity. MEPs and SSEPs are useful together to monitor spinal cord function during spine surgery.[50] While numerous modalities exist for the intraoperative analysis of the CNS and PNS, the selection of monitoring methods should be based on the specific needs of the patient, as well as, the surgical procedure and should be guided by the expertise of the clinical team.

General techniques and considerations for the neurosurgical patient

Heart rate monitors

Abnormal and significant changes in vital signs often precede adverse events among hospitalized patients.[51] Continuous monitoring using wearable or placeable devices can lead to early recognition of stress and deteriorating patients and help improve outcomes among hospitalized neurosurgical patients. Various studies have evaluated and validated the accuracy of commercial wearable devices for detecting heart rates.[52–54] Wearable devices such as Fitbit (Fitbit Inc) have been shown to deliver high specificity and positive predictive value but low to moderate sensitivity in detecting tachycardia.[52] The heart-rate values derived from Fitbit were slightly lower than those from continuous electrocardiography (telemetry), but 73% were within five beats per minute (BPM).[53] The device's performance was significantly better among patients with sinus rhythm than those without sinus rhythm.[52–54] Wearable heart rate monitors may be a valuable tool in monitoring inpatients for signs of clinical deterioration. In addition to continually monitoring a patient's ECG, options such as telemetry provide data on a patient's respiratory rate and oxygen saturation, while all this information is transmitted to a central monitor for surgeon and assistant monitoring. Such devices also have the potential to enhance data collection in neurocritical care research.

Patient position sensors

Given the debilitating nature of neurosurgical conditions, patients are more likely to spend a significant amount of time immobile in the hospital, rehabilitation centers, or at home. Such settings put patients at an increased risk of developing conditions such as hospital-acquired pressure injuries or other conditions arising due to immobility.[55] In an inpatient setting, wearable patient position sensors can help reduce the incidence of pressure injuries.[56] Wearable sensors such as The Leaf Patient Monitoring System (Leaf Healthcare, Inc) measure body position and provide feedback promoting optimal turning practices. Such technology can effectively inform care delivery, improve turning compliance time, and reduce the incidence of pressure injuries.[57]

More than half of stroke survivors experience walking deficits and reduced mobility.[58] Wearable technologies can monitor and provide feedback on walking function across different stages of stroke recovery.[59] Technologies such as wireless sensors, accelerometers, gyroscopes, pressure sensors, and personal activity monitors provide clinicians with valuable information to guide intervention.[60] This technology is being used both in inpatient and community settings to encourage physical activity and recovery post-neurovascular intervention or post-stroke.[61]

Body temperature sensors

Elevated core body temperature after TBI has been identified as a mechanism of secondary insult to the brain that can lead to worse outcomes, while low core body temperature intraoperatively leads to a higher risk of surgical-wound infection and lengthening of hospitalization.[62,63] Closely monitoring and keeping a patient's body temperature normothermic after TBI may reduce the risk of mortality and poor neurological outcomes.[64] Wearable body temperature sensors can provide continuous temperature monitoring that will be valuable in the management of hospitalized TBI patients. Temperature monitoring is often one of the multiple features of wearables that also measure other vital signs such as heart rate, respiration, or oxygen saturation. Studies comparing the accuracy of wearable wrist devices to measure vital signs in hospitalized patients show that temperature values obtained from the wearable were inconsistent with nurse-derived values.[65] Nevertheless, wearable devices may be more effectively used to monitor changes in temperature rather than the absolute value. This finding suggests a need for further research and development efforts to improve this technology.

Fluid and electrolyte balance

Imbalances in fluid and electrolytes, particularly sodium, are common after TBI.[66] Combined central diabetes insipidus (DI), characterized by polyuria and hypernatremia, and cerebral salt wasting (CSW) syndrome, characterized by excessive sodium excretion, diuresis, hyponatremia, and negative sodium balance, rarely occur concurrently after TBI.[67] Managing combined DI and CSW syndrome remains a challenge in neurosurgical critical care because it is associated with high mortality, mainly due to delayed diagnosis and improper treatment.[68] Wearable technology that monitors fluids and electrolytes in neurosurgical patients can prevent adverse events due to fluids and electrolyte imbalance in TBI patients. Wearable microfluidic sensors simultaneously and continuously monitor local sweat rates, as well as, electrolyte concentrations.[67] Current sensors have been shown to accurately derive sweat rates and salt sodium concentration.[68] However, more robust studies looking at the accuracy and effectiveness of wearable electrolyte in neurosurgical patients is warranted.

Respiratory monitoring

The most common cause of postoperative mortality is stated to be respiratory complications, while also being the fourth most common patient safety event for hospitalized patients.[69] With neurosurgical patients included in this challenge, providing ways to monitor their status closely will help ensure an appropriate recovery time and to minimize respiratory complications postoperatively. Continuous monitoring, rather than intermittent vital sign collections, supports such goals. Of the wearable biophysiologic instruments, pulse oximetry and capnography are two of the most widely studied continuous monitoring techniques that are often used together. Pulse oximetry is a non-invasive method to continually monitor a patient's oxygen saturation, typically within 2% accuracy.[70] However, pulse oximetry has limitations, as oxygen saturations may appear normal on a patient on supplemental oxygen, despite significant hypoventilation.

For this reason, capnography is an additional option useful for neurosurgeons to manage their patient's respiratory function. Capnography measures ventilation or exhaled carbon dioxide, providing data on airflow, breathing frequency, and end-tidal carbon dioxide concentration.[69] Other options to monitor respiration include bioacoustics monitors for airflow and breathing frequency, chest wall movement that can be measured with plethysmography technology, accelerometers which are used to measure breathing frequency, and piezoelectric technology under a patient's mattress that, in addition to their heart rate, can noninvasively measure breathing frequency.[69–74]

Transcranial direct current stimulation

Poor recovery from stroke drives the search for novel and effective therapies in stroke rehabilitation. Transcranial direct current stimulation (tDCS) has been investigated extensively to evaluate its safety and efficacy in various neurological disorders, including stroke and epilepsy. The tDCS device is a 13 cm × 21 cm portable box, with two rubber electrodes that are applied with a conductive gel or water-soaked pads. Continuous current of 1–2 mA is delivered to the patient for 10–20 minutes. One electrode of the device is placed in the motor cortex region, and the other in the contralateral supraorbital region.[75]

The safety of tDCS devices has been widely studied, and only a few adverse events have been reported. Reported adverse events include headache and dizziness.[76] Studies suggest that patients with chronic stroke and/or mild-to-moderate motor impairments are more likely to benefit from tDCS. The size of the improvement post-tDCS is variable, with a maximum effect size of 35.7% improvement compared to sham.[77] Additionally, tDCS is also being studied as a non-invasive therapy of neuromodulation in epilepsy.[78] However, more robust studies with larger patient populations are warranted to evaluate the efficacy and safety of tDCS in neurosurgical patients.

Ocular pressure monitoring

TBI can result in various visual problems due to increased intracranial and intraocular pressure.[79] Intraocular pressure monitoring devices can be of great significance for the diagnosis and treatment of visual problems and be a helpful indication of a patient's condition post-TBI. Intraocular pressure monitoring devices are commonly studied in glaucoma patients in an outpatient setting.[80] Currently, studies evaluating the usage of intraocular pressure monitoring in neurosurgical patients are limited, but further investigations may demonstrate their utility for the neurosurgical inpatient.

Light reactivity monitoring

Careful and repetitive clinical monitoring is an important part of the management and evaluation of TBI patients. Clinical examinations help assess the patient's level of consciousness, pupillary diameter and reactivity light, and the presence of focal neurological deficits.[81] However, clinical examinations, such as a neurological wake-up test (NWT), are controversial in critically ill patients because they elicit an undesired stress response that may worsen the patient's condition.[82] Wearable devices that monitor light reactivity without eliciting a significant stress response may be a helpful alternative to NWT, but further robust studies evaluating such technology are needed.

Future of wearable biosensors for healthcare monitoring

The future of wearable technology in neurosurgery is optimistic. Various technologies are being developed that will ultimately help patients and providers. One such technology is the development of a patient-wearable tool for the continuous monitoring of movement disorders. The current gold standard to evaluate a patient's motor function is typically a subjective description and fails to capture daily fluctuation in motor performances. Novel wearable devices are being developed that will allow for continuous monitoring of patients' motor functions.[83] Such technology can give physicians new insights into the patient's condition and offer the best treatment options. Preliminary data on the efficacy of these devices suggests that the technology has potential but warrants future research and development.

Advancements in microfluidic paper-based analytical devices are an innovative platform for on/off-site biosensing that can be especially useful in rural or remote settings. These devices are excellent tools for point-of-care diagnosis and biosensing.[84] Utilization of these tools in neurosurgery, specifically in prehospital TBI management, can give providers early data on patient conditions that will help inform better clinical decision-making.

Biosensors are widely used across neurosurgery, and new technologies continue to be developed. However, there are still a few areas within neurosurgery where further research and development of biosensor utilization can be fruitful. One such area is monitoring hormone status post-pituitary surgery. Careful monitoring of postoperative hormone status is critical to successful outcomes.[85] A biosensor that continuously monitors hormones such as prolactin, cortisol, and growth hormones will provide valuable data regarding a patient's endocrine outcomes after pituitary surgery.

Advantages and disadvantages of biophysiologic monitoring in neurosurgery

Biophysiologic monitoring in neurosurgery is incredibly useful given the objectivity and clarity it can provide in seemingly unclear and challenging situations in patients, both in, as well as, outside the operating room. Several advantages exist that should be kept in mind for the neurosurgical patient. First, biophysiologic measurements are objective and difficult, if not impossible, for the patient to distort, allowing for easier interpretation and next-step management decision-making. Second, they are highly quantifiable and well-structured, where changes in medications, fluids, or other medical interventions will demonstrate an expected response to the biophysiologic measurements currently being monitored on the patient. Such monitoring allows for efforts to be objectively and safely reproducible between patients. Third, with many biophysiologic monitoring devices becoming smaller and more advanced, continuous data can be collected and stored on each patient during their surgery and throughout recovery. Collected data provides usable measurements to assess patient care and more accurately analyze patient outcomes retrospectively in neurosurgical clinical research. With such data, future artificial intelligence-driven monitoring systems will continue to improve and assist in improving patient care and outcomes. Fourth, data can be collected continuously on each neurosurgical patient, rather than manually and intermittently by nursing staff. Such data provides a clearer picture of each patient's surgery, recovery, and where and when additional interventions may be necessary.

Some important challenges exist with biophysiologic monitoring and require consideration when planning to utilize such methods on the neurosurgical patient. First, biophysiologic monitoring devices can be quite obtrusive depending on their size and location on the patient's body. In addition, they can become cumbersome and difficult for staff to manage and individually align. If multiple monitoring devices are being used, this can quickly frustrate the patient and supportive staff throughout the recovery phase. Second, biophysiologic measurements may be too highly relied on for their reliability and validity. Depending on the monitoring device, proper placement, and quality, inaccurate measurements may be accepted as appropriate, even if the patient is symptomatic or decompensating. Lastly, as biophysiologic devices have become increasingly advanced, some have become too complex for support staff and may require additional time and training for proper usage and handling. This is important for the most accurate data to be collected for the neurosurgeon to utilize and interpret.

As a physician weighs the advantages and disadvantages of utilizing biophysiologic monitoring for their patient intraoperatively, it is important to note several factors that may influence any monitoring that is used. Neurosurgical patients often present as some of the most complicated and complex patients to care for, with their metabolic demands and autonomic functions varying significantly depending on the cause of hospitalization (*e.g.*, TBI, spinal cord injury, Guillan-Barre Syndrome, *etc*.). Similarly, a patient’s functional and coma status may make some monitoring devices more relevant or useful than others. Other factors that may influence biophysiological monitoring include proper attachment/placement of the device on or around the patient, proper software updates and setup, a patient’s size and/or body habitus, a patient’s systemic vs. local infections, a patient’s willingness to cooperate with the monitoring device’s use, and supporting staff’s willingness to ensure proper use and attachment throughout recovery. These are a few of the many factors that may influence the function of biophysiologic monitoring devices, which will require thought to their proper use before and during their placement.

Once the neurosurgeon has assessed the reason for hospitalization and potential neurosurgical intervention, they may move on to review the multiple options of biophysiological monitoring devices (Table 1) and weigh the advantages and disadvantages of each, for their patient’s current situation and medical status. Once these have been examined and determined, such monitoring devices may be added to the order of the patient’s care plan to be executed as needed throughout treatment and recovery. Such functions may be included in new protocols for different neurosurgical pathologies or surgeries, which may speed up this process for the care team. Frequent discussion on the phase of recovery may be necessary to ensure monitoring devices are adequately utilized, including when a monitoring device may no longer be needed given the recovery or decline of the patient’s health status.

Holistic discussion of biophysiologic monitoring in clinical practice

Holistic medicine is an approach to health care that addresses the psychological, familial, societal, ethical, spiritual, and biological dimensions of health and illness.[86] When considering the holistic side of medicine, biophysiologic monitoring plays an important role in a patient’s well-being, as it helps to address the biological dimension of health and illness of the patient, which is necessary to understand the overall characteristics, stages, and severity of the patient’s disease through objectively notable clues. This is similar to governing health exterior to inferior in Chinese Medicine, as external monitoring can help the physician clinically determine the extent of an individual’s disease and more accurately determine their overall recovery or worsening of their condition. Though disease processes and conditions may appear similar externally and clinically, each patient is internally unique and therefore requires close biophysiologic monitoring to assess each patient as a unique individual to ensure they are internally cared for.

Conclusions

Biophysiologic monitoring for the neurosurgical patient includes a wide variety of invasive and non-invasive options to best assess the patient's bodily function and health status, pre-, intra-, and postoperatively. Within neurosurgery, subjectivity in patient signs and symptoms plays a large role in differential diagnoses and management but can introduce challenges in clearly guiding surgical and non-surgical decision-making. Herein, the authors have provided a clear review of the commonly used biophysiologic monitoring options and their measurements within neurosurgery. The synthesis of methods contained herein may provide meaningful guidance for neurosurgeons in effectively monitoring and treating their patients while also helping guide future efforts in patient biophysiologic monitoring developments within neurosurgery.

bpm, beats per minute; cm, centimeter, dBm decibel milliwatt; dL, deciliter; Hg, mercury; hr, hour; L, liter; IMU, inertial measurement unit; kPa, kilopascal; mA, milliamps; mg, milligram; mm, millimeter; Mmol, millimole; ml, mililiter; mV, millivolt; s, second; µS, microsiemens.

Abbreviations:

BAEP	brainstem auditory evoked potentials
CCP	cerebral perfusion pressure
CNS	central nervous system
CSF	cerebrospinal fluid
CSFP	cerebrospinal fluid pressure
CSW	cerebral salt wasting
DI	diabetes insipidus
ECG	electrocardiogram
ECoG	electrocorticography
EEG	electroencephalography
EMG	electromyogram
EOG	electrooculogram
EVD	external ventricular drain
GSR	galvanic skin response
ICP	intracranial pressure
ICU	intensive care unit
JBO	jugular bulb oximetry

MAP	mean arterial pressure
MEP	motor evoked potentials
MRI	magnetic resonance imaging
NIRS	near-infrared spectroscopy
NWT	neurological wake-up test
ONSD	optic nerve sheath diameter
PbtO2	partial pressure of brain tissue oxygen
PNS	peripheral nervous system
PPA	pulse pressure amplitude
PPG	photoplethysmogram
SCPP	spinal cord perfusion pressure
SSEP	somatosensory evoked potentials
TBI	traumatic brain injury
TCD	transcranial doppler
tDCS	transcranial direct current stimulation
VEP	visual evoked potentials

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Table 1.

Wearable and placeable monitoring devices and their related biophysiological data

Monitoring instrument	**Method of use**	**Data recorded (*Units*)**
Cerebral blood oxygen saturation monitoring		
Jugular Bulb Oximetry (JBO)	A catheter is inserted into the internal jugular vein near the jugular bulb.	Oxygen saturation of blood draining from the brain. (*% oxygen saturation*)
Intracerebral microdialysis	A thin catheter is inserted into the brain tissue, collecting metabolites (*e.g.*, glucose, lactate, pyruvate)	Monitor cerebral metabolism and oxygenation by analyzing the levels of metabolites such as glucose, lactate and pyruvate (*mg/dL, mmol/L)*
Partial pressure of brain tissue oxygen monitoring (Pbt02)	Oxygen sensing probe is inserted into the brain tissue	Partial pressure of the brain tissue oxygen (*mm Hg*)
Cerebral near-infrared spectroscopy (NIRS)	A device placed on the forehead of the patient uses infrared light to measure the absorption of oxygen in the blood vessels of the brain	Cerebral blood oxygen saturation (*% oxygen saturation*)
Invasive ICP monitoring		
Strain gauge transducers	The thin wire is inserted into the brain tissue or fluid-filled space surrounding the brain	Changes in intracranial pressure (*mm Hg*)
Pneumatic sensors	Use an air-filled probe that compresses a sensor in relation to surrounding elevated ICP	Changes in intracranial pressure (*kPa*)
External ventricular drain (EVD)	Cather is placed into a lateral ventricle to measure the output and pressure of CSF	Changes in intracranial pressure and output of CSF (mm Hg, *ml/hr)*
Fiber-optic sensors	Uses changes in light reflected back from a mirror at the end of the cable	Changes in light reflected back reflect changes in ICP (*dBm)*
Subarachnoid screw	Specialized bolt is inserted into the skull and brain tissue	Changes in intracranial pressure (*mm Hg)*
Telemetric sensors	Telemetric sensor devices are inserted into the brain tissue or the cerebral ventricles for continuous ICP monitoring for a prolonged period	Continuous changes in intracranial pressure (*mm Hg)*
Noninvasive ICP monitoring		
Transcranial doppler (TCD)	Manual steering of transducer on cranium	Measures blood flow velocity in brain vessels (*cm/s, mm)*
Optic nerve sheath diameter (ONSD)	Uses ultrasound to measure the diameter of optic nerve sheath	Indirect estimate of ICP on compression of optic nerve (*mm)*
ICP wave form analysis	Analysis of the shape and characteristics of the ICP waveform	Pressure changes from fluctuations of CSF related to respiration and cardiac cycle (*mm Hg)*
Spinal cord perfusion monitoring	Microdialysis catheters are inserted into the spinal cord tissue	Spinal cord tissue oxygenation, perfusion pressure, and glucose levels (% oxygen saturation, mm Hg, mmol/L)
Electroencephalography (EEG)	Electrodes placed on the scalp	Spontaneous electrical activity via real-time voltage recordings (*mV*)
Electrooculogram (EOG)	Electrodes around the eye, between the cornea and Bruch's membrane	Eye movements and monitor depth of anesthesia via resting electrical potentials (*mV*)
Electromyogram (EMG)	Electrodes (small needles) inserted through the skin into muscles throughout body	Muscle response to electrical activity from stimulation (*mV*)

Monitoring instrument	Method of use	Data recorded (*Units*)
Galvanic skin response (GSR)	Electrodes placed at finger, foot, or shoulder over sweat glands	Measures changes in electrical conductance of skin, detects sympathetic activity (μS)
Photoplethysmogram (PPG)	Wearable device that uses a light source and a photodetector at the surface of skin to measure the changes in blood volume in the capillaries	Monitors change in blood pressure or peripheral perfusion (*mm Hg)*
Electrocardiogram (EKG/ECG)	Electrodes placed around the heart	Electrical activity of heart fibers (*bpm, ms, mm)*
Electrocorticography (ECoG)	Electrodes placed directly on the brain tissue	Cortical potentials (*mV*)
Somatosensory evoked potentials (SEP)	Electrodes placed on extremities	Measures electrical response to evoked potentials on integrity of somatosensory pathways (*mV*)
Brainstem auditory evoked potentials (BAEP)	Electrodes placed on the scalp	Measures electrical response to acoustic stimulus to assess CN VIII function (*mV*)
Visual evoked potentials (VEP)	Flash stimulation of the retina and electrodes placed on the scalp	Measures evoked potentials on visual pathway (*mV*)
Motor evoked potentials (MEP)	Transcranial or direct electrical stimulation is applied to the motor cortex through electrodes placed on the scalp/brain	Measures evoked potentials on integrity of motor pathways (*mV*)
Telemetry	Electrodes placed over patient's chest around heart and lungs	Continuous monitoring of heart rate and oxygen saturation (*bpm, % oxygen saturation*)
Patient Position sensors	Wearable patch placed on chest containing 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer	Angular rate and specific force (IMU)
Body temperature sensors	Wearable patch placed anywhere on body	Changes in temperature (*Celsius or Fahrenheit*)
Fluid and electrolyte sensor	Wearable patch	Local sweat rates and electrolyte concentrations, particularly Na^+, K^+, H^+, Mg^{2+}, Ca^{2+} (*mmol/L*)
Transcranial direct current stimulation (tDCS)	Constant low direct current is delivered to the brain via electrodes on the head with head strap	Cortical excitability from direct currents (mA)
Ocular pressure monitoring	Lens like device that is placed directly on the eye	Intraocular pressure (*mm Hg*)
Extra orbital plethysmography	Custom goggle-based device worn over the eyes.	Pressure changes in the space around the orbit (*mm Hg*)