Multimodal Neurocritical Care Monitoring: Conceptual Approach and Indications

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The neurologically critically ill patient requires a comprehensive approach to evaluation and management. Standard intensive care monitoring equipment may lead to incorrect assumptions of the underlying pathophysiology at any given time. With the advancement of neurocritical care comes the evolution of advanced neurological monitoring techniques, technologies, and concepts. Much initial knowledge of brain injury was gained via the study of head trauma. More recently, application of the same techniques to other conditions, such as stroke, hemorrhage, and metabolic brain disease has expanded the concepts, goals, and benefits of multimodal neuromonitoring. The current review attempts to summarize and update basic understanding of many of the advanced neuromonitoring tools employed in the neurocritical care unit, from basic assessments of intracranial and cerebral perfusion pressure, to advances in cerebral blood flow determination, cerebral oxygenation and temperature, and brain metabolism with microdialysis, as well as non-invasive assessments of blood flow and electrical activity. Not all neurocritical care illnesses can be approached the same, nor can all patients with similar brain injury be expected to follow the same disease course. Therefore, combination or multimodal neuromonitoring of patients becomes more important to trend different physiologic parameters in each patient as indicators of the underlying and ongoing pathophysiologic mechanisms that will enhance and guide decision making, intervention, and improve outcome.

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KEY WORDS: Neurocritical care · Intracranial pressure · Neuromonitoring · Technology.

Introduction

Although detailed multimodality neuromonitoring of the acutely injured brain is not yet performed routinely in most hospitals, it represents a logical way to evaluate, understand, and optimize the neuromedical management of the critically-ill neurologically injured individual. The overall goals are to salvage uninjured tissue and to minimize or prevent ongoing secondary brain injuries. Conceptually, a proactive mind-set to recognize as early as possible the events leading to ongoing secondary brain injury should always take priority over simple reactive approaches after worsening has already occurred. Therefore, knowledge of fundamental physiology and pathophysiologic mechanisms, combined with the tools of the modern neurocritical care armamentarium allow anticipation and proper advanced monitoring to avoid injuries that otherwise go unrecognized until clinical sequelae become pronounced, and often irreversible. As with other intensive care settings, the neuroscience critical care unit requires interplay between abundant patient care systems and monitors, as well as the various systems within the hospital setting itself. Attempts to document, detail, and advance the state of care and continually strive to improve outcomes has led to the development of expanded record keeping, research databases, and quality assessment systems interconnected with the daily activities to best serve patients (Fig. 1).

The clinical examination is one of the foundations of clinical neuroscience. However, many patients in the neurocritical care unit (NSICU) are comatose, intubated, sedated, or otherwise not accessible for a detailed examination, and hence, methods were soon adapted to facilitate monitoring of the brain performance. Traditionally, ICP and CPP have been frequently employed to provide a moment-to-moment estimate of the intracranial hemodynamics. However, other major determinants for brain tissue survival such as adequacy of cellular oxygenation, glucose metabolism, and neuronal functioning both at the larger (electrical) and regional (cellular) levels have only been recently been introduced to the

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First, neuromonitoring should ideally be performed within the acute hemodynamic and metabolic dysfunction, the greater the likelihood to recognize ongoing or developing secondary brain injury. Early detection of secondary worsening of neuronal function, or more importantly, the proactive anticipation and recognition of physiologic trends known to correlate with tissue performance. Second, depending on the predominant primary brain injury mechanism, certain brain performance measurements are more important to monitor than others; hence, a priority list should be established for each individual patient to prioritize the most informative monitoring parameters particular to that patient and to avoid the indiscriminate use of additional or suboptimally selected invasive monitoring. For example, monitoring intracranial pressure (ICP) in patients at risk for the development of secondary brain swelling after completed large ischemic infarction or the occurrence of new mass effects from delayed bleeding complications proves appropriate and effective. In contrast, ICP monitoring will not be of great value in a patient at risk for vasospasm after subarachnoid hemorrhage where regional changes in cerebral blood flow or slowing of electrical activity are more indicative of worsening brain function. Third, once monitoring parameters are obtained, there is the common danger of either discounting or misinterpreting the obtained values. For example, it takes expertise and diligence to understand the role of an abnormal monitoring result. Even simple ICP elevations may either reflect erroneous inclining values in an otherwise asymptomatic patient indicative of baseline drift of an intraparenchymal brain pressure probe, or the elevation may herald dangerous plateau waves in a noncompliant, swollen brain with autoregulatory failure.

**Intracranial Pressure (ICP), Cerebral Blood Flow (CBF), and Cerebral Perfusion Pressure (CPP)**

As widely known, continuous ICP readings are most commonly obtained from intraventricular and intraparenchymal...
devices such as external ventricular catheters (EVD), Camino™ or Ventrix™ monitors, and less frequently from subdural or epidural bolts (i.e. Richmond System, etc.). Importantly, intraparenchymal microsensors and strain gauges have a minimal associated risk (i.e. infection, local bleeding), but may experience drift (upward or downward inaccuracy of the zero point) over time, which is not seen with EVD’s. Thus, EVD catheters are still considered the gold standard for ICP monitoring. Furthermore, the EVD catheter also allows for therapeutic drainage of CSF that is not an option with standard ICP monitors alone. The monitored ICP waveform already discloses important diagnostic information about the brain compliance: for example, elevation of the second peak (P2 or tidal wave, which is the results of the cardiac dichrotic notch) seen in excess of the first peak (P1 or percussion wave) are considered to be provide valuable information for decreasing brain compliance and increasing risk of brain injury for high ICP’s (Fig. 3).1

Until recently, continuous, real-time cerebral blood flow (CBF) measurement was not possible at the bedside. Most commonly, xenon-enhanced CT scanning allowed a semi-invasive measurement of CBF at the time point of the examination. While transcranial Doppler ultrasound (TCD) allows a continuous measurement of flow velocity it can only used to approximate the concurrent blood volume flow in the insonated arterial segment. Nowadays, two direct and continuous methods are available to measure CBF. First, laser Doppler flowmetry (LDF) developed in the 1980’s functions on similar physical principles as the TCD monitoring, except that the probe is directly inserted through a burr hole into the brain white matter.2 A monochromatic laser light is emitted measuring both the concentration and velocity of red blood cells to generate a flow signal. Limitations are very small sample volume (−1 mm³) and the inability to only measure relative flow changes transcribed to the monitor as arbitrary flow units.3 The second method is based on thermal diffusion which allows a quantitative estimate of regional CBF. Thermal diffusion correlates the dissipation of heat, generated (−39° Celsius) and controlled by a small distal thermistor as it arrives at the second, more proximal thermistor outside of the direct thermal field of the distal heat generator. Based on the tissue’s ability to dissipate the heat deriving from the distal thermistor a quantitative estimate of CBF can be obtained and expressed as mL/100 g/min.4 The clinician can choose CBF monitors from several manufacturers such as Laserflow, Vasamedics Inc, St Paul, MN, USA: OxyFlo, Oxford Optronics, Oxford, UK: Bowman Perfusion Monitor, Ansprach Companies, Gloucester, MA, USA: Saber series, Flowtronics Inc, Phoenix, AZ, USA.

Measuring CBF has been applied to patients with subarachnoid hemorrhage (SAH),5 head trauma,6 and patients undergoing neurosurgical operations.7 Under physiological conditions neurons shift from aerobic to anaerobic metabolism as the CBF drops below 18 mL/100 g/min.8 Careful adjustments are required for the increased metabolic demand of injured brain tissues. In addition, CBF measurements are only obtained locally, thereby neglecting the variations in CBF throughout the remaining, non-monitored brain compartments, both injured and uninjured. However, as neurocritical care relies heavily on the principle of blood pressure augmentation in many forms of brain injury (i.e. SAH, vertebrobasilar insufficiency, stroke, revascularization, CPP salvage, etc.) CBF monitoring is certainly a very helpful adjuvant to the clinical management of such patients (Fig. 4).9

Intracranial pressure (ICP) remains the primary neuromonitoring parameter selection in general, due to the long history and simplicity by which it can now be determined. Further, most neurocritical care physicians and neurosurgeons are quite comfortable discussing ICP in patient care. As a neuromonitoring parameter it adequately allows for assessment of global pressure, but not local phenomena. A major downfall to it’s sole use is that it may remain reasonably normal along an extensive range of values, until a critical point when it becomes difficult to manage (Fig. 5). The interplay between cerebral perfusion pressure (CPP) and ICP, the latter delineating the main force counteractating arterial flow and hence arterial perfusion, are the principal determinant of the autoregulatory mechanism.
regulatory brain perfusion response (Fig. 6). Brain perfusion remains rather constant between mean arterial pressures (MAP) from 80 to 100 mm Hg. Normal ICP ranges from 5 to 10 mm Hg resulting in a CPP (MAP-ICP) of approximately 70 to 85 mm Hg. Consistent and continuous MAP measurement should be obtained from intra-arterial catheters. True (regional) CPP measurement may vary as much as 30 mm Hg from the calculated values utilizing the CPP formula when compared to CPP obtained from TCD readings. Of note is that for more accurate CPP estimation the zeroing of the arterial transducer should be done at the level of the foramen of Monro in order to obtained meaning CPP values. However, to avoid physical inconsistencies in anatomy and height, the most accurate assessment of CPP is made when the foramen of Monro, heart, and intra-arterial catheter and transducer are all at the same height (i.e. supine position), although this may be at times hazardous to assess, when ICP becomes critically elevated. Autoregulatory failure or the inability for cerebral arteries to regulate and adjust their luminal diameter in response to systemic blood pressure changes, lead to direct de-
pendency of the cerebral perfusion on the CPP (Fig. 7). Commonly, a CPP threshold of >60 mm Hg is used clinically to maintain adequate brain perfusion. However, CPP minimum of 60 has been inadequately proven in larger series and may vary significantly between patients and between disease entities and underlying pathophysiology. Both ischemic and hypoxic events are well-described, even with CPP values above 70 mm Hg. Importantly, higher than appropriate CPP can quickly lead to hyperperfusion breakthrough and subsequently to tissue hyperemia and increased ICP.

Cerebral Oxygen Monitoring

One of the tenets of neurocritical care therapy is the prevention of secondary tissue ischemia. To date, four methods exist to measure brain oxygenation: jugular venous bulb oxymetry, near infrared spectroscopy, brain tissue oxygen tension, and 18O2 PET.

Jugular venous bulb oxymetry is based on the retrograde insertion of a fiberoptic oxymeter (Abbott Opticath, Abbott Laboratories, Chicago, IL) into the jugular vein with the tip placed into the jugular bulb with radiographic position confirmation, to continuously measure the oxygenation of cerebral venous blood return (SjvO2). The oxymeter needs to be recalibrated daily and is MRI compatible; the normal SjvO2 range is 55% to 69%. Cerebral venous oxygen saturation is the difference between cerebral oxygen delivery and the brain metabolic demand of oxygen (CMRO2), given that the hemoglobin concentration, hemoglobin saturation, and hemoglobin dissociation remain unchanged. The SjvO2 provides a direct measurement of CBF in patients with normal flow-metabolism coupling as it can detect hemispheric arterial hyperperfusion, that is, a reduction in oxygen delivery (CBF), or increase in demand, that is, in oxygen extraction (oxygen extraction fraction: OEF). A high SjvO2 indicates the opposite, either a reduction in oxygen extraction (OEF) or an increase in oxygen delivery (hyperperfusion). As the hemoglobin concentration in arterial and venous blood is the same, and the difference in the amount of dissolved oxygen is usually minimal between arterial and venous samples (at low FiO2), the (AVDO2) can be estimated by comparing the difference between SaO2 and SjvO2, the so-called cerebral extraction of oxygen, or CEO2 (or, on other words AVDO2=CMRO2/CBF, where CMRO2 is the metabolic rate of oxygen consumption). The normal range of CEO2 is 24% to 42%.

The use of SjvO2 is in three categories: as a prognostication tool, to adjust the optimal rate of hyperventilation, and to monitor for intraoperative and postoperative desaturation. After traumatic brain injury about one third of patients have jugular venous desaturations and the occurrence correlates with increased mortality. In comatose patients, single episodes of low (<50%) SjvO2 for >10 minutes correlate with an increase in mortality. Experience proves that many desaturation events could have also been detected by monitoring ICP, mean arterial pressure, and systemic oxygen and end-tidal carbon dioxide (ETCO2); however, SjvO2 allows improved fine-tuning of cerebral oxygen balance. The titration of critical brain arterial perfusion thresholds can be guided by optimizing the SjvO2 in an individual patient. Further, in patients with high SjvO2 and reduced extraction fraction (CEO2), hyperventilation (inducing reduction of cerebral blood flow from arterial constriction) can be titrated to achieving normal SjvO2. Theoretically, such monitored hyperventilation will allow reduction in critically high ICP without inducing an abnormally low SjvO2 that may otherwise further aggravate brain ischemia. Intraoperative use of jugular venous oxymetry identified frequent (up to 50%) desaturations during aneurysmal surgery for patients with subarachnoid hemorrhage and during cardiac surgery (in 23%), the latter correlated with worse postoperative cognitive outcome.

However, the limitations of this method are not solely the inherent risks of placing and maintaining the catheter. The probe is prone to artifacts and, importantly, jugular venous oxymetry only measures the global oxygenation of one hemisphere, hence, will not detect contralateral oxygenation problems or smaller, regional problems ipsilateral to the transducer. Reliability is further compromised by marked changes in arterial oxygen content and prone patient positioning. Additionally, a relative but small risk of infections, venous thrombosis, arterial puncture, and pneumothorax exists. Further, it is useful to recalibrate the device not only on a regular basis (i.e., every day), but also when the device reading and a blood sample withdrawn from the catheter is >4% discordant. In the hands of an expert clinician and with selection of the right patient population (i.e. head trauma, other injuries leading to diffuse cerebral edema, etc.) jugular venous oxymetry represents a very valuable clinical monitoring method.

Transcranial cerebral oxymetry is based on near infrared spectroscopy (NIRS), using the transmission and tissue absorption of near-infrared light (700 to 1,000 nm), the latter commonly used in modern systemic oxygenation monitoring (i.e. positioning on ear lobe, fingers, or toes) as it provides a simple and cheap measure of hemoglobin saturation and systemic oxygenation. Transcranial cerebral oxymetry is based on similar principles and commercially available (NIRO series, Hamamatsu Photonics, Japan: INVOS series, Somanetics Corporation, Troy, MI, USA). These cerebral oximeters are placed directly on the skull and measure oxygen saturation of the hemoglobin directly underlying the probe (rSO2),
that is, a mixture of venous and arterial blood and brain tissue. Normal rSO2 values have been reported to be between 60% and 80%. For example, the method has been used to monitor changes in cerebral oxygenation during carotid endarterectomy. Other studies have found inconsistent results with respect to the method’s predictive outcome values. There is rather significant skepticism among experts in the reliability of this method. Not only does NIRS fail to differentiate between extra- and intracranial blood oxygenation sources, but also “normal” values were reported in studies using pumpkins, brain dead patients, and corpses. Furthermore, the degree of scatter from infrared light is unpredictable among adult patients, especially when scalp hematoma or swelling is present. These disadvantages and monitoring inconsistencies have greatly limited cerebral NIRS for adults with brain injuries. Possible intracranial use of similar technology may become more useful, but becomes far more invasive.

Brain tissue oxygen tension (brain PtiO2 or PbtO2) directly measures the oxygenation of brain parenchyma using a small, flexible microcatheter inserted through a small burr hole into the white matter. The catheter is fixated at the burr hole site by a special bolt or may be tunneled and secured alternately. Two competing technologies are currently commercially available, Licox™, Integra Neuro Sciences, San Diego, CA, USA; Neurotrend™, Codman, Raynham, MA, USA. The Licox™ system uses polarography (using the so-called Clark electrode). In contrast, the Neurotrend™ employs optical luminescence to measure PbtO2, PbtCO2, and brain tissue pH. Both systems are generally MR-compatible except for the expected image artifacts. Normal values range at 40 mm Hg and the measured volumes is estimated at 17 mm3. However, measurements will vary depending on the placement region and be highest in the cortex and hippocampus and lower in the white matter. Microcatheter placement can be into the region of interest and should reach into the white matter: the external connections can be tunneled after craniotomy or placed through a single double or triple lumen bolt. Cerebral tissue oxygenation reflects largely tissue perfusion but also the local extraction fraction. Studies suggest that brain ischemia, defined as <18 mg/100 g/min on xenon-CT, correlates with a PbtO2 of 22 mm Hg using the Neurotrend™ system, jugular bulb venous desaturation (threshold at 50%) correlated with a PbtO2 of 8.5, and ischemia determined by SPECT correlates with an average PbtO2 of 10±5 mm Hg compared with values of 37±12 mm Hg in normal brain. Low PbtO2 values are frequently found immediately after head injury (Fig. 8) and when CPP is compromised in the setting of raised intracranial pressure.

Low PbtO2 has been shown to correlate with poor outcome after traumatic brain injury: for example, Zauner et al. found in patients with severe head injury that the mean PbtO2 was 39±4 mm Hg, 31±5 mm Hg, and 19±8 mm Hg for good, moderate to severe disability, and poor outcome. Further, episodes of 30 minutes or more of PbtO2 <10 mm Hg appear to indicate poor outcome. PbtO2 monitoring has been applied during neurosurgical procedures, especially with approaches employing temporary arterial occlusions, where it indicates tissue hypoxemia more reliably than jugular venous oxymetry when appropriately placed into the tissue region at risk. Conversely, in subarachnoid hemorrhage patients, the value of PbtO2 monitoring for the detection of vasospasm is rather due to its small sample volume and the regional heterogeneity of vasospasm; however, PbtO2 values do improve with successful vasospasm treatment. As expected and discussed further above, in regions with focal pathology jugular venous oxymetry is less sensitive than PbtO2, and in a larger study comparing jugular venous and brain tissue oxygenation global ischemia was detected at 64%, 70%, and 90% for monitoring at the jugular versus brain tissue versus both sites. PbtO2 will provide real-time measurements of autoregulation (and its impairment) and the effect of therapeutic interventions. Therefore, it is expected to have a clear impact in many patients with traumatic or larger focal, acute brain lesions. Further, PbtO2 may facilitate early detection of worsening or expansion of ischemic areas, such as penumbra of ischemic or hemorrhagic stroke (Fig. 9). PbtO2 is a valuable monitoring parameter for multimodality monitoring of the
Cerebral Metabolism Monitoring—Intracerebral Microdialysis

Brain microdialysis monitors the biochemical environment of the extracellular space. Developed in 1966 as the first use of a dialysis membrane, modern microdialysis devices contain a blood capillary-like dialysis probe (~0.62 mm in diameter) which is inserted into the brain region of interest and infused (ultralow at 0.1 to 0.2 μL/min) using either lactated Ringers solution or normal saline. The saline equilibrates with the interstitial fluid to compensate for the difference in ionic and biochemical interstitial fluid components (usually of a size smaller than 10−20 kD) between the two spaces. The dialysate is extracted after equilibrium perfusion (usually after 10 to 60 minutes) and then analyzed by enzyme spectro photometry or high-performance liquid chromatography at the bedside. Common measures included glucose, lactate, and pyruvate to monitor carbohydrate metabolism; glutamate as a reflection of ongoing cell injury; and glycerol and choline to indicate cell membrane breakdown. A variety of additional substances can be monitored with advanced microdialysis membrane equipment that allow permeation of substances up to 300 kD, for example, urea, amino acids and peptides, cytokines, antibiotics, nitrates and nitrates, and adenosine. The catheter is MRI-compatible and commonly fixated at the cranium via a bolt, tunneled through craniotomy site, or inserted and fixated through a simple burrhole. Referred insertion sites are located directly within or close to the injury focus or at a standardized right frontal lobe site (Kocher’s point) in patients with global brain injury.

During hypoxemia and ischemia, lactate metabolism and glutamate release increase which can be reliably detected by microdialysis and is further supported with concomitant declines in monitored PbtO2 and CBF. Metabolites referring to increased cellular membrane damage such as choline and glycerol often precede permanent neurological injury. Much of the microdialysis experience has been gained from studying patients following traumatic brain injury; subarachnoid hemorrhage and clinical vasospasm, intracerebral hemorrhage, and intraoperatively. Increases in the lactate/pyruvate ratios indicate incomplete glucose metabolism and ischemia and predict poor outcome in traumatic brain injury. Many other variables and ratios are currently under investigation in various neurosurgical and cerebrovascular patient populations, especially with respect to their prognostic value and potential reversibility of biochemical abnormalities under therapeutic maneuvers. Generally, observing the trends of microdialysis parameters seems to be more academic than simply applying absolute numerical values for each individual value. Cerebral microdialysis provides a powerful research instrument, that when coupled to other near monitoring technology, stands to teach neurocritical care physicians the cellular and molecular pathophysiology of brain injury and the direct impacts of our therapeutic maneuvers.

Transcranial Doppler Ultrasound

Several important, continuous, flow-dependent variables of the cerebral arterial tree can be reliably and noninvasively assessed by means of transcranial Doppler sonography (TCD). For example, TCD can yield a noninvasive ICP monitoring method to identify and monitor the pressure effects of unilateral hemispheric mass lesions indicated by a decrease in ipsilateral mean flow velocities and reduced ipsilateral-to-contralateral pulsatility index ratio due to increases in ipsilateral pulsatility.

In addition, several TCD examination methods have been described to access cerebral autoregulation. Most are not feasible to be employed for continuous monitoring. However, the technology allows for: a) assessments of cerebral autoreactivity using relative changes of the arterial carbon dioxide concentrations which inversely correlates with changes in cerebral flow velocity profiles when vascular reactivity is preserved; this leads to ICP increases when reactivity has been exhausted; b) measurement of middle cerebral artery flow velocities during iatrogenic increases in mean arterial

FIGURE 9. Schematic representation of brain tissue oxygenation (PbtO2) in a pericontusional area. Monitoring allows early recognition of physiologic deterioration as a contusion enlarges, manifest by a remarkable decrease in the PbtO2. Focal metabolic changes may not be detected by global monitors of cerebral function, such as ICP or SjvO2 until much later, possibly delayed beyond outside of a therapeutic time window.
pressure and expression of the rise as autoregulatory reserve by dividing the vascular resistance by the percentage rise of CPP [(CPP/FV)/CPP];\(^\text{49}\) c) delineation of the phase shift of superimposed MCA flow velocities, and arterial pressure and respiratory curves where a zero degree phase shift indicates lack of autoregulation, that stands in contrast to a 90° phase shift indicating preservation of autoregulation;\(^\text{50}\) and d) absence of cerebral autoregulation if a stepwise deflation of compressive leg cuffs leads to a parallel decline in bilateral MCA flow velocity.\(^\text{49}\) It is of note that none of these methods as been accepted into regular clinical practice as these tests are time consuming and operator dependent and yet have not been rigorously evaluated for their predictive clinical value. We do not advocate testing for the transient hyperemic response identified on MCA flow monitoring after manual, temporary ipsilateral extracranial internal carotid artery compression.\(^\text{51}\)

While there are many complicated techniques for measuring advanced intracranial hemodynamics with TCD that at present appear too cumbersome to be routinely useful in the NICU, TCD represents a powerful tool that continues to increase its clinical utility, including measurement of flow velocities to screen for and follow vasospasm after subarachnoid hemorrhage, altered perfusion and flow dynamics following branch stroke, revascularization and re-establishment of blood flow following administration of thrombolytic medications either intravenously or endovascularly delivered, determination of mass lesions at the bedside in patients too critically ill to be transported to imaging centers, and flow diagnosis of cerebral circulatory arrest, among others.

Continuous EEG (CEEG) and Evoked Potentials (CEP) Monitoring

Prolonged monitoring of electrical cerebral activity, with and without video surveillance, has gained increasing favor in the neurocritical care setting. Several indications, some of them more distinct than others, support the argument to perform continuous electroencephalography (CEEG) monitoring. Spot and continuous EEG facilitates diagnosis and augments streamlined care in patients with known or suspected seizure disorder, especially if the level of consciousness is altered by brain injury or medications, patients during and after status epilepticus, patients with difficult to characterize motor abnormalities such as tremor, unusual or repetitive ocular, facial, or oropharyngeal movements, and patients with unexplained or abrupt dysautonomia unexplained by the primary injury mechanisms. Further, EEG allows determination of level of consciousness in patients suffering paralysis or requiring continuous sedation, and titration of induced coma to burst suppression, detection of delayed ischemic events after aneurysmal or traumatic subarachnoid hemorrhage. While we generally do not use EEG for brain death determination, it remains a helpful adjuvant for prognostication in severely brain injured victims.

Traditionally, CEEG was first employed in status epilepticus patients and in the operating room during carotid endarterectomy.\(^\text{52}\) Other earlier reports identified a correlation between repetitive slow waves or ‘axial bursts’ as indicator for delayed ischemia in patients with clinical and angiographic vasospasm.\(^\text{53}\) More modern approaches include quantitative analyses of epochs of stored data allowing trend analyses to indicate changes suggestive of regional ischemia in subarachnoid hemorrhage patients, among them, reduction of total power, relative alpha variability, and post-stimulation alpha/delta ratio.

Further, cortical spreading depression can be detected, defined as prolonged, repeated, slow electrical depolarizations possibly indicative of ongoing focal injury.\(^\text{54}\) However, CEEG has practical limitations beyond its non-specificity and variable sensitivity, such as difficulties to obtain real-time data interpretations, MRI-incompatibility of most surface electrodes, applicability problems post craniotomy and during concurrent invasive brain monitoring, environmental artifacts, and need for continuous technical staffing. In contrast, increasing availability of networking, power spectrographic displays compressing hours of data into single time frames, accessibility over the internet, and software supporting recognition of event-related electrographic changes make CEEG a useful tool in selected cases even in non-academic critical care settings.

Evoked potential recordings are very useful in prognostication after serve head trauma, especially in patients remaining in coma after cardiac arrest. For example, somatosensory evoked potentials (SSEP’s) are frequently used in postcardiac arrest patients. Normal conduction times of the N13 and N20 components indicate a 60% chance of good neurologic outcome after 12 months in patients with severe head trauma. A delayed component reduces this percentage by more than half, and their absence make death and severe disability much more likely.\(^\text{55}\)

Bilateral absence of the N20 cortical components, together with a lack or severe impairment of brainstem reflexes strongly support an overall poor prognosis.\(^\text{56}\) Additionally, we use continuous somatosensory and auditory evoked potentials to monitor the brainstem function in comatose patients at risk for downward displacement (central herniation) from bilateral hemispheric brain swelling leading to high, intractable ICP. Recently, a description of combined EEG and EP monitoring became available.\(^\text{57}\)
Multimodal Neuromonitoring

Ongoing brain tissue ischemia and hypoxia is one of the common pathophysiologic mechanisms for worsening brain injury in the acute and subacute phase of trauma, intracerebral and subarachnoid hemorrhage, ischemic stroke, post-cardiopulmonary arrest, and many other acute neurological illnesses and deterioration.

New and exciting bedside brain monitoring techniques are available providing a crucial, moment-to-moment update of the hemodynamic, electrical, and cellular environment of the injury site and its surrounding, potentially salvageable tissue areas (Table 1). While currently no single monitoring parameter provides reliably sufficient crucial information to detect secondary injury there is a definite advantage of combining and integrating the information of a choice of monitoring devices to improve outcome in brain injuries. New devices reducing invasive access continue to emerge. Hummingbird™ (Innerspace Incorporated, Tustin, CA, USA) provides a cannulated access system to place various different neuromonitoring devices, depending on the individual patient’s circumstances and the desired neuromonitoring parameters. Other such technologies are in development and will offer the advanced neurocritical care practitioner the ability to acquire patient data more easily and safely.

We currently can measure cerebral blood flow both quantitatively and qualitatively in real-time and integrate the flow values with tissue oxygenation data and cellular performance measures from microdialysis in order to carefully track brain tissue ‘performance measures’ and therapeutic interventions. However, the true strength and depth of brain monitoring comes not as much from the addition of single parameters, but rather from novel approaches to analyze the relationship of the parameters in order to detect trends indicative of functional worsening and to allow interfering therapeutically in a proactive rather than reactive approach. Multimodality neu-

<table>
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<th>Monitoring technology</th>
<th>Invasive</th>
<th>Physiologic parameters</th>
<th>Normal ranges</th>
<th>Pathology</th>
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<td>Yes</td>
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<td>&lt;20 mm Hg</td>
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<td>CPP</td>
<td>≥60 mm Hg</td>
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<td>PbCO2</td>
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<td>Brain temperature</td>
<td>37°C</td>
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<td>Jugular venous oximetry</td>
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<td>SjO2</td>
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<td>Cerebral blood flow</td>
<td>Yes</td>
<td>CBF</td>
<td>50 mL/100 g/min</td>
<td>&lt;20 mL/100 g/min leads to loss of neuronal function and ischemia</td>
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<td>Cerebral microdialysis</td>
<td>Yes</td>
<td>Glucose</td>
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<td>2,900 ± 900 μmol/L</td>
<td>markers of ischemia, followed by</td>
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<td>Pyruvate</td>
<td>166 ± 47</td>
<td>increased lactate/pyruvate ratio, decreased glucose, and increased glycerol.</td>
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| Continuous EEG        | No       | Brain electical activity| Alpha/Delta ratio <50% | Alpha/Delta ratio >50%
|                       |          | Epileptiform activity   | No epileptiform discharges | Epileptiform discharges |
|                       |          | Normal reactivity to stimuli | Unreactivity to stimulation | |
| Transcranial Doppler ultrasound (TCD) | No | MPV | MCA 30–75 cm/s | MCA MFV 140–200 cm/s, indeterminate probable of vasospasm after SAH |
|                       |          | ACA 20–75 cm/s | MCF MFV >200 cm/s, high probability of vasospasm after SAH |
|                       |          | PCA 15–55 cm/s | SAH |
|                       |          | VA 13–66 cm/s | |
|                       |          | Pulsatility Index       | PI 4.0–1.2 in any vessel | PI ratios ipsilateral/contralateral |
|                       |          | CO2 Reactivity          | CO2R>2% increase | >1.25 suspicious for compartmentalized ICP or mass effect |
|                       |          | Lindegaard Ratio        | LR <3.1       | CO2R<2% increase |
|                       |          |                         |               | LR-3: 1 mild vasospasm |
|                       |          |                         |               | LR-6: 1 severe vasospasm |

ACA: anterior cerebral artery, CBF: cerebral blood flow (mL/100 g brain/min), CO2R: CO2 Reactivity, CPP: cerebral perfusion pressure (mm Hg), EDV: end diastolic velocity (cm/s), EEG: electroencephalography, ICP: intracranial pressure (mmHg), LR: lactate-pyruvate ratio, LR: Lindegaard Ratio Index, MCA: middle cerebral artery, MPV: mean flow velocity (cm/s), OEF: oxygen extraction fraction, PbCO2: brain tissue oxygen tension (mmHg), PCA: posterior cerebral artery, PI: pulsatility index (PSV/EDV/MFV), PSV: peak systolic velocity (cm/s), SjO2: jugular venous oxygen saturation (%), SAH: subarachnoid hemorrhage, VA: vertebral artery
romonitoring, neuroimaging, and neurophysiologic decision support systems are already an indispensable tool for the neurocritical care physician. Computer-assisted graphical analyses are already improving the patient’s benefits from multimodal monitoring and we need to define further our insights and understanding into the critical conditions ultimately leading to worsening brain injury.

REFERENCES


