The Role of Brain Tissue Oxygen Monitoring in Traumatic Brain Injury
Traumatic Brain Injury

The Role of

Brain Tissue Oxygen Monitoring
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Overview

Traumatic brain injury (TBI) is a serious and costly public health challenge. Each year in the United States, an estimated 1.5 million people sustain traumatic brain injuries. Traumatic brain injury leads to 50,000 deaths each year and leaves as many as 90,000 people struggling with long-term disability. Today, an estimated 5.3 million Americans are living with a permanent, TBI-related disability. As a result of this high prevalence, the combined direct and indirect costs of TBI are enormous for patients, their families, and society. In 1996, hospitalization costs alone for TBI totaled $5.4 billion. For society, the total economic burden from TBI was estimated at a staggering $37.8 billion in 1985, the most recent date available for this projection.

Important research into the pathophysiology of TBI indicates that much of the neurological damage associated with poor outcomes does not occur during the initial injury, but instead evolves over the ensuing hours and days—primarily due to inadequate cerebral oxygenation. Interest in preventing secondary injury from TBI has led to the creation and implementation of evidence-based clinical practice guidelines, as well as the development of new technologies to monitor cerebral oxygenation and new treatment approaches. Taken together, these advances have the potential to reduce the significant morbidity and mortality of brain injuries in this country and lessen their cost and impact on society.

In particular, brain tissue oxygenation, long understood to positively impact outcomes if kept at adequate levels, has until recently been monitored only indirectly or not at all—primarily due to the lack of effective monitoring technology. Now, commercially available technology enables placement of an oxygen-sensing catheter into the
injured tissue of the brain, offering clinicians the ability to obtain direct, accurate, real-time measurements of regional brain tissue oxygenation in patients with severe head injuries and other serious conditions. Brain tissue oxygen monitoring—included in a multimodality monitoring strategy for the care of patients with brain injuries and guided by evidence-based clinical protocols—provides new hope for improving outcomes and reducing the economic burden of this devastating and costly condition.¹
The brain is one of the most oxygen-sensitive tissues in the body—reduction in cerebral oxygenation for even the briefest time has devastating consequences.

TBI—Challenges in Clinical Care

The brain is one of the most oxygen-sensitive tissues in the body—reduction in cerebral oxygenation for even the briefest time has devastating consequences. As a result, clinical practice guidelines developed by the Brain Trauma Foundation (BTF) and the American Association of Neurological Surgeons (AANS) stress that the first priority in the care of head-injured patients is complete and rapid physiologic resuscitation—restoration of circulating blood volume, blood pressure, oxygenation, and ventilation. The aim of these efforts is to ensure adequate cerebral blood flow to maintain oxygenation in order to meet the ongoing metabolic demands of the brain.

Preventing Secondary Injury

The goals of survival and functional recovery from TBI are impacted by the severity of the initial injury and by the extent of secondary injury following the traumatic event. A growing body of evidence supports the current understanding that secondary injury to the brain, incurred during the hours and days following the initial brain injury, happens often and has a profound adverse effect on outcome after severe head injury. Secondary insults arise from both extracranial and intracranial sources and include hypotension, hypoxia, and anemia, which involve failure to deliver adequate oxygen to the brain.

Unlike the traumatic injury itself, secondary ischemic insults can be caused or affected by medical intervention. In particular, cerebral hypotension—which results in failure to deliver sufficient blood flow to the brain—has been found to be a primary predictor of negative
outcome from severe head injury. A single hypotensive episode generally is associated with a doubling of mortality and a marked increase in morbidity from a given head injury. According to the Brain Trauma Foundation, the estimated improvement in outcome that would result from the elimination of hypotensive secondary brain insults is enormous.

Preventing secondary injury in brain-injured patients, however, presents a number of challenges for healthcare providers. Patients often have concurrent, complex medical issues. Effective around-the-clock vigilance requires coordination of a multispecialty clinical care team, with each member clear about the goals of interventions and, optimally, following an algorithm based on evidence-based practice guidelines for the care of patients with severe head injuries. In particular, to prevent secondary injury, critical care nurses at the bedside require targeted, real-time information about patients’ conditions and the assistance of clinical protocols in order to react quickly to physiologic changes and ensure that the brain is receiving adequate oxygenation at all times.

Role of Multimodality Monitoring
Multimodality monitoring has become standard in neurointensive care units. The need for and effects of therapeutic interventions supported by clinical guidelines are monitored by numerous technologies, including those that measure intracranial pressure (ICP), systemic mean arterial pressure, cerebral perfusion pressure (CPP), pH, partial pressures of blood oxygen and carbon dioxide, hemodynamic indices (cardiac function), and concentrations of metabolites such as lactate and glutamate. All these variables are tracked with the goal of optimizing cerebral oxygenation, and modern intensive care units (ICUs) could not function without these technologies. Clinical care teams that implement new, complementary technologies, such as regional brain tissue oxygen monitoring, as they become available can further improve the quality of care provided to patients.
Limitations of Conventional Technologies for Assessing Cerebral Oxygenation

Given the importance of maintaining adequate cerebral oxygenation in traumatic brain injury patients, a number of technologies have been developed that provide surrogate markers for brain oxygenation in order to further the goals of preventing secondary injury and allowing the brain to heal.\textsuperscript{11,20} As mentioned, secondary injury nearly always results from hypoxemia.\textsuperscript{11} Significant hypoxemia occurs in 30% or more of TBI patients, and these hypoxemic episodes have been associated with markedly worse outcomes. One study found that in patients with significant hypoxemia, mortality was 50%, and all survivors were severely disabled.\textsuperscript{21} In contrast, in nonhypoxemic head trauma patients, mortality was 14.3%, with a 4.8% rate of severe disability.\textsuperscript{21}

\textbf{Pressure Measurements—ICP & CPP}

The commonly tracked parameters of intracranial pressure and cerebral perfusion pressure often are viewed as indirect indicators of cerebral perfusion that, therefore, indicate brain oxygenation. Although ICP monitoring has never been studied in a prospective, randomized clinical trial, clinical experience indicates that therapeutic interventions to reduce abnormally high ICP can improve cerebral perfusion. Monitoring ICP also helps to limit indiscriminate use of therapies to control ICP, as the therapies themselves can be harmful.\textsuperscript{11}

Because monitoring of ICP appears to help in determining prognosis and may improve outcome after head injury, it is not surprising that ICP monitoring is used by most head injury experts in the United States.\textsuperscript{11} Yet ICP has been observed to change as a result of therapeutic intervention without a concomitant change or improvement in oxygenation—an indication that other monitoring technologies are needed.\textsuperscript{22}
Cerebral perfusion pressure is another variable commonly tracked during acute hospital care of severely head injured patients. CPP is the difference between mean arterial pressure and ICP. A CPP of 70 mm Hg is likely to enhance perfusion to ischemic regions of the brain following severe TBI, and maintenance of CPP above that threshold may be associated with a substantial reduction in mortality and improvement in quality of survival. Such maintenance is felt to be safe because the incidence of intracranial hypertension, morbidity, or mortality has never been shown to increase in association with active maintenance of CPP higher than 70 mm Hg, even in the face of induced systemic hypertension. But like ICP, CPP can increase as a result of therapeutic intervention without a corresponding change in oxygenation.

**Jugular Bulb Oximetry**

Another monitoring tool, jugular bulb oximetry (SjvO2), measures oxygen saturation of venous blood returning from the brain. While jugular bulb oximetry can identify global reductions in cerebral oxygenation, SjvO2 is unable to identify regional cerebral ischemia—which often leads to secondary brain injury—due to the anatomical mixing of venous blood from cerebral veins. This measurement has the additional shortcoming of being unreliable, as studies have shown that good quality data are obtained only about 50% of the time that SjvO2 monitoring is in place. In addition, clinicians have found that SjvO2 monitoring may not be possible in young children—frequent victims of head trauma and more susceptible than adults to secondary brain injury—due to the small size of their veins. This limitation significantly hampers the care of children with severe traumatic brain injury—the leading cause of death and disability among children in this country.

While providing valuable contributions to clinical care, surrogate indices of brain tissue oxygen levels such as ICP, CPP, and SjvO2 provide only inferential information and do not always reflect true oxygen delivery. Furthermore, they may not provide the accurate, timely information required by clinicians at the bedside to react quickly to correct oxygenation problems and prevent secondary injury.
Measurement of local tissue oxygenation can highlight focal differences in regional cerebral oxygenation that are disguised when measuring $S_jvO_2$. Thus, monitoring of $P_{btO_2}$ is a useful addition to multimodal monitoring of patients with traumatic head injury.\textsuperscript{32}

Direct measurement of brain tissue oxygen levels more accurately portrays actual cerebral oxygenation than do pressure measurements\textsuperscript{1} or jugular bulb oximetry.\textsuperscript{32} This “holy grail” of TBI monitoring—direct, accurate, reliable, real-time measurement of regional partial pressure of oxygen in brain tissue, or $P_{btO_2}$—now is possible using the LICOX\textsuperscript{®} Brain Tissue Oxygen Monitoring System (Integra NeuroSciences, Plainsboro, N.J.).\textsuperscript{33} The system has been shown to be safe and accurate. It delivers important clinical information that, when combined with other monitored parameters, provides an early warning of oxygenation problems that can lead to secondary brain injury and helps guide the care of TBI patients.\textsuperscript{1,13}

The core technology for measuring partial pressure of brain tissue oxygenation has been available for some time but until recently has not been applied to brain tissue oxygenation. This technology now has been incorporated into a catheter that can be safely introduced at or near the injured part of the brain and...
can provide accurate, direct, real-time measurement of PbtO2 in injured brain tissue. PbtO2 monitors have been successfully used in the management of severe brain injury for several years in Europe\cite{34,35} and, more recently, at leading trauma centers in the United States\cite{19} with excellent results.

**Proven Reliability & Safety**

Several studies have shown that the PbtO2 monitor is a reliable source of data. A German study involving 55 patients with severe head injury reported acquisition of good quality data during 95% of the monitoring time.\cite{29} More recently, a group of investigators found that the “time of good quality data” in their study was 99%.\cite{36} In addition, a study of 17 comatose patients with severe brain injury found that PbtO2 monitors provided good quality data up to approximately eight days and as long as 12 days after placement,\cite{37} providing continuous monitoring of brain tissue oxygenation during this most critical phase of a patient’s recovery. Additional studies have concluded that the probe technology used for monitoring PbtO2 also is extremely accurate and has been proven to be useful in a clinical setting.\cite{38} For example, in a study from Rotterdam, postmeasurement calibration of 67 catheters used to monitor severely head-injured patients found very low zero drift and acceptable sensitivity drift.\cite{34}

Monitoring of PbtO2 also has been found to be safe in a number of studies. In one study of 82 patients with nonpenetrating severe head injury, no adverse events or complications related to catheter introduction and monitoring (for 3–156 hours) were seen.\cite{34} A separate study of 101 patients with severe head injury or subarachnoid hemorrhage reported two (1.7%) iatrogenic hematomas, neither requiring evacuation, and no infection was seen after a mean 6.7 days of monitoring.\cite{39–41}

**Vital Clinical Information**

Most importantly, PbtO2 monitoring provides critical information about regional brain tissue oxygenation that is not consistently predicted by other widely measured variables. As mentioned, while ICP and CPP often correlate with PbtO2,\cite{28,42} these variables can change in response to therapeutic interventions, while PbtO2 remains unchanged or worsens.\cite{22} Similarly, early brain tissue hypoxia frequently has been observed despite aggressive treatment to maintain adequate ICP and CPP.\cite{12} In a study of 25 moderately and severely head-injured patients in Italy, low PbtO2 (<14 mm Hg) was seen in the presence of normal and above-normal CPP.\cite{43} In nine patients studied in Spain, low PbtO2 was associated with normal CPP, thus indicating that CPP could be an inaccurate estimate of regional cerebral blood flow in focal ischemic areas.\cite{44}

**Improved Patient Outcomes**

There is increasing evidence that reliable, continuous monitoring of cerebral blood flow and oxygen metabolism are necessary to prevent secondary ischemic injury after severe head trauma.\cite{45} PbtO2 is the only direct measure of regional brain tissue oxygenation. By opening a window into local areas of brain
tissue, its implementation may lead to better patient care by providing an early warning about brain tissue hypoxia that may rapidly lead to secondary brain injury. Early detection of brain tissue hypoxia provides an opportunity for immediate intervention using a number of readily available treatment options, such as oxygen therapy and a variety of medications, possibly avoiding irreversible ischemic injury.46

In a number of studies, PbtO2 has been shown to have prognostic value. For example, in a study of 35 patients with severe TBI, the frequency and duration of brain tissue hypoxia correlated with death and poor neurological outcome at the time of hospital discharge and six months later.47 In an outcome analysis of 35 patients with severe head injury, age and initial Glasgow Coma Scale score (a widely used measure of the severity of head injury) did not differ between the good and bad outcome groups. In the four time intervals examined (0–24 hours, 0–48 hours, 0–72 hours, and 0–6 days), the bad outcome group had lower average PbtO2—in particular ≤10 mm Hg (PbtO2 of 20 mm Hg or greater is considered adequate). In addition, in the bad outcome group, 35% of PbtO2 values from 0–24 hours were ≤10 mm Hg, compared with 11% in the good outcome group.48

In another study of patients with severe head injury, PbtO2 less than 15 mm Hg for longer than 30 minutes was seen in 57 patients. Despite aggressive intervention to maintain ICP and CPP, in the first 24 hours after injury, PbtO2 fell below 10 mm Hg in 42 patients, and below 5 mm Hg in 22 patients. Depth and duration of brain tissue hypoxia were related to patient outcome at six months and were independent predictors of unfavorable outcome and death.12 Similarly, investigators at the Medical College of Virginia used a multiparameter sensor to monitor PbtO2, arterial CO2, pH, and temperature, and found that brain tissue oxygen was the strongest predictor of outcome in 60 study patients with severe head injury.49 In a study of 43 severely head-injured patients in the neurosurgical ICU of a Level I trauma center in Houston, investigators showed an association between duration of PbtO2 below 15 mm Hg, or any episode below 6 mm Hg, and death.50 Monitoring of PbtO2 also provides the necessary information to allow individualized patient care. A case study of two patients with severe TBI showed different responses to hyperventilation treatment of acute elevation of ICP: one patient had improved local cerebral oxygenation (PbtO2). In the second patient, local oxygenation was reduced. The authors concluded that cerebral oxygenation should be continuously monitored during hyperventilation to avoid iatrogenic ischemia and a potential resulting secondary injury.51

In a study of 23 patients in a neurosurgical ICU who were comatose due to severe traumatic brain injury (21 patients) or intracerebral hematoma (2 patients), monitoring of PbtO2 showed that interventions previously believed to improve brain oxygenation need reevaluation.9 One such intervention is hyperventilation. In one study, hyperventilation improved CPP
by reducing ICP in 15 severely head-injured patients, yet brain tissue oxygenation worsened.\textsuperscript{52} In several studies of patients with severe head injury, hyperventilation significantly reduced brain tissue oxygenation, and the risk of compromising cerebral oxygenation by hyperventilation increased over time.\textsuperscript{45,53} Indeed, the BTF/AANS clinical practice guidelines recommend that chronic prophylactic hyperventilation therapy should be avoided during the first five days after severe TBI, and particularly during the first 24 hours.\textsuperscript{11}

These and a growing number of other studies conducted in Europe and the United States point to the importance of direct regional brain tissue oxygen monitoring as a valuable addition to a multimodality monitoring strategy for TBI patients. PbtO\textsubscript{2} monitoring technology promises to help prevent secondary ischemic brain injury and avoid poor outcomes from brain tissue hypoxia, while allowing for individualized patient care. There is strong evidence that the end result may be greatly improved outcomes for TBI patients.
High-quality care of the traumatic brain injury patient demands the integrated activities of a number of different medical and nursing specialties. The best patient outcomes today are achieved by those healthcare providers that are able to focus as a team on the collective goal of minimizing secondary brain injury.\textsuperscript{15} “

Leveraging Multispecialty Collaboration Among Clinical Caregivers

A team approach to the critical care of TBI patients allows informed caregivers to detect suboptimal clinical conditions and perform needed interventions around-the-clock.\textsuperscript{15,54,55} Use of a standardized protocol helps the critical care team prioritize and implement interventions quickly and effectively. Agreement and collaboration among caregivers—including trauma specialists, neurosurgeons, intensivists, anesthesiologists, critical care nurses, and others—is vital to ensure consistent, effective care. Integration of standardized protocols and coordination among critical care team members require ongoing education and training, which should be a priority for critical care teams caring for TBI patients.

This collaboration among the critical care team must begin in the emergency department and continue through to the operating room and ICU. Several authors have suggested that a specialized critical care nurse remain with the patient in order to assist the trauma specialists and anesthesiologists to ensure adequate ICP and brain tissue oxygenation.\textsuperscript{13,19} This coordination and collaboration among caregivers is vital because management of TBI patients is a complex process, involving numerous clinical variables that must be balanced with ongoing adjustments to ventilator settings, medications, and other therapies in order to achieve the best possible outcome for the patient.

Clinical pathways can help focus the attention of the team on the primary endpoint—ensuring adequate cerebral oxygenation. By using PbtO\textsubscript{2}-targeted clinical guidelines in the care of head injury and continuous, real-time information about brain tissue oxygenation, critical care nurses at the bedside can react quickly to conditions requiring intervention and can immediately assess the efficacy of those interventions.\textsuperscript{13,56}”
The Brain Trauma Foundation estimates that if all healthcare professionals followed evidence-based guidelines for the management of head injuries, 20,000 lives could be saved in the United States every year, and the incidence of long-term disability would fall. Yet, although guideline-based care is known to improve outcomes,11 five years after publication of the BTF/AANS guidelines, only 16% of trauma centers in the United States complied fully with those recommendations.57 This lack of compliance is a key focus of educational efforts by the Brain Trauma Foundation.11

Importantly, those trauma centers that have implemented protocol-driven, multimodality monitoring strategies that include the use of brain tissue oxygen monitoring report dramatic improvement in patient outcomes. One community hospital applied the BTF/AANS Guidelines for the Management of Severe Traumatic Brain Injury and tracked outcomes for patients with severe TBI. After implementation of a practice pathway based on recommendations in the guidelines and incorporating brain tissue oxygen monitoring (initially SjvO2 and then, as direct-monitoring technology became available, PbtO2), a study of 93 patients with severe TBI found that 75% had good outcomes or moderate disability, compared with 27% of the

### Impact of Evidence-Based Guidelines & PbtO2 Monitoring on TBI Outcomes

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<th>BEFORE Adoption of TBI Guidelines</th>
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<tbody>
<tr>
<td>Mortality</td>
<td>43%</td>
<td>13%</td>
</tr>
<tr>
<td>Severe Disability</td>
<td>30%</td>
<td>12%</td>
</tr>
<tr>
<td>Good Outcome</td>
<td>27%</td>
<td>75%</td>
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Outcomes are for traumatic head injury patients with Glasgow Coma Scale scores of 3–8. A score of 8 or less indicates severe brain injury.
37 patients treated during the 3.5 years preceding implementation of the guideline recommendations. Now, only 12% of patients with severe TBI have a six-month outcome of severe disability to persistent vegetative state, compared with 30% before the guidelines and brain tissue oxygen monitoring were implemented. After applying the recommendations, just 13% of patients died at six months, compared with 43% before implementation.
Future Clinical Considerations

In light of the seriousness of TBI, much progress has been made, including increased understanding about the pathophysiology of the injured brain, the development of new monitoring technologies and treatment approaches, and better coordination and education among critical care teams. This important work is continuing on a number of fronts. For example, clinicians at Creighton University Medical Center have developed and are studying the clinical utility of brain tissue oxygen-directed critical care guidelines in the care of TBI and other brain-injured patients, with excellent results. The university also is using PbtO₂ monitoring as the cornerstone of research evaluating the relationship between cerebral oxygenation, trauma scores, and patient survival. Among the insights gained from this and other research:

- A large number of head trauma patients exhibit cerebral ischemia upon admission to the ICU.
- Despite standard resuscitation protocols, more than 50% of patients with traumatic brain injury exhibit some level of cerebral hypoxemia, indicating that the current guidelines may not be adequate to prevent cerebral ischemia.⁵⁸

- A number of widely used trauma scoring systems may not correlate well with patient outcomes and survival, while low PbtO₂ correlates significantly with poor outcomes.
- Rapid identification of hypoxemia and quick intervention are required to improve outcomes.
- Even patients with milder head trauma can experience hypoxemia, especially if their conditions are complicated by other injuries.

These important findings point to the need for expanded use of brain tissue oxygen monitoring to advance the level of patient care.⁵⁸
**Economic Issues**

The financial impact of severe traumatic brain injury in the United States is enormous. Although overall rates of hospitalization for TBI declined from 1980 through 1995, using the 1996 National Inpatient Sample, which contains all payor data on hospital inpatient stays from 906 hospitals in 19 states, researchers found that an estimated 254,500 patients with traumatic brain injury required hospitalization, for which $5.4 billion was charged for treatment of the acute injury.3

A study that evaluated inpatient records for 8,700 people ages 16 and older who were hospitalized for TBI between January 1, 1997 and June 30, 1999 found that the cost of hospitalization alone averaged $8,100 for moderate injury (12.5%), $14,600 for serious injury (44.8%), $16,800 for severe injury (29.6%), and $33,500 for critical TBI (13.2%). 59

In the subset of critically head-injured patients who survived the TBI, the cost of hospitalization averaged more than $50,000 each.59 Other studies show, however, that the cost for acute care hospitalization often is far higher—one study of TBI patients in a community hospital setting found a mean length of stay in the ICU of 21 days, with mean hospital charges exceeding $196,000.19

These figures do not take into account admission to rehabilitation hospitals, physical therapy, ongoing medical care required after discharge from the hospital, and the significant cost of rehospitalizations. Rehabilitation can be extensive and ongoing for many patients who have suffered a severe brain injury. Furthermore, after traumatic brain injury, the rate of patient rehospitalization remains relatively high for at least five years.60,61 Thus, these additional costs must be considered when assessing the direct economic impact of TBI.
Besides direct financial cost, TBI results in significant indirect costs, including lost productivity for businesses and lost wages for patients, as well as for family members who must care for them. The $37.8 billion estimated total cost for TBI in 1985 included $20.6 billion in injury-related work loss and disability and $12.7 billion in lost income from premature death. Impossible to quantify were the intangible costs incurred by families of those who die prematurely from TBI, or the physical and emotional tolls on TBI patients and their families.5,62

This less tangible psychosocial burden on families of patients with TBI, however, is large. A study looked at the neuropsychological, emotional, and functional status and the quality of life of adults 3–5 years after they incurred moderate-to-severe TBI. Significant functional limitations were observed in all areas, with recovery to preinjury levels ranging from 65% of cases in personal care to about 40% in cognitive competency, major activity, and leisure and recreation.6

Another recent study found that the functional status of patients with traumatic head injury correlated with the number of episodes of low brain tissue oxygenation.63 In particular, the researchers showed that TBI patients who had a greater number of episodes of cerebral hypoxia had significantly worse scores on a battery of tests designed to measure intelligence and immediate- and recent-term memory—despite the fact that this group had fewer multitrauma patients with less complications during intensive care treatment. Patients with more episodes of low PbtO₂ also experienced decreased professional status and performance. Based on this and other research, the authors concluded that regional brain tissue oxygenation may be as important as other monitored parameters, such as ICP and CPP.53

A separate study recruited a sample of children ages 6–12 from hospital trauma and inpatient units. Of the sample, 53 had severe TBI, 56 had moderate TBI, and 80 had orthopedic injuries without central nervous system damage. Measures of injury-related burden, parental distress, and family function were administered to the person primarily responsible for the child’s care soon after the injury and at six and 12 months after injury. Caregivers in the severe TBI group reported significantly higher levels of family burden, injury-related stress, and negative parental psychological symptoms than caregivers in the orthopedic injury group, suggesting that severe TBI is a source of considerable caregiver morbidity, even compared with other traumatic injuries.7

Thus, the magnitude of morbidity from TBI is high, and long-term consequences and their cost implications are borne by survivors, their families, and the public subsidy system.6

In light of this enormous economic and psychosocial burden, efforts are underway to improve the care and reduce the cost of TBI using evidence-based clinical protocols as well as advanced therapies and monitoring technologies. The University of Louisville School of Medicine found that use of a clinical protocol helped improve the care of patients with severe traumatic brain
injury, with fewer complications and a potential cost savings of approximately $14,000 per patient.\textsuperscript{64}

In addition, despite the incremental costs of adopting new technology, early users of brain tissue oxygen monitoring have concluded that the added costs associated with implementing and using PbtO\textsubscript{2} monitoring were justified by significantly improved outcomes. Along with implementation of appropriate protocols, technologies that improve patient care also can lead to better use of resources.\textsuperscript{65} In fact, studies have shown that use of such pathways for TBI patients may reduce ventilator days, ICU days, and overall hospital days—resulting in a significant reduction in resource utilization as well as a dramatic improvement in patient outcomes and survival.\textsuperscript{54,65}

In the face of the enormous costs associated with traumatic brain injury, it is not surprising that efforts to add monitoring technologies in the neurointensive care unit for TBI patients may encounter resistance among those charged with controlling the cost of patient care. These incremental costs, however, must be considered in light of the overall economic burden of TBI, as well as the value of saving and improving lives from this devastating condition.

Along with implementation of evidence-based protocols, technologies that improve patient outcomes, increase societal productivity, and reduce dependence on long-term care have the potential to significantly reduce the overall high cost of severe brain injury.\textsuperscript{19}
Here is no doubt that TBI is a prevalent and costly public health issue—one that demands the attention of the medical community. In severe TBI, significant secondary brain injury often occurs in the hours and days after the initial traumatic event. Prevention of secondary injury, which is mainly ischemic in nature, is a critical goal in the acute management of TBI. Multimodality monitoring is standard in the clinical care of patients with severe TBI. Among the most commonly monitored variables are ICP and CPP, which provide only indirect information about perfusion and, therefore, oxygenation of the brain. Recent evidence, however, has demonstrated that the correlation between pressure measurements and brain tissue oxygenation is not always reliable—pointing to the need for the direct measurement of brain tissue oxygenation for TBI patients.

Problems in cerebral blood flow have been called the “one final common pathway” toward significant morbidity and mortality in patients with TBI and other conditions. Now, for the first time, a technology is available that allows direct, accurate, reliable, real-time monitoring of regional brain tissue oxygenation. As a result, PbtO₂ has become a key component of an advanced neuromonitoring strategy for TBI patients in a growing number of trauma centers. Studies have demonstrated that monitoring of regional brain tissue oxygenation contributes to better patient care by providing continuous data about the oxygen status of brain tissue identified as being at a high risk for secondary ischemic injury. It also provides clinicians with immediate feedback about the impact of therapeutic interventions. This growing body of research also confirms that brain tissue...
oxygenation impacts not only patient morbidity and mortality, but functional status and other neuropsychological outcomes as well. Implementation of PbtO2 monitoring as the cornerstone of an evidence-based clinical pathway has been shown to greatly improve outcomes for severe TBI at both academic centers and regional community hospitals. This important technology, in the hands of clinicians at the bedside, provides an opportunity to improve outcomes and offer hope of a better life for TBI patients and their families, as well as to reduce the direct and indirect costs of this devastating and prevalent public health problem.
References


