# The Safety of Multimodality Monitoring Using a Triple-Lumen Bolt in Severe Acute Brain Injury

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■ BACKGROUND: **Multimodality monitoring is used frequently to guide care of patients with severe acute brain injury. The aim of this study was to examine the safety and reliability of multimodality monitoring.**

■ METHODS: **From a prospective observational database at a Level I trauma center, 501 patients, including 300 men and 201 women (mean age 58 ± 39 years) were identified retrospectively. Each patient received a triple-lumen bolt and 3 monitors: intracranial pressure, brain temperature, and brain oxygen. Intensive care unit and hospital records were examined to identify complications, reasons for device replacement, malfunction and infection. Head computed tomography (CT) scans performed before and after the monitors were inserted were examined for evidence of monitor-related adverse effects.**

■ RESULTS: **A total of 696 triple-lumen bolts were placed. Median duration of monitoring was 78.88 hours (interquartile range, 33.0–133.2 hours). Bilateral monitors were inserted in 22 (3.16%) patients. Ten (1.43%) monitors were replaced to allow magnetic resonance imaging, and 40 (5.74%) monitors were replaced to facilitate additional cranial surgery. Of 35 (5.02%) monitors that were replaced because they were thought to not be functioning properly, 19 (54.29%) were subsequently found to be functioning normally. Follow-up CT scans were compared with CT scans obtained before insertion of monitors; 9 (2.13%) small contusions and 10 (2.36%) extra-axial hematomas associated with the devices were identified. Based on the CT findings, the hematomas were thought to be associated with the insertion technique rather than the device; 4 hematomas required treatment. Twenty-two (3.16%) devices were incorrectly placed (e.g., the probe was in an infarct or an already existing contusion). Only 1 associated infection was identified.**

■ CONCLUSIONS: **Placement of intracranial monitors for multimodality neuromonitoring using a triple-lumen bolt appears to be safe. The complication rate is similar to published complication rates for single-lumen bolts and single monitors.**

## INTRODUCTION

Critical care of patients with severe acute brain injury (ABI) (e.g., traumatic brain injury [TBI], spontaneous intracerebral hemorrhage, subarachnoid hemorrhage) is centered on the early identification and removal of mass lesions and on the detection, prevention, and management of secondary brain insults.[1-5] This frequently involves a multimodality monitoring (MMM) approach, that is, the simultaneous collection of

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- Brain oxygen
- Intracranial hemorrhage
- Intracranial pressure
- Intraventricular hemorrhage
- Multimodality monitoring
- Neuromonitoring
- Subarachnoid hemorrhage
- Traumatic brain injury

**Abbreviations and Acronyms**
**AANS**: American Association of Neurological Surgeons
**ABI**: Acute brain injury
**CT**: Computed tomography
**EVD**: External ventricular drain
**GCS**: Glasgow Coma Scale
**ICP**: Intracranial pressure
**ICT**: Intracranial temperature
**MMM**: Multimodality monitoring
**MRI**: Magnetic resonance imaging
**$PbtO_2$**: Brain tissue partial pressure of oxygen
**TBI**: Traumatic brain injury

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data from multiple diverse sources in a patient coupled with the ability to view the data in an integrated and time synchronized manner. In addition to clinical examination and laboratory assessments, bedside physiologic monitoring with continuous or noncontinuous techniques is employed in MMM approaches.[6,7] Several commercially available advanced invasive neuromonitoring tools are used. Among the most commonly used bundles is a combination of intracranial pressure (ICP), brain tissue partial pressure of oxygen ($PbtO_2$), and intracranial temperature (ICT) probes. The International Multidisciplinary Consensus Conference on Multimodality Monitoring in Neurocritical Care from the Neurocritical Care Society and the European Society of Intensive Care Medicine suggests that $PbtO_2$ monitoring can be used to help guide therapy in ABI.[8,9]

Data from several clinical series and a recent phase II trial (BOOST-II) suggest that therapy guided by $PbtO_2$ and ICP monitoring is feasible, safe, and possibly associated with improved outcome.[10-12] Consequently, a multicenter phase III trial is forthcoming. Whereas the safety and complication risk of individual monitors (e.g., parenchymal ICP monitor, external ventricular drain [EVD]) are well described,[13-16] there are few data on the safety and reliability of bundled monitors, or, specifically, the combined use of ICP, ICT, and $PbtO_2$ probes. Only 1 small study comprising 43 patients has examined this question.[17]

In the present study, we examined the safety and reliability of MMM, specifically the Licox fiberoptic system equipped with a triple-lumen bolt for continuous ICP, ICT, and $PbtO_2$ measurements in 501 patients with severe ABI. We did not address the necessity for, or benefit of, MMM; this has been done elsewhere.[10-12] Our analysis includes the total number of devices placed, median duration of monitoring, frequency of device malfunction and replacement, events associated with replacement, complications identified on postinsertion imaging, and adverse effects.

## MATERIALS AND METHODS

### Study Population

Patients who were admitted to a university-affiliated Level I Trauma center and a stroke center certified by the Joint Commission on Accreditation of Healthcare Organizations over an 8-year period were retrospectively identified from the Brain Oxygen Monitoring Outcomes database, a prospective observational database of $PbtO_2$ monitoring. Patients were selected using the following inclusion criteria: 1) age $\geq$18 years; 2) severe ABI, with Glasgow Coma Scale (GCS) score $\leq$8[18]; and 3) simultaneous intracranial monitoring using an ICP and $PbtO_2$ monitor for >24 hours. Patients who had fixed and dilated pupils on admission or were declared brain dead within 48 hours of initiating monitoring were excluded from this analysis. Institutional review board approval was obtained to allow prospective data collection.

### Patient Management

Patients were managed in the neurocritical care unit using local protocols for goal-directed therapy based on published recommendations for subarachnoid hemorrhage, spontaneous intracerebral hemorrhage, and TBI.[19-27] In general, this included 1) intubation and mechanical ventilation when GCS score was $\leq$8; 2) adjustment of fraction of inspired oxygen and positive end-expiratory pressure to maintain arterial oxygen saturation >93% and to avoid partial arterial oxygen pressure <60 mm Hg; 3) adjustment of minute ventilation to maintain partial arterial carbon dioxide pressure between 35 and 45 mm Hg when ICP was normal and between 30 and 40 mm Hg when ICP was elevated; 4) placement of an EVD for symptomatic hydrocephalus; 5) maintenance of systolic blood pressure >90 mm Hg; 6) glycemic control (blood glucose 90–130 mg/dL); 7) seizure prophylaxis for 1 week (or longer if seizures were observed); 8) correction of coagulopathy to ensure international normalized ratio $\leq$1.4 and platelet count $\geq$100,000/μL; and 9) transfusion to maintain hemoglobin $\geq$7–8 g/dL.

### Physiologic Monitoring

The following physiologic variables were monitored continuously: mean arterial blood pressure, central venous pressure, pulse oximetry, electrocardiogram, ICP, brain temperature, and $PbtO_2$. For cerebral perfusion pressure calculations (mean arterial blood pressure − ICP), mean arterial blood pressure was measured with the transducer leveled at the phlebostatic axis. The head of the bed typically was maintained at 30°–45°.

### Intracranial Monitoring

It was our standard practice to monitor all patients with severe ABI with a GCS score $\leq$8 at admission or who later deteriorate with an ICP monitor (Camino; Integra LifeSciences Corporation, Plainsboro, New Jersey, USA) and $PbtO_2$ monitor (Licox; Integra LifeSciences Corporation). Intracranial monitors were inserted at the bedside, usually in the neurocritical care unit, via a twist drill burr hole and through a triple-lumen bolt. The $PbtO_2$ monitor was placed in white matter that appeared normal on admission head computed tomography (CT) and on the side of maximal pathology. When there was no asymmetry in brain pathology on CT, the probes were preferentially placed in the right frontal region. If the patient had undergone a craniotomy, the probes were also inserted through a triple-lumen bolt contralateral to the craniotomy or on the same side as the injury if the craniotomy flap permitted. Follow-up noncontrast head CT scans were performed in all patients within 24 hours of placement to confirm correct placement of the various monitors (e.g., not in a contusion or infarct). Probe function and stability were confirmed by an oxygen challenge (fraction of inspired oxygen of 1.0 for 5 minutes). Overall, the goals of therapy included maintaining ICP $\leq$20 mm Hg, cerebral perfusion pressure $\geq$60 mm Hg, and $PbtO_2$ $\geq$20 mm Hg). MMM was continued until patients stabilized and no longer required mechanical ventilation, until patients were able to follow commands, until resolution of intracranial hypertension and hypoxia, or until goals of care changed (e.g., institution of palliative care only). The details of our management approach are described elsewhere.[28-30]

### Imaging

All patients underwent imaging with noncontrast CT on admission and follow-up noncontrast CT within 24 hours of ABI. Some patients also had short-term follow-up imaging (i.e., 6–8 hours after ABI). These studies were generally after monitor insertion.

Thereafter, noncontrast CT scans were performed as clinically indicated. Magnetic resonance imaging (MRI) was not indicated as a primary evaluation tool. Instead MRI was performed 48–72 hours after ABI in patients when results on head CT were normal and there were persistent unexplained neurologic findings. Monitor placement was verified on CT scans obtained within 24 hours after placement, and available postinsertion CT scans were compared retrospectively with preinsertion CT scans. A neurointensivist, neuroradiologist, and non–intensive care unit neurologist examined admission head CT scans in random order. They were blinded to study outcome (i.e., device-associated complications). Noncontrast CT scans obtained within 24 hours of monitor placement were reviewed by a neurointensivist and postgraduate year 4 neurosurgical resident for adverse effects and proper placement. The CT images were displayed on a 1024 × 1024 pixel workstation and examined at different sessions and in different orders.

### Data Collection and Analysis

The Brain Oxygen Monitoring Outcomes prospective observational database was queried for all results of this study. Data from the Brain Oxygen Monitoring Outcomes database (Microsoft Access; Microsoft Corporation, Redmond, Washington, USA) were extracted, and descriptive analyses were performed using Stata 11.2 (StataCorp LLC, College Station, Texas, USA). The following demographic variables were included: age, sex, mechanism of injury, admission GCS score, and type of intracranial pathology. Brain physiologic variables ($PbtO_2$, ICP, and cerebral perfusion pressure) were monitored at the bedside and recorded every 15 minutes (Component Monitoring System M1046–9090C; Hewlett Packard Enterprise, Andover, Massachusetts, USA). This computerized system was examined to determine when the $PbtO_2$ device was disconnected (e.g., due to reoperation, MRI, possible malfunction) during respiratory therapy or if data points fell outside expected ranges. The following were assessed for each patient individually: time from hospital admission to triple-lumen bolt insertion, duration of monitoring, placement of bilateral monitors, reason for device replacement, and adverse events associated with placement. All statistical analyses were performed with Stata 11.2. Normally distributed data were summarized with mean and standard deviation, and other data were summarized with median and interquartile range. Comparisons among patient characteristics were performed with $t$ tests for parametric continuous variables, Wilcoxon rank sum tests for continuous nonparametric variables, and $\chi^2$ tests for categorical variables.

## RESULTS

### Patients

This analysis included 501 consecutive patients, including 300 men and 201 women (mean age 58 ± 39 years). Patient pathologies included the following: nonpenetrating TBI ($n = 286$ patients); subarachnoid hemorrhage ($n = 133$ patients); intracerebral hemorrhage ($n = 25$ patients); penetrating TBI ($n = 20$ patients), 19 of which were gunshot wounds; and other diagnoses ($n = 37$ patients), including cerebral arteriovenous malformation, intracranial infections, hepatic encephalopathy, and cerebral edema from ornithine transcarbamylase deficiency.

### Monitors

A total of 696 triple-lumen bolts were placed in 501 patients (Table 1). All monitors were inserted by a neurosurgery resident (postgraduate year 2, 3, or 4) under supervision of a neurosurgery chief resident or attending physician. The median duration of monitoring for all devices was 78.88 hours (interquartile range, 33.0–133.2). Bilateral monitors were inserted in 22 (3.16%) patients. Ten (1.43%) devices were replaced when patients underwent MRI, and 40 (5.74%) devices were replaced when patients underwent additional surgery. There were 35 (5.02%) $PbtO_2$ devices replaced because they were thought to be nonfunctioning (based on fraction of inspired oxygen challenge); of these, 19 (54.29%) were confirmed to be functioning normally. Device malfunction was not identified in any ICP monitors.

### Complications

In a case-by-case review of clinical and laboratory data, only 1 (0.2%) infection associated with a monitor was discovered in 501 patients (Table 2). In this instance, improper bolt placement technique resulted in a faulty seal that caused a cerebrospinal fluid leak. This device was replaced; however, the patient developed bacterial meningitis, which was managed with systemic antibiotics.

CT scans performed before and after device insertion were compared. There were 22 (3.16%) devices incorrectly placed, either in an infarct or in an already existing contusion, which required replacement. Nine (2.13%) small contusions and 10 (2.36%) extra-axial hematomas, which were believed to have resulted from insertion technique, were identified on CT performed after insertion. Four of these contusions or hematomas required treatment (Table 2).

## DISCUSSION

Several lines of evidence suggest that therapy based on MMM may benefit patients with severe ABI.[10–12,31] Clinical series and a recent phase II trial have suggested benefit when care is directed toward brain oxygenation and ICP targets,[10,11] and a phase III study is nearing inception. Given the limited data on the safety and reliability of placing multiple simultaneous probes, we examined the safety and reliability of a MMM approach that combines ICP, $PbtO_2$, and ICT. Our data suggest that insertion of a bundle of probes through a triple-lumen bolt for MMM is safe and reliable

**Table 1.** Device Use

| Variable | Median (IQR), Number, Number (%) |
|---|---|
| Duration of monitoring, hours | 78.88 (33.0–133.2) |
| Number of devices | 696 |
| Bilateral devices | 22 (3.16) |
| Device replaced for MRI | 10 (1.43) |
| Device replaced for surgery | 40 (5.74) |

IQR, interquartile range; MRI, magnetic resonance imaging.

**Table 2.** Complications Thought to Be Associated with Device Use

| Complication | Number (%) |
|---|---|
| Thought to be nonfunctional and replaced | 35 (5.02) |
| Associated intraparenchymal contusions on CT | 9 (2.13) |
| Associated extra-axial hematomas on CT | 10 (2.36) |
| Hematomas requiring treatment | 4 (0.8) |
| Incorrectly placed devices on CT | 22 (3.16) |
| Infections | 1 (0.2) |

CT, computed tomography.

and that the complication rate is similar to complication rates published for single-lumen bolts and monitors.

### Complications Associated with Invasive Intracranial Monitoring

There are several potential complications associated with ICP monitors, including intracranial hemorrhage (e.g., parenchymal, subdural, subarachnoid), infection, and technical failure. These complication rates have been studied for EVDs and for parenchymal ICP monitors. The overall risk of clinically significant complications is low, and compared with EVDs, intraparenchymal ICP monitors have a lower risk of hemorrhage (<2% vs. 2%–10%) and infection (0–1% vs. 5%–20%).[32-39] Most device-related hemorrhages are associated with insertion technique, and few are of clinical consequence (0.5%–1%).[34] Furthermore, duration of monitoring with a parenchymal ICP monitor does not appear to influence risk.[40] By contrast, long-term use of an EVD is associated with an increased risk of infection, although there are several well-described strategies to reduce this risk.[13,36,38] Technical failures, including EVD blockage, monitor breakage, and device displacement or accidental removal, are uncommon. Overall, technical complications are observed in about 5% of intraparenchymal devices. Most occur during patient transport or when a patient is moved. Few of these complications influence patient outcome because they usually are recognized.[14]

A few small clinical series have addressed the safety of the Licox device.[41-46] These studies, similar to studies of parenchymal ICP monitors, demonstrate a low complication rate (about 1%). A recent small study ($n = 43$) examined the safety and reliability of multiple invasive probes (ICP, $PbtO_2$, cerebral blood flow, and intracranial electroencephalography) placed into brain tissue via a quad-lumen bolt[17] and reported a major hemorrhage rate of 2.4% ($n = 1$), device malposition in 13.9%, and inadvertent device discontinuation in 58% of subjects usually associated with transport. The present study also suggests that clinically significant complications are rare (1%) and that device failure requiring replacement is uncommon (5%). The safety and success of invasive intracranial monitoring may be enhanced when standardized protocols or bundles are used and there is adherence to basic core competencies.[47-50] These have been described for EVDs and parenchymal ICP monitors, but no protocols specifically exist for $PbtO_2$ monitors. Despite a variety of recommendations and guidelines,[49-51] such protocols are not often used. For example, in a survey of 7217 recipients in the American Association of Neurological Surgeons (AANS) membership database, less than half of the respondents ($n = 1143$) indicated that their institution used a formal protocol for EVD placement. If a respondent's institution had a protocol, only 36.1% always complied with the protocol.[52]

### Methodologic Limitations

Our study has several potential limitations. First, the data were examined retrospectively, and this may have biased our results. However, the data were entered prospectively according to standard case report forms. Second, the study was performed on patients treated at a single institution, so it may lack external validity. However, all patients were treated according to a standard protocol, and each patient met clearly delineated inclusion criteria. Third, we included patients with heterogeneous causes of severe ABI. However, we do not think this should influence the findings because we did not examine how MMM affected care or outcome. Instead, this study focused on the device, its reliability, and complications. It is unlikely that patient pathology will influence these variables. Fourth, all devices were inserted by junior neurosurgery residents. Whether insertion by more experienced surgeons, by intensivists, or by nonphysicians influences the risk of complications is unclear.[53,54] Fifth, there is no consensus on the preferred components of MMM; rather, that MMM should be considered and used (in some combination of devices) according to local expertise and resources. Hence our analysis does not include the use of other invasive monitors (e.g., microdialysis, cerebral blood flow, or cortical spreading depression) because we do not use these devices in clinical practice. Instead, they are inserted in very select patients under research protocols. However, we believe the likelihood of complications associated with these devices also would be rare, as it is our impression that when using a bolt, complications are generally associated with insertion rather than the device per se. The exception to this may be an infection when using a tunneled monitor rather than one inserted through a bolt. Finally, the median duration of monitoring was 3.25 days. Several factors, including bilateral devices, early replacement of devices, palliative care when monitors were removed, and U.S. Food and Drug Administration regulations that limit use of a Licox device to 5 days, may have biased the overall duration of monitoring. However, we did not observe a relationship between duration of monitoring and complications; rather, complications appear to be associated with technical issues at insertion. Despite these potential limitations, our findings are strengthened by a large sample size (501 patients, 696 devices).

### Conclusions

Invasive monitoring of brain function has the potential to play an important role in the care of patients with severe ABI. Whereas the safety of using single monitors has been established, this study suggests that using multiple monitors in combination is similarly safe. It is anticipated that the upcoming BOOST-3 trial will provide further data regarding the efficacy and benefit of a monitoring bundle that includes $PbtO_2$, ICP, and ICT.

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