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A Survey of Neuromonitoring Practices in North American Pediatric Intensive Care Units

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Abstract

Background: Neuromonitoring is the use of continuous measures of brain physiology to detect clinically important events in real-time. Neuromonitoring devices can be invasive or non-invasive and are typically used on patients with acute brain injury or at high risk for brain injury. The goal of this study was to characterize neuromonitoring infrastructure and practices in North American pediatric intensive care units (PICUs).

Methods: An electronic, web-based survey was distributed to 70 North American institutions participating in the Pediatric Neurocritical Care Research Group. Questions related to the clinical use of neuromonitoring devices, integrative multimodality neuromonitoring capabilities, and neuromonitoring infrastructure were included. Survey results were presented using descriptive statistics.

Results: The survey was completed by faculty at 74% (52 of 70) of institutions. All 52 institutions measure intracranial pressure and have electroencephalography capability, whereas 87% (45 of 52) use near-infrared spectroscopy and 40% (21/52) use transcranial Doppler. Individual patient monitoring decisions were driven by institutional protocols and collaboration between critical care, neurology, and neurosurgery attendings. Reported device utilization varied by brain injury etiology. Only 15% (eight of 52) of institutions utilized a multimodality neuromonitoring platform to integrate and synchronize data from multiple devices. A database of neuromonitoring patients was maintained at 35% (18 of 52) of institutions. Funding for neuromonitoring programs was variable with contributions from hospitals (19%, 10 of 52), private donations (12%, six of 52), and research funds (12%, six of 52), although 73% (40 of 52) have no dedicated funds.

Conclusions: Neuromonitoring indications, devices, and infrastructure vary by institution in North American pediatric critical care units. Noninvasive modalities were utilized more liberally, although not uniformly, than invasive monitoring. Further studies are needed to standardize the acquisition, interpretation, and reporting of clinical neuromonitoring data, and to determine whether neuromonitoring systems impact neurological outcomes.

Keywords

Neuromonitoring; Pediatric neurocritical care; Intracranial pressure; EEG

Introduction

Acquired brain injury is a major contributor to morbidity and mortality in critically ill children.[1,2] Approximately 20% of patients in pediatric intensive care units (PICUs) have new brain injury or a neurological complication of critical illness.[1,3,4] Devices that measure cerebral physiology can detect markers of secondary brain injury and aid in clinical decision support toward mitigation of brain injury. Neuromonitors can be invasive like intraparenchymal intracranial pressure (ICP) monitors or noninvasive like electroencephalography (EEG) and near-infrared spectroscopy (NIRS).[5,6] When data

from several devices are synchronized and integrated in a single platform, it is termed multimodality neuromonitoring.[6,7] Neuromonitoring has been integrated into national guidelines for conditions like traumatic brain injury (TBI) and hypoxic-ischemic brain injury after cardiac arrest.[8,9] There is limited research regarding patient selection for neuromonitoring, which aspects of cerebral physiology are most vital to monitor, and whether specific monitoring practices impact patient outcomes.

The field of pediatric neurocritical care has steadily evolved over the past 15 years, with many centers now supporting specialized neurocritical care programs.[3,10,11] Data are needed to inform future research and clinical guidelines about how neuromonitoring technology can be used to reduce morbidity and mortality of patients with acute brain injury and those at high risk for acquiring secondary brain injury. Training for physicians and nurses is needed to guide safe interpretation and clinical decision-making based on information from these devices. A first step is to define the landscape of how invasive and noninvasive neuromonitors are currently being used. Thus, the objective of this study was to characterize neuromonitoring practices and infrastructure in North American PICUs.

Methods

The survey was designed by neuromonitoring work group of the Pediatric Neurocritical Care Research Group (PNCRG). Questions related to the clinical use of neuromonitoring devices in the PICU, integrative multimodality neuromonitoring capabilities, and neuromonitoring infrastructure were included. The anonymous survey was distributed via PNCRG to the faculty member contact at each member institution in the United States between April and June 2021. For institutions where the survey was not completed, two subsequent e-mail attempts were made to reach a representative neurocritical care (neurology or critical care) faculty member. Faculty members at 16 PICUs in Canada were contacted via email to complete the survey. Only 1 survey response was allowed from each institution. The study was determined to be exempt by institutional review board at The Children's Hospital of Philadelphia. Survey results were presented using descriptive summary statistics.

Results

The survey was distributed to 70 institutions and completed by faculty at 74% (52 of 70) institutions (55 United States; 15 Canada) with wide variability in PICU clinical volume (Table 1). Seventy-one percent (37 of 52) were free-standing children's hospitals, and 29% (15 of 52) were children's hospitals within adult institutions. Surveys were primarily completed by faculty in critical care (79% [41 of 52]) or neurology who consult in the PICU (21% [11 of 52]).

Neuromonitoring practices

Invasive and noninvasive neuromonitoring devices used are summarized in Tables 2 and 3. All institutions measured ICP with either an externalized ventricular drainage system or intraparenchymal monitor, and all institutions had EEG monitoring capabilities, with 96% (50 of 52) using continuous EEG. Eighty-seven percent (45 of 52) of institutions used NIRS, whereas 40% (21 of 52) used transcranial Doppler (TCD), although the type

of device and specialty of the provider who performed and interpreted results varied. Patient selection for neuromonitoring was driven by both institutional protocol and attending decision, with shared decision-making between critical care, neurology, and neurosurgery attendings (Table 4). Reported utilization of neuromonitoring devices varied by acute brain injury etiology (Table 5). Invasive ICP monitoring was used most commonly for severe TBI (98%), intracranial hemorrhage (71%), meningitis/encephalitis (52%), and brain tumors (48%). Brain tissue oxygenation was used at 19% (10 of 52) of institutions for severe TBI.

Neuromonitoring infrastructure

Fifteen percent (eight of 52) of institutions utilized multimodality neuromonitoring systems to integrate and synchronize data from multiple devices (Table 6). These were all free-standing children's hospitals with 75% (six of eight) having more than 2000 PICU admissions annually. Data from these systems were primarily stored on hospital servers and reviewed by critical care and neurology providers at bedside and remotely.

No institution reported faculty with specialty training in multimodality neuromonitoring, and a single institution had a specialized neuromonitoring team. No institution had a dedicated reading room for integrated multimodality data. Multimodality data interpretation was primarily communicated via physician progress notes. Three institutions computed metrics of cerebral autoregulation, although each used different metrics and analysis software. One institution computed measures of autonomic function and brain compliance.

Thirty-five percent (18 of 52) of institutions reported maintaining a database of patients who underwent neuromonitoring. Funding for neuromonitoring was through the hospital or department (19%, 10 of 52), private donations (12%, six of 52), or research funds (12%, six of 52). Seventy-three percent (38 of 52) had no dedicated funds allocated for neuromonitoring. Of institutions with multimodality neuromonitoring systems, 63% (five of eight) reported funding. Funding sources included the hospital or department (n = 3), private donations (n = 3), or research (n = 4). Seven of these institutions had support through hospital-based information technology specialists, technicians, or engineers, and four had dedicated nursing support.

Discussion

Neuromonitoring technology was used at all surveyed institutions, although device availability and indications varied substantially. All institutions have ICP and EEG capabilities, and the majority used NIRS. Monitoring initiation was collaborative between critical care, neurology, and neurosurgery. Only 15% of institutions had an integrated multimodality neuromonitoring system, although the systems used, devices integrated, and infrastructure varied.

There is limited guidance regarding indications for placement of intracranial monitors in pediatrics, especially for patients without severe TBI. In alignment with pediatric TBI guidelines, nearly all institutions reported using ICP monitors for patients with severe TBI.[9] ICP monitoring was also reported in patients with conditions that cause increased ICP (e.g., intracranial hemorrhage, subarachnoid hemorrhage, infections). Four institutions reported

using ICP monitors in patients with severe hypoxic-ischemic brain injury after cardiac arrest. Although this practice is not guideline recommended, it has been reported in small adult cohorts.[12,13] Nineteen percent of institutions invasively measured brain tissue oxygenation, primarily in patients with severe TBI, although it is not a specific recommendation by Brain Trauma Foundation Guidelines due to lack of data.[14] Utilization for non-TBI etiologies was uncommon, although a few institutions likely placed these devices routinely in conjunction with ICP monitors. Other invasive modalities such as jugular venous oximetry, cerebral microdialysis, and cerebral blood flow monitoring were reportedly used rarely or not at all, in contrast to adults.[6]

Noninvasive monitoring was heavily weighted toward EEG with national consensus guidelines likely influencing this higher utilization rate.[15,16] Based on guideline recommendations, there was underutilization reported for some indications including patients with status epilepticus and those at high risk of brain injury requiring pharmacologic paralysis. Interestingly, nearly 40% of institutions reported using quantitative EEG, which can assist with detection of seizures, medication titration, and assessment of hepatic encephalopathy.[17,18] NIRS was used by most institutions despite a lack of guidelines, particularly for patients at risk for cerebral hypoperfusion and impaired cerebral oxygenation. TCD was only used by 40% of institutions, despite publication of normative values and practice recommendations for image acquisition, interpretation, and reporting.[19–21] A recent PNCRG survey found that 27 centers utilize TCD compared with 21 centers in this study, which may be a result of which centers responded to each survey.[22]

Eight institutions used a multimodality neuromonitoring system to integrate and synchronize data. Some systems automatically extract data from bedside devices or the electronic health record (e.g., Etiometry T3 [Etiometry, Boston, MA], Sickbay [Medical Informatics Corp, Houston, TX], Bedmaster [Anandic Medical Systems, Feuerthalen, Switzerland]), whereas others require specialized connections between a multimodality neuromonitoring computer stationed at the bedside and individual monitoring devices (e.g., ICM+ [ICM+, Cambridge, UK], Moberg [Moberg Research Inc, Ambler, PA]). These systems facilitate trending relationships between data streams over time both visually and computationally and calculate parameters like metrics of cerebral autoregulation, autonomic function, and brain compliance.[23–25] Small studies in pediatrics have associated impaired cerebral autoregulation with outcomes after cardiac arrest and TBI.[26–29] Standards for how high-resolution data recorded by these systems should be cleaned, processed, analyzed, and displayed are lacking. In addition, although these systems are gaining popularity, training for physicians and nurses is needed on how to interpret these data and incorporate them into clinical decision-making. Further research is needed on whether physiology-guided patient management using these systems is cost-effective or impacts neurological outcomes.[30]

Limitations included selection bias from distribution of surveys only to North American institutions who participated in PNCRG leading to enrichment for academic hospitals with resources for neuromonitoring. In addition, neurosurgeons were not surveyed because they are not PNCRG members. Our results only reflect neuromonitoring practices in North American PICUs and not internationally. Our survey only queried neuromonitoring device availability, and thus, the results do not reflect frequency of use or how data gathered from

these devices were incorporated into patient care. Last, faculty who completed the survey may not have been aware of all devices available or utilized at their institution.

Conclusions

Neuromonitoring technology was used commonly in PICUs, although device selection, initiation indications, and systems of care varied. Ongoing research is needed to standardize acquisition, interpretation, and reporting of neuromonitoring data. Establishing this framework is essential to improving our ability to utilize neuromonitoring data to identify intervenable markers of secondary brain injury and improve outcomes.

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Table 1.

Distribution of PICU Clinical Volume for Responding Institutions

Number of PICU Admissions per year	Number of Institutions (%)
<499	4 (8)
500–999	8 (15)
1000–1499	11 (21)
1500–1999	12 (23)
2000–2499	6 (12)
≥3000	9 (17)
Unknown	2 (4)

Abbreviation:

PICU = Pediatric intensive care unit

Table 2.

Neuromonitoring Device Utilization

Neuromonitoring Device	Number of Institutions (%) (n = 52)
Invasive devices	
ICP	52 (100)
Externalized ventricular drain	51 (98)
Intraparenchymal monitor	47 (90)
Subdural monitor	12 (23)
Epidural monitor	2 (4)
Brain tissue oxygenation	10 (19)
Jugular venous oximetry	1 (2)
Cerebral microdialysis	1 (2)
Cerebral blood flow	0 (0)
Noninvasive devices	
Electrophysiology *	52 (100)
Continuous EEG	50 (96)
Quantitative EEG	20 (38)
Routine EEG	36 (69)
Sensory evoked potentials	12 (23)
Visual evoked potentials	7 (13)
Depth electrodes	2 (4)
NIRS	45 (87)
TCD	21 (40)
Continuous	2 (10)
Intermittent	21 (100)
Imaging US machine	18 (86)
Nonimaging US machine	5 (24)
Performs and interprets TCD	
Radiologists	19 (90)
Neurologists †	5 (24)
Intensivist	5 (24)
Pupillometry	17 (33)
Optic nerve sheath diameter	4 (8)

Abbreviations:

BIS = Bispectral index

cEEG = Continuous electroencephalography

EEG = Electroencephalography

ICP = Intracranial pressure

NIRS = Near-infrared spectroscopy

TCD = Transcranial Doppler

US = Ultrasound

[*] 1 institution reported using BIS monitor; 1 reported use Cerebell EEG when cEEG not available.

[†] Adult neurointensivist at 1 institution.

Table 3.

Neuromonitoring Device Vendor

Neuromonitoring Device Vendor	Number of Institutions (%)
Intraparenchymal ICP	47/52 (90)
Codman (Integra)	31 (60)
Camino (Natus)	22 (47)
Cerelink (Integra)	1 (2)
NEUROVENT (Raumedic)	3 (6)
Brain tissue oxygenation	10/52 (19)
Licox (Integra)	10 (100)
NIRS	45 (87)
Nonin SenSmart	2 (4)
Edwards Foresight	4 (9)
Medtronics Invos	30 (67)
Masimo O3	10 (22)
TCD	21/52 (40)
Phillips	14 (67)
Sonosite	4 (19)
GE	2 (10)
Spencer	1 (5)
Viasonix	2 (10)
DWL	3 (14)
NovaSignal	1 (5)

Abbreviations:

ICP = Intracranial pressure

NIRS = Near-infrared spectroscopy

TCD = Transcranial Doppler

Table 4.

Patient Selection for Neuromonitoring Device Use

Device (Number of Institutions That Use the Device)	Institutional Protocol (%)*	PICU Attending (%)	Neurosurgery Attending (%)	Neurology Attending (%)
ICP (52)	25 (48)	35 (67)	49 (94)	9 (17)
Brain tissue oxygenation (10)	3 (30)	6 (60)	10 (100)	-
EEG (52)	28 (54)	42 (81)	12 (23)	47 (90)
NIRS (45)	25 (56)	40 (89)	5 (11)	10 (22)
TCD (21)	5 (24)	15 (71)	10 (42)	13 (62)
Pupillometry (17)†	10 (59)	10 (59)	4 (24)	6 (35)

Abbreviations:

EEG = Electroencephalography

ICP = Intracranial pressure

NIRS = Near-infrared spectroscopy

PICU = Pediatric intensive care unit

TCD = Transcranial Doppler

*Percentages based on the number of institutions that use each device.

†PICU nurse decision (n = 1).

Table 5.

Utilization of Neuromonitoring Devices by Disease Etiology

Etiology of Brain Injury (n = 52 Institutions)	Invasive Monitors		Non-invasive Monitors			
	ICP, %	Brain Tissue Oxygenation, %	cEEG, %	NIRS, %	TCD, %	Pupillometry, %
Traumatic brain injury						
Severe TBI	98	19	92	48	29	27
Mild/moderate TBI	10	2	44	21	10	19
Hemorrhage						
Intracranial	71	4	62	31	29	23
Subarachnoid	37	2	50	31	33	21
Ischemic stroke						
Arterial ischemic stroke	23	-	52	31	27	23
Cerebral sinus venous thrombosis	15	-	48	25	13	21
Infectious/inflammatory						
Meningitis/encephalitis	52	4	79	31	21	23
Inflammatory/demyelinating	13	-	54	21	13	23
Neoplastic						
Brain tumor	48	2	38	19	13	19
Hypoxic-ischemic brain injury after cardiac arrest						
Severe HIBI	8	2	88	56	19	29
Mild/moderate HIBI	-	-	67	35	13	23
Seizure/epilepsy						
Status epilepticus	2	-	92	23	13	19
Other etiologies of brain injury						
Hepatic encephalopathy	8	2	58	25	23	23
Cerebral edema with no clear underlying etiology	37	6	65	33	17	25
Patients at high risk for brain injury without overt brain injury						
Altered mental status	6	-	79	21	15	23
Sepsis	2	-	31	37	13	13
Extracorporeal membrane oxygenation	-	-	73	69	23	23
Neuromuscular blockade	–	–	40	19	10	21

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Abbreviations:

cEEG = Continuous electroencephalography

EEG = Electroencephalography

HIBI = Hypoxic-ischemic brain injury

ICP = Intracranial pressure

NIRS = Near-infrared spectroscopy

TCD = Transcranial Doppler

TBI = Traumatic brain injury

Table 6.

Characteristics of Institutions With Multimodality Neuromonitoring Systems

Multimodality Neuromonitoring Systems	Number ofInstitutions (%) (n = 8)
Data integration and synchronization platform	
Moberg ICU solutions	4 (50)
Intensive Care Monitoring (ICM+)	1 (13)
Etiometry T3	1 (13)
Sickbay	2 (25)
Bedmaster	2 (25)
Locally developed platform	2 (25)
Devices integrated and synchronized	
ICP	7 (88)
Brain tissue oxygenation	3 (38)
Jugular venous oximetry	1 (13)
Brain temperature	3 (38)
NIRS	8 (100)
Pupillometry	2 (25)
TCD	3 (38)
EEG	5 (63)
Data storage	
Local computer	2 (25)
Hospital server	7 (88)
Data review	
Bedside	
Critical care attending	6 (75)
Neurology attending	7 (88)
Specialized neuromonitoring team	1 (13)
Remotely	
Critical care attending	4 (50)
Neurology attending	3 (38)
Specialized neuromonitoring team	1 (13)
Frequency of assessment	
Real-time	4 (50)
Twice daily	1 (13)
Daily	1 (13)
As needed	2 (25)
Documentation	
Nursing flowsheets	2 (25)
Physician progress notes	7 (88)
Specialized neuromonitoring report	1 (13)
Not formally documented	1 (13)

Abbreviations:

EEG = Electroencephalography

ICP = Intracranial pressure

NIRS = Near-infrared spectroscopy

TCD = Transcranial Doppler