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Multimodal Monitoring in the Pediatric Intensive Care Unit: New Modalities and Informatics Challenges

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We review several newer modalities to monitor the brain in children with acute neurologic disease in the pediatric intensive care unit, such as partial brain tissue oxygen tension (PbtO2), jugular venous oxygen saturation (SjvO2), near infrared spectroscopy (NIRS), thermal diffusion measurement of cerebral blood flow, cerebral microdialysis, and EEG. We then discuss the informatics challenges to acquire, consolidate, analyze, and display the data. Acquisition includes multiple data types: discrete, waveform, and continuous. Consolidation requires device interoperability and time synchronization. Analysis could include pressure reactivity index and quantitative EEG. Displays should communicate the patient's current status, longitudinal and trend information, and critical alarms.
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Introduction

Caring for critically ill children with acute neurologic illness or injury in the pediatric intensive care unit (ICU) demands that physicians integrate multiple, time-sensitive, and complex types of physiological data.[1] In addition to routine physiological monitoring for cardiorespiratory support, these patients also require specific brain monitoring. Recent advances in neurologic critical care have expanded the tools available for brain monitoring, adding new modalities to more classical tools such as intracranial pressure (ICP) monitoring and electroencephalography (EEG).

These data are increasingly digitized and stored, as hospitals adopt electronic health record (EHR) systems.[2] The amount of data often become overwhelming, which may paradoxically impair decision making.[3] A relatively new area of specialization, neurocritical care bioinformatics,[4] has the potential to bring advances in both critical care neurology and medical informatics together. This synergy can help clinicians rapidly observe and act upon early changes in brain physiology to improve care for these children.

In this article, we review several newer brain monitoring modalities, largely pioneered in adult neurologic critical care, which may facilitate the gathering of important clinical information for pediatric neurocritical care patients. In addition, we outline the informatics challenges that must be addressed to fully integrate these measurements into clinical practice. Several recent excellent reviews have addressed these advances in adult neurocritical care.[4-6] Here, we highlight the evidence and the applications relevant to pediatric neurocritical care. In preparing this article, we drew upon expertise from pediatric neurology (Z.G. and B.K.), pediatric neurosurgery (J.G.), pediatric critical care (S.P.), and clinical informatics (S.M.).

Monitoring the Brain for Secondary Injury Prevention

Traumatic brain injury (TBI), stroke, bleeding, infections, tumors, seizures, or hypoxia may cause rapid and

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irreversible injury to the central nervous system. Following this primary insult, however, subsequent physiological events can worsen the primary injury, and even cause new damage. A fundamental goal of critical care neurology is to avoid or minimize these secondary brain injuries. To do so, the ICU team monitors neurophysiological parameters and works to prevent them from reaching values associated with poor outcomes through standard interventions that manipulate cardiovascular, metabolic, and respiratory parameters.

ICP management is the most common example of this and reviewed in detail elsewhere in this volume. For example, the guidelines from the Brain Trauma Foundation[1] recommend that physicians target therapy (ie, via vasopressors, temperature control, intravascular volume management, and hyperosmolar therapy) to maintain ICP and cerebral perfusion pressure (CPP) within age-specific thresholds.[7]

However, changes in ICP and CPP may be late signs of progressive cerebral injury, and hypoxia and ischemia may still occur despite adequate management of ICP.[8-11] Thus considerable effort has been devoted to develop other modalities to monitor for secondary brain injury to provide additional targets for therapy.

Newer Modalities for Brain Monitoring

In addition to ICP, neurophysiological monitoring devices can measure 4 important aspects of brain physiology: oxygenation, cerebral blood flow (CBB), metabolic state, and electrical activity (Table). The expectation is that derangement of these variables will prompt physicians to intervene earlier, target therapy to improve brain physiology, and thus improve outcomes.

Measures of Cerebral Oxygenation

Partial brain tissue oxygen tension ($PbtO_2$) can be measured directly through a device placed into the brain parenchyma, typically through a burr hole.[4] For TBI, the current guidelines recommend maintaining cerebral brain oxygenation at more than 15 mm Hg in adults[12] and more than 10 mm Hg in children.[1] In adult neurologic critical care, several authors suggest that $PbtO_2$ should be incorporated into clinical algorithms for severe TBI to find "$PbtO_2$ responders" who may particularly benefit from $PbtO_2$-targeted therapy.[6,13]

However, in children with TBI, the evidence supporting the clinical use of $PbtO_2$ is mixed. Two recent studies came to opposite conclusions: One study of 52 children suggested a strong independent association of low $PbtO_2$ values with poor outcomes and mortality,[14-16] whereas another of 46 children suggested that $PbtO_2$ values did not provide additional prognostic information after controlling for CPP.[17] The differences in techniques and in clinical protocols may explain the discrepancy.[18]

$PbtO_2$ may also be useful for other neurologic injuries in children. For example, case reports suggest that $PbtO_2$ may

Table Summary of Newer Modalities for Brain Monitoring in the Pediatric Intensive Care Unit.

Physiologic Concept	Modality	Goal Values in Children	Reports of Clinical Use in Children	References
Cerebral Oxygenation	Partial Brain Tissue Oxygen Tension (PbtO2)	Greater than 10mm Hg (consensus)	Prospective cohort studies show feasibility, though results are mixed on the effect of measurement on outcomes.	15–21
	Jugular Venous Oxygen Saturation (SjvO2)	50 - 75% (based on adult values)	Not found	22,23
	Near Infrared Spectroscopy (NIRS)	Utility undetermined	Utility undetermined	24–28
Cerebral Blood Flow	Thermal Diffusion	Unknown	Not found	29–33
Cerebral Metabolic State	Cerebral Microdialysis	Unknown	Case studies and case series demonstrate feasibility.	40–42
Electrical Activity	Continuous EEG (cEEG)	Not applicable	Used commonly. Helpful for seizure detection, event characterization, titration of coma, prognosis.	43–51