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# Building a Pediatric Neurocritical Care Program: A Multidisciplinary Approach to Clinical Practice and Education from the Intensive Care Unit to the Outpatient Clinic

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We describe our 10-year experience developing the Ruth D. & Ken M. Davee Pediatric Neurocritical Care Program at Northwestern University Feinberg School of Medicine. The neurocritical care team includes intensivists, neurologists, and an advanced practice nurse who have expertise in critical care neurology and who continue care in long-term follow-up of intensive care unit patients in a dedicated neurocritical care outpatient clinic. Brain-directed critical care requires collaboration between intensivists and neurologists with specific expertise in neurocritical care, using protocol-directed consistent care, and physiological measures to protect brain function. The heterogeneity of neurologic disorders in the pediatric intensive care unit requires a background in the relevant basic science and pathophysiology that is beyond the scope of standard neurology or critical care fellowships. To address this need, we also created a fellowship in neurocritical care for intensivists, neurologists, and advanced practice nurses. Last, we discuss the implications for pediatric neurocritical care from the experience of management of pediatric stroke and the development of stroke centers.

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## Introduction

There have been a number of reports and position articles on the practice of pediatric neurocritical care or inpatient neurology at academic medical centers in the United States<sup>1-6</sup> and recent proposals on the training required for a pediatric neurointensivist.<sup>3,7-9</sup> Here we describe our specific 10-year experience developing the Ruth D. & Ken M. Davee pediatric neurocritical care program at Northwestern University Feinberg School of Medicine, including long-term follow-up of intensive care unit (ICU) patients in a dedicated neurocritical care follow-up clinic. We describe the design of our fellowship program in neurocritical care for intensivists and neurologists and the rationale for this approach. Last, we discuss the implications for neurocritical care from the experience of management of pediatric stroke and the development of stroke centers.<sup>10-13</sup>

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## Published Experience of Pediatric Neurocritical Care in the United States

The models of pediatric neurocritical care reported to date are from Children's National Medical Center (CNMC)<sup>1</sup> and the Boston Children's Hospital Pediatric Critical Nervous System Program.<sup>2,3</sup> Both share common features, which are distinctly different from the practice of adult neurocritical care.

The CNMC group was multidisciplinary and comprised an intensivist, neurologist, and 3 pediatric neurosurgeons.<sup>1</sup> The decision to involve this team in particular cases was at the discretion of the critical care service. Importantly members of this service were relieved of other duties for part of the day to evaluate ICU consults. In addition to providing expert and consistent care, this team established guidelines for the management of common ICU neurologic diseases, ensured a consensus with other specialties for their use, and introduced multiple new brain monitoring techniques. They combined these clinical initiatives with a quarterly teaching conference.

The Boston Children's service uses a rotating group of pediatric neurology attending physicians, also exempted from other clinical duties during the 2-week block of service.<sup>2</sup> Again, the request for neurocritical care involvement is at the discretion of the attending intensivist. In contrast to the CNMC model, the Boston neurocritical care service comprises

only neurologists, but each neurologist has a subspecialty expertise (epilepsy, neurovascular, neuromuscular, behavioral, or neonatal) relevant to neurocritical care.<sup>3</sup>

Between these published data and our own experience (Table 1), there are common themes. The successful clinical practice of pediatric neurocritical care requires a close collaboration between neurologists and intensivists. The neurologists must have a certain level of subspecialty training relevant to acute brain insults. The neurocritical care team requires protected time to allow rounds in the ICU, which may be lengthy, and to allow time to evaluate often highly complex patients. With a dedicated team, protected time, and collaboration with the intensivists, care can then be consistent and follow specific protocols.

## Structure of the Lurie Children's Hospital Davee Neurocritical Care Program

Ann & Robert H. Lurie Children's Hospital of Chicago is a 288-bed institution located on the campus of the Northwestern University Feinberg School of Medicine. In 2013, the total number of admissions to the hospital was 11,500. The ICUs comprise a 40-bed pediatric ICU (PICU) and 36-bed cardiac intensive care unit (CICU), in addition to a 44-bed neonatal ICU. The average annual number of PICU

**Table 1** Essential and Ideal Components of a Pediatric Neurocritical Care Program

Organization	ICU Care	Follow-up Care	Education	Administration and Support
Multidisciplinary team of neurologist (s) and intensivist(s)	Protocol-driven care	NCC team follows patients in hospital after leaving the ICU	Create a culture of brain-directed critical care	Department or hospital support or both, recognizing the need to protect team members time
Specialty-trained APN with expertise in NCC	Iterative modification of care practices based on outcome data		Training rotations in NCC for fellows in critical care, psychiatry, and anesthesia	
Protected time for the NCC service	Involvement of bedside nurses	Dedicated NCC follow-up clinic	Training rotation in NCC for APNs	Data collection for all patients used to link long-term outcome to ICU care and to modify practice
Joint rounds with critical care	Internal guidelines based on best available preclinical and clinical research		Weekly NCC teaching conference and joint conference with adult stroke and NCC teams	
Stable NCC team for consistency of care	Use of all available monitoring tools (e.g., NIRS, pupillometry, optic nerve ultrasound, and brain tissue oxygen monitoring)	Staffed with neurologist, intensivist, physiatrist, and APN	Monthly NCC teaching conference	Participation in multicenter studies
Responsible for Neonatal, Cardiac, and Pediatric ICUs	24/7 EEG monitoring with interpretation by the NCC service	Outcome measures collected for all patients	Emphasis on the integration of ICU neurologic examination with fundamental cellular mechanism of cerebral injury	Emphasis on publication and sharing of experience and protocols

NCC, neurocritical care; NIRS, near infrared spectroscopy; APN, advanced practice nurse.

and CICU admissions is approximately 2200. The pediatric neurocritical care service began in 2005 with a single neurology attending physician responsible 24/7 for all neurologic evaluations in the PICU and CICU. This 1-person service addressed a common problem for the care of children with neurologic insults in the ICU: variable and inconsistent levels of neurology involvement in their care. This single-provider model was not sustainable in an ICU environment, and expanded to 2 neurologists after 3 years.

### Composition of the Neurocritical Care Team

The neurocritical care team at Lurie Children's Hospital now comprises 2 neurology attending physicians, an intensivist with additional training in neurocritical care, a neurocritical care fellow, and a neurocritical care advanced practice nurse (APN). One of the neurology attending physicians is board certified in epilepsy and is responsible for interpretation of all continuous electroencephalography (EEG) monitoring studies performed in the ICU. Both neurologists have extensive experience with critical care neurology and are the only neurology attending physicians responsible for the ICUs. The responsibility for ICU neurology consultations rotates between the 3 attending physicians with support by child neurology and neurocritical care fellows and the APN. The APN received additional training through the Davee neurocritical care program and is based in the PICU. This team makes morning rounds with the critical care team to discuss patient management and to enhance teaching for pediatric residents and critical care fellows.

### Neurocritical Care Service Activity 2005-2012

We analyzed the activity of the neurocritical care service in the PICU and CICU from its inception in 2005 until the move of the children's hospital in 2012 (Fig. A). Of the 9920 PICU and CICU admissions during this period, 1942 (19%) required evaluation by the neurocritical care service. The average ICU length of stay for these patients was 23 days, which was significantly higher than the 7 days for other PICU admissions. EEG monitoring was used frequently in 63% of cases. These patients were medically complex, and the majority were intubated or treated with pressors (Fig. B). The mortality in these 1942 patients was almost twice (9%) that of the other ICU admissions during the same time period (Fig. C). Approximately 35% of the consults in the ICU were related to seizures or management of status epilepticus (Fig. D). Vascular insults (stroke and cerebral hemorrhage) and altered mental status represented the other 2 leading pathologies (30% of all consults). Other common disorders (each 5%-10% of the overall total) included traumatic brain injuries (TBIs), mostly inflicted trauma, metabolic and autoimmune disorders, and central nervous system (CNS) infections.

### Clinical Practice in the ICU

All consultations to the neurocritical care service originate from the critical care or neonatology services. Our practice is

to involve the neurocritical care service in the care of patients in the ICU as soon as possible to help with setting physiological goals optimized to protect CNS function in the context of the specific systemic or neurologic insult. The early involvement of an intensivist or neurologist with this subspecialty expertise recognizes the importance of early intervention for effective neuroprotection and addresses the diverse and complex pathophysiology, which is a feature of pediatric neurocritical care (Table 2).

For certain conditions (e.g., acute liver failure and cardiac arrest), the neurocritical care service is automatically involved. Here, the purpose is to establish an examination even for patients who appear to be neurologically intact in disorders which may have unpredictable neurologic complications<sup>14</sup>, or early neuromonitoring and neuroprotective measures in patients with an evolving CNS injury.<sup>15</sup> Importantly, the neurologic examination is discussed with the entire team, including the bedside nurse, and specific interventions agreed on in advance, depending on the changes in that examination.

Our clinical practice emphasizes consistent care based on the best available clinical and preclinical evidence. The critical care and neurocritical care services have jointly agreed on standard practices for physiological management appropriate for neuroprotection, with a particular emphasis on meticulous control of temperature. Wherever possible, we have developed written guidelines for management of specific conditions (e.g., acute liver failure, stroke, autoimmune encephalopathies, and refractory status epilepticus) jointly between the critical care and neurocritical care services. This approach recognizes the dearth of level I or II evidence to support the clinical practice of pediatric neurocritical care and the heterogeneous disorders that fall within the purview of the pediatric neurointensivist (Table 2).

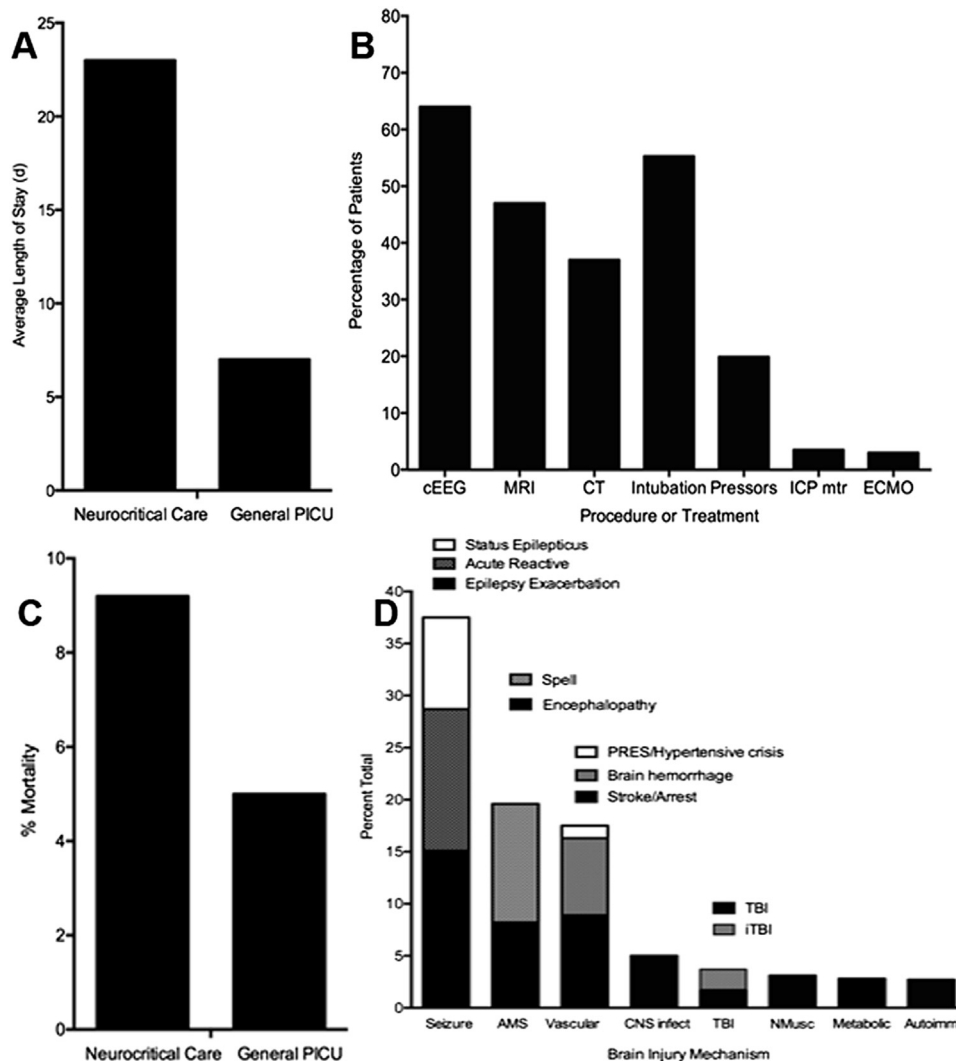
### Neurologic Monitoring and Neuroimaging

The importance of the neurologic examination linked to the cellular mechanisms of CNS injury as the foundation of pediatric neurocritical care practice cannot be overstated. We consider this to be the guiding principle for our neurocritical care service.<sup>16</sup> Continuous EEG is available at any time and is used extensively in our practice as is common in many PICUs.<sup>17</sup> In addition, the neurocritical care service has introduced the use of transcranial Dopplers, pupillometry, optic nerve sheath diameter measurement by ultrasound, and NIRS (near infrared spectroscopy).

The neurocritical care team works closely with the neuro-radiology service to refine protocols for imaging and to ensure timely imaging for specific disorders such as stroke. This level of cooperation, iterative modification of imaging protocols, and emergent availability of an interventional neuroradiologist with expertise in pediatrics is essential.

### Follow-up Care

In 2007, we began a dedicated neurology ICU follow-up clinic. This biweekly clinic is staffed by a combination of



**Figure** Characteristics of patients evaluated by the neurocritical care service between 2005 and 2012 at the Ann & Robert H. Lurie Children's Hospital of Chicago Davee Neurocritical Care Program. (A) Average length of stay (days) for patients requiring evaluation by the neurocritical care service and all other PICU or CICU patients. (B) Use of cEEG, continuous EEG, brain imaging, and other procedures in patients evaluated by the neurocritical care service. (C) Greater mortality in the patients evaluated by the neurocritical care service compared with other PICU or CICU patients during the same period. (D) Classes in injury mechanisms in this group of patients. AMS, altered mental status; CNS infect, CNS infections; ECMO, extracorporeal membrane oxygenation; ICP mtr, intracranial pressure monitor; iTBI, inflicted traumatic brain injury; Metabolic, metabolic disorders; Autoimm, autoimmune; NMusc, neuromuscular disorders; PRES, posterior reversible encephalopathy syndrome.

neurology attending physicians, neurocritical care fellows (both neurology and critical care trained), a neurocritical care APN, and a physiatrist. Patients who do not have an established neurologist and who need neurology evaluation after hospital discharge are seen in this clinic an average of 4-8 weeks after leaving the hospital. Given the complexity of the majority of these patients, the standard appointment duration (including return visits) in this clinic is 1 hour. In addition to the management of common neurologic complications such as motor deficits, spasticity, and seizures, this clinic emphasizes timely referral to rehabilitation outpatient and mental health services.

As other centers have reported,<sup>2,18</sup> our data also indicate greater risk for mortality in patients who require involvement of the neurocritical care service (Fig. C). Our

experience from this clinic is that the children make remarkable long-term functional recoveries despite major deficits at the time of discharge from the PICU or CICU, but it is likely that the long-term morbidity of all critical illnesses in children is underestimated.<sup>19</sup>

## Education in Pediatric Neurocritical Care

### A Culture of Brain-Directed Critical Care in the ICU

In our experience, nearly 20% of patients in the PICU require the involvement of the neurocritical care service,

Table 2 Spectrum of Disease Pathophysiology and Cellular Mechanisms for Pediatric Critical Care Neurology

Acute CNS Injury	CNS Infection	Autoimmune Disorders	Neurologic Complications of Common Critical Illness	Neuromuscular Disorders	Seizures	Neurodegenerative and Metabolic Disorders
TBI	Bacterial meningitis	ADEM and postinfectious neurologic disorders	Acute liver failure	Guillain-Myrasthenic crisis	Refractory status epilepticus	Gray and white matter disorders
Coma and altered mental status						
CNS tumors		CNS complications of systemic autoimmune disorders (SLE, sarcoid, and HLH)	Stem cell and solid organ transplant	Guillain Barré syndrome		Mitochondrial disorders
Stroke and ICH						
Cardiac arrest	Encephalitis	Autoimmune encephalopathies	Diabetic ketoacidosis	Transverse myelitis	Nonconvulsive seizures	Inborn errors of metabolism
SAH						
Spinal cord injury			Septic encephalopathy	ICU-acquired paresis	Conversion disorders	
Intracranial hypertension			Medical complications of chronic neurologic disorders			
Cellular mechanisms of injury	Ischemia-reperfusion; BBB regulation	Inflammation and glial activation	Autonomic dysfunction	Neuromuscular transmission	Neurovascular bundle; CBF regulation	Cerebral metabolism; biochemistry of mitochondria

Summary of common disease entities and core cellular mechanisms of disease relevant to expertise needed for the practice of pediatric neurocritical care. ADEM, acute disseminating encephalomyelitis; BBB, blood-brain barrier; CBF, cerebral blood flow; HLH, hemophagocytic lymphohistiocytosis; ICH, intracerebral hemorrhage; SAH, subarachnoid hemorrhage; SLE, systemic lupus erythematosus; TBI, traumatic brain injury.

consistent with data from other centers.<sup>1,2</sup> It is therefore unlikely that there will ever be sufficient numbers of pediatric neurologists or intensivists with subspecialty training in neurocritical care to meet this level of need. Therefore, the Lurie program also focuses on developing the skills of critical care fellows in critical care neurology. These fellows spend two 2-week blocks with the neurocritical care service during which they are responsible for neurocritical care consultations in the PICU, NICU, and CICU. In addition, both child psychiatry fellows (half day per week for 3 months) and anesthesia residents (1 week) rotate on this service as observers.

We augment clinical teaching in neurocritical care in weekly teaching conferences, which focus on cellular mechanisms of CNS injury and also include a weekly EEG review. An important element of the curriculum includes interactions with the adult stroke and neurocritical care service in the form of weekly joint pediatric and adult neurocritical care case reviews with the adult stroke and neurocritical care teams. Last, the pediatric critical care, neurosurgery, and neurocritical care services hold a monthly teaching conference to both review core topics in neurocritical care and address controversies in the management of shared patients.

“Brain-directed critical care” begins with the ability of the bedside nurse to recognize changes in the patient’s neurologic examination. The education and involvement of nurses and APNs is therefore essential to creating a culture of brain-directed critical care. In our program, all new critical care APNs rotate with the neurocritical care service as part of their training in critical care. During this training period, they are responsible for neurologic consultations in the ICU. In addition, the neurocritical care APN provides scheduled teaching conferences for the ICU nursing staff.

## Fellowship Training in Pediatric Neurocritical Care

The proposed training pathways generally agree that fellowship training in neurology or critical care alone is insufficient.<sup>2,3,7,8</sup> Beginning in 2010, we created a 1-year neurocritical care fellowship open to either a fellowship-trained intensivist or neurologist. By 2015, the Davee neurocritical care program at Lurie Children’s Hospital will have graduated 7 fellows, 3 of whom are intensivists. The training program is founded on the principle that the practice of pediatric neurocritical care requires an in-depth understanding of cerebral physiology, metabolism, and cell biology, and that the lack of evidence-based practice requires the neurointensivist to make clinical decisions based on a sophisticated understanding of the cellular mechanisms of disease underlying common ICU neurologic disorders (Table 2). Thus, the training in the management of disorders such as acute demyelinating encephalomyelitis, intracranial hypertension, or refractory status epilepticus is integrated with education in related cellular mechanisms including structure and function of the neurovascular bundle and blood-brain barrier.

The Lurie fellowship program varies for the neurologist and the intensivist (Table 3). Both pathways include 8 months of ICU rotations in pediatric and adult units. Recent pediatric data indicate that electrographic seizures occur in approximately one-third of children with structural brain injuries, prior in-hospital convulsive seizures, or with interictal EEG abnormalities.<sup>20</sup> Similarly, electrographic seizures occurred in 36%-46% of children with acute encephalopathy.<sup>21,22</sup> To address the need for expertise in neurophysiology, the intensivist receives 1 month of training in neurophysiology together with weekly ICU EEG reviews and extensive exposure to interpretation of EEGs and other monitoring devices at the bedside. We also emphasize care after the patient leaves the ICU with both fellows responsible for their patients in the neurocritical care ICU clinic.

The training of specialists in pediatric neurocritical care cannot be restricted to physicians if this discipline is to address the scale of neurologic morbidity in critically ill children and have an effect on outcome. We have therefore begun a pediatric neurocritical care APN fellowship starting in November 2014. This 1-year program follows a similar structure to that required of the physicians.

### Administrative Support and Barriers to Sustaining a Neurocritical Care Program

The challenges to creating and maintaining such a program are considerable. For a multidisciplinary clinical practice to be effective there must be a consensus on practices among at least critical care, neurosurgery, cardiothoracic surgery, cardiac critical care, nursing, and neurology. The support of emergency medicine, psychiatry, and physiatry is also important to long-term success. Because practices will

change based on institutional experience and published data, the program needs a venue (teaching conferences) in which new approaches to management can be discussed. Last, it is unlikely the members of the neurocritical care team can generate sufficient revenue to protect their time for ICU rounds, and this program needs to have some level of financial support from the various divisions or departments.

### Assessment of the Effect of a Neurocritical Care Service on Outcome

Multiple studies of adults with acquired brain injuries show that the direction of care by a neurointensivist or admission to a dedicated neurointensive care unit leads to reduction in mortality. This finding has been consistent across different insults including stroke,<sup>23</sup> intracerebral hemorrhage,<sup>24</sup> and TBI.<sup>25</sup> The institution of a neurocritical care service led to a significant improvement in outcome following severe TBI in children.<sup>26</sup>

To quantify the effect of ICU care on outcomes, the neurocritical care program must incorporate long-term follow-up, the use of validated outcome measures, and resources for the collection, entry, and analysis of all these data. This investment in personnel time is essential if there is to be a meaningful way to link clinical practice to outcome. We have used retrospective analyses of our protocols for the management of acute liver failure and ECMO to change our practice.<sup>14,15</sup>

### Lessons from Cardiac Critical Care and Pediatric Stroke

The American Heart Association has proposed the creation of tiered CICUs with a level I capable of managing all cardiovascular and major noncardiovascular comorbid conditions.<sup>27</sup> This ICU would be staffed by either cardiac or general intensivists working in collaboration with cardiologists. This level of care would apply at most tertiary medical centers. The published experience with stroke centers from 2000-2011 suggests that the use of these centers also improves outcome.<sup>13</sup> To be designated as a primary stroke center, specific resources are required including the use of protocols, availability of a stroke team and emergency neuroimaging, a stroke registry, educational programs, and defined time windows for many of these procedures.<sup>28</sup> For pediatric stroke, the International Pediatric Stroke Study group has made significant advances in our understanding of stroke etiology and approaches to management.<sup>10</sup> Although the Thrombolysis in Pediatric Stroke trial was terminated, the preparation for this study resulted in the establishment of pediatric acute stroke centers ready to evaluate children using emergent neuroimaging and to follow a protocol for administration of tPA.<sup>11</sup> The precedent from cardiac critical care and stroke and experience with the Thrombolysis in Pediatric Stroke trial suggest that the use of specific metrics (e.g., training relevant to neurocritical care, multidisciplinary team, rapid availability of neurosurgery, a

**Table 3 Neurocritical Care Fellowship Structure**

Rotation	Duration (months)	
	Intensivist	Neurologist
ICU consults	6	6
Adult neurosciences unit	2	2
CICU		1
Pediatric neurosurgery	1	1
Neurophysiology didactic course	1	
Rehabilitation medicine	1	1
Neuroanesthesia	0.5	0.5
Interventional neuroradiology	0.5	0.5

Schedule customized for a neurocritical care fellow trained in either critical care or neurology. In addition to the clinical rotations, both fellows attend a yearlong weekly didactic session focused on core topics in physiology and cell biology relevant to pediatric neurocritical care. Both fellows attend a monthly neurocritical care follow-up clinic and are responsible for the outpatient management of their ICU patients. There is extensive exposure to EEG interpretation including a weekly review of EEGs. For the intensivist, this is augmented by a 1-month comprehensive educational program in clinical neurophysiology. To begin to develop greater expertise in cardiac critical care, the neurologist spends 1 month in the CICU.

neurointerventionalist, neuroimaging, neuromonitoring, use of protocol-driven care, and a data registry) may be an effective next step toward defining centers of pediatric neurocritical care.

## Conclusions

A neurocritical care program, which encompasses clinical practice and training of fellows and nurses is feasible with the collaboration of critical care, neurosurgery, neuroradiology, and neurology, and should extend to include the long-term care of these patients with the involvement of psychiatry, neuropsychology, and physiatry. The heterogeneity of neurologic disorders in the PICU requires a background in the relevant basic science and pathophysiology that is beyond the scope of standard neurology or critical care fellowships. The frequency of neurologic morbidity in critically ill children suggests there will always be a relative shortage of neurointensivists. This deficit can be overcome by the practice of brain-directed critical care, collaboration between nurses and physicians using a good neurologic examination, protocol-directed consistent care, and simple physiological measures to protect CNS function. In the future, the practice of pediatric neurocritical care may be consolidated within designated centers, which have the personnel and resources to identify and manage acute brain injuries in children.

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