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Review Article

PAEDIATRIC NEURO CRITICAL CARE NAVIGATING CHALLENGES AND OPPORTUNITIES

AZMATULLAH M*[1], DIN N[1], ALI H[2], KHAN, M[3]

[1]*Saidu Group of Teaching Hospital Swat, Pakistan*
[2]*Swat Medical Complex Swat, Pakistan*
[3]*Puran Medical Complex Khyber Pakhtunkhwa, Pakistan*
**Corresponding author`s email address:* drazmatkhan1209gmail.com

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Abstract: *Paediatric neurocritical care is a rapidly evolving field aimed at managing critically ill children with severe neurological conditions such as traumatic brain injury (TBI), hypoxic-ischemic encephalopathy (HIE), status epilepticus, and central nervous system (CNS) infections. These conditions are significant contributors to childhood morbidity and mortality, particularly in low- and middle-income countries (LMICs) like Pakistan, where healthcare resources are limited. This review examines the current challenges and opportunities in paediatric neurocritical care, with a focus on improving outcomes in resource-limited settings.* ***Methods:*** *This review synthesizes recent research (2014-2024) on the pathophysiology, risk factors, early diagnostic tools, and treatment strategies for paediatric neurocritical conditions. It highlights the role of multidisciplinary care and long-term rehabilitation while addressing the challenges faced in LMICs, including healthcare infrastructure limitations, shortage of specialized professionals, and socio-economic barriers. Emerging therapies, including neuroprotective strategies, and innovations such as artificial intelligence (AI) and telemedicine, are explored.* ***Results:*** *Paediatric neurocritical care in Pakistan faces significant challenges due to delays in diagnosis, limited access to advanced diagnostics, and a shortage of specialized healthcare providers. Multidisciplinary care and family-centred care have improved outcomes in tertiary care centres, but rural areas remain underserved. Recent advances in neuroprotective therapies, AI, and telemedicine show promise in addressing these challenges, but further research and infrastructure development are needed to make these solutions widely accessible.* ***Conclusion:*** *Paediatric neurocritical care presents both challenges and opportunities, particularly in LMICs like Pakistan. While emerging therapies and technological innovations offer hope for improving care, significant efforts are needed to address healthcare disparities and expand access to neurocritical care services. Strengthening healthcare infrastructure, developing local expertise, and investing in international collaborations will be key to navigating the challenges and enhancing neurocritical care outcomes for children globally.*

Keywords: Paediatric neurocritical care, Traumatic brain injury (TBI), Hypoxic-ischemic encephalopathy (HIE), Neuroprotection, Low- and middle-income countries (LMICs)

Introduction

Paediatric neurocritical care is an emerging subspecialty that deals with the management of critically ill children suffering from severe neurological conditions. These conditions include traumatic brain injuries (TBI), stroke, status epilepticus, central nervous system (CNS) infections, and neuro-inflammatory diseases, among others. Globally, neurological disorders are a leading cause of morbidity and mortality in children, and managing these conditions in critical care settings presents unique challenges due to the complex pathophysiology and age-related vulnerabilities of the paediatric brain (1).

In Pakistan and other low- and middle-income countries (LMICs), the burden of paediatric neurocritical care is compounded by limited healthcare resources, lack of specialized neurocritical units, and inadequate access to advanced diagnostic and therapeutic tools. Traumatic brain injury, resulting from road accidents, falls, and physical trauma, is one of the most common reasons for paediatric neurocritical care admissions in Pakistan, with a high rate of associated mortality and long-term disability (2).

This review aims to explore the challenges and opportunities in paediatric neurocritical care, with a focus on improving outcomes in resource-limited settings like Pakistan (4). By examining advances in diagnostic tools, early intervention strategies, and collaborative care models, we aim to provide a comprehensive overview of the current state of paediatric neurocritical care and propose future directions for improving care in LMICs.

2. Pathophysiology of Paediatric Neurological Conditions

Paediatric neurocritical care encompasses a wide spectrum of neurological disorders, including traumatic brain injury (TBI), stroke, status epilepticus, central nervous system (CNS) infections, and hypoxic-ischemic encephalopathy (HIE). Understanding the pathophysiology of these conditions is crucial for developing effective treatment strategies and improving outcomes (5).

2.1 Traumatic Brain Injury (TBI) TBI remains one of the most common causes of paediatric neurocritical admissions worldwide, particularly in Pakistan, where road traffic accidents and falls are frequent (6). The pathophysiology of TBI in children involves both primary and secondary brain injuries. Primary injury occurs at the time of trauma and includes direct damage to brain tissue, such as contusions and haemorrhages. Secondary brain injury, which develops hours to days after the trauma, results from a cascade of

biochemical processes, including inflammation, oxidative stress, and excitotoxicity (7).

Fig 1 **Traumatic Brain Injury (TBI)**

Children's brains are particularly vulnerable to TBI due to the ongoing development of neuronal networks and a higher water content compared to adults, making them more susceptible to brain swelling (8). The immature brain's increased plasticity also means that even minor injuries can lead to significant long-term deficits, including cognitive and behavioural problems.

2.2 Hypoxic-Ischemic Encephalopathy (HIE) HIE is a

Figure 1

common neurological condition that occurs due to a lack of oxygen or blood flow to the brain, often as a result of birth asphyxia or cardiac arrest (9). In LMICs like Pakistan, perinatal asphyxia remains a significant cause of neonatal morbidity and mortality, leading to long-term neurological disabilities such as cerebral palsy, epilepsy, and developmental delay (10). (Figure 1)

The pathophysiology of HIE is characterized by an initial phase of energy failure, resulting in neuronal cell death, Reactive oxygen species (ROS) and inflammatory mediators further damage brain tissue (11). Therapeutic hypothermia has emerged as a standard treatment for HIE, aiming to reduce secondary brain injury by lowering metabolic demands and inhibiting inflammatory pathways (12). However, access to therapeutic hypothermia in Pakistan is limited due to resource constraints, and alternative strategies need to be explored.

Fig 2 **Hypoxic-Ischemic Encephalopathy (HIE)**

2.3 Status Epilepticus Status epilepticus (SE) is a neurological emergency that occurs when a seizure lasts longer than 5 minutes or when multiple seizures occur without recovery of consciousness between episodes (13). SE can be caused by various factors, including CNS infections, trauma, metabolic disturbances, and genetic disorders. In Pakistan, CNS infections, such as meningitis and encephalitis, are common causes of SE in children due to poor vaccination coverage and inadequate access to healthcare (2).

The pathophysiology of SE involves excessive neuronal firing, leading to excitotoxicity and neuronal damage. Prolonged seizures result in impaired cerebral perfusion, increased intracranial pressure, and neuronal death, which can cause long-term neurological deficits, including cognitive impairments and epilepsy (14). Early recognition and treatment of SE are critical to preventing irreversible brain injury, but delayed presentations are common in LMICs due to limited access to emergency care.

2.4 CNS Infections, such as bacterial meningitis, viral encephalitis, and tuberculosis meningitis, are the leading causes of paediatric neurocritical care admissions in Pakistan. The high prevalence of infectious diseases, compounded by malnutrition and overcrowded living conditions, makes children in Pakistan particularly vulnerable to CNS infections (15).

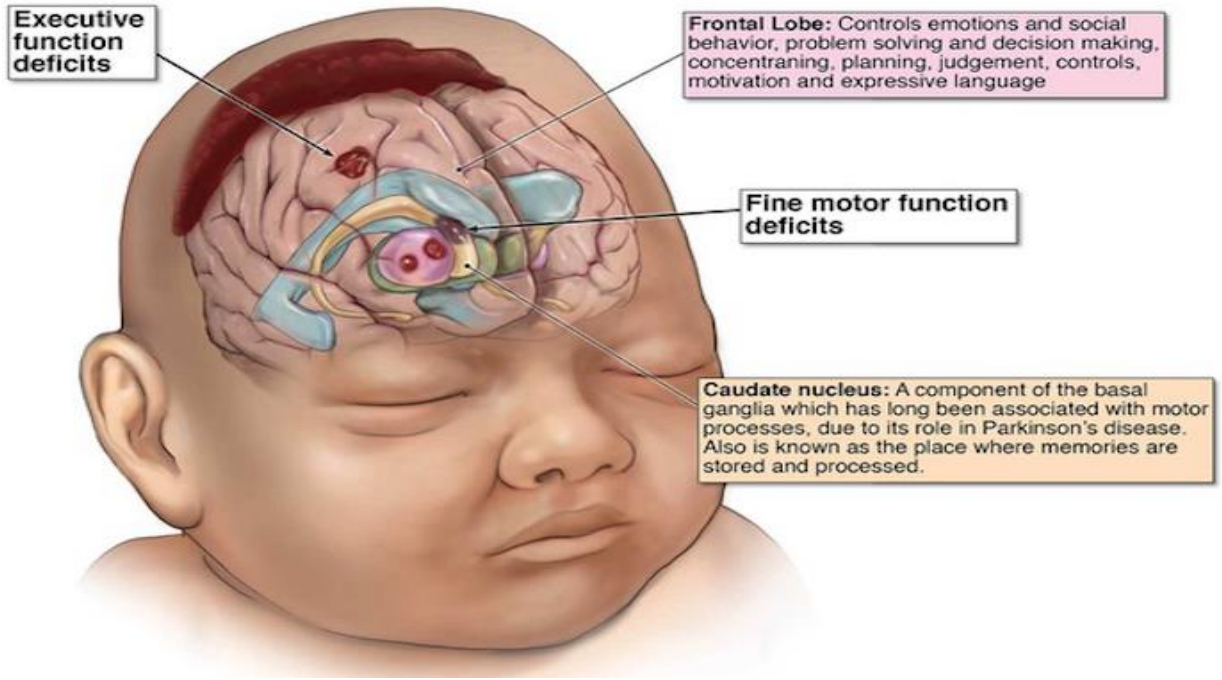

Figure 2

followed by a secondary phase of reperfusion injury, where

The inflammatory response to CNS infections leads to increased intracranial pressure, cerebral oedema, and disruption of the blood-brain barrier (BBB), resulting in neuronal injuries and potential long-term neurological sequelae, such as hearing loss, intellectual disability, and seizures (16). In Pakistan, delays in diagnosis and treatment, particularly in rural areas, contribute to the high morbidity **and mortality associated with CNS infections. Early**

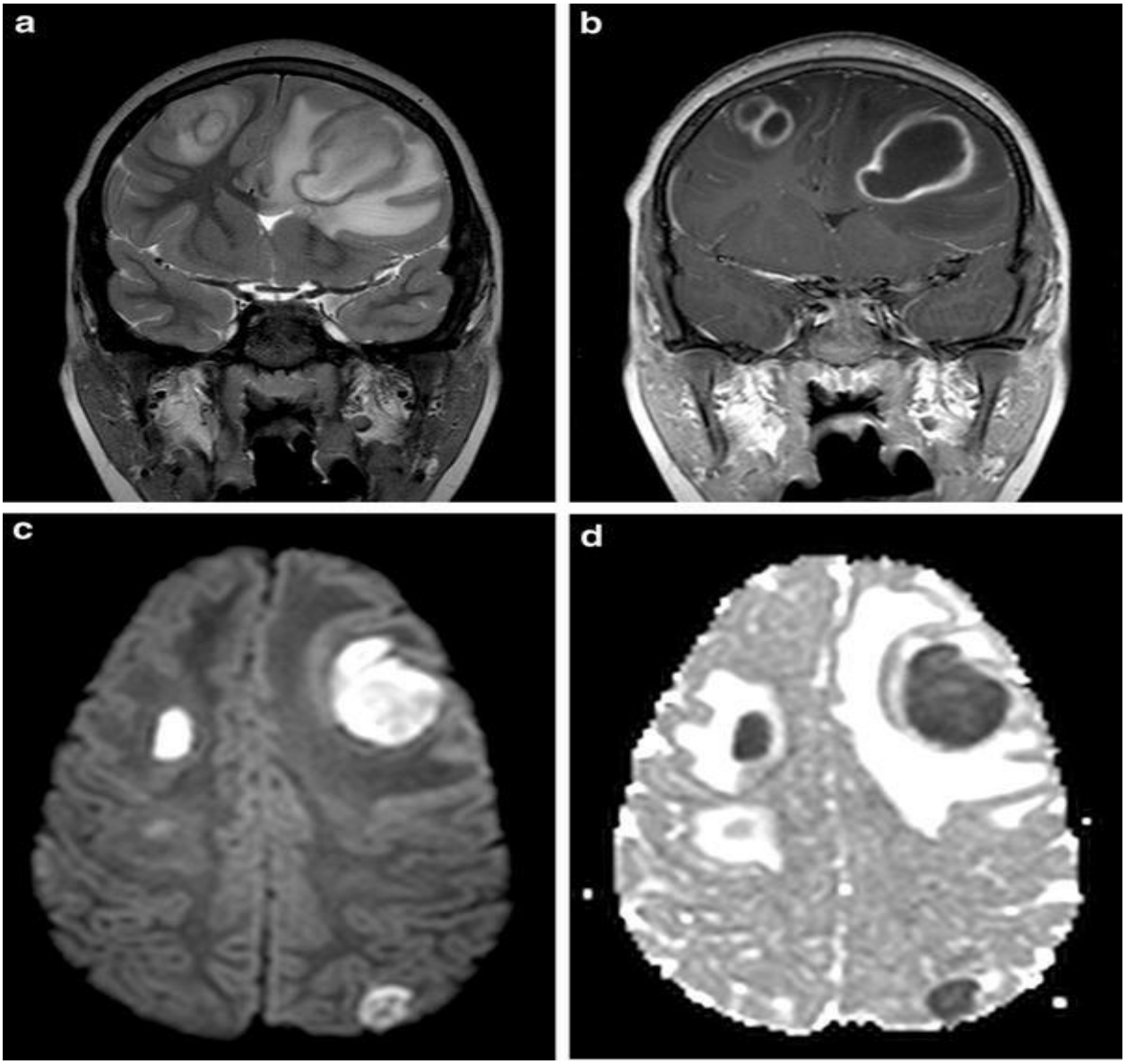

Fig 3 Imaging of Pediatric Infection within the Central Nervous System

Recognition and appropriate antimicrobial therapy are essential to reducing neurological damage and improving outcomes.

3. Risk Factors and Predictors of Neurological Deterioration in Paediatric Patients

Identifying risk factors and predictors of neurological deterioration is crucial for early intervention in paediatric neurocritical care (17). Children with certain pre-existing conditions, socio-economic challenges, and environmental exposures are at higher risk of poor neurological outcomes, particularly in resource-limited settings like Pakistan.

3.1 Prematurity and Congenital Conditions Premature infants are at increased risk of neurological complications due to the immaturity of their brain structures, particularly the white matter tracts, which are vulnerable to injury from hypoxia, ischemia, and inflammation (1). Conditions such

Intraventricular haemorrhage (IVH) and periventricular leukomalacia (PVL) are common in preterm infants and can lead to long-term neurodevelopmental disabilities, including cerebral palsy and cognitive impairments (18).

Congenital conditions, such as neural tube defects, hydrocephalus, and genetic syndromes, also predispose children to neurological deterioration. In Pakistan, the high prevalence of consanguineous marriages and limited access to prenatal care contributes to an increased incidence of congenital disorders, many of which require neurocritical care (19).

3.2 Traumatic Brain Injury and Infections As discussed, traumatic brain injury is a significant risk factor for neurological deterioration in paediatric populations, particularly in countries like Pakistan, where road safety measures are poorly enforced, and access to immediate trauma care is limited (6). Infections, including CNS infections, are also leading causes of neurocritical admissions in Pakistan, with delayed treatment often resulting in severe neurological sequelae (15).

3.3 Socio-Economic and Environmental Factors Socio-economic disparities play a critical role in determining outcomes in paediatric neurocritical care. Children from low-income families are more likely to experience delays in seeking medical care, particularly in rural areas where healthcare infrastructure is underdeveloped (20). Poor nutritional status, inadequate sanitation, and exposure to environmental toxins, such as lead and pesticides, further increase the risk of neurological disorders in children from disadvantaged backgrounds (21).

3.4 Gender Disparities in Access to Care In many LMICs, including Pakistan, gender disparities in access to healthcare disproportionately affect female children. Cultural norms often prioritize the healthcare needs of male children, leading to delayed presentation and treatment for girls with neurological conditions (22). This disparity contributes to worse outcomes in female children, particularly in critical care settings where timely intervention is essential for preventing neurological deterioration.

4. Advances in Diagnostic Tools for Paediatric Neuro Critical Care

Timely diagnosis is critical for improving outcomes in paediatric neurocritical care. Recent advances in neuroimaging, electrophysiological monitoring, and biomarker research have enhanced our ability to detect and monitor neurological injuries in critically ill children. However, access to these technologies remains limited in resource-poor settings like Pakistan (23).

4.1 Neuroimaging Techniques Neuroimaging plays a central role in diagnosing and managing paediatric neurological disorders in critical care settings. Magnetic resonance imaging (2) Is the gold standard for detecting brain injuries, including TBI, hypoxic-ischemic injury, and CNS infections (Eapen et al., 2020). Advanced MRI techniques, such as diffusion-weighted imaging (DWI) and functional MRI (fMRI), have improved the detection of microstructural brain injuries and helped guide treatment decisions (24).

Computed tomography (CT) remains widely used in emergency settings due to its accessibility and speed. However, concerns about radiation exposure in children have led to a preference for MRI when available. In Pakistan, access to advanced neuroimaging is limited, particularly in rural areas, where CT is often the only imaging modality available (6).

4.2 Electrophysiological Monitoring (EEG) Electroencephalography (EEG) is a valuable tool for diagnosing and monitoring neurological conditions such as seizures, status epilepticus, and encephalopathy. Continuous EEG monitoring is particularly important in critically ill children, as many seizures in this population are subclinical and can go undetected without EEG (25). Advances in portable EEG technology have made it easier to monitor children in real time, but access to EEG remains limited in Pakistan, particularly in rural hospitals.

4.3 Biomarkers in Neurological Injury Biomarkers are emerging as potential tools for early diagnosis and prognosis in paediatric neurocritical care. Serum biomarkers such as neuron-specific enolase (3), S100 calcium-binding protein B (S100B), and glial fibrillary acidic protein (GFAP) have shown promise in detecting brain injuries, particularly in cases of traumatic brain injury and hypoxic-ischemic encephalopathy (26). However, the use of biomarkers in clinical practice is still limited, and more research is needed to validate their efficacy in paediatric populations.

4.4 Telemedicine and AI in Neuro-Critical Care Telemedicine and artificial intelligence (AI) are increasingly being integrated into paediatric neurocritical care to improve access to specialized care and enhance diagnostic accuracy (27). In Pakistan, several pilot programs have demonstrated the potential of telemedicine in providing remote consultations for critically ill children in rural areas. AI-driven diagnostic tools, such as algorithms that predict seizure activity or identify early signs of neurological deterioration, are also being developed, but their implementation in Pakistan is still in its early stages.

5. Early Interventions and Treatment Strategies

Timely intervention is paramount in managing paediatric neurocritical conditions, particularly in low-resource settings like Pakistan, where delays in diagnosis and treatment often lead to poorer outcomes. A range of neuroprotective strategies and pharmacological treatments have been developed to manage acute neurological emergencies, though their accessibility and application in countries like Pakistan remain limited. This section outlines current treatment approaches and emphasizes their relevance in the context of resource-limited environments.

5.1 Neuroprotective Strategies in Hypoxic-Ischemic Encephalopathy (HIE) Hypoxic-ischemic encephalopathy (HIE) remains a significant cause of morbidity and mortality in neonates, especially in low- and middle-income countries like Pakistan. Therapeutic hypothermia is widely recognized as the standard of care for HIE, as it has been shown to reduce the extent of brain injury by lowering metabolic demand and attenuating secondary inflammation (12). However, therapeutic hypothermia is not widely available in many regions of Pakistan due to infrastructural limitations.

In rural areas, where therapeutic hypothermia is not feasible, alternative neuroprotective strategies such as the use of magnesium sulfate or xenon are being investigated. Magnesium sulfate has neuroprotective properties that may help reduce the extent of neuronal injury in HIE, although its use remains experimental and has not been widely adopted in clinical practice (28). Similarly, xenon, a noble gas with neuroprotective effects, has been shown to improve outcomes in animal models of HIE, but its high cost and need for specialized equipment make it less feasible for widespread use in LMICs (29).

5.2 Management of Status Epilepticus (SE) Status epilepticus (SE) is a life-threatening neurological emergency that requires immediate intervention to prevent long-term brain damage. The management of SE in paediatric populations follows a stepwise approach, beginning with the administration of benzodiazepines, such as lorazepam or diazepam, as first-line therapy (13). If

seizures persist, second-line treatments, such as phenytoin, levetiracetam, or phenobarbital, are administered.

In Pakistan, access to anti-epileptic drugs (AEDs) is inconsistent, particularly in rural hospitals, where drug shortages are common (6). Furthermore, the lack of continuous EEG monitoring in many healthcare facilities hampers the ability to accurately diagnose and manage SE, resulting in delays in treatment and worse neurological outcomes. Ensuring the availability of essential AEDs and improving access to EEG monitoring are critical steps in enhancing the management of SE in Pakistan.

5.3 Ventilatory and Hemodynamic Support Children with severe neurocritical conditions often require ventilatory and hemodynamic support to stabilize their condition. For example, in cases of traumatic brain injury, maintaining adequate cerebral perfusion and preventing hypoxia are critical to reducing secondary brain injury (8). Mechanical ventilation is often necessary to ensure adequate oxygenation, while vasopressors may be used to maintain blood pressure and ensure sufficient cerebral blood flow.

In Pakistan, access to advanced ventilatory support, such as high-frequency ventilation or extracorporeal membrane oxygenation (ECMO), is limited to tertiary care centres in major cities (9). Many smaller hospitals, particularly in rural areas, lack the necessary equipment and trained personnel to provide advanced respiratory support, leading to higher mortality rates in children with severe neurocritical conditions. Expanding access to basic ventilatory support and training healthcare professionals in its use is essential for improving outcomes in these settings.

5.4 Pharmacological Interventions: Anti-Epileptics, Corticosteroids, and Neuroprotective Agents In addition to AEDs, corticosteroids and neuroprotective agents play a critical role in managing paediatric neurocritical conditions. Corticosteroids, such as dexamethasone, are commonly used to reduce inflammation and cerebral oedema in cases of CNS infections and brain tumours (14). However, the use of corticosteroids remains controversial in some conditions, such as traumatic brain injury, where studies have shown mixed results regarding their efficacy (30).

Neuroprotective agents, such as N-acetylcysteine and erythropoietin, are also being explored for their potential to limit neuronal damage in neurocritical conditions. N-acetylcysteine, an antioxidant, has been shown to reduce oxidative stress and improve outcomes in animal models of TBI, while erythropoietin has demonstrated neuroprotective effects in both animal and human studies of HIE (31). However, these treatments are still experimental, and their use in paediatric neurocritical care is not yet widespread.

5.5 Role of Surgery in Managing Severe Neurological Trauma and Brain Tumors Surgical interventions are often necessary in managing severe neurological trauma, such as hematomas or depressed skull fractures, as well as brain tumours (32). In children with TBI, decompressive craniectomy is sometimes performed to relieve intracranial pressure and prevent further brain injury. Similarly, in cases of CNS tumours, neurosurgical resection may be required to reduce the tumour burden and improve neurological function.

Access to neurosurgical care in Pakistan is limited, particularly in rural areas, where there is a shortage of trained neurosurgeons and specialized equipment (13). Most neurosurgical interventions are performed in tertiary care centres in major cities, such as Karachi and Lahore, leaving children in rural areas without access to life-saving surgical care. Expanding neurosurgical training programs and improving access to specialized surgical equipment are critical steps toward improving paediatric neurocritical care in Pakistan.

6. Multidisciplinary and Collaborative Care in Paediatric Neuro Critical Care

The management of paediatric neurocritical conditions requires a collaborative approach that involves multidisciplinary teams, including neurologists, intensivists, nurses, respiratory therapists, and rehabilitation specialists. Effective teamwork is crucial for ensuring that critically ill children receive comprehensive care that addresses both their immediate medical needs and their long-term neurological recovery.

6.1 The Role of Multidisciplinary Teams in Neurocritical Care In paediatric neurocritical care, multidisciplinary teams work together to assess the child's neurological status, initiate appropriate interventions, and continuously monitor the child's progress. Neurologists and intensivists play a central role in diagnosing the underlying neurological condition, while respiratory therapists and critical care nurses provide essential supportive care, including mechanical ventilation and fluid management (8).

In Pakistan, the lack of formalized multidisciplinary teams in many hospitals poses a challenge to effective neurocritical care. In rural and district-level hospitals, paediatric neurocritical care is often provided by general physicians with limited training in neurology and critical care. Tertiary care centres, such as Aga Khan University Hospital and Children's Hospital Lahore, have begun to implement formalized multidisciplinary care models, but expanding this approach to smaller hospitals remains a significant challenge (20).

6.2 Family-Centered Care in Neurocritical Settings Family-centered care is an integral component of paediatric neurocritical care, as the child's family often plays a critical role in decision-making and providing emotional support. Involving family members in the care process has been shown to improve outcomes by ensuring that care decisions align with the family's preferences and cultural values.

In Pakistan, where family involvement in medical care is a cultural norm, integrating family-centred care into paediatric neurocritical units is essential for improving the child's experience and outcomes. However, many hospitals lack formal policies for family-centred care, and cultural barriers, such as gender dynamics and limited healthcare literacy, can complicate the process of involving families in critical care decisions (6). Developing standardized protocols for family-centred care and providing education to families about neurocritical care practices are important steps in addressing these challenges.

6.3 Integration of Neurocritical Care Protocols across Paediatric ICUs in Pakistan Standardized protocols are critical for ensuring that paediatric neurocritical care is delivered consistently across healthcare facilities. Protocols, such as those developed by the Society of Critical Care Medicine (SCCM), provide evidence-based guidelines for managing conditions such as traumatic brain injury, status epilepticus, and CNS infections (9). However, in Pakistan, the lack of standardized neurocritical care protocols across paediatric intensive care units (ICUs) has led to variability in the quality of care provided.

Some tertiary care centres in Pakistan have begun to adopt

International neocritical care protocols, but these guidelines are not yet widely implemented in smaller hospitals. Furthermore, local adaptations of these protocols are needed to account for the unique challenges faced in Pakistan, such as limited access to advanced diagnostic tools and specialist care. Developing and disseminating standardized neocritical care protocols that are tailored to the local context is essential for improving care in Pakistan.

7. Long-Term Management and Rehabilitation

While the primary focus of neurocritical care is stabilizing the child during the acute phase of illness or injury, long-term management and rehabilitation are equally important for ensuring optimal neurological recovery. Children who survive neurocritical conditions, such as TBI, HIE, or CNS infections, often face significant challenges in terms of cognitive, motor, and behavioural development. Comprehensive rehabilitation programs, involving physical therapy, occupational therapy, and psychological support, are critical for helping these children regain function and improve their quality of life (10).

7.1 Post-Discharge Challenges: Cognitive, Motor, and Behavioural Outcomes Children who survive neurocritical conditions often experience long-term deficits in cognitive function, motor skills, and behaviour. For example, children with a history of traumatic brain injury may develop cognitive impairments, such as difficulties with memory, attention, and executive function, as well as motor deficits, such as weakness or spasticity (7). Behavioural problems, such as irritability, impulsivity, and aggression, are also common in children who have sustained brain injuries or neurological disorders.

In Pakistan, the availability of post-discharge rehabilitation services is limited, particularly in rural areas, where access to specialized rehabilitation centres and therapists is scarce (20). Many children who survive neurocritical conditions do not receive the long-term rehabilitation they need, resulting in poorer functional outcomes and reduced quality of life. Expanding access to rehabilitation services and integrating these services into the broader healthcare system are essential for improving long-term outcomes for these children.

7.2 Role of Early Rehabilitation and Physiotherapy Early rehabilitation, initiated during the acute phase of illness or injury, has been shown to improve long-term outcomes in children with neurocritical conditions (30). Physical therapy and occupational therapy play a critical role in helping children regain motor function, improve coordination, and build strength. In cases of severe brain injury or stroke, early rehabilitation can also help prevent complications such as contractures, pressure ulcers, and muscle atrophy.

In Pakistan, physiotherapy services are limited, and access to early rehabilitation is often restricted to tertiary care centres in major cities (6). Expanding rehabilitation services to district-level hospitals and training healthcare professionals in early rehabilitation techniques are key strategies for improving neurocritical care outcomes in Pakistan.

7.3 Care Coordination between Critical Care Units and Rehabilitation Centers

Effective care coordination between paediatric intensive care units (PICUs) and rehabilitation centres is essential to ensuring continuity of care for children recovering from neurocritical conditions. Transitioning from critical care to rehabilitation can be challenging, particularly in settings where healthcare resources are scarce and specialized rehabilitation services are not widely available. Care coordination involves collaboration among critical care teams, rehabilitation specialists, and primary care providers to ensure that children receive the appropriate post-discharge care and rehabilitation services (21).

In Pakistan, care coordination remains a significant challenge due to the lack of integrated healthcare networks and limited communication between critical care and rehabilitation providers. Many children who survive neurocritical conditions are discharged to their homes without clear follow-up plans, leading to delays in accessing rehabilitation services and poorer long-term outcomes (20). Establishing formal care coordination programs, particularly in tertiary care centres, can help improve the transition from PICUs to rehabilitation centres and ensure that children receive the ongoing care they need.

7.4 Addressing Psychological and Developmental Outcomes Post-Neurocritical Care

Children who survive neurocritical conditions often experience significant psychological and developmental challenges, including cognitive impairments, behavioural issues, and emotional difficulties. Conditions such as traumatic brain injury (TBI), hypoxic-ischemic encephalopathy (HIE), and central nervous system (CNS) infections can lead to long-term deficits in cognitive function, including memory, attention, and executive function, which can impact a child's ability to succeed in school and social settings (7).

In addition to cognitive challenges, children recovering from neurocritical conditions are at increased risk for anxiety, depression, and post-traumatic stress disorder (PTSD). These psychological effects can significantly impact a child's quality of life and may require long-term psychological support and counselling (8). Addressing these psychological and developmental outcomes is critical to ensuring that children can lead healthy, fulfilling lives after neurocritical care.

In Pakistan, access to mental health services for children is limited, particularly in rural areas, where there is a shortage of child psychologists and psychiatrists (20). Expanding access to mental health services and incorporating psychological support into paediatric rehabilitation programs can help address the emotional and developmental needs of children recovering from neurocritical conditions.

8. Challenges in Paediatric Neurocritical Care in LMICs

While significant progress has been made in improving paediatric neurocritical care in high-income countries, children in low- and middle-income countries (LMICs) like Pakistan continue to face significant challenges. These challenges are multifactorial, involving limitations in healthcare infrastructure, a shortage of trained healthcare professionals, barriers to early diagnosis and intervention, and socio-economic and cultural factors that limit access to care.

8.1 Healthcare Infrastructure Limitations in Pakistan

One of the primary challenges in providing paediatric neurocritical care in Pakistan is the lack of adequate healthcare infrastructure. Many hospitals, particularly those in rural areas, lack the specialized equipment and facilities needed to provide advanced neurocritical care. For example,

access to neuroimaging technologies, such as MRI and CT scanners, is limited in many parts of the country, and paediatric ICUs with specialized neurocritical care capabilities are concentrated in a few major cities (9).

The lack of healthcare infrastructure also affects the availability of essential medications and supportive care, such as ventilators and intravenous fluids. Drug shortages are common in rural hospitals, and many healthcare facilities lack the necessary equipment to provide basic life support, let alone advanced neurocritical interventions (6). Improving healthcare infrastructure, particularly in underserved areas, is critical to ensuring that children with neurocritical conditions receive the care they need.

8.2 Shortage of Specialized Healthcare Professionals

A shortage of trained healthcare professionals is another major challenge in paediatric neurocritical care in Pakistan. There is a significant shortage of paediatric neurologists, neurosurgeons, and neurocritical care specialists in the country, particularly in rural areas, where general physicians with limited training in neurology are often tasked with managing neurocritical cases (19).

The shortage of specialized nurses and respiratory therapists also impacts the quality of care provided in paediatric ICUs. Many healthcare professionals in Pakistan lack formal training in neurocritical care, which limits their ability to manage complex cases effectively. Expanding neurocritical care training programs for physicians, nurses, and allied health professionals is essential to improving care for children with neurological conditions (20).

8.3 Barriers to Early Diagnosis and Intervention

Early diagnosis and intervention are critical to improving outcomes in paediatric neurocritical care, but children in LMICs like Pakistan often experience delays in receiving the care they need. These delays are often due to a lack of awareness about neurological conditions among healthcare providers and the general population, as well as limited access to diagnostic tools such as EEG and neuroimaging (6). In rural areas, children with neurocritical conditions may not present to healthcare facilities until their condition has progressed to a severe stage, at which point treatment options are limited.

The lack of standardized protocols for diagnosing and managing neurocritical conditions in children also contributes to delays in care. While some tertiary care centres in Pakistan have begun to implement standardized neurocritical care protocols, these guidelines are not yet widely adopted in smaller hospitals, leading to variability in the quality of care provided. Developing and disseminating standardized protocols for paediatric neurocritical care, particularly in rural areas, is essential to improving early diagnosis and intervention (15).

8.4 Socio-Economic and Cultural Challenges

Socioeconomic and cultural factors also play a significant role in limiting access to paediatric neurocritical care in Pakistan. Poverty is a major barrier to accessing healthcare in many parts of the country, and families may delay seeking care due to financial constraints or a lack of transportation to healthcare facilities (21). In rural areas, where healthcare services are limited, families may rely on traditional healers or home remedies before seeking medical attention, further delaying diagnosis and treatment (20).

Cultural beliefs and gender dynamics also impact access to care, particularly for female children. In many parts of Pakistan, cultural norms prioritize the healthcare needs of male children over females, leading to delays in seeking care for girls with neurocritical conditions (22). Addressing these socio-economic and cultural barriers is critical to ensuring that all children in Pakistan have access to the neurocritical care they need.

9. Recent Advances and Future Directions

Significant advances in neurocritical care have been made in recent years, and ongoing research continues to explore new therapies and interventions aimed at improving outcomes for children with neurological conditions. While these advances have primarily been made in high-income countries, there is increasing interest in adapting these innovations to low-resource settings like Pakistan. This section highlights some of the most promising recent advances in paediatric neurocritical care and explores future directions for improving care in LMICs.

9.1 Emerging Therapies in Neuroprotection

Emerging therapies in neuroprotection have the potential to significantly improve outcomes for children with neurocritical conditions. For example, stem cell therapy is being explored as a potential treatment for traumatic brain injury and hypoxic-ischemic encephalopathy (HIE). Stem cells can promote neurogenesis, reduce inflammation, and enhance tissue repair, making them a promising option for children with neurological injuries (13). While still in the experimental stage, early studies of stem cell therapy in animal models and human trials have shown encouraging results.

Gene therapy is another emerging area of research with potential applications in paediatric neurocritical care. Gene therapy involves the use of viral vectors to deliver therapeutic genes to specific areas of the brain, to correct genetic mutations or promote neuroregeneration (19). While gene therapy is still in the early stages of development, it holds promise for treating a range of neurocritical conditions, including genetic epilepsies and neurodegenerative disorders.

9.2 Potential of AI, Machine Learning, and Telemedicine in Neurocritical Care

Artificial intelligence (AI) and machine learning are increasingly being used in neurocritical care to improve diagnostic accuracy and optimize treatment strategies. AI algorithms can analyze large datasets to identify patterns that may not be apparent to human clinicians, allowing for earlier detection of neurological deterioration and more personalized treatment plans (17). For example, AI-driven tools are being developed to predict seizure activity in children with epilepsy and identify early signs of brain injury in children with traumatic brain injury (2).

Telemedicine also holds great potential for improving access to neurocritical care in resource-limited settings like Pakistan. Telemedicine allows healthcare providers to remotely monitor critically ill children and provide real-time consultations with specialists in urban centres, reducing the need for costly and time-consuming transfers to tertiary care centres (27). Several pilot programs in Pakistan have demonstrated the feasibility of using telemedicine to improve access to neurocritical care, particularly in rural areas where specialized care is not readily available.

9.3 International Collaborations and Initiatives to Improve Neurocritical Care in LMICs

International collaborations and initiatives play a critical role in improving neurocritical care in LMICs by providing

funding, training, and technical support to healthcare providers in resource-limited settings. Organizations such as the World Health Organization (WHO) and the Global Initiative for Child Health & Development (GICHD) have developed programs aimed at strengthening healthcare infrastructure, improving access to diagnostic tools, and training healthcare professionals in neurocritical care practices (29).

Collaborations between hospitals in high-income countries and those in LMICs have also been successful in improving neurocritical care capacity in resource-limited settings. For example, the Aga Khan University Hospital in Karachi has partnered with several international institutions to develop training programs for paediatric neurologists and intensivists, to build local capacity in neurocritical care (19). Expanding these collaborations and investing in long-term partnerships between high- and low-resource hospitals can help improve neurocritical care outcomes for children in LMICs.

9.4 Future Directions in Research and Practice

Conclusion

The study concluded a significant prevalence of upper cross syndrome in female physiotherapists. Variables like working hours posed serious risks for initiating UCS among professionals. Upper Cross Syndrome (UCS) prevalence was 27% in working physiotherapists; however, females and people who work long hours were more likely to develop Upper Cross Syndrome (UCS). It was also discovered that there is a strong correlation between Upper Cross Syndrome and Work-Related Musculoskeletal Disorders (WRMDs.

Declarations Data Availability statement

All data generated or analyzed during the study are included in the manuscript.

Ethics approval and consent to participate

Approved by the department concerned.

Consent for publication

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The authors declared the absence of a conflict of interest.

Author Contribution

MUHAMMAD AZMATULLAH (Lecturer)
Conception of Study, Development of Research Methodology Design, Study Design, Review of manuscript, final approval of manuscript.
Conception of Study, Final approval of manuscript.
NAJMUD DIN (Consultant Pediatrics)
Coordination of collaborative efforts.
Study Design, Review of Literature.
HAIDER ALI (MEDICAL OFFICER)
Manuscript revisions, critical input.
Coordination of collaborative efforts.
MUBARAK KHAN (Consultant Paediatrician)
Data acquisition, and analysis.
Manuscript drafting.
Data acquisition, and analysis.

The future of paediatric neurocritical care lies in developing new therapies, optimizing existing treatments, and improving access to care in resource-limited settings. Ongoing research into neuroprotective therapies, such as stem cell therapy, gene therapy, and neuroplasticity research, holds promise for improving outcomes for children with severe neurological conditions. Additionally, the integration of AI and machine learning into neurocritical care practices has the potential to revolutionize the field by providing clinicians with real-time data-driven insights that can guide treatment decisions.

In LMICs like Pakistan, the focus must be on building local capacity for neurocritical care, expanding access to diagnostic tools and medications, and addressing socio-economic and cultural barriers that limit access to care. Developing standardized neurocritical care protocols that are adapted to the local context, investing in healthcare infrastructure, and providing training for healthcare professionals are critical steps toward improving outcomes for children with neurocritical conditions in Pakistan.

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