Review

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Current status of neurotrauma management in resource-limited settings

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Abstract

Over the last several decades neurotrauma has become recognized as a significant contributor to poor health outcomes, with growing physical, cognitive, social, and economic burdens. Although it serves as a significant contributor globally, it disproportionately affects low- and middle-income countries (LMIC). In this manuscript, we will be comparing how neurotrauma is managed across the globe with special consideration on how variations in environment, resources, infrastructure, and access can influence patient care and outcomes. Moreover, we will be examining the challenges faced by health care systems in LMIC and exploring strategies for quality improvement.

Keywords: high-income countries, low and middle-income countries, neurotrauma, resource-limited settings

Introduction

Neurotrauma remains among the most fatal yet avertable causes of morbidity and mortality worldwide, with approximately 69 million expected traumatic brain injury (TBI) annually[1]. Neurotrauma refers to brain- or spinal-related traumas brought upon by sudden injuries most commonly caused by road traffic collisions (RTCs), sports, falls, blunt and force traumas namely due to violent assault, and tumors[2,3]. Clinical manifestations of these forms of neurotrauma can include skull and spinal fractures, concussions, and chronic traumatic encephalopathy[4].

Over the last several decades, growing bodies of literature have also recognized neurotrauma's significant physical, cognitive, and economic impact[5]. From a neurocognitive lens, neurotrauma can impair individual mobility and function, with broad impacts across the globe. It is estimated that 7.7 million people in Europe and 5.3 million people in the United States live with TBI-related dysfunction[6]. Neurotrauma can lead to confusion, memory changes, and mental health challenges, all of which impair daily duties and activities[7]. Approximately 35% of individuals report ongoing symptoms 3–6 months post-trauma with higher prevalence rates in those with complicated injury[8]. Other studies have shown persistent memory loss, depression, harmful alcohol use, and sleep disturbances for up to 2 years after the initial injury[9]. The acute and chronic sequelae of neurotrauma include changes like excitotoxicity, inflammation, and impaired neurogenesis, all of which can impair physiology and predispose the brain to neurodegenerative disorders in the long term[10]. Beyond the physical and neurocognitive impacts, neurotrauma contributes to poor economic and social challenges, ultimately reducing the quality and quantity of life[5,11].

Although neurotrauma cases are widespread globally, 89% of these incidences tend to disproportionately affect patients living within low- and middle-income countries (LMIC) compared to those residing in high-income countries (HICs)[6], which have been associated with having sustainable and advanced health care systems. Yet in an advancing world, this raises the question: why is it still difficult to maintain appropriate health care provisions within LMICs?

LMICs have acquired an unfortunate reputation for having limited resources and infrastructure, which prevents quality health care provision, along with late adoption of widely recognized practices. The biggest challenges surrounding the management of neurotrauma in LMIC include a lack of access to trained health care professionals (HCPs), alongside specialized diagnostic tests and equipment[12]. In addition, the high treatment costs within LMICs and the general lack of awareness regarding

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neurotrauma prevent early medical interventions from taking place, which can significantly increase the risk of poor treatment outcomes[13]. These challenges suggest the crucial need for improvements within the current state of health care in LMICs to provide adequate and fair care for affected patients.

This narrative review explores the current state of neurotrauma within LMICs compared to their HIC counterparts, along with current limitations, improvements, and overall central lessons learned about neurotrauma management from a global perspective.

Methods

In conducting this narrative review on the current status of neurotrauma management in resource-limited settings, a meticulous and systematic methodology was employed. A comprehensive search of published literature was conducted with a primary focus on studies addressing neurotrauma within the context of resource-limited settings (Table 1).

The inclusion criteria encompassed studies of diverse designs, including Observational and experimental studies. Both pediatric and adult populations were considered, reflecting the inclusive nature of the review. The scope included all types of neurotrauma, acknowledging the multifaceted challenges associated with traumatic injuries to the nervous system. Articles published in English from the inception of available literature up to the present were included, ensuring a comprehensive overview of the evolving landscape of neurotrauma management in resource-limited settings. However, abstracts and unpublished papers have been excluded.

Key databases such as PubMed, EMBASE, and Scopus were thoroughly searched to retrieve relevant articles. The search terms were carefully selected and included terms such as "neurotrauma," "traumatic brain injury," "spinal cord injury," and "resource-limited settings." These terms were complemented by additional descriptors such as specific geographic identifiers, "LMICs," "low-middle-income countries," and "global health disparities" to ensure a nuanced exploration of the topic within the specified context. Additional sources were identified through a manual search of references cited within selected studies.

This comprehensive approach aimed to capture a broad spectrum of literature that could shed light on the variations in neurotrauma management globally, with particular emphasis on the challenges and strategies employed in resource-limited settings. The methodologies employed in identified studies were critically reviewed, and a synthesis of findings was conducted to provide a comprehensive understanding of the current state of neurotrauma management in resource-limited settings. Through this methodical process, the narrative review aspires to contribute valuable insights for health care practitioners, policymakers, and researchers working toward improving neurotrauma outcomes in resource-limited settings.

Table 1

Summary table of methodology for this narrative review

Methodology steps	Description
Literature search	• PubMed, Scopus, EMBASE, and Scopus
Inclusion criteria	• Articles published entirely in English • Pediatric and adult population • Articles available in the literature from inception to date with a primary focus on neurotrauma within the context of resource-limited settings • Various study designs such as Observational and experimental studies
Exclusion criteria	• Articles published in languages other than English • Unpublished studies
Search terms	• "neurotrauma," "traumatic brain injury," "spinal cordinjury," and "resource-limited settings." These terms were complemented by additional descriptors such as specific geographic identifiers, "LMICs," "low-middle-income countries," and "global health disparities"
Additional search	• A thorough inspection of references mentioned in selected studies through manual examination • No predefined restriction on the number of studies to be considered

Results and discussion

A total of 71 studies were included in this review. The studies covered various aspects of neurotrauma, including incidence rates, clinical outcomes, treatment protocols, and health care resource allocation. A notable disparity in both treatment outcomes and access to care was evident between LMICs and HICs. Figure 1 provides an overview of some findings of this study.

Epidemiology

The burden of neurotrauma is growing at an increasingly alarming rate. The creeping "endemic" of neurotrauma accounts for an incidence rate of 500–800 per 100 000 and has caused 8.1 million disability-adjusted life years (DALYs) as recognized by the World Health Organization (WHO) and Global Burden of Disease TBI consortium[14,15]. We must also not ignore the significant economic impacts that neurotrauma causes in LMICs and HICs with estimates of over $400 billion being required for indirect and direct health care costs[15]. Given these detrimental effects, there is an urgent need to better understand the etiology, prevalence, and outcomes associated with neurotrauma to develop improved and personalized prevention and treatment strategies.

Epidemiological factors behind neurotrauma

Etiology.

As previously discussed, neurotrauma etiology can be multifactorial, leading to TBI and/or spinal cord injuries (SCI). In LMICs, the development of neurotrauma is driven by RTCs, particularly in vulnerable groups (including pedestrians, cyclists, and motorcyclists). Given the reduced rate of developed infrastructure and the threatening lack of road safety regulations, on average, at least 56% of neurotrauma cases can be attributed to RTCs in areas such as Africa and Southeast Asia, despite the global average being estimated to be around 30%[16-18]. In comparison, the rate of neurotrauma due to RTCs in HICs was reported to be at 24% in 2012[16], with most TBIs caused by falls, particularly in older individuals (≥ 65 years of age) with

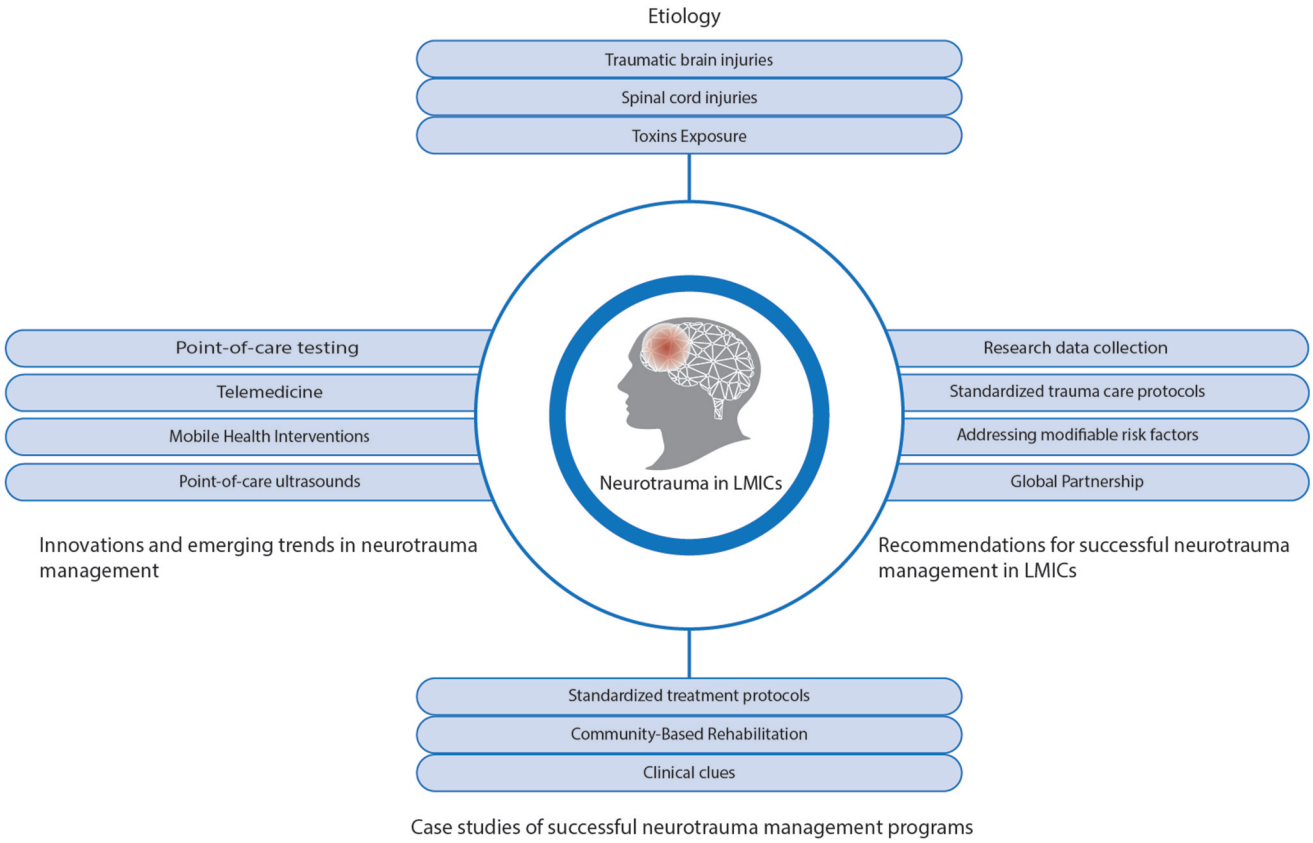

Figure 1. Central illustration of neurotrauma in LMICs. LMICs, low- and middle-income countries.

pre-existing medical conditions and risk factors (such as general weakness and alcohol misuse)[19]. It is worth noting, however, that infrastructure limitations in LMICs are only one part of the problem. It is the growing emphasis on urbanization without simultaneous emphasis on safety regulations that contribute to this discrepancy. This is further complicated by population compliance to existing safeguarding measures and specifics regarding collision dynamics[18].

Beyond RTCs, neurotrauma can be precipitated by environmental factors, as well including certain living conditions, occupations, and social factors. Aside from poor infrastructure, overcrowding and limited access to clean water and sanitation serve as key challenges in LMICs[20]. Physical overcrowding, in particular, can increase the risk of falls and has been associated with increased rates of street violence, all of which can predispose individuals to sustaining a traumatic injury. Many occupations within LMICs can also give rise to developing neurotrauma, with positions in agriculture and manufacturing remaining abundant, which can create a "tragic opportunity" for accidents and RTCs to occur due to long commutes involved within these sectors[21]. In comparison, HICs tend to have more refined systems and diverse industry sectors. Despite this, however, the burden of neurotrauma is still evident – for instance, the HIC Finland reported 16 000 cases of head-related injuries between the years 2010 to 2017 due to workplace-related incidents[22]. As such, greater emphasis on occupational safety in the industry sector is warranted, in both LMICs and HICs alike.

Prevalence.

In LMICs, neurotrauma has been reported highest in young adults 20–29 years of age, more commonly seen in males, with a 3:1 ratio compared to females[23]. Similarly, within HICs, studies have shown neurotrauma also typically favors the younger population, with a mean age of injury approx. 30.8 years of age, disproportionately affecting males[24]. In pediatric populations (0–17 years of age), the prevalence of neurotrauma is highest in LMICs, double that of HICs[25].

Outcomes.

The quantity and quality of life of neurotrauma patients are often subjective within developing and developed nations of the world. When neurotrauma management practices are subpar, poorer outcomes are inevitable. For instance, an observational study held in Sri Lanka revealed that out of 101 patients, only 45.5% survived 6 months after their initial injury, and 30.4% became financially dependent on government assistance[26]. Such outcomes are also common in many other LMICs reflected by high DALYS[27], further highlighting the detrimental impact that arises from a lack of efficient healthcare. Financial constraints, coupled with the physical, emotional, and cognitive dysfunction seen following neurotrauma, can severely disrupt social networks and lead to isolation, ultimately limiting quality of life[28].

In comparison with HICs where access to efficient healthcare is relatively abundant, the negative impacts of neurotrauma tend to be slightly reduced. However, patients still encounter complications reducing their overall quality and quantity of life. For instance, a study conducted in 2017 focusing on 16 countries around Europe estimated that 374 636 years of life have been lost through TBIs[29]. Furthermore, in the United States, TBI has become one of the leading causes of death due to injury with an estimated 64 000 deaths, in 2020[30]. Similarly, in the Netherlands, detrimental outcomes are often prevalent with 171 200 total disability years being attributed to neurotrauma, which was found to be among the leading causes of death and disease burden[31].

Management of neurotrauma in LMICs

Overview of current neurotrauma management guidelines in LMICs

Despite a wealth of published literature and evidence on the clinical approach to neurotrauma, the majority of discussions and implementation are focused on the HICs. However, health care workers in LMICs often rely on guidelines developed in HICs, and many interventions may not be validated for implementation in LMICs due to variations in infrastructure, medical personnel, technology, and environmental conditions. It is, therefore, necessary to critically appraise clinical guideline recommendations in the context of LMICs[32].

In 2004, the International Association of the Surgery of Trauma and Surgical Intensive Care and WHO formulated a guideline to address the difficulties that confront trauma care in LMICs. The guideline lists 14 categories of trauma services that are achievable in virtually every setting worldwide and includes the human and physical resources that would ensure their provision[33]. However, these guidelines are situational, and there are currently no comprehensive guidelines for each of the 14 categories of trauma care[34].

The Beyond One Option for Treatment of Traumatic Injury: A Stratified Protocol (BOOTStraP) is a recently stratified recommendation from the Colombian Consensus Committee for the management of TBI in prehospital, emergency department (ED), surgery, and intensive care. Developed to supplement the shortfalls of national clinical practice guidelines, the protocol allows medical providers to select the best treatment option depending on the available resources. Although still in the testing phase, the BOOTStraP guideline is expected to organize a better strategy for interventions in varying resource settings[35]. The BOOTStraP protocol has only two dimensions. Prehospital care, ED, surgery, and intensive care unit (ICU) comprise the first dimension of treatment. The level of resources is the second factor. The accessibility of resources varies constantly in LMICs. Even a high-resource facility may experience staffing shortages or a lack of medication. A system may also have adequate resources for one stage of treatment (such as the ED) but insufficient resources for another (such as emergency transport)[35]. The exclusion of patients under the age of 15, the use of experimental therapies or tools, and the direct omission of primary prevention and the rehabilitation process, because they fell outside the purview of this consensus, are all limitations of this project[35].

A qualitative study by Lepard *et al*. found that despite relatively good compliance to many TBI and traumatic spinal injury guideline recommendations, environmental context and financial availability serve as barriers to compliance for some recommendations[36]. This is supported by the findings of Jin *et al*.[37], which emphasize that the implementation of neurotrauma guidelines in countries such as Uganda (i.e., LMICs) can be hindered due to factors such as limited access to essential equipment, inadequate money, and a shortage of sufficiently trained medical personnel. Therefore, additional effort must be made to develop context-specific approaches that can capture actual practice patterns and record short-term and long-term outcomes of interest.

Comparison of neurotrauma management guidelines in LMICs and HICs

The management of neurotrauma in LMICs and HICs differs significantly due to variations in infrastructure, medical personnel, technology, and environmental conditions. A scoping review on neurotrauma and RTC prevention presented that while many preventative measures such as legislation/policy strategies and intervention are shared by HICs and LMICs, LMICs lack several interventions such as technology utilization and engineering. Moreover, there is a lack of research on secondary and tertiary preventative measures in LMICs, as well as the applicability of HIC interventions in LMICs[38].

The discrepancy in the management of neurotrauma between LMICs and HICs is evident in the applicability of Advanced Trauma Life Support (ATLS), which is considered the worldwide "gold standard" of advanced trauma care. Studies have demonstrated that ATLS significantly contributes to improved trauma patient outcomes by reducing the rates of potentially preventable or preventable deaths[39,40]. However, ATLS is not widely available in LMICs, as most training institutions are located in North America, Europe, and other HICs. In addition to the difficulty of access, the financial burden of becoming ATLS certified is considered a challenge[41]. Importantly, several recommendations for ATLS are based on using resources that are not generally available in many LMIC countries, which question the applicability of the ATLS in LMIC settings[42].

While many of the preventive measures and interventions for neurotrauma management are similar between LMICs and HICs, the lack of resources and availability of guidelines specific to LMICs present significant challenges. The BOOTStraP protocol and standardized neurosurgical management have shown promise in addressing these challenges, but more research and context-specific approaches are needed to improve outcomes in LMICs.

Challenges faced by health care systems in LMICs in managing neurotrauma

One of the major inhibiting factors of neurotrauma management in LMICs is their general lack of resources and their flawed infrastructures (Fig. 2). De Silva *et al*. conducted a study that found that the mortality rate for neurotrauma was higher in LMICs compared to HICs, which was attributed to inadequate health care infrastructure and a lack of access to timely and appropriate care[43]. Inequitable access to quality care, despite charitable and state-funded efforts, also remains a major challenge[44]. Many patients may require emergency neurosurgical intervention at a specialized institution, yet traveling between hospitals for specialized care can be lengthy, costly, and

Figure 2. Challenges associated with the management of neurotrauma in LMICs. LMICs, low- and middle-income countries.

hazardous[33]. A study by Roger *et al*. demonstrated the association between prehospital care and mortality, that is, a 50% increase in mortality associated with the indirect transfer of TBI patients[45].

Most LMICs suffer not only from a lack of appropriate health care infrastructures but also experience a shortage of trained and specialized medical personnel and limited diagnostic and treatment resources[46]. A reflective analysis by Smith *et al*. described that the lack of workforce is a significant cause of limits on treatment beyond acute care[44]. According to the WHO (2004), the median number of neurosurgeons per 100 000 individuals is 0.03 for low-income countries and 0.97 for HICs[47]. What further complicates this problem is the lack of long-term, capacity-building educational initiatives. A study conducted in Ethiopia stressed that the lack of education is the main barrier preventing training doctors from providing optimal surgical training to local residents[48].

Rehabilitation for neurotrauma patients is particularly complex and requires a multidisciplinary team, as the patients are understood to have numerous ongoing physical, psychological, and cognitive sequelae. It is estimated that only 2% of the population living in LMIC have access to rehabilitation services[49]. In addition, the chronic post-injury phase of traumatic brain care imposes socioeconomic challenges on the patients and their families[50].

Despite the significant burden of neurotrauma in LMIC, the clinical data, including outcome, disability, and long-term functional outcomes remain poorly recorded. Laytin *et al*. describe the difficulty of collecting outcome data in resource-poor settings, due to the weak health care infrastructure and limited regular follow-up of trauma patients[51]. Crucial aspects, such as the relationship between prehospital care and outcomes for patients with SCI are difficult to analyze in LMICs because prehospital care is not widely available[52]. Inappropriate management compromises the outcome of neurotrauma patients, leading to decreased economic productivity due to the loss of the working population and long-term health care costs[53].

Case studies of successful neurotrauma management programs in LMICs

Standardized neurosurgical management is effective in improving outcomes for neurotrauma patients in LMICs. For example, a study conducted in Colombia implemented a standardized treatment protocol (STP) based on the clinical trauma paradigm of a tertiary care hospital, which resulted in significantly improved outcomes. The use of STP led to increased early vital interventions, decreased overall length of stay, and reduced mortality rates for both surgical and nonsurgical patients[42]. Similarly, a 2016 study on severe TBI patients receiving ICU care at a trauma center found that adherence to early ICU guidelines was associated with lower in-patient mortality rates. A greater than 65% adherence rate to ICU guidelines was associated with nearly a two-fold reduction in in-patient mortality[54]. These studies suggest that standardized protocols

and adherence to established guidelines can be effective in improving neurotrauma management and outcomes in LMICs.

In resource-limited settings where advanced diagnostic tools like magnetic resonance imaging (MRI) scanners and intracranial pressure (ICP) monitors are not readily available, clinical clues can be used to manage neurotrauma. For instance, a study conducted in Argentina on the management of minor pediatric head injuries demonstrated that skilled clinical staff using a well-organized protocol of care can produce good recovery outcomes in the ICU without ICP monitoring. The study reported no difference in outcomes between patients with severe TBI managed using ICP monitoring and those without[55]. In addition, a prospective study in Malawi found that basic trauma tools such as the Glasgow Coma Scale (GCS) and heart rate can effectively triage head injury patients, who comprise the most critically ill trauma patients in resource-limited settings. The study suggested that monitoring changes in the GCS and heart rate strongly correlated with mortality and could be used effectively for the triage of critically ill patients with TBI[56].

A systematic review conducted by Iemmi *et al.* has demonstrated the effectiveness of community-based rehabilitation (CBR) for individuals with disabilities in LMICs. CBR is a community-based approach to rehabilitation that aims to improve the functioning and quality of life of individuals with disabilities and their caregivers. It focuses on five key developmental areas: health, education, livelihood, social inclusion, and empowerment. By promoting mainstreaming and empowerment of people with disabilities and their families, CBR can be an effective approach for improving clinical outcomes and enhancing the functioning and quality of life of individuals with disabilities and their caregivers. Although no studies have examined the specific use of CBR for neurotrauma, the available evidence suggests that CBR can be a useful tool in LMICs for improving outcomes in individuals with disabilities resulting from neurotrauma. Additionally, involving the community in the rehabilitation process can help reduce the stigma and social isolation experienced by individuals with neurotrauma, which can have a significant impact on their overall well-being[57].

Recommendations for successful neurotrauma management in LMICs

Addressing modifiable risk factors

Neurotrauma has many modalities of preventable mechanisms, such as RTCs, falls, and interpersonal violence. Among these, RTCs are the leading cause of neurotrauma in LMICs. More effective strategies via legislation, as well as education and public awareness campaigns, need to be enforced to reduce the fatality of road traffic fatalities and injuries. Further investigation is needed to delineate local and regional neurotrauma incidences and causes, especially in LMICs[58,59].

Standardized trauma care protocols

Implementing readily accessible STPs is crucial to improving hospital trauma care in LMICs. A predictive model can be used to allocate resources to areas where STPs are most needed, allowing for more efficient use of resources. Studies have shown that implementing an STP at a university hospital in an LMIC increased the use of early vital interventions and improved outcomes of neurotrauma patients. However, improved patient categorization is necessary to prevent the over-triage of TBI patients and limit the inadequate management of other conditions. Non-physician health care providers should also be trained according to the STP to create the greatest impact in providing effective and standardized care[42,60]. Moreover, national surgical, obstetrics, and anesthesia plans are warranted to achieve surgical benchmarks and standardize care following traumatic injuries[61].

Research and data collection

Despite the high burden on neurotrauma in low-resource settings, the full picture of neurotrauma epidemiology in LMIC is yet unknown. However, the collection of long-term data in LMIC is critical for providing epidemiological data and assessing the efficacy of patient treatment and management decisions[44]. The importance of data collection through neurotrauma registries, capacity building for advanced education in neurotrauma-care provision and research, and integration of teams within a trauma care system have been recently proposed. Multicentre collaborative approaches toward data collection may be an efficient and productive strategy for TBI research LMIC[6].

Ultimately, however, to meet such objectives, national resource allocation in LMICs requires further analysis and restructuring. Interestingly, 54.7% of the neurosurgical RCTs in LMICs have been institutionally funded in the past, with only 3.8% of studies funded by industry, in comparison to 33.7% of industry funding in HICs[62]. This funding discrepancy within the LMIC industry sector does not appear solely mediated by resource scarcity but may be secondary to the disproportionate prioritization of research funds irrespective of public health needs and burdens. Wong *et al.* have shown that between 1998 and 2008, 42% of the oncology RCTs done in LMICs were industry-funded[63]. As such, it is not surprising that the current paucity of neurotrauma data in LMICs, as funding, particularly from non-government organizations, is limited. Ultimately, a call to action is warranted for national government and non-government organizations to prioritize neurotrauma research and allocate sufficient resources across both public and private sectors[62].

Global partnership

Global partnerships are vital in building capacity and improving neurotrauma management in LMICs. Collaboration between HCPs and organizations from HICs and LMICs can enable knowledge and resource sharing, facilitate training and education, and establish sustainable programs. Improved neurotrauma care in underserved regions requires the involvement of societies and global governance. An effective approach to enhancing the number of competent and accessible neurosurgeons is to invite meaningful participation from the workforce in LMICs. This can be achieved by organizing a workforce of members interested in cross-national education and training and allocating resources such as activities, meetings, and funding to support international education and research initiatives. These efforts can contribute significantly to strengthening the capacity of neurosurgical programs in LMICs and contribute to improved neurotrauma care[64].

Addressing sociocultural barriers

Cultural beliefs and practices are also crucial factors to consider when implementing guidelines in LMICs. In many settings, trauma-related conditions such as TBI may be stigmatized, or patients may lack trust in modern medical interventions like telemedicine or mobile health (mHealth). This distrust can prevent adherence to treatment plans and reduce the effectiveness of follow-up care[13]. To address these challenges, community-based health programs that involve local leaders and emphasize culturally appropriate health education have been shown to improve patient trust and engagement. For instance, initiatives in Kenya have successfully employed mobile health interventions to raise awareness about TBIs and improve patient outcomes by working within the sociocultural context to build trust and understanding[44].

Innovations and emerging trends in neurotrauma management

Overview of current research and development in neurotrauma management in LMICs

The research and development in neurotrauma management in LMICs are greatly hindered by circumstances unique to their countries and hence differ in both their guidelines and approaches to neurotrauma management when compared with HICs. Despite several challenges, which include limited resources, broken infrastructure, and a shortage of medical personnel, there is continuous development and ongoing research focused on enhancing their response to neurotrauma. Most importantly, the aim is to improve the diagnosis, treatment, and outcomes of patients in LMICs. The research of Khan *et al*. supports the importance of such research to establish cost-effective neurotrauma guidelines in LMICs[65].

In HICs, the golden standard in neurotrauma diagnosis is the use of MRI and computed tomography. Although LMICs rarely have access to such technology, they still recognize the importance of quick diagnosis as it allows for early intervention. To combat these issues, LMICs use strategies such as the GCS[60] to determine severity and influence surgical interference rapidly[60]. Additionally, in recent years, point-of-care ultrasounds (POCUS) have shown to be a promising tool for timely diagnosis. A study in Nepal noted the ability of POCUS to detect intracranial injuries with high specificity and sensitivity, which is a valuable diagnostic instrument in LMICs[66]. In LMICs, the treatment of neurotrauma patients shows higher mortality rates as they lack the equipment and required training[65] and hence are focused on creating better facilities and getting more personnel, as well as adequately trained personnel, an effort supported by Smith *et al*.[67].

Related to an increase and improvement of primary and secondary facilities is a focus on rehabilitation of neurotrauma patients in LMICs. Access to rehabilitation is often hindered by lack of transport, cultural stigmas, and inadequacy of funding. A study in India[68] found that the use of a CBR program was a successful multidisciplinary approach to neurotrauma therapy and rehabilitation. Prevention is also an essential component of neurotrauma management as it decreases the influx of neurotrauma cases and hence allows more efficient use of the rest of the patients they receive. LMICs show an increased incidence of TBIs from road accidents due to poor road systems and insufficient safety standards. A study by Li *et al.* in Vietnam found a 60% reduction in the risk of TBIs associated with the use of helmets[69].

Discussion of potential innovation and emerging trends in neurotrauma management

Growing attention has been shown in recent years to potential advancements and new patterns in LMIC neurotrauma therapy, most notably telemedicine. This method utilizes technology to remotely provide LMIC health care providers to consult with specialists and hence deliver care to patients in underserved and under-equipped environments. Khanna *et al*. showed that patients who utilized telemedicine experienced a lower incidence of mortality and disability[68].

The "Sm@rtEven project," for example, demonstrated how telemedicine could be used for the remote evaluation of patients after surgery. By leveraging mobile applications and continuous monitoring systems, this approach enabled HCPs to maintain contact with patients over an extended period, ensuring timely interventions and rehabilitation[70]. The success of such initiatives underscores telemedicine's potential to provide continuity of care even in the absence of physical health care facilities – a critical advantage in LMICs where infrastructure is limited.

Moreover, telemedicine has been shown to facilitate remote consultations, reducing the need for travel, lowering health care costs, and preventing delays in critical care. For instance, the Sm@rtEven project observed high levels of patient compliance and satisfaction when using telemedicine for postoperative follow-ups, even during the pandemic. This is particularly relevant for LMICs where specialists are often concentrated in urban centers, making access difficult for rural populations[70].

Telemedicine has proven to be an effective tool for reducing disability and mortality by enabling early intervention. In resource-limited settings, the delay in accessing specialized neurotrauma care can lead to long-term disabilities or fatalities that could have been avoided with timely treatment. The Sm@rtEven project reported high patient compliance, which ensured that health care providers could promptly address any postoperative complications[70]. This continuous monitoring significantly improves patient outcomes in neurotrauma cases, where timely intervention is often critical to prevent long-term damage.

Beyond individual patient care, telemedicine also has broader implications for healthcare in LMICs. It has been identified as a means to combat healthcare disparities, allowing specialists to extend their reach to underserved areas. Marinelli *et al*. emphasized that the adoption of telemedicine services in various medical disciplines has been instrumental in providing access to care for populations who would otherwise be excluded due to socioeconomic or geographical barriers[71].

Furthermore, telemedicine has the potential to address the digital divide – a significant issue in LMICs – by ensuring that more people have access to the care they need regardless of their social or financial status. This is especially critical for patients with neurotrauma, where timely access to specialist care can significantly reduce the burden of disability[71].

The Italian Supreme Court ruling (n. 38485/2019) highlights the legal need for health authority authorization when offering telemedicine services. Although telemedicine operates in virtual spaces, national guidelines emphasize the importance of meeting functional and logistical requirements, ensuring accountability for healthcare providers and facilities. This ruling is particularly

relevant in cross-border health policies, where varying regulations can impact the legitimacy of telemedicine services. By adhering to strict oversight, telemedicine in neurotrauma can ensure patient safety, improve outcomes, and foster trust in this evolving mode of care[72].

Another potential enhancement to neurotrauma care in LMICs is the utilization of point-of-care testing (POCT), which involves portable diagnostic tests that can be rapidly carried out right at a patient's bedside. This is essential to countries, such as LMICs, that lack diagnostic equipment and laboratories. Reynolds *et al*. conducted a study in Tanzania that highlighted the effectiveness of POCT's ability to identify TBI and was linked with improved outcomes[73].

The Latin America and Caribbean Neurotrauma Registry (LATINO-TBI) exemplifies how POCT is integrated into neurotrauma care. By tracking cases of TBI and SCI, the registry has improved care outcomes and resource allocation in the region[74].

In India, a POCT device combining electroencephalogram and near-infrared spectroscopy has been developed to assess neurovascular coupling in stroke survivors. This device helps in the real-time detection of cerebrovascular reactivity impairments, offering the potential to reduce stroke-related complications[75].

Global neurotrauma registries in LMICs highlight the value of hospital-based data collection systems in improving trauma care. Although national databases are scarce, regional systems have provided critical data for targeted health interventions and better patient outcomes[27].

As well as POCT, mHealth interventions have emerged as an effective form of reducing neurotrauma incidence and improving the outcome for patients. mHealth interventions consist of the use of wireless devices to provide health services, especially including the delivery of healthcare information and the monitoring of many patients simultaneously. This is especially effective in LMICs because although they may have a struggling medical infrastructure, statistics show that the majority of patients in LMICs own a mobile phone. According to a recent study from Njoroge *et al*. in Kenya, an mHealth intervention created to enhance TBI outcomes was successful in raising awareness of TBIs and enhancing results for TBI patients[76]. mHealth interventions are also useful for improving follow-up care and highlight the importance of improving education and neurotrauma research in LMICs as they offer an optimistic opportunity to improve their current neurotrauma management.

A key challenge in LMICs is the high rate of patients lost to follow-up after discharge, often due to geographical barriers, health care resource limitations, and socioeconomic factors. mHealth platforms, such as short message service reminders and mobile health applications, offer a practical solution to this issue by facilitating continuous monitoring and communication with patients' post-discharge, thus improving adherence to follow-up protocols[44].

Additionally, mHealth tools have demonstrated effectiveness in remote assessments, where clinicians can monitor symptoms and provide timely interventions, reducing the need for in-person visits and ensuring patients in remote areas receive ongoing care. This is particularly relevant in LMICs, where mobile phone penetration is high, making mHealth an accessible option for health care delivery. Research indicates that mHealth can reduce the burden on health care systems by enabling patients to report symptoms and receive care instructions through digital platforms, improving outcomes and reducing the risks of complications[77]. Furthermore, mHealth has been shown to enhance patient engagement by providing education and facilitating follow-up care, which has been critical for improving neurotrauma outcomes in LMICs[78].

Limitations

Several limitations must be considered in the interpretation of findings from this narrative review on neurotrauma management in resource-limited settings. The heterogeneity of the included studies, stemming from variations in study designs and methodologies, introduces challenges in synthesizing consistent conclusions. For instance, disparities in the reporting of neurotrauma outcomes across studies, compounded by inconsistent data collection, may skew the representativeness of findings, particularly in regions where reliable neurotrauma registries do not exist[6]. The potential for publication bias further complicates the reliability of conclusions, as positive outcomes may be over-reported, while challenges faced in implementing solutions in LMICs could be underrepresented. The absence of high-quality data from LMICs, where neurotrauma management often suffers from infrastructural gaps, raises concerns about the applicability of conclusions drawn from the review. The limited availability of robust data could lead to an overemphasis on success stories from more well-documented regions while downplaying the unique barriers LMICs face, including poor access to health care resources, lack of trained personnel, and cultural factors influencing treatment adherence. This data gap hinders the ability to draw fully representative conclusions regarding the effectiveness of certain interventions, particularly in rural or remote settings.

International guidelines for neurotrauma management, primarily developed in HICs, may be difficult to implement in LMICs without contextual adaptation. The successful implementation of these guidelines must account for resource constraints, sociocultural factors, and health care system limitations in LMICs. One example is the BOOTStraP program, which emphasizes resource-stratified guidelines designed specifically for low-resource settings. This initiative tailors neurotrauma management strategies to the realities of LMICs, addressing gaps such as the lack of intravenous fluids or proper transport systems in rural areas, which are critical for timely trauma care[65]. Programs like BOOTStraP illustrate that with proper adaptation, it is possible to deliver high-quality trauma care, even with limited resources.

Another example is the successful implementation of neurotrauma registries in Latin America and the Caribbean. Despite facing infrastructural challenges, these regions adopted a shared neurotrauma registry, which allowed for standardized data collection and improved tracking of TBI outcomes. The registry facilitated better clinical decision-making and policy development, serving as an example of how standardized guidelines can be adapted to fit local needs through regional collaboration[79].

Conclusion

Neurotrauma continues to be a major public health challenge globally, with a disproportionate impact on LMICs. This review highlights the disparities in neurotrauma management between

LMICs and HICs, focusing on resource availability, infrastructure, and access to care. In LMICs, the lack of trained HCPs, inadequate diagnostic tools, and high treatment costs are key factors contributing to poor outcomes. However, innovations such as POCUS and telemedicine have shown promise in improving care in resource-limited settings. To bridge the gap in neurotrauma management, global partnerships are essential. Capacity-building initiatives, such as training HCPs and improving access to diagnostic tools in LMICs, are crucial for improving outcomes. Future efforts should focus on developing context-specific guidelines that address the unique challenges faced by LMICs, ensuring that the global burden of neurotrauma is addressed equitably. By prioritizing investment in health care infrastructure and promoting research in LMICs, we can work toward reducing the global disparities in neurotrauma outcomes.

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Consent

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Author's contribution

Conceptualization of ideas: T.A.-R. and M.K. Methodology, data curation, and visualization: T.A.-R. Supervision: T.A.-R., T.T., and V.H. Writing of initial draft: S.M.B., S.L., M.W., M. K., and M.Z., P.R., J.D., S.O., E.A., and S.B.B. Writing – review and editing: T.A.-R., A.A.W., O.A., S.D., T.T., and V.H.

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