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Review Article

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Modern Aspects of Post-haemorrhagic Hydrocephalus in Infants: Current Challenges and Prospects

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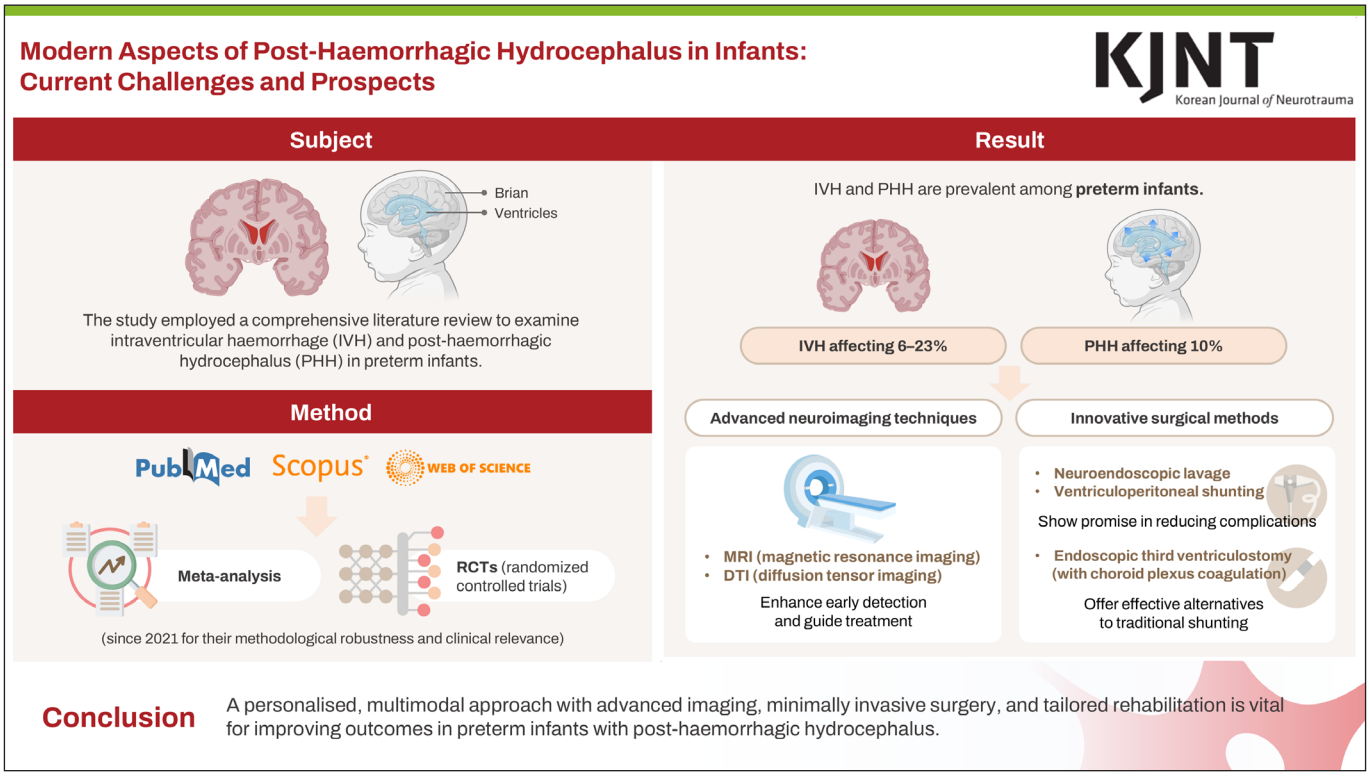
ABSTRACT

This article aimed to assess and discuss the current diagnostic and treatment approaches for post-hemorrhagic hydrocephalus (PHH) in preterm infants with the goal of enhancing their quality of life and minimizing long-term complications. This literature review used a multilevel analysis of contemporary studies on intraventricular hemorrhage (IVH) and PHH in preterm neonates from PubMed, Scopus, and Web of Science databases, applying strict selection criteria and double independent assessments to ensure the reliability and relevance of the findings. This review emphasizes the complexity of IVH and PHH in preterm neonates and highlights diverse approaches in diagnosis, treatment, and rehabilitation. Recent studies have highlighted the importance of advanced neuroimaging for accurate diagnosis and the potential of neuroendoscopic lavage in reducing shunt dependency and the risk of infections; however, there is a clear need for further research into long-term outcomes and the development of less invasive treatments. The efficacy of combined techniques using temporary manipulation followed by permanent drainage systems, which ensure normal positioning of the postnasal drainage system and provides time for specialists to consider the optimal strategy, has also been demonstrated. This study will aid health professionals in making timely decisions, reducing neurological complications, and improving patient prognoses and quality of life.

Keywords: Innovative therapies; Surgery; Medical research; Treatment outcome; Intracranial pressure

GRAPHICAL ABSTRACT



Informed Consent

This type of study does not require informed consent.

Ethics Approval

This research did not require ethical approval as it does not involve human subjects, their data, or biological samples.

INTRODUCTION

This study highlights the significant impact of post-hemorrhagic hydrocephalus (PHH) on the health and development of premature newborns, which poses complex challenges for the medical community in the diagnosis, treatment, and rehabilitation of these infants. The number of newborn infants, including preterm infants, is increasing worldwide. In recent decades, in accordance with the World Health Organization (WHO) standards, Kazakhstan has introduced the categories of very low and extremely low birth weight babies. These infants are morphologically and functionally immature and are prone to diseases, such as bronchopulmonary dysplasia, retinopathy, necrotizing enterocolitis, and intraventricular hemorrhage (IVH). Given the increasing survival rate of premature infants and the associated risk of developing severe neurological disorders, new methods and approaches need to be developed and tested to improve the outcomes and quality of life of infants.[39]

Kizatova and Dyusembaeva[24] indicated that over the last 10 years, infant mortality in Kazakhstan has decreased by 2.6 times to 7.9%. This can be explained by the increased survival rate of premature children. Chuvakova et al.[8] demonstrated that the most vulnerable newborns with the highest mortality are premature newborns with body weights of up to 1,500 g, as intraventricular hemorrhage occurs in 20% of cases. In the population of preterm neonates with birth weights less than 750 g, that percentage reaches 50%.[46] This indicates a high prevalence of IVH in this category of preterm infants.[35] PHH significantly affects neurological development and quality of life in premature infants, which can lead to various complications, including motor impairment, cognitive deficits, and delayed psychomotor

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development.[36] According to Smagulova et al.,[46] these problems require long-term medical supervision and rehabilitation, imposing a significant burden on patients' families and social services. The current methods of treatment for PHH, such as surgery for shunt placement, are not without risks and complications.[29] Current approaches often involve the need for repeated surgeries and may be associated with infections, mechanical damage to the shunt, and other problems, emphasizing the need to identify safer and more effective methods for treating and managing this condition.[32]

PHH in preterm newborns is a difficult and frequently under-studied illness in neonatal medicine and neurology. This study addresses the important knowledge gaps in this area. Current diagnostic, therapeutic, and rehabilitation procedures need to be urgently improved because of the significant risk of neurodevelopmental problems linked to PHH, particularly as survival rates of preterm newborns continue to increase. This study offers a solid basis for improving infant care by thoroughly examining the etiology, pathophysiology, and clinical symptoms of PHH. It examines the possibilities of new technologies and materials in medical practice and focuses on both conventional and cutting-edge therapeutic modalities, including conservative and surgical techniques. With the ultimate goal of raising the standard and effectiveness of therapy for this susceptible patient population, this study helps improve the long-term results and quality of life of newborns affected by PHH by providing insights and useful suggestions for individualized care.

MATERIALS AND METHODS

To achieve the study's objective, a comprehensive review of the research related to IVH and the subsequent development of PHH in preterm infants was conducted. A rigorous selection process was used to identify significant and relevant studies from reputable medical and scientific databases, including PubMed, Scopus, and Web of Science. The inclusion criteria were strictly defined during the study selection process; meta-analyses and randomized controlled trials were given a special priority because of their high methodological rigor and ability to provide objective validated data. Special attention was also given to papers characterized by a clear research methodology, reliability and reproducibility of results, and relevance of clinical findings in practice. To ensure the relevance and currency of the collected information, the literature review utilized studies published from 2021 onwards. This allowed us to include the most up-to-date data and scientific findings in the field of IVH and PHH in preterm infants. A literature search was conducted using keywords, such as intraventricular hemorrhage, post-hemorrhagic hydrocephalus, and premature infants, as well as more specific terms related to the mechanisms of onset and management of these conditions. The approach involved an in-depth literature review, using double independent assessment methods to extract data from the selected studies and assessing the quality of the studies using standardized risk of bias scales. These methods ensure the reliability and validity of the analyses, allowing the formation of sound conclusions based on relevant scientific evidence.

RESULTS AND DISCUSSION

IVH and PHH occupy a special place in the morbidity of premature newborns owing to their high incidence, high lethality, adverse effects on the neuropsychiatric development of the

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child, and association with the development of a wide range of neuropsychiatric disorders.[24] As part of a review of the current literature, more than 45 scientific papers devoted to the study of PHH in infants were analyzed. Studies conducted in different parts of the world, from North and South America to Europe, Asia, and Australia, emphasize the global nature of the problem and the diversity of approaches to its solution. The time span of the reviewed studies covered the period from the early 2000s to the present, which allowed us to trace the evolution of methods of diagnosis, treatment, and rehabilitation, as well as changes in the understanding of the mechanisms of disease development.

Bębenek et al.[4] indicated in their article that IVH is a significant clinical problem, especially in neonatal populations, with an incidence of 6% to 23% among premature infants in countries with developed health care systems. Cohen and Flibotte[9] reported that 10% of all neonates with IVH and 20% of infants with severe IVH develop progressive post-hemorrhagic ventricular dilatation (PHVD) syndrome, which requires surgical intervention to prevent parenchymal damage in the developing brain. In a study conducted on newborns in Puerto Rico between 2013 and 2017, 261 IVH survivors were analyzed to elucidate the risk of developing PHH.[17] The overall mortality rate was 19.4%, whereas the risk of hydrocephalus was 7.7%. Statistical analyses showed no significant association between the development of PHH and the child's sex, birth weight, or gestational age. However, logistic regression analyses showed that children with grade 3 and 4 IVH were 20 times more likely to develop this complication. Germinative matrix fibrosis occurs in approximately three cases per thousand live newborns.[52]

Etiology and pathophysiological mechanisms of the development of PHH

PHH in infants, especially premature infants, often develops as a result of IVH, which occurs because of hemorrhage in the germinal matrix region or in the ventricular system of the brain itself.[11] According to current scientific research, the cerebral germinal matrix is a specific region of the brain that is located near the fetal ventricular system and is composed of neuroglial cells. This matrix is filled with numerous immature large rapidly growing capillaries, making it an important element in brain development. However, the germinative matrix completely regresses and disappears by the 36th week of gestation.[14] Interestingly, in almost all cases of IVH, it is observed in preterm infants precisely in the area of the germinative matrix. Hemorrhages are usually bilateral and tend to be localized in the ependymal region of the lateral ventricles, the caudate nucleus, or the area between the caudate nucleus and the thalamus. In most cases, hemorrhage occurs in the first hours after delivery, but very rarely, it can occur a few days or even longer after birth.[43] Prematurity is a key risk factor for IVH because of the immaturity of the brain and vascular system, which makes blood vessels particularly vulnerable to rupture due to stressors such as hypoxia, blood pressure fluctuations, and birth trauma. Additional risk factors include sepsis, clotting disorders, and mechanical ventilation.

After hemorrhage, blood in the ventricular system can interfere with the normal outflow and absorption of cerebrospinal fluid (CSF), causing it to accumulate, resulting in ventricular dilatation or hydrocephalus. This ventricular enlargement exerts pressure on the surrounding brain tissue, which can cause additional damage and disrupt normal brain development.[12] Hydrocephalus after IVH can be caused by mechanical obstruction when blood clots physically block CSF outflow pathways, especially in the Sylvian aqueduct and the outlets of the fourth ventricle. In addition, blood degradation products can cause inflammatory responses leading to fibrosis and fusion around the arachnoid villi, which reduce CSF

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absorption and increase its volume in the ventricular system. Hemorrhage can also impair the function of the ventricular ependymal layer, which contributes to the development of hydrocephalus.[15] Despite significant progress in the study and treatment of PHH in infants, there are significant challenges and limitations, such as difficulties in early diagnosis, risk of complications after surgical treatment, and uncertainty in long-term outcomes. In addition, the influence of various factors, such as genetics, on the development and progression of the disease needs to be better understood. Understanding these mechanisms is critical for developing strategies for the prevention, diagnosis, and treatment of PHH to reduce the risk of neurological and cognitive complications in affected children. To illustrate the relationships among the key factors contributing to the development and management of PHH in preterm infants, **FIGURE 1** summarizes the progression from risk factors to diagnosis and treatment approaches.

TABLE 1 is presented below to improve the comprehension of the main pathophysiological and etiological elements influencing the development of PHH in preterm infants. It shows the main covered points, emphasizing important connections among different risk factors, their consequences on the development of PHH, and the difficulties in managing them. Descriptions regarding the interactions of these elements and their effects on the condition are also provided.

Efficiency of diagnostic methods

The characteristic signs of hydrocephalus in newborn infants include bulging or tension of the fontanelle, suture separation, frequent vomiting, oculomotor dysfunction, and a rapid increase in head size. Rapid head enlargement was defined as an increase >2 mm/day. The most reliable indicator of neonatal hydrocephalus is the gradual enlargement of the sagittal suture.[51]

Among the diagnostic methods, special attention has been paid to improvements in neuroimaging. Magnetic resonance imaging (MRI), computed tomography (CT), and brain ultrasonography (BUS) have demonstrated high efficiency in determining the extent and nature of brain ventricular dilation, which is critical for the diagnosis of hydrocephalus.[2,18]

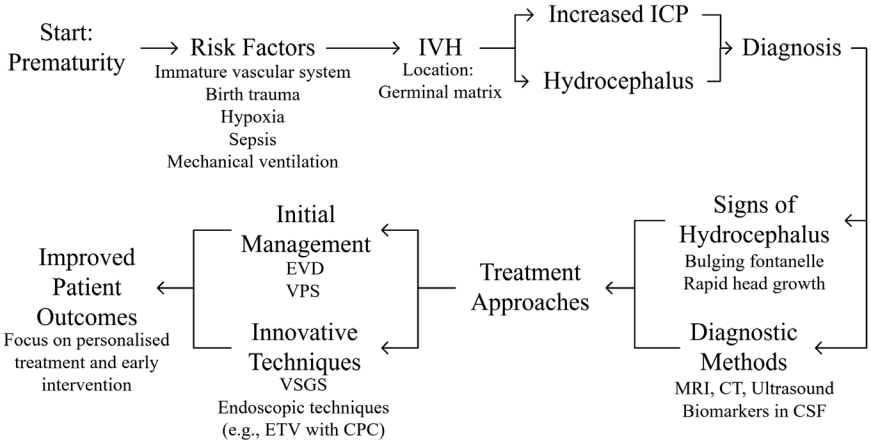

FIGURE 1. PHH development and management in preterm infants.
Source: compiled by the authors.
PHH: post-hemorrhagic hydrocephalus, IVH: intraventricular hemorrhage, ICP: intracranial pressure, MRI: magnetic resonance imaging, CT: computed tomography, CSF: cerebrospinal fluid, EVD: external ventricular drainage, VPS: ventriculoperitoneal shunting, VSGS: ventriculosubgaleal shunt, ETV: endoscopic third ventriculostomy, CPC: choroid plexus coagulation.

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TABLE 1. Aetiological and pathophysiological factors contributing to the development of PHH in preterm infants

Factor	Description	Implications for PHH development
IVH	Haemorrhage in the germinal matrix area, where immature and quickly expanding capillaries are more prone to rupture, is the cause of IVH in premature newborns. IVH is mainly found in the caudate nucleus, lateral ventricles, or between the thalamus and caudate nucleus.	Blood enters the ventricular system as a result of IVH, raising the possibility of CSF flow restriction.
Germinative matrix	The germinative matrix, which regresses by 36 weeks of gestation, is an area close to the fetal ventricular system that contains a significant number of immature neuroglial cells and quickly expanding capillaries. This area frequently experiences haemorrhage, particularly in preterm infants.	Because of the capillaries' structural weakness in the germinative matrix, preterm infants are at high risk of bleeding.
Risk factors	Prematurity, hypoxia, blood pressure fluctuations, birth trauma, sepsis, coagulation issues, and the use of mechanical ventilation are important risk factors.	Increased vulnerability to IVH as a result of exposure to different physiological stresses and underdeveloped vascular systems.
Ventricular dilatation	Hydrocephalus occurs due to blood in the ventricular system obstructing normal CSF flow and absorption. Ventricular enlargement brought on by CSF buildup raises the pressure on brain tissue.	As ventricles dilate and CSF accumulates, hydrocephalus occurs, increasing potential risks to the nervous system and the developing brain.
CSF obstruction and inflammation	CSF routes may be blocked by blood clots, particularly in the vicinity of the fourth ventricle outputs and the Sylvian aqueduct. Products of blood breakdown hinder the absorption of CSF by causing fibrosis, inflammation, and arachnoid villi fusion.	Treatment becomes more difficult when physical obstruction and an inflammatory reaction worsen the course of hydrocephalus.
Challenges in PHH management	PHH is still difficult to diagnose early, and there is a chance of problems with treatment alternatives such as surgical shunts. Long-term results are likewise unknown, and little is known about the genetic variables impacting the course of PHH.	Improved diagnostic instruments and safer, more efficient treatment approaches are required, as is genetic research to guide treatment.

Source: compiled by the authors.
PHH: post-hemorrhagic hydrocephalus, IVH: intraventricular hemorrhage, CSF: cerebrospinal fluid.

Current research emphasizes the role of advanced techniques, such as 3-dimensional (3D) imaging and diffusion-tensor imaging, in clarifying the diagnosis and determining treatment tactics. Despite the significant progress in diagnosis, the literature has often discussed the problem of early disease detection when clinical manifestations were not yet obvious.[26] Roy et al.[41] analyzed the relationship between changes in cerebral ventricular volume in premature neonates with IVH and the need for subsequent ventriculoperitoneal shunting (VPS). The use of 3D ultrasonography to measure the ventricular volume before and after ventriculoperitoneal (VP) puncture revealed that a significant decrease in ventricular volume was correlated with a greater likelihood of shunting. The study included 92 neonates, of whom 19 required ventricular punctures and showed a statistically significant correlation between the change in ventricular volume and the need for shunting.

Benavente-Fernández et al.[5] included 59 patients from four centers, performing early and late ventricular dilatation interventions. Ventricular volume was studied using 209 3D and 1,226 2-dimensional ultrasound scans. The results showed that the maximum ventricular volume before reservoir placement and gestational age at birth correlated with the need for VP shunt placement. A defined ventricular volume threshold of 17 cm^3 allowed correct classification in 79.31% of cases. Various quantitative indices have been actively used in scientific literature, among which the ventricular index defined as the distance between the cerebral sickle and lateral wall of the anterior horn of the ventricle in the coronal plane at the level of Monroe's foramen, is of particular importance. Exceeding the ventricular index value by more than 4 mm above the 97th percentile was interpreted as the criterion for initiating active therapeutic measures for hydrocephalus. This means that when the measured ventricular index exceeds the established normative limit by 4 mm or more, it serves as a signal that the volume of

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the brain ventricles has increased to a degree potentially requiring medical intervention to prevent or reduce the adverse effects of hydrocephalus.[41]

MRI plays an important role in the diagnosis of hydrocephalus by providing unique opportunities to evaluate brain structures with a high resolution. MRI allows visualization of not only ventricular dilation, which is a key sign of hydrocephalus, but also the underlying causes of this condition, such as obstruction of the CSF circulation, developmental anomalies, tumors, or inflammatory processes.[25] Because of its ability to image soft tissue in detail, MRI provides valuable information about the condition of the brain tissue, presence of hemorrhages, involvement of adjacent structures, and extent of transependymal migration of the CSF. Thus, MRI is an essential tool in the comprehensive diagnosis of hydrocephalus, facilitating accurate treatment planning and monitoring treatment efficacy. A study by Isaacs et al.[23] demonstrated the use of fast brain MRI with diffusion measurements to analyze brain changes in children with hydrocephalus before and after treatment. It included 40 patients, including children with post-hemorrhagic and congenital hydrocephalus. Fast MRI avoids sedation and provides a reliable diffusion of data. The results showed a reduction in ventricular volume and improved diffusion indices after treatment, approaching the values observed in healthy children. These findings highlight the potential of fast diffusion MRI (dMRI) in evaluating the treatment of hydrocephalus in childhood.

Morales et al.[33] investigated the relationship between dMRI findings and CSF biomarkers in preterm infants with PHH. Fourteen premature infants with PHH and 46 controls were included in the study. The study measured CSF biomarker levels and dMRI indices, such as fractional anisotropy (FA) and mean diffusivity (MD), in different brain regions. Elevated levels of biomarkers in the CSF were found in children with PHH compared with controls, as well as differences in FA and MD between the groups. The correlations between biomarker levels and dMRI scores revealed a specific relationship between CSF biomarkers and white matter changes in infants with PHH. **TABLE 2** summarizes the main traits, conclusions, and ramifications of each diagnostic method used in the assessment of PHH in infants in order to promote a better knowledge of the condition.

TABLE 2. Summary of diagnostic methods for PHH in infants

Diagnostic method	Characteristics	Key findings/indicators	Implications for PHH diagnosis
Clinical signs	Oculomotor dysfunction, frequent vomiting, suture separation, bulging fontanelle, and rapid head enlargement (>2 mm/day).	An accurate sign of hydrocephalus is the progressive expansion of the sagittal suture.	For prompt intervention, hydrocephalus symptoms must be identified early.
MRI	High-resolution imaging allowing visualisation of brain structures and ventricular dilation.	Able to recognise developmental abnormalities and obstructions in CSF circulation as causes of hydrocephalus.	Vital for thorough diagnosis, treatment planning, and effectiveness tracking.
CT	Helpful in identifying ventricular dilation and evaluating brain structure.	Allows for quick evaluation of structural abnormalities and ventricular size.	Useful for quick diagnosis in emergency situations.
BUS	Imaging method that is widely accessible and non-invasive for tracking ventricular size.	Useful for identifying variations in ventricular capacity, particularly in neonates.	crucial for ongoing observation, especially in preterm infants.
dMRI	Sophisticated imaging methods that offer comprehensive details on the anatomy and physiology of the brain.	Following therapy, fast dMRI revealed better diffusion indices and decreased ventricular volumes.	Promising for comprehending white matter alterations and assessing therapy efficacy.
Ventricular index	Defined as the separation between the anterior horn of the ventricle's lateral wall and the cerebral sickle.	Medical intervention is required if the ventricular index is more than 4 mm above the 97th percentile.	Essential for planning interventions and detecting hydrocephalus early.
CSF biomarkers	Biomarker measurement in cerebrospinal fluid to assess the course of a medical condition.	Changes in dMRI indices in infants with PHH were associated with elevated levels of CSF biomarkers.	May help drive individualised treatment plans and reveal information about underlying pathology.

Source: compiled by the authors.
PHH: post-hemorrhagic hydrocephalus, MRI: magnetic resonance imaging, CSF: cerebrospinal fluid, CT: computed tomography, BUS: brain ultrasonography, dMRI: diffusion magnetic resonance imaging.

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Treatment approaches

Surgical treatment remains the main method of correcting PHH in infants. VPS and subgaleal intraventricular shunts are the most common types of surgery.[30] These techniques have been effective in controlling symptoms of hydrocephalus but are associated with the risk of complications, such as infections, shunt obstruction, and the need for reoperation. A comparison of the results of different studies revealed both agreements and disagreements in assessing the efficacy of diagnostic and therapeutic methods. Most researchers agree that modern neuroimaging methods and surgical interventions are highly efficient.[50] However, opinions are divided regarding rehabilitation, especially the long-term effectiveness of different approaches. The adaptation of treatment and rehabilitation techniques to different patient populations and subgroups, considering age, disease stage, and comorbid conditions, has also been debated.

In a meta-analysis by Sobana et al.,[47] based on 12 publications, it was found that children with noninfectious hydrocephalus who had a VP shunt had significantly higher risks of cerebral palsy, visual and hearing impairment, epilepsy, and mental and motor developmental delays than healthy children. However, differences in the risk of behavioral abnormalities between these groups were not significant. These findings emphasize the importance of ongoing rehabilitation to achieve optimal potential and quality of life in children with noninfectious hydrocephalus who undergo VP shunt placement. According to the Cochrane analysis, the data did not provide evidence in favor of the efficacy of lumbar or ventricular puncture compared to conservative treatment in reducing mortality, disability rates, and the need for subsequent permanent shunt implantation; however, the advantage of this technique is the possibility of delaying the placement of a shunt and stabilizing the patient, which can significantly improve prognosis.[1]

Therefore, Bock et al.[6] reported that the installation of the shunt, especially in combination with the installation of a temporary system of communication with the ventricles of the brain at the beginning and a later implantation of a permanent VP shunt, significantly reduced the risk of neurological complications and provided time for optimal implantation of a permanent system. An advanced medical technique was introduced in Kazakhstan in 2022 to minimize the risks associated with subgaleal pocket sticking, which was previously a serious problem during shunt implantation and could lead to the disruption of shunt systems. This problematic issue has attracted the attention of medical specialists because it significantly influences the long-term effectiveness of the treatment of patients with neurological diseases. The technique includes a set of procedures starting with cranial trephination, which is a critical step in providing access to hematomas. This operation requires high precision and professionalism by surgeons to adapt the catheter to the anatomical features of the pocket, which significantly increases the chances of successful restoration of the shunt function. A key aspect of this technique is the use of a special latex spacer placed in the subgaleal pocket, together with the catheter. This innovation has created a reliable barrier that prevents unwanted tissue fusion and ensures shunt stability. Surgical sutures were used to further secure the spacer and catheter, and the procedure was completed using an aseptic dressing that protected the surgical field from infection and promoted faster healing. This integrated approach not only reduces the risks associated with surgery, but also significantly improves the quality of life of patients after surgery, ensuring a higher treatment efficiency and shorter rehabilitation time.

In recent years, there has been a trend towards the development of less invasive and safer surgical approaches, such as the use of endoscopic techniques, to reduce the intervention

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and risk of complications.[42] The ventriculosubgaleal shunt (VSGS), external ventricular reservoir (EVR), and external ventricular drainage (EVD) are important techniques for treating PHH and other conditions associated with impaired CSF circulation. VSGS involves redirecting excess CSF from the brain ventricles to the subgaleal space located under the scalp. This method temporarily reduces pressure in the ventricles, minimizing the risk of damage to the brain tissue and allowing CSF to be absorbed through the subgaleal space. Isolation from the external environment, which characterizes a temporary drainage method, is an important advantage. This helps reduce the risk of infectious complications, as contact with the environment where pathogens may be present is minimized. In addition, the lack of direct contact with the external environment helps prevent fluid and electrolyte loss, which is a critical aspect in ensuring the stability of the water-electrolyte balance in patients. Thus, this method of temporary drainage not only has the potential to reduce the risk of complications, but can also provide a more effective maintenance of physiological parameters of the body.[28] Fountain et al.,[19] and Frassanito et al.[20] conducted a meta-analysis based on the results of 338 studies and found that patients receiving VSGS had a significantly lower need for CSF puncture compared to those receiving ventricular access devices (VAD). However, no significant differences were found between VAD and VSGS in the incidence of infection, obstruction, and dependence on insertion. Sil et al.[45] also demonstrated the high efficiency of this technique, specifically in premature infants with PHH.

EVR is a system in which a catheter is placed in one of the ventricles of the brain, and the other end of the catheter is connected to a reservoir located outside the body.[31] This method allows for the regular removal of excess CSF, monitoring of pressure in the ventricles, and obtaining CSF samples for analysis. However, this technique has many disadvantages and is not used because of the high risk of infection and the need for routine removal of excess CSF. Data from a meta-analysis conducted in 2021 demonstrated that the proportion of patients requiring permanent bypass after the use of VSGS widely varies from 70% to 100%. This wide range may reflect differences in patient sampling, treatment modalities, and efficacy assessment criteria across the studies. In addition, the reported mortality rate among this group of patients also showed considerable variations, ranging from 0% to 28%, which may reflect differences in the severity of the patients' conditions and the variety of treatment and care approaches used. Approximately from 60% to 85% of cases required the placement of a subgaleal shunt. These data emphasized the high probability of subsequent permanent shunting in most patients.[33] Christian et al.[7] found that patients with a ventricular reservoir transitioned to permanent drainage much earlier, which may be related to these problems.

EVD allows temporary drainage of CSF from the ventricles of the brain to an external reservoir, thereby providing intracranial pressure (ICP) control. EVD is often used in critical and acute situations, where it is necessary to rapidly lower ICP.[37] A recent study examined the use of EVD as a method of temporarily lowering ICP in preterm neonates with PHH. The study showed that EVD was effective in controlling ICP in this population, with a relatively low percentage (53.6%) of patients requiring subsequent conversion to VPS. However, this study also identified significant difficulties in predicting the long-term outcomes of EVD. These difficulties may be due to several factors, including differences in neonatal prematurity, volume, and localization of ventricular hemorrhage as well as the presence of other associated neurological and systemic complications.[10] Another large study evaluating the efficacy of EVD in preterm neonates with PHH analyzed the outcomes of 99 patients. The results of this study demonstrated that in the vast majority of cases (95%) after the initial use of EVD, there was a need for further VPS placement, indicating a high degree of transition

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to a shunt-dependent state after the use of EVD as an initial treatment step. These data emphasized the limitations of EVD as an exclusively temporary solution for ICP management in the context of PHH in preterm neonates.[22] Although EVD can effectively reduce ICP in the short term, the results of this study have suggested that most patients require a more permanent solution in the form of VPS for the long-term control of hydrocephalus.[27]

Ventricular punctures are invasive neurosurgical procedures that involve puncturing the cerebral ventricles to diagnose or treat various conditions affecting the central nervous system (CNS). This technique is widely used to reduce ICP caused by hydrocephalus, measure ICP, collect CSF for laboratory analysis, inject medications directly into the cerebral ventricles, and relieve symptoms in certain neurological disorders; however, in the context of PHH, it is only used in acute clinical situations despite being safe regarding infectious complications.[13,25] In a study by Whitelaw,[54] the authors did not find a statistically significant increase in the risk of infectious complications of periodic ventricular punctures compared to other techniques.

Innovative approaches for the diagnosis, treatment, and rehabilitation of PHH in infants have opened new opportunities to improve disease outcomes.[16] In particular, the introduction of new technologies in neuroimaging, the development of less invasive surgical techniques, and the creation of individualized rehabilitation programs are promising areas that can significantly improve patients' quality of life. The newest method is endoscopic third ventriculostomy (ETV) with coagulation of the choroid plexus, which is a minimally invasive procedure that creates a new pathway for CSF outflow and reduces its production.[44] The use of endoscopic ventriculostomy with choroid plexus coagulation in PHH is a subject of scientific debate and research. In some cases, this technique may offer an alternative treatment for PHH; however, its efficacy and safety in this patient population may be limited due to several reasons. In a study by Baticulon and Dewan,[3] it was found that this technique was more frequently associated with unfavorable procedural outcomes when used for PHH. This technique has shown encouraging results in the treatment of hydrocephalus in infants, avoiding the need for shunt placement in some cases. In a study involving 18 patients, successful control of hydrocephalus was achieved in 50% of the cases. Direct endoscopic observation has shown that obliteration of the choroid plexus can be maintained long-term, sustaining control of the disease.[34]

ETV was assessed in patients undergoing surgery for posterior fossa masses in a recent comparative study by Tabibkhooei et al.,[48] showing promise for lowering hydrocephalus and minimizing the requirements for shunt insertion. According to their research, ETV may be a useful treatment, especially in situations where disorders that interfere with CSF pathways are the cause of hydrocephalus. In pediatric populations where long-term shunt care and problems are common concerns, this decrease in shunt reliance is particularly beneficial. The effectiveness of ETV in treating pediatric hydrocephalus, including PHH, is further supported by a systematic review and meta-analysis conducted by Texakalidis et al.[49] According to their study, which contrasted ETV with shunt implantation, ETV may improve patient outcomes by reducing the need for repeated surgical procedures and shunt modifications. These data highlight ETV as a less risky and more sustainable treatment option for hydrocephalus that eliminates mechanical and infection hazards associated with shunts. According to Haq et al.,[21] ETV had positive results in pediatric patients with hydrocephalus, slowing the development of the condition and demonstrating long-term efficacy in CSF diversion. These findings imply that ETV offers a reliable, long-term alternative to treating baby hydrocephalus in addition to being an instant fix. Taken together, these trials demonstrate that ETV is a

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viable therapeutic option for PHH, with the potential to reduce complication rates and to offer long-term CSF control without the need for shunt systems.

The use of a VP shunt for PHH is a common treatment option to reduce ICP and control the symptoms caused by excess CSF in the ventricular system of the brain. PHH often develops in newborns and infants as a result of hemorrhage in the ventricular system, which can occur due to a number of causes including birth trauma, intraventricular hemorrhage in premature infants, or other vascular anomalies. VPS involves the surgical insertion of a system of tubes and valves that allow excess CSF to be drained from the cerebral ventricles into the abdominal cavity, where it can be absorbed. The procedure begins with a thorough diagnostic workup, including neuroimaging studies such as CT, ultrasonography, or MRI, to assess the degree of hydrocephalus and determine the best site for the catheter. Despite the high efficacy of VP shunting in controlling PHH, this technique carries the risk of various complications, including infections, shunt obturation, mechanical damage, and the need for reoperation to correct or replace the shunt in cases of shunt dysfunction or child growth. Thus, patients with VP shunts in place require regular medical follow-up and may require additional surgical interventions during their lifetime.[17] In a meta-analysis of 12 publications from 1929, Sobana et al.,[47] identified studies that evaluated the neurodevelopment and health of children with noninfectious hydrocephalus who had EP shunts placed. The analysis showed that the risks of cerebral palsy, visual and hearing impairments, epilepsy, and seizures were significantly higher in these children. In addition, a meta-analysis of intellectual quotient (IQ) scores and mental development indices found that children with shunted noninfectious hydrocephalus tended to have lower IQ scores and a greater risk of mental retardation.

In some cases, the neuroendoscopic removal of hematomas from the ventricular system may be required. Ventricular lavage (VL) effectively reduces shunt dependence in PHH and the risk of shunt-related infections. Early use of VL may improve neurocognitive outcomes in patients.[16,40] In a meta-analysis by Parenrengi et al.,[38] the authors analyzed clinical trials comparing VL with the conventional treatment for PHH in neonates with intraventricular hemorrhage.[38] The study showed that VL potentially reduces the need for subsequent bypass surgeries in patients with PHH and is associated with a lower risk of infection than the standard treatment. Although the effects on severe neurofunctional outcomes were similar between the groups, the early use of VL may improve neurocognitive outcomes. In a study by Dvalishvili et al.,[14] the authors analyzed medical cases of 60 patients treated in the neonatal intensive care unit from 2016 to 2021. Nineteen neonates underwent neuroendoscopic lavage (NEL) of the ventricular system and evacuation of post-hemorrhagic deposits as the initial neurosurgical intervention. Another 36 neonates were treated using conventional surgical techniques, including ventricular reservoir implantation and ventriculostomy. Five patients were directly treated using VPS. The results showed that the neuroendoscopic method provided better neurological outcomes and was associated with fewer CNS infections than conventional methods. Fatal outcomes were absent in the group that received NEL unlike that treated using conventional methods, in which 25% of the patients died. The study examined the use of NEL in the treatment of neonatal PHH in two different hospitals. The outcomes of 56 patients who underwent NEL were analyzed, including the efficacy of blood removal assessed using BUS, complications, frequency of VP shunt placement, and subsequent shunt adjustments. NEL avoided shunt placement in 43% of newborns with PHH.[53]

IVH and PHH represent significant problems in neonatology, especially in preterm infants, due to their high incidence, lethality, and negative impact on neurological development.

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Studies have shown that IVH occurs in from 6% to 23% of preterm infants in countries with advanced medicine, with 10% of newborns developing progressive PHVD syndrome that required surgical intervention. IVH usually occurs due to hemorrhage in the germinal matrix region, which is often a consequence of prematurity or immaturity of the cerebral vascular system, making it vulnerable to rupture. Hemorrhage can lead to mechanical obstruction of CSF outflow and inflammatory responses, contributing to the development of hydrocephalus. Neuroimaging techniques, including MRI, CT, and BUS, play key roles in the diagnosis of hydrocephalus. The use of 3D imaging and diffusion-tensor imaging helps clarify the diagnosis and select therapeutic strategies. VP and subgaleal intraventricular shunting are common surgical techniques for the treatment of PHH despite their associated risks and complications. Innovative techniques, including the use of special spacers and cerebral coagulation, aim to minimize risks and improve outcomes. Less invasive surgical techniques, such as ETV with choroid plexus coagulation (CPC), represent new directions for the treatment of PHH. These techniques may offer alternatives to conventional shunting; however, their efficacy and safety require further investigation.

For preterm children with PHH, the following useful suggestions focus on early diagnosis, tailored care, and all-encompassing rehabilitation strategies to optimize clinical management and outcomes. These recommendations offer practical advice that medical professionals may use to maximize treatment outcomes for this susceptible group.

1. Early diagnosis and monitoring:
   a. Use advanced imaging techniques, such as diffusion MRI and 3D ultrasonography, to identify early ventricular dilatation in at-risk preterm infants.
   b. For newborns weighing less than 1,500 g, perform regular neuroimaging during the first 72 hours of delivery to track the development of IVH and PHH and enable early management.

2. Treatment protocols:
   a. To control CSF accumulation and reduce the necessity for permanent shunts, consider early neuroendoscopic procedures or temporary VSGS in newborns exhibiting increasing ventricular dilation.
   b. Adjust the choice of surgical intervention according to the severity of the disease and the individual's anatomy; in appropriate situations, ETV combined with CPC may provide a less invasive option.

3. Post-surgical management and complication prevention:
   a. Schedule regular imaging follow-ups to track shunt performance and identify any issues, such as infections or mechanical failure.
   b. To avoid tissue fusion and guarantee long-term shunt stability, use innovative materials such as latex spacers in subgaleal shunt placement.

4. Rehabilitation and neurodevelopmental support:
   a. Implement early intervention programs that are individualized for each child and focus on motor and cognitive development. Frequent evaluations can assist in modifying treatments to maximize developmental results.
   b. To address any neurodevelopmental delays and enhance the long-term quality of life, take into account multidisciplinary assistance, such as physical and occupational therapy.

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5. Research and genetic screening:
   a. As genetic insights may soon influence individualized therapy choices, stay up to date with new biomarkers that may predict the course of PHH or response to treatment.

Thus, the challenges and prospects in the study on IVH and PHH in preterm neonates include improving the diagnostic methods through developing and improving neuroimaging technologies that will enable more accurate and earlier detection of the disease. A focus on developing new therapeutic approaches, especially less invasive and safer surgical treatments, such as endoscopic techniques and innovative shunt systems, should also be present. Genetic and molecular research is important for understanding the mechanisms underlying these diseases and identifying new therapeutic targets. The development and testing of individualized rehabilitation programs are also key challenges in improving neurological and cognitive outcomes in children.

Prospects in this area include the continued development and implementation of minimally invasive surgical approaches such as ETV with CPC, which may offer an alternative to traditional shunting. Personalized medicine based on genetic and biomarker data promises to optimize the therapeutic strategies for each patient. Integrating the latest neuroimaging technologies into clinical practice will help improve diagnosis, monitoring, and treatment planning. In addition, interdisciplinary research projects that combine the efforts of specialists from different fields will facilitate an integrated approach to the study and treatment of IVH and PHH, which will improve treatment efficacy and patient outcomes. To enhance our understanding of various treatment approaches for PHH in infants, **TABLE 3** summarizes the key characteristics, findings, and implications of each method.

TABLE 3. Summary of treatment approaches for post-haemorrhagic hydrocephalus in infants

Treatment approach	Description	Key findings/challenges	Implications for PHH management
VP shunt	A surgery that removes extra CSF from the ventricles and transfers it to the abdominal cavity.	Although it is linked to risks including infections, blockages, and the requirement for repeat surgeries, it is effective in controlling symptoms.	Common therapy that may cause problems and need frequent follow-up.
Subgaleal intraventricular shunt	A less used surgical technique that introduces CSF into the subgaleal area.	Lowers the chance of shunting-related problems; however, shunt implantation may still be necessary in the future.	Offers a short-term fix; long-term effectiveness requires monitoring.
Endoscopic techniques (e.g., ETV with CPC)	Less invasive techniques to decrease production and redirect CSF.	Preliminary research indicates potential for lowering problems and dependency on permanent shunts.	Potential substitute for traditional techniques that might produce better results with fewer threats.
VSGS	Transfers extra cerebrospinal fluid from the ventricles to the subgaleal area beneath the scalp.	Effective in controlling ICP, but more research is needed to determine its long-term effectiveness. Less CSF punctures are required than with other approaches.	Reduces the chance of infection and keeps patients' physiological characteristics stable.
EVD	Controls ICP by temporarily draining CSF from the ventricles to an external reservoir.	Efficient for controlling ICP in the short run, although most patients may switch to VPS later, suggesting poor long-term effectiveness.	helpful in urgent circumstances but not a long-term fix; close observation is necessary.
VL	A process to clear the ventricular system of debris and blood.	Can lower the incidence of infection and shunt dependency; early usage may enhance neurocognitive results.	It is a potentially effective solution for enhancing PHH long-term results.
NEL	Hematomas and debris are removed from the ventricular system using an endoscopic approach.	In many situations, it eliminates the insertion of a shunt and produces better neurological results and fewer infections than traditional approaches.	Efficient PHH control solution that lessens the requirement for shunts.

Source: compiled by the authors.
PHH: post-hemorrhagic hydrocephalus, VP: ventriculoperitoneal, CSF: cerebrospinal fluid, ETV: endoscopic third ventriculostomy, CPC: choroid plexus coagulation, VSGS: ventriculosubgaleal shunt, ICP: intracranial pressure, EVD: external ventricular drainage, VL: ventricular lavage, NEL: neuroendoscopic lavage.

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CONCLUSIONS

Since the high rate of IVH in at-risk preterm newborns necessitates thorough therapy for this complicated illness, the current elements of PHH in infants are essential for clinical practice. According to various studies, a considerable percentage of patients require surgery because of the progressive nature of hydrocephalus. These findings emphasize the importance of early diagnosis and prompt treatment initiation.

Modern neuroimaging techniques, including MRI, CT, and ultrasonography, are indispensable for accurate diagnosis and effective treatment planning for PHH in preterm neonates. Advanced methods, such as 3D and diffusion-tensor imaging, further enhance the diagnostic precision, enabling clinicians to tailor interventions more effectively. Although traditional surgical approaches, such as VP shunting, remain the cornerstone of PHH management, they are often associated with complications and the need for subsequent shunt revisions. This has spurred an increasing interest in less invasive treatments such as ETV with CPC and endoscopic ventriculostomy of the third ventricular fundus, which show promise in reducing shunt dependency and minimizing complications. Determining the optimal timing and method of surgical intervention remains a key challenge, necessitating a personalized approach based on each patient's specific condition. Individualized rehabilitation programs and long-term developmental support are crucial for optimizing neurocognitive outcomes and enhancing the quality of life of affected children.

To reduce shunt dependency and enhance neurodevelopmental outcomes, recent developments in the management of PHH in preterm infants have placed a strong emphasis on a multimodal approach that combines sophisticated neuroimaging, minimally invasive procedures such as ETV/CPC, and customized rehabilitation therapies. Supporting a multidisciplinary approach to the management of PHH, including the active collaboration of pediatricians, neurologists, neurosurgeons, and rehabilitation specialists, and continuously incorporating new research evidence into clinical practice remain key factors in achieving the best treatment outcomes. Prospects for further research in the field of PHH include investigating the molecular and biological mechanisms of hydrocephalus development, searching for new biomarkers for the early diagnosis and assessment of treatment efficacy, and developing and testing new therapeutic approaches, including pharmacological agents, to reduce CSF production and improve its resorption.

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