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The Role of Cranial Ultrasound in Early Detection of Intraventricular Hemorrhage in Preterm Neonates

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ABSTRACT

Intraventricular Hemorrhage (IVH) is a major neurological complication of prematurity, affecting primarily preterm neonates born before 32 weeks of gestation or with very low birth weight. Despite its contribution to neonatal morbidity and mortality, it has potential long term neurodevelopmental consequences such as cerebral palsy, cognitive impairment and hydrocephalus. Early and accurate detection is critical to the initiation of timely interventions and to improving neurological outcomes. Because of noninvasiveness, portability, cost effectiveness and safety profile, cranial ultrasound (CUS) has become the preferred imaging modality for early detection of IVH in Neonatal Intensive Care Units (NICUs). Current evidence on the role of cranial ultrasound in diagnosing, grading and monitoring IVH in preterm infants is synthesized in this review. The technical aspects, optimal timing and frequency of ultrasound screening are examined and its diagnostic accuracy compared to other neuroimaging modalities such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). In addition, the prognostic value of ultrasound findings is discussed, including in relation to the Papile grading system and emerging innovations such as high frequency transducers, Doppler techniques and AI based interpretation tools are evaluated. Critical appraisal of limitations such as operator dependency and decreased sensitivity in posterior fossa assessment, is performed. Cranial ultrasound is an important tool for early detection and management of IVH and improving outcomes in vulnerable preterm populations.

Keywords: *Preterm neonates, Intraventricular hemorrhage, Cranial ultrasound, Early diagnosis, Neonatal neuroimaging, Neonatal Intensive Care Units, Brain injury*

1. INTRODUCTION

Intraventricular hemorrhage (IVH) is one of the most serious neurological complications of preterm neonates, especially for babies born before 32 weeks gestation or weigh less than 1500 grams [1]. IVH is more likely to happen in babies born too early or too small, with the lowest birth weight babies (< 1000 grams) being at the greatest risk. IVH is still a common problem (15–45% among very low birth weight babies) because of how early the child is born, the availability of neonatal care and the rules in each hospital[2]. “Posthemorrhagic hydrocephalus”, “cerebral palsy”, “epilepsy” and “cognitive impairment” are all short and long term morbidities that result from this condition and therefore, these infants and their families are burdened for life [3].

The pathophysiology underlying IVH is complex and results from the fragile germinal matrix vasculature of the preterm newborn. The germinal matrix is found in the subependymal area of the developing brain and is very active in metabolism during the fetal period, from 24 to 32 weeks[4]. This area is particularly vulnerable to variations in cerebral blood flow, hypoxia, hypercapnia and variations in venous pressure because of the thin walled capillaries. In many cases, these factors are accompanied by systemic instability such as sepsis, respiratory distress syndrome and rapid volume expansion which

cause rupture of the vasculature and bleeding into the ventricular system [5]. Perinatal asphyxia, chorioamnionitis, mechanical ventilation, coagulation disorders, hemodynamic instability, in particular in the early postnatal period, are other risk factors [6].

IVH is typically a disease that develops within the first three days of life and early diagnosis is critical to obtain the best clinical outcomes. Early detection of IVH has been shown to not only lead to proper grading of the hemorrhage, early therapy, surveillance for complications such as hydrocephalus, but also family counselling [7]. The Papile system is often used to determine how severe an IVH is and how it may affect a child's brain development. Grades I and II usually have few consequences, but Grades 3rd and 4th are associated with greater risks of complications, death and poor brain function [8].

Early diagnosis is so important in NICUs that the choice of the neuroimaging modality becomes critical. Because of these characteristics, cranial ultrasound (CUS) has become the first line for screening and monitoring IVH in preterm neonates. Unlike "Computed Tomography (CT) and Magnetic Resonance Imaging (MRI)" that often necessitate neonatal transport and sedation, and in particular for CT, ionizing radiation exposure, cranial ultrasound provides a movable, non-invasive, and bedside compatible imaging alternative that does not interfere with neonatal care in progress [9]. It enables serial imaging to follow the course or resolution of hemorrhage and can be repeated without risk. Additionally, it offers real-time evaluation of ventricular size, parenchymal integrity, and related maladies like cyst formation and hydrocephalus [10].

Further improvements in the diagnostic accuracy of CUS have been achieved through technological advances. High-frequency linear probes, Doppler capabilities to assess cerebral blood flow, and three-dimensional imaging have dramatically improved visualization of subtle lesions, especially anterior and periventricular regions [11]. More recently, application of the combination of ML (Machine Learning) and AI (Artificial Intelligence) in ultrasound imaging has created new opportunities for automated detection and categorisation of IVH, which may decrease operator dependency and interobserver variability [12].

Even though it has several benefits, CUS does have disadvantages. It is operator-dependent, and interpretation of the image requires professional training and experience. Visualisation of some brain structures, particularly the posterior fossa and cerebellum, may be inadequate through the classical anterior fontanelle window, where posterior hemorrhages may be missed [13]. CUS is still indispensable in the early prediction and management of IVH with the right technique and training [14].

Multiple national and international guidelines recommend routine CUS screening for new babies before 32 weeks of gestation or weighing less than 1500 grams. Screening time is standardised at initial scan within 1 week of life, with further scans at 14 days, and again at 36-40 weeks corrected gestational age or before discharge [15]. These guidelines emphasize the critical role of CUS in the neonatal neuroimaging protocols and its continued relevance in achieving better long-term neurological outcomes in preterm infants.

With such a huge burden of IVH and urgent need for early, accurate, and safe diagnosis, overall knowledge of the role of cranial ultrasound in the above context is critical. CUS has become routine in many NICUs, while variability in protocols, grading, interpretation, and follow-up strategies exists between different health care settings [16]. The increasing use of innovations and advanced imaging technologies requires a critical review of the current evidence base, critical evaluation of limitations and strengths of CUS, and identification of areas where future research and clinical optimization are needed.

Hence, the aims of this review is to critically review the role of cranial ultrasound in early prediction of intraventricular hemorrhage in preterm neonates, emphasizing its diagnostic accuracy, prognostic significance, technological progress, limitations, and clinical relevance in the treatment decision-making and care protocols of neonates.

2. MATERIALS AND METHODOLOGY

2.1 Study Design

The current studies on using cranial ultrasound (CUS) to detect intraventricular haemorrhage (IVH) in premature neonates are summarised and analysed using a narrative approach. The results from studies, images and guidelines for newborn care are brought together to show how CUS helps with diagnosis and prognosis in this situation.

2.2 Literature Search Strategy

Databases like, "PubMed", "Scopus", "Web of Science", and "Google Scholar" were used to search for studies published from January 2000 to February 2025. Some of the main terms in the search were: "Intraventricular haemorrhage," "Preterm neonates," "Cranial ultrasound," "The Papile Classification," "Protocols for imaging in the NICU," and "Machine learning in neonatal imaging." Boolean operators and truncations were used to focus the search, and extra studies were found by reading through the references of the chosen articles.

2.3 Inclusion and Exclusion Criteria

All the included studies were peer-reviewed journal articles, systematic reviews, clinical guidelines, and observational studies published in English about using cranial ultrasound to check for and follow intraventricular haemorrhage (IVH) in preterm infants, as well as studies on new technologies, grading methods, and clinical results. The search did not include studies on

term infants, diseases unconnected to neurology, studies with only MRI or CT imaging, or unreviewed content such as commentaries and incomplete abstracts from conferences.

2.4 Data Extraction and Organization

Data was collected from the selected studies and grouped into important areas, including causes and incidence of IVH in premature babies, use of cranial ultrasound (CUS) and its procedures, Papile's grading method, differences with MRI and CT, new devices such as Doppler and 3D ultrasound and international guidelines on CUS use in neonatal intensive care units (NICUs). The findings were described in descriptive format and presented in tables and figures to make them clearer.

2.5 Quality and Relevance Assessment

The methodological strength, clinical relevance, sample characteristics and clarity in reporting imaging outcomes of each included study were assessed. Particular emphasis was given to studies that provided practical insights into CUS deployment and technological improvements in NICU settings.

3. CLASSIFICATION AND GRADING OF INTRAVENTRICULAR HEMORRHAGE

The amount of bleeding in preterm infants and their possible neurodevelopmental outcomes can be predicted by classifying IVH. The most widely used system is the Papile grading system which was first developed using cranial computed tomography, but is now applied routinely on cranial ultrasound imaging because of its ease and safety in the neonatal setting [17].

In preterm babies, hemorrhage in the germinal matrix which is rich in blood vessels, is limited to this region. If bleeding reaches the lateral ventricles but does not cause them to widen, it is called grade II. When a Grade III hemorrhage occurs, blood inside the ventricles causes them to quickly expand. In Grade IV, called periventricular hemorrhagic infarction, blood spreads into the nearby brain tissue because of venous infarction and congestion, rather than from direct hemorrhaging[18]. The papile grading system for IVH in neonates is mentioned in Table 1 with features, implications, and imaging considerations.

This grading system is highly correlated with clinical outcomes. Grades I and II are usually associated with good prognoses and may even recover with no lingering complications in the long run. Those assigned to Grades III and IV are associated with poor outcomes of hydrocephalus, cerebral palsy, and cognitive impairment, calling for close surveillance and neurosurgical intervention in some cases [19].

MRI provides high-resolution imaging, and CT can detect acute bleeds. MRI/CT has limitations in the neonatal context. MRI tends to involve sedation and is not always reliable in unstable neonates, and CT involves radiation exposure and is not as sensitive in detecting early or low-grade IVH. Cranial ultrasound remains the modality of choice to grade IVH as it is bedside applicable, provides real-time imaging, diagnostic accuracy to detect Grades I to III hemorrhages [9].

Table 1. Papile Grading System for Intraventricular Hemorrhage in Preterm Neonates: Features, Prognostic Implications, and Imaging Considerations

Grade	Ultrasound Findings	Clinical Prognosis	Limitations of CT/MRI in This Context
Grade I	Hemorrhage confined to the germinal matrix with no ventricular involvement.	Usually benign; minimal to no long-term neurological impairment	May miss subtle germinal matrix hemorrhages due to lower contrast sensitivity in CT
Grade II	Hemorrhage extends into the lateral ventricles, but without ventricular dilation	Often favorable outcome; close follow-up required	MRI can detect blood products but may require sedation; CT involves ionizing radiation
Grade III	Intraventricular hemorrhage with ventricular dilation (hydrocephalus without parenchymal injury)	Higher risk of neurodevelopmental delay; may require ventriculoperitoneal shunting	Serial follow-up challenging with CT; MRI limited in unstable neonates due to need for transport
Grade IV	Hemorrhage extends into periventricular brain parenchyma, often due to venous infarction	Associated with severe neurodevelopmental outcomes including cerebral palsy and epilepsy	CT may miss evolving parenchymal injury; MRI is sensitive but not feasible for routine surveillance

4. CRANIAL ULTRASOUND: TECHNIQUE AND TIMING

CUS is the main imaging method used to study the brains of preterm infants who may have IVH. The procedure is non-

invasive, portable, and can be repeated and safely done at the bedside without sedation or transporting the patient, making it suitable for critically ill neonates [14]. High-frequency transducers (7.5-10 MHz) are used to acquire adequate resolution for imaging neonatal brain structures, whereas deep visualization in larger infants may be achieved with lower-frequency curvilinear probes [20]. Anterior fontanelle is the major acoustic window utilized for a routine neonatal cranial ultrasound. It offers excellent access to supratentorial structures (the lateral ventricles, germinal matrix, and periventricular regions) [21]. To enhance visualization of posterior fossa structures, including the cerebellum and brainstem, the mastoid (posterolateral) fontanelle is applied. The posterior fontanelle may be used to improve viewing of occipital horns and periventricular white matter, particularly in suspected pathology in those areas [22].

First scans should be performed during the first 3 days of life, day 1 or day 3, to detect early-onset hemorrhage. A second scan is usually carried out on Day 7 to look for late or evolving bleeds, whereas further imaging at the 3-4 weeks postnatal age is recommended to investigate for complications like post-haemorrhagic ventricular dilatation or cystic evolution [23]. Weekly follow-up scans may be indicated in the extremely preterm neonate based on clinical condition and initial findings.

Most NICUs follow standardized serial CUS regimens based on birth weight and gestational age. CUS is typically done at certain intervals, such as Days 1-3, 7, 14, and followed up at 36-40 weeks corrected GA or before discharge, for children delivered at less than 32 weeks or weighing less than 1500 grams. These serial evaluations are critical for monitoring the course or resolution of IVH, guiding interventions, and predictions [24]. Such protocols not only expedite early therapeutic decision making but also prevent the development of a surveillance gap in high-risk neonates.

5. DIAGNOSTIC ACCURACY AND SENSITIVITY

For IVH diagnosis in premies, CUS remains the most widely used approach due to its safety, bedside usability, and predictable diagnostic value. When carried out with proper technique and timing, CUS has high sensitivity and specificity, especially with clinically significant hemorrhages. Studies reveal 85–95% sensitivity rates in detecting Grade III and IV IVH, where ventricular dilation and parenchymal involvement are vividly observed through the anterior fontanelle window [25]. For low-grade hemorrhages (Grade I and Grade II) that are localised to the germinal matrix or ventricles but without dilatation, sensitivity may be 65-85%, depending on the resolution of the equipment used and operator competence [26].

Compared to “Magnetic Resonance Imaging (MRI)”, which provides excellent soft tissue contrast and is very sensitive to subtle white matter injuries and posterior fossa hemorrhages that may be missed on ultrasound [27]. MRI has its clinical use constrained due to the aforementioned reason. CT is very useful for diagnosing acute haemorrhage, but is infrequently used due to the exposure to radiation and lower sensitivity for early or small IVH lesions [7].

False negatives in CUS are possible, especially with immature or obscure germinal matrix hemorrhages or when poor acoustic windows were used. In addition, inter-observer variability, particularly in grading mild hemorrhages, may affect diagnostic consistency, and the need for uniform training and interpretation protocols is emphasized [28]. The diagnostic pathway and accuracy of CUS ion IVH are illustrated in Fig. 1.

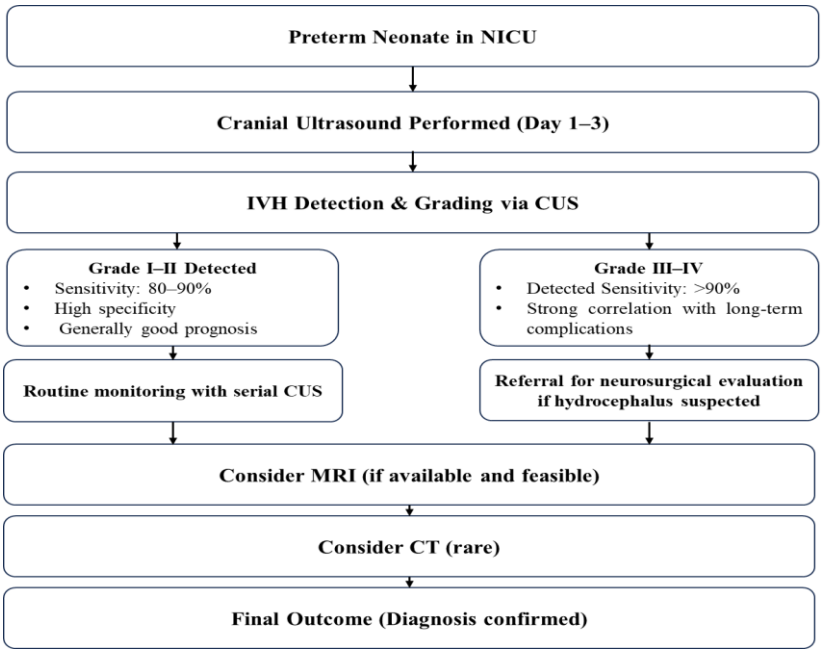

Fig. 1. Diagnostic Pathway and Accuracy of Cranial Ultrasound in IVH Detection

6. ADVANCES AND INNOVATIONS IN CRANIAL ULTRASOUND

Recent progress in CUS has dramatically improved its diagnostic accuracy, range, and usefulness in neuroimaging of preterm neonates. The most remarkable innovation is the Doppler imaging introduction which enables assessment of cerebral blood flow patterns and vascular resistance. Color and spectral Doppler techniques are important for cerebral perfusion and help identify early hypoxic-ischemic injury and autoregulatory impairment in critically ill neonates [29]. High-frequency transducers (10-15 MHz) have enhanced image resolution, especially for superficial structures such as the germinal matrix and periventricular areas. When used in conjunction with three-dimensional (3D) ultrasound, these probes enable more precise volumetric determinations of ventricular size, thus enabling a better assessment of post-hemorrhagic hydrocephalus and subtle parenchymal abnormalities [30].

The application of machine learning algorithms and Artificial Intelligence (AI) has revolutionized neonatal imaging. These technologies make automated detection and grading of IVH possible, reduce inter-observer variability, and accelerate clinical decision making using standardized interpretations [31]. Portable Point of Care Ultrasound (POCUS) systems have transformed bedside neuroimaging. Such devices allow for live scanning without interrupting NICU care and are particularly useful in remote or resource-poor environments. Access to expert interpretation is further extended through integration with telemedicine platforms [32]. These innovations reinforce CUS as more than a screening modality, but as a dynamic tool for individualized and precision-based care for the neonate. The overview of innovations in CUS for preterm neonatal neuroimaging is illustrated in Fig.2.

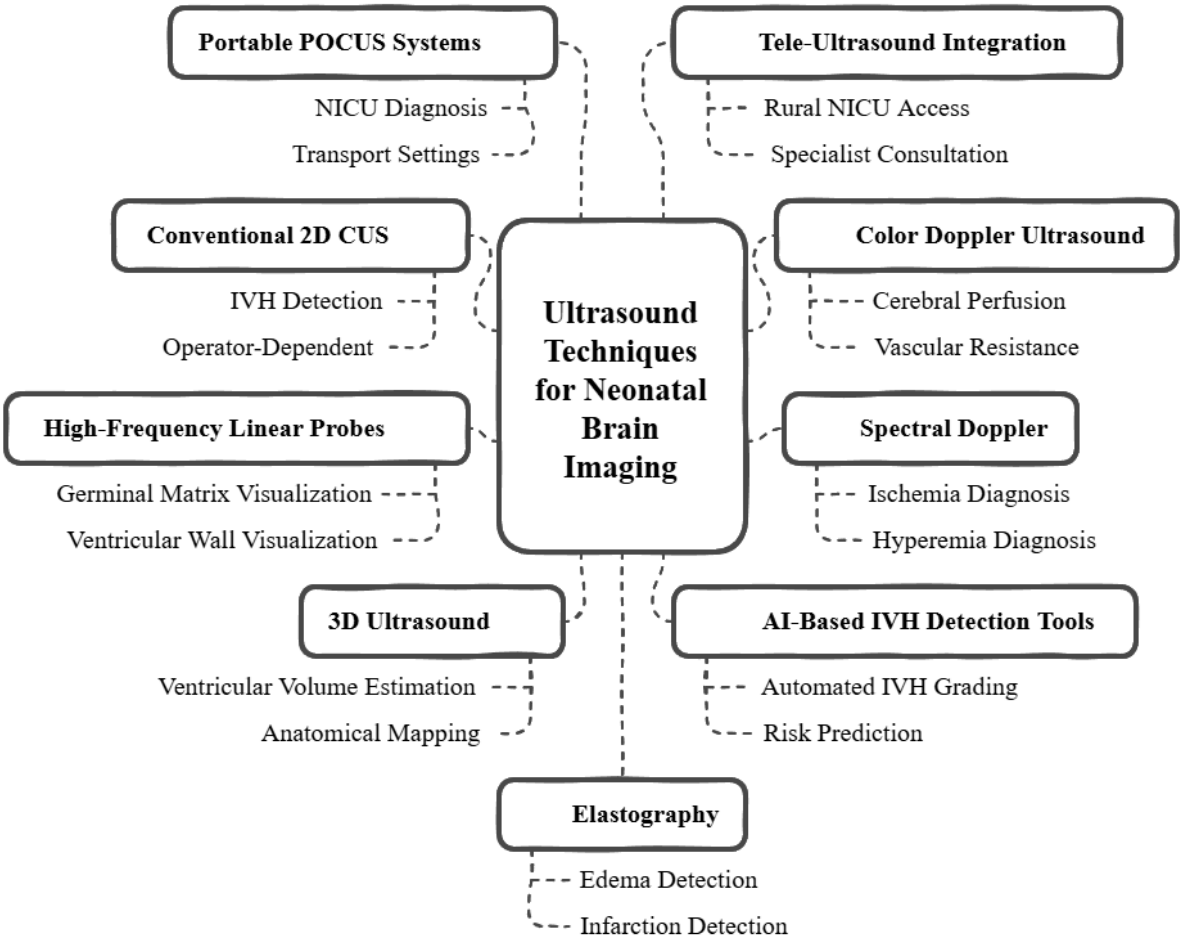

Fig. 2. Comparative Overview of Innovations in Cranial Ultrasound for Preterm Neonatal Neuroimaging

7. LIMITATIONS AND CHALLENGES

CUS has some advantages, but it has several limitations that can undermine its diagnostic accuracy and clinical utility in specific situations. Its operator dependency is one of the major challenges. The quality of image acquisition and interpretation is very much dependent on the training, experience, and familiarity of the sonographer with the neonatal neuroanatomy, which adds variability and a potential for subjective interpretation to diagnosis [32]. There is an extensive learning curve, especially in the correct grading of IVH and detection of subtle brain abnormalities.

The incomplete view of the posterior fossa and cerebellum during anterior fontanelle imaging is another limitation. Although mastoid and posterior fontanelle windows may enhance access to these areas, they are not used routinely or are not available in all clinical settings. Cerebellar haemorrhages 10–20% of ELBW (Extremely Low Birth Weight) infants may not be detected if not specifically evaluated [33]. The diagnostic utility of CUS diminishes with advancing postnatal age, particularly in term infants or older neonates with closed or narrowed fontanelles, with poor acoustic access to intracranial structures.Also, CUS is less sensitive in detecting subtle parenchymal injuries like diffuse white matter injury or punctate ischemic lesions that could be more reliably diagnosed on MRI [34]. These limitations highlight the need for all-inclusive protocols, adequate training, and in appropriate cases, the use of complementary modalities of imaging, for complete neurodiagnostic evaluation.

8. CLINICAL GUIDELINES AND RECOMMENDATIONS

CUS is an essential part of neuroimaging in preterm neonates and is actively supported by international professional organizations such as “American Academy of Pediatrics (AAP)”, “European Society for Paediatric Radiology (ESPR)”, and “World Health Organization (WHO)”. The AAP and ESPR suggest an initial cranial ultrasound at days 1 to 3 of life, followed by scans at day 7, day 14, and at term-equivalent age (around 36-40 weeks corrected gestation), or before discharge. These planned intervals are meant to diagnose not only the primary hemorrhagic events but also progressive states such as post-hemorrhagic ventricular enlargement, and periventricular white matter injury [35]. The guidelines also recommend serial imaging protocols, especially in extremely low birth weight infants, where progressive changes cannot be missed.

In national neonatal care standards, in high-resource countries, CUS is part of structured screening programs for preterm infants. Standardized protocols are also used in most tertiary-level NICUs, which include Doppler studies and posterior fossa imaging by mastoid fontanelles, thus increasing the diagnostic reach [36]. Some countries have introduced quality assurance programs that will help achieve uniformity in the acquisition of images and interpretation from centers. Compliance with these evidence-based guidelines is critical for early detection, appropriate intervention, and better neurodevelopmental outcomes in preterm populations. The standard CUS imaging protocols are mentioned in Table 2.

Table 2: Standardized Cranial Ultrasound Imaging Protocols for Preterm Neonates Based on International Guidelines

No.	Organization	Target Population	Recommended Imaging Schedule	Primary Purpose	Reference
1	AAP	Newborns born at <30 weeks of gestation	Initial scan between days 7–10 of life; follow-up based on clinical condition or findings	Early detection of IVH, white matter injury, and decision support	[37]
2	ESPR	Preterm babies are more likely to suffer brain injury	Initial scan within the first week of life; serial imaging depending on clinical evolution	Evaluation of IVH, periventricular leukomalacia, and parenchymal abnormalities	[38]
3	WHO	All preterm neonates in facility-based care	Initial CUS within first 3 days of life; repeated as clinically indicated	Surveillance of neonatal brain injury in resource-limited and standard settings	[39]
4	CPS	Infants born at ≤31+6 weeks gestation	First scan at 4–7 days of life; second at 4–6 weeks; third at term-equivalent age if <26 weeks	Monitoring for IVH and white matter injury; guiding neurodevelopmental planning	[40]

AAP - American Academy of Pediatrics; ESPR - European Society for Paediatric Research; WHO - World Health Organization; CPS - Canadian Paediatric Society; CUS - Cranial Ultrasound

9. FUTURE DIRECTIONS

While CUS remains the leading modality for preterm infant’s brain evaluation, its effectiveness, availability, and practicality within the clinical setting urgently require research-supported and technologically advanced improvement. One of the major gaps in current literature is the absence of multicentric longitudinal studies that focus on the long-term neurodevelopmental

outcomes of infants diagnosed and followed up via serial CUS protocols. Such studies are critical to establish high-level evidence of the association between early imaging findings and clinical prognosis across varied healthcare settings [41]. The need for standardized reporting criteria that specify essential measurements, hemorrhage grading, and terminology is rising. Standardised templates for reporting and sharing findings could enhance inter-center consistency and minimise diagnostic variations among clinicians and sonographers [42].

The use of telemedicine with remote ultrasound interpretation as a method shows great potential, especially in low-resource or rural NICU settings. The ability of real-time image transmission and cloud-based platforms to engage experienced radiologists to support frontline clinicians in a situation where expertise is lacking increases diagnostic accuracy [43].

Another major frontier is represented by the emerging AI-based models for automated IVH detection and risk stratification. Large datasets have been used to train machine learning algorithms that have shown promise for grading IVH, predicting outcome, and decreasing observer bias, but clinical validation is still being performed [44]. Pursued collectively, these future directions are intended to improve the reliability, standardization, and availability of CUS in the global neonatal care context.

10. CONCLUSION

Cranial Ultrasound (CUS) remains a basic neuroimaging modality for early diagnosis and grading of Intraventricular Hemorrhage (IVH) in preterm neonates. The non-invasive nature, bedside feasibility, and diagnostic value of the tool make it the first-line tool in the neonatal intensive care setting, especially for infants born at <32 weeks of gestation or with very low birth weight. The use of the Papile grading system by CUS continues to be critical for prognostic evaluation, to guide proper clinical management, and neurodevelopmental surveillance. With the advances of Doppler techniques, high-frequency and three-dimensional ultrasound, and artificial intelligence-driven analysis, the accuracy and the functional domain of CUS have considerably increased. However, some constraints still exist, including operator dependency, poor posterior fossa viewing, and reduced sensitivity for subtle parenchymal injuries in older neonates. These limitations need to be addressed with standardized protocols and better clinician training to improve diagnostic reliability. Serial CUS imaging is recommended by the leading international bodies, including the American Academy of Pediatrics (AAP), European Society for Paediatric Radiology (ESPR), and World Health Organization (WHO) as part of usual neonatal care pathways. Further research should be multicentric outcome-based studies, universal reporting criteria, and integration of a remote diagnostic support system. However, CUS is still an important factor in improving outcomes in vulnerable preterm populations.

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