The neonatal cerebellum

Steggerda, S.J.

Chapter 3

Cranial ultrasonography in neonates: role and limitations

Gerda van Wezel-Meijler
Sylke J. Steggerda
Lara M. Leijser

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Abstract

In experienced hands, cranial ultrasonography (CUS) is an excellent tool to detect the most frequently occurring brain abnormalities in preterm and full-term neonates, to study the evolution of lesions, and to follow brain maturation. It enables screening of the brain and serial imaging in high-risk neonates. However, CUS also has limitations and magnetic resonance imaging is needed in most neonates with (suspected) parenchymal brain injury and/or neurological symptoms and in very preterm infants. In this review, we discuss the applications, possibilities, indications, predictive value, and limitations of neonatal CUS. We will pay attention to the standard CUS procedure and expand on optimizing the possibilities of CUS by using supplemental acoustic windows and changing transducers and focus points. For illustration numerous CUS images are provided.

Introduction

Neonates born prematurely and sick full-term neonates are at risk for brain injury. Although advances in neonatal (intensive) care have greatly improved the survival and outcome of these vulnerable patients, brain injury remains of major concern. Early diagnosis is important for prognostication, optimal treatment and neurologic outcome.

Cranial ultrasonography (CUS) is the preferred modality to image the neonatal brain (1). The advantages of CUS are numerous: it can be performed at the bedside with little disturbance to the infant, it is relatively safe, and can be repeated whenever needed, enabling visualization of ongoing brain maturation and the evolution of lesions (2,3). However, CUS also has several limitations: quality of imaging depends on the skills and experience of the ultrasonographer, some areas of the brain are difficult to visualize, and several abnormalities remain beyond its scope (1,4,5). In this review, we discuss the applications and indications of neonatal CUS. We briefly describe the standard procedure, several options to improve image quality, the use of supplemental acoustic windows, and imaging of the posterior fossa. We list the most frequently occurring abnormalities of the neonatal brain, as seen on CUS in preterm and full-term neonates. Finally, we discuss the limitations of CUS.

Examples of ultrasound images are provided throughout this review. All CUS images shown were performed with an Aloka α10 scanner with multifrequency transducers (Biomedic Nederland B.V., Almere, the Netherlands).

Standard CUS procedure

For a standard neonatal CUS procedure, the anterior fontanel is used as the acoustic window. Standard settings are applied and scanning is performed with a transducer frequency of around 7.5 MHz. The whole brain is scanned from frontal to occipital and from right to left. Images of at least 6 standard coronal planes and 5 standard sagittal planes are recorded (1). In addition, of all (suspected) abnormalities, images are recorded in 2 planes. Details on the standard CUS procedure have recently been described (1).

Scanning protocols

Neonatal scanning protocols have recently been described in detail (1, 6). In summary, very preterm infants (gestational age < 32 weeks) admitted to an intensive care unit are scanned shortly after birth, on the third and seventh day of life and weekly thereafter until discharge. CUS is repeated around term equivalent age. Older, apparently healthy preterm infants (gestational age > 32 weeks) are scanned on the third day and, thereafter, weekly until discharge. In sick full-term neonates and full-term neonates with congenital malformations or neurological symptoms, we recommend a CUS examination shortly after birth and subsequent examinations depending on symptoms and previous CUS findings.

Regardless of standard scanning protocols, the frequency of CUS examinations should be intensified in the following circumstances: sudden deterioration in clinical state, sepsis, necrotizing enterocolitis, episodes of apneas and/or bradycardias, sudden decrease in hemoglobin level, neurological symptoms, ventricular dilatation, and before and after major surgery.

Advanced CUS

Transducers

The transducer needs to be appropriately sized. We use 2 different transducers: a phased array (PA) and a convex (CV) transducer. The PA transducer has a very small footprint, allowing a perfect fit to the anterior fontanel. However, due to the divergent ultrasound beam, the far-field resolution of this probe is limited (Figure 1). The CV transducer has a larger footprint, thereby enabling better near-field resolution. Although the ultrasound beam is still divergent, leading to some loss of far-field resolution, it is superior to the PA probe (Figure 2). Therefore, if the size of the fontanel allows, we use the CV probe for standard CUS examinations. If, in the individual patient, this leads to loss of contact area (eg, due to a small fontanel or the use of an infant flow hat), it is better to use the smaller PA probe (7).

Transducer frequencies

With higher transducer frequencies, the resolution improves at the expense of penetration and vice versa (7). A standard transducer frequency set at 7.5 MHz allows

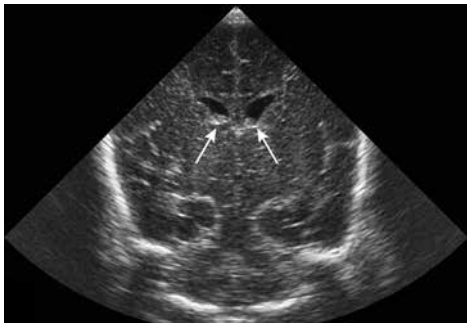

Figure 1. Coronal ultrasound scan at the level of the frontal horns of the lateral ventricles performed with phased array transducer, showing a good near-field but less far-field resolution (preterm infant, gestational age 29 wk). Bilateral grade 1 intraventricular hemorrhage (arrows) and mildly dilated frontal horns.

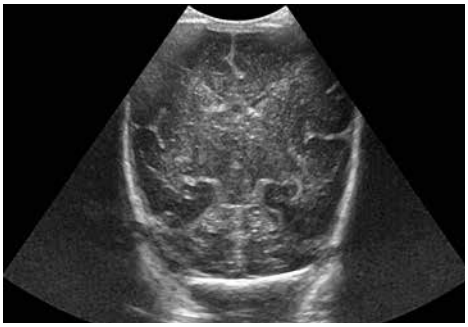

Figure 2. Coronal ultrasound scan at the level of the bodies of the lateral ventricles, performed with convex transducer, showing a good near-field resolution. The far-field resolution is superior to that of the phased array transducer (preterm infant, gestational age 27 wk).

optimal visualization of the ventricular and periventricular areas in most neonates (Figure 1). In small, preterm neonates, this transducer frequency is also appropriate for visualization of the basal ganglia and thalami. However, in larger neonates or neonates with thick, curly hair, deeper penetration, and thus additional scanning with lower frequencies down to 5 MHz may be needed. This low transducer frequency also enables visualization of deeper structures (ie, the basal ganglia/thalami in large infants and the posterior fossa) (Figure 3). In tiny infants, where less penetration is needed, or for detailed visualization of superficial areas, such as the cortex, subcor-

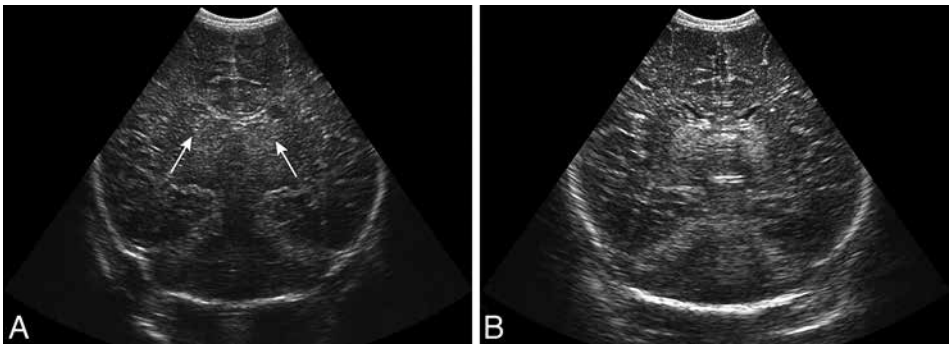

Figure 3. Coronal ultrasound scans in a full-term neonate with severe hypoxic-ischemic encephalopathy. **(A)** Scan frequency of 7.5 MHz, showing subtle echogenicity of the thalami (arrows). **(B)** Scan frequency of 5 MHz, the echogenicity is now more obvious.

tical white matter and brain's convexity, the transducer frequency can be increased (up to 10 MHz), allowing a very high resolution but limited penetration (Figure 4).

Focus points

For standard CUS procedures, it is best to have the focus point aimed at the ventricular or periventricular areas. In individual cases it may be useful to adapt the focus point, aiming it at a (suspected) abnormality or region of interest.

Supplemental acoustic windows

The use of supplemental acoustic windows allows positioning of the transducer closer to the area of interest, thereby allowing scanning with a high transducer frequency and obtaining detailed images. Using these supplemental acoustic windows requires additional skills and knowledge of the brain's anatomy. The different supplemental acoustic windows and ways to use them have recently been described (1). In short, the temporal windows are used to visualize the brain stem, upper part of the cerebellum and circle of Willis, and for Doppler flow measurements (Figure 5). The posterior fontanel allows visualization of the occipital horns of the lateral ventricles (enabling early detection of intraventricular hemorrhage) the occipital parenchyma and the cerebellum (Figure 6). The mastoid fontanels provide optimal and detailed visualization of the cerebellum (vermis and hemispheres), fourth ventricle, aqueduct and cisterna magna. Using this mastoid view allows early detection

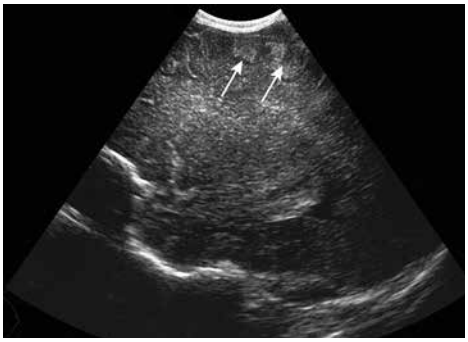

Figure 4. Parasagittal ultrasound scan in the same infant as in Figure 3, showing abnormal echogenicity of the cortex and subcortical white matter (arrows). Scan frequency is set at 10 MHz, allowing good visualization of the superficial structures. The far-field resolution is insufficient with this scan frequency.

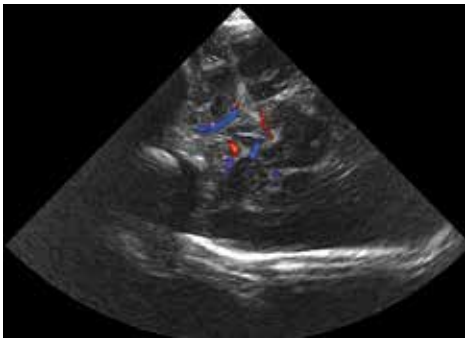

Figure 5. Axial ultrasound scan through the temporal window in preterm infant, showing the brain stem and color flow in the circle of Willis.

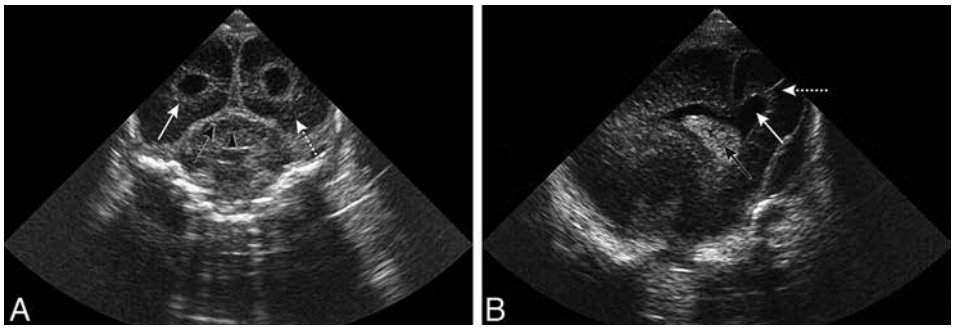

Figure 6. (A) Coronal and **(B)** parasagittal ultrasound scan in very preterm infant (gestational age 26 wk), using the posterior fontanel as acoustic window, showing the occipital horn(s) of the lateral ventricles (white arrows), choroid plexus in the body of the lateral ventricle (black arrow in B), occipital white matter (dotted white arrow), tentorium (dotted black arrow in A), and cerebellum (black arrowhead in A).

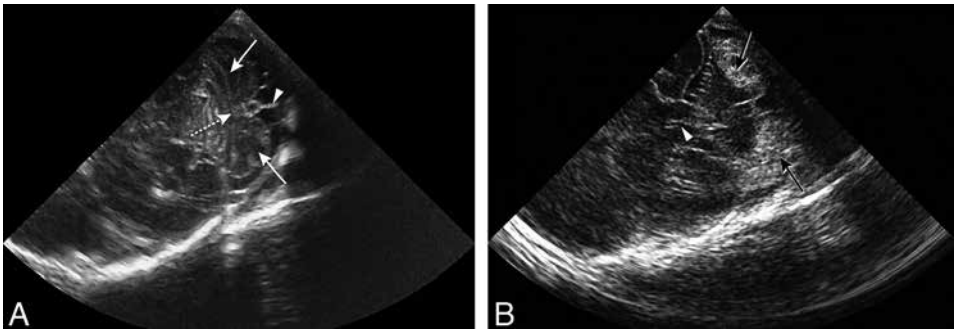

Figure 7. Coronal ultrasound scans in two very preterm infants (gestational age respectively 29 and 26 wk), using the mastoid fontanel as acoustic window. **(A)** Normal appearing cerebellar hemispheres (arrows), cerebellar vermis (dotted arrow) and cisterna magna (arrowhead). **(B)** Echogenic lesions in both cerebellar hemispheres (black arrows), representing hemorrhages. Also showing the aqueduct (arrowhead).

of posterior fossa hemorrhages that may have major impact on neurologic outcome (Figure 7) (8-10). Use of the supplemental acoustic windows is specially recommended in the following conditions:

- Prematurity (gestational age < 30 weeks), to exclude posterior fossa hemorrhage
- Intraventricular hemorrhage, to exclude posterior fossa hemorrhage and dilatation of the aqueduct
- Ventricular dilatation without obvious explanation
- To enable Doppler flow measurements
- (Suspicion of) congenital anomalies of the central nervous system

Although, so far, experience with detection of ischemic cerebellar injury using the mastoid fontanels is limited, we believe that additional use of these fontanels is also indicated in cases with significant supratentorial ischemic brain injury.

Ultrasound imaging of the preterm infant's brain

In infants born prematurely, serial CUS throughout the neonatal period is indicated. This enables early detection of brain injury typically occurring in the preterm neonate (including peri- and intraventricular hemorrhage (P/IVH) and periventricular leukomalacia (PVL)) and following the evolution of lesions and brain maturation.

Peri- and intraventricular hemorrhage

In preterm infants, P/IVH usually originates from the immature germinal matrix and may subsequently spread throughout the ventricular system (11). Although the incidence of P/IVH has declined over the last decades, it is still high and P/IVH remains one of the major complications of premature birth (12). We recently found an incidence of 28% in a large cohort of very preterm infants (5). P/IVH is reliably detected with CUS (Figure 1). It is generally seen during the first few days after birth, mostly as low grade (grade 1 or 2) hemorrhage, but may extent over subsequent days and, in addition, lead to significant complications. The first well-recognized complication of P/IVH is post hemorrhagic ventricular dilatation (PHVD) (Figure 8). The risk of PHVD is related to the amount of blood in the ventricular system. PHVD may develop days to weeks after the initial P/IVH. As ventricular dilatation may lead to parenchymal injury, prompt detection is necessary and treatment may be indicated

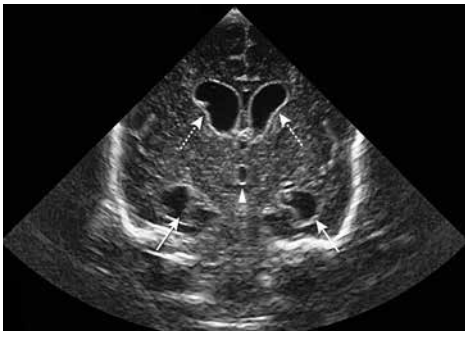

Figure 8. Coronal ultrasound scan in preterm infant (gestational age 29 wk) with post hemorrhagic ventricular dilatation, showing dilated frontal (dotted arrows) and temporal (arrows) horns of the lateral ventricles and dilated third ventricle (arrowhead). Also showing echogenic ventricular lining, representing ventriculitis, as often seen in cases with intraventricular hemorrhage.

(13). We therefore recommend early and repetitive CUS scans within the first week of birth in neonates born very prematurely and in case of P/IVH, repetitive CUS scans with measurements of the lateral ventricles throughout the subsequent weeks (1). If, after a few weeks, no or only mild, non-progressive PHVD develops, the frequency of CUS can be decreased.

Another important complication of P/IVH is periventricular hemorrhagic infarction (PVHI). This results from venous infarction due to obstruction of the terminal veins by the hemorrhage, impairing blood drainage from the medullary veins (14). The risk of PVHI depends on the size of the hemorrhage and the gestational age of the neonate. We recently found an incidence of 6% in very preterm infants with P/IVH (5). PVHI mostly develops shortly (within days) after the initial hemorrhage. On CUS it is characterized by a unilateral or strikingly asymmetric echodensity in the periventricular white matter, ipsilateral to the hemorrhage (Figure 9A). The echogenicity of the lesion will gradually decrease and change to echolucency, the ultrasonographic end-stage generally being a porencephalic cyst or several smaller cystic lesions (Figure 9B) (5,14). The neurological outcome of infants with PVHI depends on the size, extent, and location of the lesion (15,16). Early detection is important for prognostication and initiation of early intervention (including physiotherapy, occupational therapy, and speech therapy).

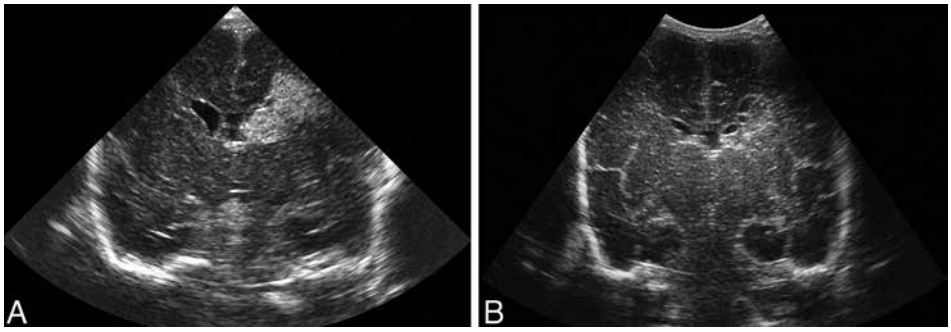

Figure 9. Coronal ultrasound scans in very preterm infant (gestational age 27 wk) with intraventricular hemorrhage, complicated by periventricular hemorrhagic infarction (PVHI). **(A)** The PVHI is presented by a large echogenic lesion in the frontal white matter, ipsilateral to the intraventricular hemorrhage. **(B)** End stage PVHI, presented by cystic lesions in the previously echogenic area.

Periventricular leukomalacia

Periventricular leukomalacia (PVL) can be subdivided into the "classic" focal PVL that is easily detectable, and a more diffuse form that is less easily detectable with CUS. The "classic PVL", is characterized by regions of coagulation necrosis and liquefaction in the periventricular white matter with loss of all cellular elements (17,18). Classic PVL generally first presents on CUS as areas of increased, mostly inhomogeneous echogenicity that may gradually normalize over time or evolve into cystic lesions (Figure 10) (19). Although its incidence has considerably declined over the last decades (currently the incidence is estimated to be less than 3%) (17), cystic PVL is still a strong predictor of neurological impairment (5,17,20,21). The size, location, and extent of the cystic lesions are related to neurological outcome.

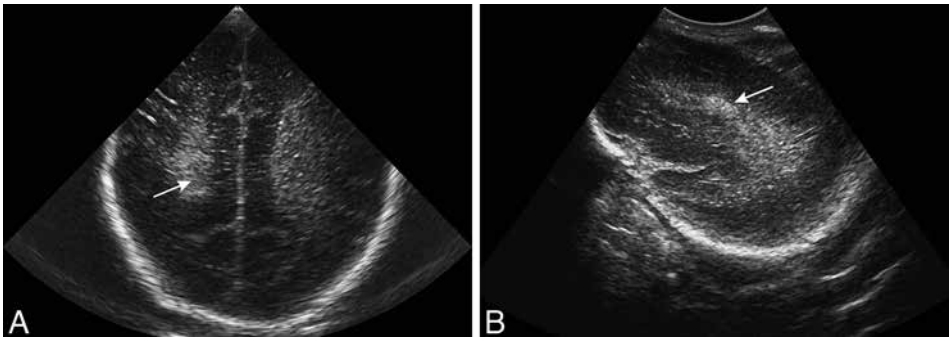

Figure 10. Coronal **(A)** and parasagittal **(B)** ultrasound scans in preterm infant (gestational age 32 wk), showing inhomogeneously increased echogenicity (arrows) in the parietal white matter on the right side.

The diffuse, noncystic form of PVL is characterized by central cerebral white matter injury with loss of premyelinating oligodendrocytes, astrogliosis, and microglial infiltration (18). On CUS it may be represented by periventricular echodensities, not evolving into cystic lesions. However, it has been reported that CUS is less sensitive for detecting this form of white matter injury than magnetic resonance imaging (MRI) (22-24). MRI generally shows diffuse signal intensity changes and/or punctate white matter lesions and signs of white matter volume loss (4,23,24). Infants with diffuse white matter injury are at risk for motor and cognitive impairment, as well as behavioral problems (18). Early detection is therefore important, probably warranting MRI in all very preterm infants.

Cerebellar injury

It is increasingly recognized that the preterm infant is at risk of cerebellar injury with potential major impact on neurological outcome (8-10,25). Both hemorrhages and infarctions have been reported in very preterm infants (10,25). CUS studies in preterm infants have shown that the incidence of cerebellar lesions ranges from 3% in infants weighing less than 1500 g to 19 % in infants weighing less than 750 g (25). Although MRI is superior to CUS for detection of cerebellar hemorrhages and can even detect punctate hemorrhages, CUS will detect most hemorrhagic lesions when the mastoid fontanels are used as additional acoustic windows. Using the mastoid fontanels routinely, we detected cerebellar hemorrhages in 7/77 (9%) very preterm infants, with the highest incidence in neonates with a gestational age < 28 weeks and in infants with P/IVH (Figure 7). In 5 of 7 (71%) infants, cerebellar hemorrhage occurred in combination with supratentorial hemorrhage, whereas hemorrhage was isolated to the cerebellum in only 2 infants (10). Cerebellar injury was detected on CUS within the first 3 days of admission in most and within the first week in all cases. We therefore recommend obtaining additional mastoid fontanel views in these high-risk infants (gestational age < 30 weeks and/or supratentorial hemorrhage).

Brain maturation

In very preterm infants, maturational processes, normally taking place during the last trimester of pregnancy, continue to take place after birth. These processes include gyration, myelination, glial cell migration, and deep grey matter changes, and result in important changes in ultrasound appearance of the brain over time (1). It is important to recognize these maturational changes and to distinguish them from (mild) pathology. The most important changes that can be recognized on CUS and are:

Gyration

This process, strikingly showing as ongoing folding and increase in complexity of existing gyral pattern over time, changes the aspect of the brain's surface from (nearly) smooth in the early preterm period to complexly folded around term equivalent age (Figure 11).

Echogenicity changes in the white matter

Some echodensities within the periventricular white matter can be considered normal maturational phenomena in the preterm infant's brain, probably reflecting glial cell migration, changes in water and cell content and maturation of brain structu-

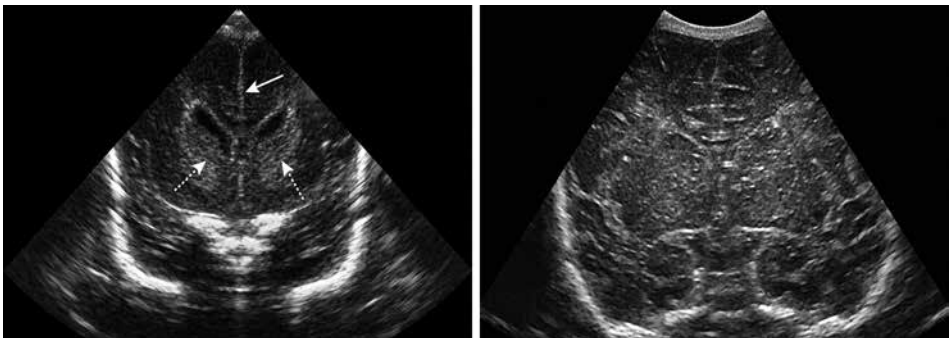

Figure 11. Coronal ultrasound scans at the level of the frontal horns in **(A)** very preterm infant (gestational age 26 wk) and **(B)** full-term infant. Showing a very smooth interhemispheric fissure (arrow) and lack of cortical windings in (A), as compared to complexly folded interhemispheric fissure and multiple cortical windings in (B). Also showing diffuse, subtle echogenicity in the basal ganglia (dotted arrows) in (A), being a normal finding in preterm infants.

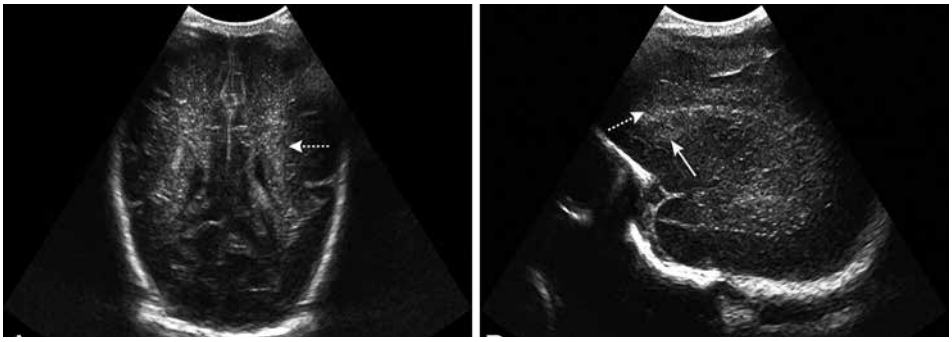

Figure 12. (A) Coronal and **(B)** parasagittal ultrasound scan in very preterm infant (gestational age 27 wk), showing subtle, homogeneously increased echogenicity in the frontal and parietal white matter(dotted arrows). Also showing mild, subtle echogenicity in the head of the caudate nucleus (arrow) in (B).

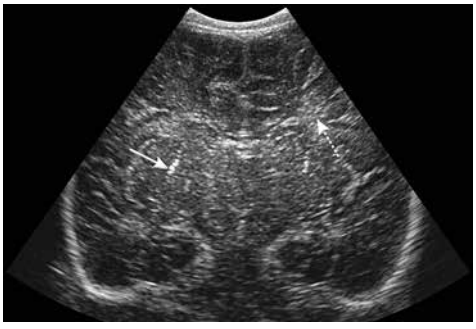

Figure 13. Coronal ultrasound scan in a full-term neonate (age 10 d) with viral encephalitis, showing lenticulostriate vasculopathy (arrow) and increased echogenicity of the white matter (dotted arrow).

res (1, 26-28). We believe that homogeneous grade 1 periventricular echodensities, the echogenicity being less than that of the choroid plexus, are normal in very preterm infants before term equivalent age (26). These normal echodensities (Figure 12) should be distinguished from more inhomogeneous and/or echogenic areas, that probably represent white matter injury (Figure 10) (4,19).

Echogenicity changes in the deep grey matter

In very preterm infants, the echogenicity of the basal ganglia and occasionally also of the thalami is increased as compared to the echogenicity of the surrounding brain structures (Figure 11A and 12B) (1,29). This diffuse, subtle echogenicity is visible within the first day of birth, gradually fades with age, and is no longer seen after term equivalent age. It is present in over 90% of very preterm infants and associated with normal maturation of the basal ganglia and thalami around term equivalent age. No MRI equivalent is found for this CUS finding (unpublished data). We therefore feel that it is a normal maturational phenomenon in very preterm infants, probably related to the high water content and/or low fiber density of the immature grey matter (29). This subtle, diffuse echogenicity of the basal ganglia should be distinguished from more linear or punctate echogenicity in the basal ganglia as seen in lenticulostriate vasculopathy, from focal lesions within the basal ganglia/thalami often ascribed to hemorrhage or infarction (29-31), and from diffusely increased echogenicity in the basal ganglia/thalami originating from hypoxic-ischemic injury (Figure 3, 13 and 14). The first two are generally not visible immediately after birth and have a more focal appearance, whereas the latter occurs mainly in full-term and older preterm neonates after a severe hypoxic-ischemic event (29-33).

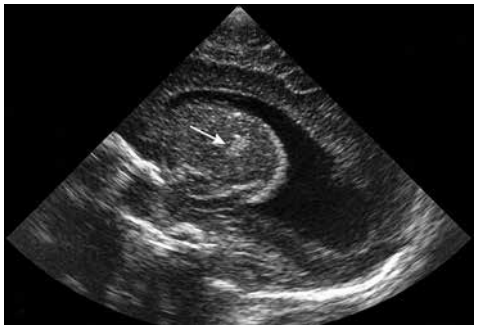

Figure 14. Parasagittal ultrasound scan in preterm infant (gestational age 31 wk), showing focal echogenic lesion in the left thalamic area (arrow), ascribed to infarction. Also showing dilated lateral ventricle.

Myelination

This process is not depicted by CUS, although some CUS features seem to be related to myelination (27). Myelination can be optimally assessed in the preterm infant using MRI.

Ultrasound imaging of the full-term infant's brain

For the following reasons the brain of the full-term infant is slightly more difficult to visualize with CUS than the preterm infant's brain: As the head is larger, most brain structures are further away from the transducer; areas of the brain that are prone to hypoxic-ischemic or hemorrhagic injury are mostly located at the brain's convexity and/or in the central region, these areas are less easy to access than the ventricular and periventricular areas; in addition, mineralization of the skull is more advanced in full-term infants than in preterm infants and the fontanels may be small, making the brain less accessible for ultrasound imaging; finally, unsedated full-term infants may be restless, often making CUS scanning more challenging than in preterm infants. However, in skilled hands, CUS in full-term infants will give invaluable information on the anatomy and maturation of the brain and on possible injury or congenital abnormalities (6). We therefore strongly recommend that at least 1 CUS examination is routinely performed in sick full-term infants. Serial examinations are necessary in infants with (suspected) injury and/or neurological symptoms.

Hypoxic-ischemic lesions

CUS in full-term infants with hypoxic-ischemic encephalopathy and/or a hypoxic-ischemic event has several purposes. It helps to time the onset of lesions, that is, whether the injury was inflicted antenatally, perinatally, or after birth. In addition, the evolution of lesions can be monitored and CUS can assist in distinguishing hypoxic-ischemic injury from other causes of neonatal encephalopathy, such as metabolic disease. Finally, CUS contributes to outcome prediction. Several patterns of hypoxic-ischemic brain injury can be distinguished in (near) full-term neonates (33-37).

Predominant injury to the deep grey matter

This pattern of injury may occur after a severe hypoxic-ischemic event. On CUS it is characterized by a gradual increase in echogenicity in the basal ganglia or thalami, mostly first present hours to days after the event and becoming more prominent

over time (Figure 3). Early detection may be facilitated by additional scanning with a low transducer frequency of 5 MHz (mentioned earlier in the text). MRI is a necessary adjunct to determine the exact site and extent of injury and involvement of the posterior limb of the internal capsule, being of major importance for the neurological prognosis (38).

Predominant injury to the cortex and subcortical white matter ("watershed pattern")

This pattern, with or without basal ganglia or thalamic involvement, may occur not only after an acute, severe hypoxic-ischemic event, but also after longer lasting or repetitive hypoxic periods. Due to its localization at the brain's convexity, this injury pattern is not easily detectable with CUS. It often shows as a "tramline appearance" of the cortex, that is, broadening of the hypoechogenic cortical rim and relative enhancement of the echogenic fissures, in many cases combined with increased echogenicity of the subcortical white matter (Figure 4). Increasing the transducer frequency to 10 MHz will improve detection of this injury pattern with CUS. However, confirmation by MRI is indicated (1,34). Neurological outcome depends on the extent of injury and whether basal ganglia/thalamic injury co-exists (35,36).

Global brain injury

In very severe cases, the whole brain may be affected, including the deep grey matter, cortical grey matter and white matter. In some cases, the cerebellum may also be affected. CUS imaging is characterized by diffuse brain swelling with diffusely increased echogenicity, loss of normal architecture, loss of sulci, and narrowing of

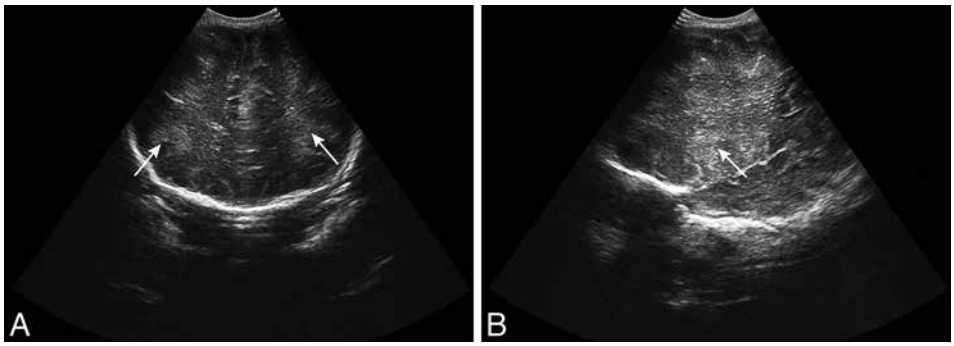

Figure 15. (A) Coronal and **(B)** parasagittal ultrasound scan in preterm infant, scanned around term equivalent age after a severe hypoxic-ischemic event, showing diffusely increased echogenicity of the parenchyma (arrows) and loss of the normal anatomical landmarks, reflecting severe global brain injury.

the lateral ventricles (Figure 15). Diffuse brain injury mostly shows within hours of the event. Abnormalities may (partially) be transient in cases with reversible swelling, but if the abnormalities persist for more than 24 hours, this is ominous for adverse neurological outcome. In these cases the added value of MRI will be limited, as it will only confirm CUS findings. However, MRI confirmation may help the clinician to make important decisions on withdrawal or continuation of intensive treatment.

Arterial infarction

Although arterial infarction is generally not considered the result of a global hypoxic-ischemic event, we and others have encountered cases of arterial infarction after perinatal asphyxia (37). This pattern of injury may be difficult to detect with CUS (39,40). It may first show as a slight asymmetry in appearance of the hemispheres, an abnormal aspect of the Sylvian fissure or a focal region of (subtle) echogenicity in the territory of a (branch of a) main artery (Figure 16). The abnormalities mostly become more prominent over the subsequent days. However, small infarctions may remain beyond the scope of CUS. MRI is always indicated to confirm the diagnosis and to assess the exact localization and extent of injury, which is of importance for the neurological prognosis (40,41).

Hemorrhage

As large hemorrhages at the brain's convexity (subdural and subarachnoid hemorrhages) are rare and smaller hemorrhages are often not well detected with CUS, this section is limited to intraventricular and intraparenchymal hemorrhages.

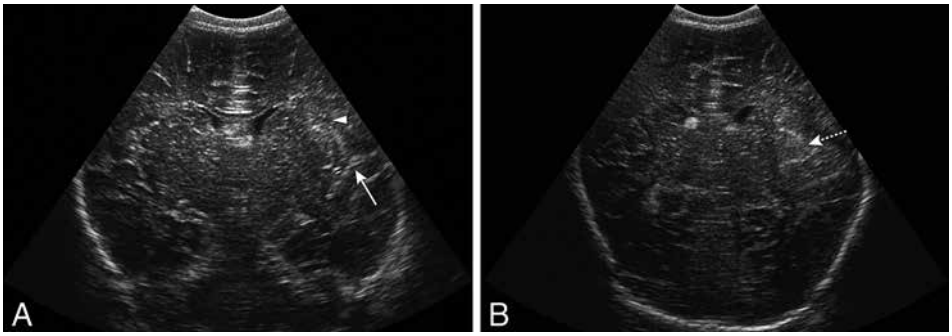

Figure 16. Coronal ultrasound scans in full-term neonate presenting with convulsions, showing asymmetry of the Sylvian fissures (arrow) and subtle increased echogenicity in the parenchyma on the left side (arrowhead) in **(A)**, and area of increased echogenicity in the left parietal lobe (dotted arrow) in **(B)**. The increased echogenicity represents infarction in the territory of the left middle cerebral artery.

Intraventricular hemorrhage

This type of hemorrhage is less common in full-term than in preterm infants. It mostly originates from the choroid plexus but may also arise from the residual germinal matrix (42). It may be associated with trauma, coagulation disorders, sinovenous thrombosis (especially in case of thalamic hemorrhage), or vascular anomaly. Intraventricular hemorrhage is well recognized if the diagnosis is considered (ie, in cases with traumatic delivery and/or neurological symptoms) and CUS is performed. MRI is needed if an underlying vascular cause is suspected, and follow-up CUS examinations are indicated as PHVD may develop.

Intraparenchymal hemorrhage

Primary parenchymal hemorrhages are rare. These hemorrhages mostly occur in combination with intraventricular hemorrhage and have the same risk factors. They need to be distinguished from PVHI. On CUS these hemorrhages can be recognized as rather circumscribed echogenic lesions. They are mostly seen in the temporal lobe after traumatic deliveries (Figure 17), but may also occur in other lobes and, rarely, the cerebellum.

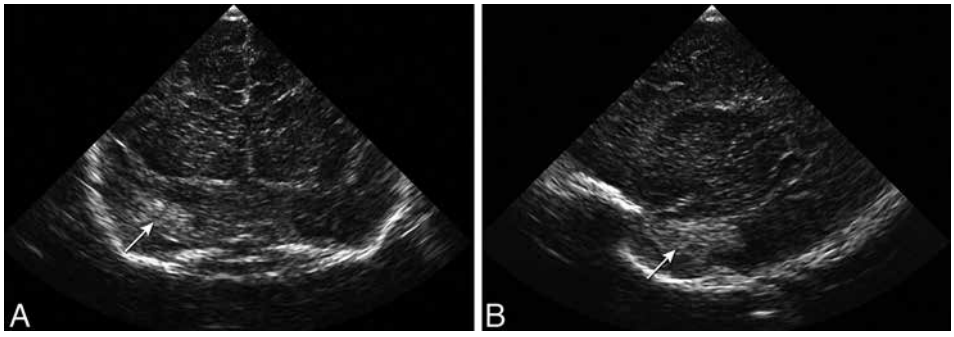

Figure 17. (A) Coronal and **(B)** parasagittal ultrasound scan in full-term neonate, presenting with convulsions, showing echogenic lesion in the right temporal lobe (arrow), reflecting hemorrhage.

Ultrasound imaging of brain infections

Infections of the central nervous system can be subdivided in acquired bacterial, viral, and fungal, as well as congenital TORCH infections (43). CUS may show a range of changes, including increased echogenicity in the periventricular and/or subcortical white matter (Figure 13), probably related to encephalitis, smaller echogenic lesions within the parenchyma, ascribed to (micro) abscesses (Figure 18), echolucent lesions, mostly with an echogenic rim, reflecting larger abscesses, and ventricular dilatation and/or echogenic ventricular lining, ascribed to ventriculitis. In neonates with congenital TORCH infections, other abnormalities, such as calcifications, lenticulostriate vasculopathy, and germinolytic cysts, can be encountered.

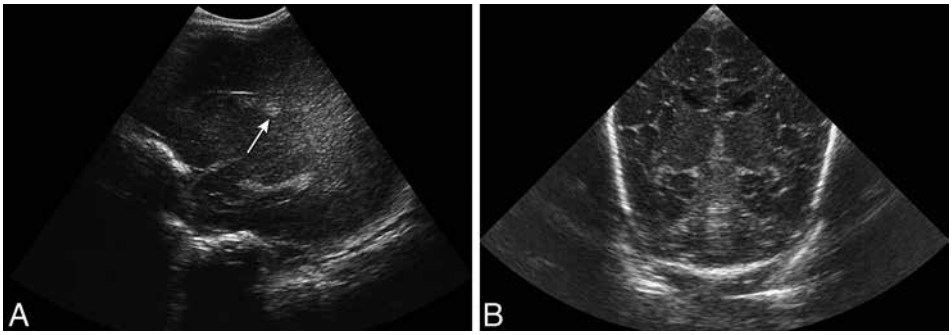

Figure 18. (A) Parasagittal ultrasound scan in very preterm infant (gestational age 30 wk) with Gram-negative sepsis, showing round echogenic lesion (arrow) in the periventricular area, representing beginning abscess formation. **(B)** Coronal ultrasound scan in very preterm infant (gestational age 26 wk) with disseminated *Candida* infection, showing multiple small echogenic lesions, representing micro abscesses.

Limitations of CUS

As briefly mentioned earlier, CUS has several limitations. Despite adapting the transducer frequency and focus, abnormalities at the brain's convexity (such as hemorrhages and cortical abnormalities) are not easily depicted, and MRI is needed to demonstrate or confirm these abnormalities. Although the use of supplemental windows greatly improves the abilities of CUS, the posterior fossa may not be well visualized, and MRI is necessary to confirm suspected abnormalities in this area. In addition, myelination is not depicted by CUS, whereas in case of very preterm birth or suspected brain injury,

progress of myelination is of importance for prognostication, making MRI invaluable. Diffuse white matter injury is probably not well detected but of prognostic relevance (22-24). Finally, metabolic disease or metabolic disturbances, including hypoglycemia may cause serious brain injury, not always easily detected by CUS (44,45). We feel that, if the safety of the neonate during transportation and the scanning procedure are guaranteed and ample experience with neonatal MRI is available, MRI is an invaluable and excellent complimentary technique to image the neonatal brain. Indications for neonatal MRI examinations have recently been described (1,46). While there are many indications for MRI, there is hardly any indication for CT of the brain in modern neonatology, the only indication being (suspected) large hemorrhages at the convexity or in the posterior fossa, if emergency access to MRI is unavailable.

In Summary

CUS is an excellent tool for serial, bedside imaging of the newborn infant's brain. Recent advances in CUS imaging, including the use of additional (high frequency) transducers and acoustic windows, allow reliable visualization of not only the ventricular system and periventricular white matter but also of the subcortical white matter, the cortical and deep grey matter, and the cerebellum.

The non-invasive character of this bedside tool enables frequent examinations in high-risk neonates, thereby allowing the monitoring of normal brain maturation and growth and the evolution of lesions. Very early imaging helps to determine the timing of injury. Some lesions are better depicted by CUS than by MRI. Because of these unique properties and the relatively low cost of CUS, it is an irreplaceable technique.

Future perspectives of CUS include the standard use of supplemental acoustic windows. In addition, efforts should be directed towards reliable detection of diffuse white matter injury in very preterm infants and of ischemic cerebellar injury in both preterm and high risk full-term neonates. Although further improvement of image quality will probably expand the possibilities of CUS, the role of 3D and 4D imaging techniques may be explored. Finally, while the use of neonatal CT should be discouraged, we feel that frequent and standard use of CUS should be stimulated among pediatricians and radiologists involved in neonatal care, thereby increasing the experience and skills of these specialists with this invaluable imaging technique.

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