Magnetic Resonance Imaging of the Neonatal Brain

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ABSTRACT

Neonatal magnetic resonance (MR) imaging is rapidly becoming the preferred modality for the evaluation of central nervous system disorders in the newborn. Recent literature supports the value of this imaging technique in diagnosing ischemic, hemorrhagic and infectious disease processes in the premature and full-term neonatal brain. Recent data in premature newborns with neurological injury also suggest a role for MR imaging in determining long-term neurodevelopmental outcomes. This review article provides a framework and overview on neonatal MR imaging techniques and examines the literature or radiological disease patterns and prognostic implications in common neurological disorders.

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Key words : Neonate; Magnetic resonance imaging; Central nervous system; Neurodevelopmental outcomes

Neonatal magnetic resonance (MR) imaging is a relatively new technique which has rapidly become the study of choice for the evaluation of central nervous systems disorders in newborns. MR imaging provides excellent anatomical depiction of the brain which far surpasses cranial ultrasound and computed tomography. The multiple specialized MR sequences allow for greater sensitivity and specificity for the detection of parenchymal and extra-axial processes. In addition, MR imaging is the only technique which can distinguish the presence or absence of myelin in the neonatal brain. This technique has become more widely available with the universal increase in hospital-based MR scanners in close proximity to the neonatal intensive care unit. The development of MR compatible incubators and neonatal coils has improved patient safety and image quality. Neonatal MR imaging is rapidly becoming important in predicting neurodevelopmental outcomes, and the future of MR imaging is directed at understanding the prognostic implications of CNS disease within newborns. This article provides a basic framework and overview on neonatal MR imaging techniques, applications, disease patterns and prognostic implications in common neurological disorders.

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MR Coils

Over the last few years, the quality and safety of neonatal MR imaging has steadily increased with the development of dedicated neonatal MR scanners, neonatal imaging coils and MR compatible incubators. In certain institutions, dedicated neonatal MR scanners have been installed in close proximity to the neonatal intensive care unit. However, these dedicated MR scanners are currently expensive for most institutions to acquire. In addition, these MR scanners usually have low field magnets, which have a lower to signal-to-noise ratio (SNR) than a high field 1.5 Tesla scanner. Another option is to use a dedicated neonatal head coil in a conventional 1.5 Tesla MR scanner to optimize imaging.

At the authors’ institution they use an MR compatible incubator with an attachable dedicated neonatal head coil (Neonate Imaging Sub System, Advanced Imaging Research, Cleveland OH). The signal-to-noise ratio of images obtained with an MR compatible incubator with a dedicated head coil is 2.3 times that of a standard MR coil in age-matched patients. The incubator is easy to transport from the neonatal intensive care unit to the MR scanner. The device, in addition to being an incubator with temperature and humidity controls, has a ventilator, infusion pumps, physiologic monitors, tanks, and MR-compatible intravenous lines and poles. By moving the patient into the incubator in the NICU, the time that the newborn spends outside the NICU or outside the incubator can be minimized. This type of device enhances both patient safety and the quality of MR imaging.

MR Techniques

The conventional MR brain protocol includes T1-weighted sequences, T2-weighted sequences and gradient echo (GRE) sequences. T1-weighted and inversion recovery sequences provide excellent anatomic information as well as high contrast between gray and white matter. Three-dimensional inversion recovery techniques provide thin sections through the entire brain with a short acquisition time and T1-weighted contrast. T2-weighted sequences provide good contrast resolution between gray matter, unmyelinated white matter and myelinated white matter. The authors typically use fast spin-echo (FSE) T2-weighted sequences to limit the acquisition time while maintaining adequate contrast resolution between the gray and white matter. The disadvantage of the FSE T2-weighted sequence is the reduction of magnetic susceptibility for the detection of intracranial hemorrhage. For this reason, gradient echo sequences are part of the protocol. Gradient echo (GRE) sequences provide increased sensitivity for the detection of T2*-weighted magnetic susceptibility. This is especially important for diagnosing intracranial hemorrhage, which locally distorts the magnetic field because of the presence of the Fe molecule within blood products. Subtle germinal matrix or intraventricular hemorrhage may sometimes only be detectable with the GRE sequence.

Diffusion-weighted imaging (DWI) measures the random motion of water molecules. The directionality or anisotropy of diffusion within the brain is affected by the presence or absence of myelin within white matter tracts. Myelinated white matter tracts allow greater water diffusion parallel to the tract and restrict diffusion perpendicular to the tract. This anisotropy of diffusion necessitates the acquisition of diffusion-weighted images in three perpendicular directions to form the composite DWI image, called the trace or isotropic diffusion image. Diffusion can also be quantified by measuring an apparent diffusion coefficient (ADC). Acute infarcts demonstrate a marked reduction of water diffusion through an incompletely understood mechanism, which is postulated to be related to cytotoxic edema. Therefore, acute infarcts typically have increased signal on DWI and have decreased apparent diffusion coefficients. Diffusion-weighted imaging also has a role in the detection of acute hypoxic-ischemic injury in neonates.

Proton MR spectroscopy provides a chemical analysis of the tissue within the brain. Different protons within the brain experience slightly different magnetic fields depending on their local molecular environments. There are specific metabolites which have been identified on MR spectroscopy of the brain. Using the pattern of the metabolites which include n-acetyl aspartate, choline, creatine, lactate, amino acids and other molecules, certain diseases and disorders can be diagnosed and followed. Unmyelinated white matter characteristically has elevated choline which distinguishes it from myelinated white matter. Choline peaks are, therefore, normally elevated in most of neonatal white matter. N-acetyl aspartate is a normal neuronal marker and is nonspecifically decreased in a variety of disorders. Lactate is elevated in situations in which anaerobic metabolism predominates such as ischemia, hypoxic-ischemic injury, and other metabolic disorders.

Sedation

Sedation is usually unnecessary for neonatal MR imaging. A newborn usually sleeps for most of the day and usually falls sound asleep after regular breast-feeding or bottle-feeding. Therefore, pharmacologic sedation is usually not used for MR imaging if the study is performed after a regular feeding and after a period of sleep-deprivation of the newborn. In a small subset of neonates, chloral hydrate (50 mg/Kg) is used for sedation and monitored by a pediatric anesthesiologist or neonatal intensive care staff.

NORMAL MR APPEARANCE OF THE NEONATAL BRAIN

The most characteristic finding in the normal neonatal
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brain is the almost complete lack of myelination. MR imaging is exquisitely sensitive to the myelination of white matter. Unmyelinated white matter is hyperintense on T2-weighted images and hypointense on T1-weighted images. There is a predictable course of myelination based on the gestational age of the newborn. Although most neonatal white matter is unmyelinated, term neonates typically demonstrate myelination of the corona radiate, primary motor and sensory cortex, ventroposterolateral nuclei of the thalami, medial lemnisci, medial longitudinal fasciculus, and gracile and cuneate nuclei. Superior and inferior cerebellar peduncles but not middle cerebellar peduncles are myelinated at term. Portions of the vermis but not the cerebellar peduncles are myelinated. The absence of myelin at the appropriate age can signal delayed myelination or dysmyelinating disorders.

INJURIES OF PREMATURITY

White Matter Injury of Prematurity

Neonatal white matter injury is a common complication of prematurity and is often an end-result of perinatal hypoxic-ischemic events in this population. While hypoxic-ischemic encephalopathy (HIE) is the most common cause, other etiologies include infections, metabolic disease, and hydrocephalus. The pattern of white matter injury is traditionally described as small, non-hemorrhagic, gliotic lesions appearing symmetrically in periventricular areas – particularly in the trigone and adjacent to the foramen of Monro. This distribution of injury has earned the classic title of periventricular leukomalacia (PVL). However, several authors caution that white matter involvement is not always confined to periventricular zones and may in fact extend deep into adjacent subcortical white matter or the centrum semiovale. The gliotic lesions may become cystic and cavitated. Alternatively, the lesions may remain non-cystic. Sie and colleagues suggest that clinical outcome correlates more with the extent of injury than with lesion morphology. Neonatal MR imaging allows the recognition of patterns of injury which may predict the prognoses of the newborns. There is no consensus yet as to the exact etiology of these lesions, but the propensity for white matter damage in preterm infants is likely related to the intrinsic vulnerability of the premature tissue in the face of oxygen deprivation. Several factors conferring this vulnerability are proposed including oligodendrocytic susceptibility to damage from free radicals, the absence of compensatory hyperemia during hypotension, and an increase in anaerobic glycolysis during hypoxia. Neonatologists should be aware of the various imaging techniques that allow for early recognition and evaluation of this potentially devastating disease process.

As one of the first methods studied in PVL, cranial ultrasonography remains unpromising in the acute setting with its relatively poor sensitivity for non-cavitary white matter lesions. One study demonstrated that up to 70% of hypoxic-ischemic white matter lesions are missed in the acute phase on ultrasound. Acute lesions demonstrate slight to intense echogenicity in the trigone. The sonographic features of PVL are more prominent in the subacute phase (2-6 weeks) when necrotic tissue begins to dissolve, leaving behind distinct hypoechoic cavitations. Nevertheless, ultrasound, a relatively simple technique, remains the initial survey of choice in premature infants experiencing cerebral oxygen deprivation because of its portability and ready availability for follow-up imaging.

Conventional MR imaging exhibits superior sensitivity for non-cavitary PVL, especially in the acute setting (2-5 days). Lesions appear as small punctate hyperintense areas on T1-weighted images, which are likely to be a product of reactive gliosis. Cavitations are also visible as areas of hypointensity on T1-weighted images and hyperintensity on T2-weighted images. MR imaging is capable of detecting structural changes of chronic PVL including white matter atrophy, callosal thinning and ex vacuo ventricular dilatation. However, Childs et al caution that MR evaluation of frontal periventricular white matter becomes difficult in neonates of less than 34 weeks gestational age, due to migrating glia that interfere with white matter signal.

Diffusion-weighted imaging (DWI) is yet another promising technique for early detection of PVL. Thompson et al suggests that DWI can reveal changes that are not observed on any other imaging modality. Findings include hyperintensity on DWI and diminished apparent diffusion coefficients in the periventricular white matter in the first few days after injury. DWI findings are most advantageous in the acute setting as these are observed before any abnormality appears on ultrasound or conventional MR images. Decreased apparent diffusion coefficients are usually limited to the acute phase as parenchymal changes normalize within the first five days of injury.

Germinat Matrix and Intraventricular Hemorrhage

Intraventricular hemorrhage (IVH) comprises a spectrum of pathological processes that result from blood filling in and around the ventricles. The incidence of IVH is directly related to prematurity and rarely occurs in full term neonates. Though multifactorial in etiology, the tendency for hemorrhage is most likely associated with exceptionally fragile capillaries in residual germinal matrix that are subjected to oscillating blood pressure. Blood from ruptured capillaries may remain confined to the ependymal surface or extravasate into the ventricles, leading to subsequent complications. Of particular concern is the potential for clot obstruction within the CSF pathways, resulting in hydrocephalus. Severe hydrocephalus is predictive of a poor developmental
Papile 30-32 Isolated subependymal
36 33 13 38, 39 11 13 35 29 grade IVH with hydrocephalus and PVHI. The possibility
complications of GMH may be severe and include high-
hemorrhage can in fact be clinically silent. Subsequent
studies proportional to gestational age and birth weight. Several
modalities for early detection of GMH. According to
Triulzi and colleagues, cranial ultrasonography is
established a grading system for the sonographic evaluation of IVH severity.
Grade I hemorrhage is defined as an isolated germinal matrix hemorrhage (GMH) without extension into the ventricular cavity. A grade II classification is assigned to GMH with accompanying intraventricular blood filling less than half of the ventricular space. Grade III hemorrhage refers to GMH with blood filling greater than half of the ventricular area. A grade IV classification is reserved for cases of GMH with secondary periventricular hemorrhagic venous infarction (PVHI). This grading system is now widely accepted as a reliable prognostic tool in the evaluation of IVH.

GMH is the most common form of neonatal intracranial hemorrhage and is typically seen in preterm infants. As a subtype of IVH, GMH is classified as an injury of prematurity with an incidence inversely proportional to gestational age and birth weight. Several studies have shown that GMH shows a marked decline in incidence after 34 weeks of gestation. This observation can be explained by the tendency for matrix involution beginning in the final weeks of the second trimester. Germinal matrix tissue in the caudothalamic notch is the last to involute and is, therefore, statistically the region of greatest concern for hemorrhage. The onset of hemorrhage is variable but up to 40% of cases occur within the first five hours after birth. GMH falls on a continuum of intraventricular hemorrhage (IVH) and is considered to be the injury of best prognostic outcome when found alone. Isolated subependymal hemorrhage can in fact be clinically silent. Subsequent complications of GMH may be severe and include high-grade IVH with hydrocephalus and PVHI. The possibility of GMH in preterm infants that exhibit acute neurological decline within the first four days of life should be considered.

Cranial ultrasonography and conventional MR imaging have been two widely studied modalities for early detection of GMH. According to Triulzi and colleagues, cranial ultrasonography is initially the technique of choice for evaluating GMH as it is sensitive and easiest to perform. In addition, ultrasound can be repeated multiple times to monitor for ventricular enlargement in anticipation of complicated IVH. Findings on ultrasound include areas of increased echogenicity in the ventricular wall. While ultrasound can be useful in detecting blood within the subependymal space, some researchers argue that conventional MR imaging is as sensitive and probably more specific, especially in the acute setting. MR imaging exhibits a superior capacity to differentiate blood from other lesions after the hyperacute phase (Fig. 1). Acute hemorrhagic foci on T1-weighted images appear as small areas of normal to increased signal and can be confirmed on T2-weighted sequences as ovoid areas of distinct hypointensity. MR also offers the advantage of identifying subependymal bleeds in the subacute and chronic phases with substantial sensitivity for hemorrhage. Gradient echo (GRE) sequences are exquisitely sensitive to hemosiderin deposits which may be missed on other MR sequences and on neurosonography. Moreover, MR imaging is superior to ultrasound in detecting and evaluating a wider array of GMH complications including IVH, hydrocephalus, and PVHI. In the experience of Zuerrer and colleagues, conventional and gradient echo MR sequences can identify acute (3-7 days) and chronic (several months) phases of IVH. Barkovich recommends rescanning the patient one week after initial documentation of IVH to exclude subsequent ventricular enlargement. In summary, conventional MR is currently the preferred imaging modality for the diagnosis and evaluation of acute or subacute GMH and its IVH sequelae. Cranial ultrasonography remains useful for the hyperacute setting, for repeated follow-up imaging or when MR facilities are unavailable.

Periventricular Hemorrhagic Infarction

Intraventricular hemorrhage can cause mass effect, resulting in obstruction of venous outflow from periventricular parenchymal tissue and culminating in hemorrhagic infarction secondary to venous hypertension. Approximately 15% of neonates with an initial diagnosis of IVH progress to this form of venous infarction, which is also known as periventricular hemorrhagic infarction (PVHI). Most cases of PVHI occur within the first 96 hours after birth. These lesions eventually undergo liquefaction leaving behind cysts that may communicate with the ventricles. In contrast to the symmetric multicystic pattern seen in PVL, the lesions of PVHI tend to be asymmetric or unilocular in character. Clinical presentations of PVHI are variable but may include apnea, bradycardia, cyanosis, severe motor impairment, seizures or loss of consciousness. Early diagnosis and management of PVHI is crucial in preventing further neurodevelopmental deficits.

While PVHI is detectable on cranial sonography, MR imaging is more sensitive than ultrasound in the detection and quantification of PVHI. The deep location of these periventricular lesions allows detection on cranial ultrasonography. Occlusion of draining veins can sometimes be demonstrated with color doppler. Ultrasound lacks the ability to quantify the amount of hemorrhage present. Conventional MR offers the advantage of differentiating hemorrhagic and necrotic components of PVHI (Fig. 1). T2-weighted sequences display hemorrhage as regions of low signal, contrasted against the neighboring venous infarct which appears hyperintense. The superior tissue differentiation of MR imaging allows for more precise estimates of infarct size and location.
HYPOXIC-ISCHEMIC INJURY

Inadequate brain oxygenation is the major recognized cause of perinatal morbidity and mortality and may result from either hypoxic, ischemic or combined processes. Some of the more common prenatal and perinatal processes include birth injury, hematologic abnormalities and hypovolemia. Significant parenchymal injury may occur with prolonged oxygen deprivation – a condition known as hypoxic-ischemic encephalopathy (HIE). Without appropriate intervention, the neonate may sustain severe motor and cognitive impairment. Clinical risk factors for developing HIE are linked to perinatal state and include fetal heart rate abnormalities directly preceding birth, low Apgar scores, acidosis and major resuscitation during delivery. Clinical manifestations of HIE vary and may appear as early as 24-48 hours after the onset of hypoxic or ischemic events. A distinction should be made between HIE and brain infarction as their clinical presentations are similar. However, infarction is a focal vascular insult with a relatively good prognosis while HIE is a diffuse process with a less favorable outcome.

Both term and preterm neonates are susceptible to hypoxic-ischemic brain injury but their disease patterns differ. Chugani et al suggest that changes resulting from hypoxic-ischemic injury are strictly related to the state of brain development and maturation. While HIE in adults manifests as diffuse gray matter injury, neonatal disease patterns involve select regions of both gray and white matter. Regional selectivity for neonatal HIE is dependent on the varying metabolic demands across different brain tissue, which in turn varies with the level of brain development.

Fig 1a, Fig 1b, Fig 1c

Fig 1. This preterm infant developed germinal matrix hemorrhage (GMH), intraventricular hemorrhage (IVH) and periventricular hemorrhagic infarction (PVHI). Axial T2-weighted image (Fig. 1a) demonstrates hypointense right frontal PVHI (arrow) with surrounding white matter injury which is hyperintense. Gradient echo (GRE) image (Fig. 1b), which is the most sensitive MR sequence for detecting hemorrhage, shows the subtle germinal matrix hemorrhage (arrow) in addition to the PVHI. Sagittal T2-weighted image demonstrates the IVH in the occipital horn (arrow) of the lateral ventricle as well as PVHI.
maturity. As discussed earlier, HIE in preterm infants exhibits predominantly white matter injury (i.e. PVL). In contrast, the pattern observed in term infants involves necrosis of select gray and white matter structures. Mild to moderate hypotension in term neonates tends to yield parasagittal injury consisting of cortical necrosis and necrosis of underlying white matter in a vascular watershed distribution (Fig. 2). Parenchymal injury resulting from severe hypotension has a predilection for the basal ganglia as well as the lateral thalamus, hippocampus, and corticospinal tracts. The vascular boundary zones are usually spared. Basal ganglia injury is more common than the parasagittal pattern and bares the worst prognosis. Severe gray matter injury may eventually give rise to multicystic encephalopathy. The availability of new time-bound therapies for HIE such as neuroprotective agents reaffirms the importance of early radiologic diagnosis.

Imaging features of HIE will vary depending on gestational age and severity of oxygen deprivation. Term neonates with mild to moderate hypoperfusion will develop parasagittal injury. Cranial ultrasonography and computed tomography (CT) cannot detect parasagittal or watershed injury in the acute phase. Conventional MR imaging with the addition of DWI has increased sensitivity for acute parasagittal lesions which are hypointense on T1-weighted images, hyperintense on T2-weighted images and hyperintense on DWI. MR scans of term infants with chronic HIE may reveal cortical atrophy and thinning on T1-weighted and T2-weighted sequences.

Several authors argue that proton spectroscopy is the most sensitive modality for detecting parasagittal HIE within the first 24 hours of injury. Findings include increased brain lactate and a diminished N-acetylasparate level. These results are promising and may advocate...
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This newborn presented with severe hypoxic-ischemic encephalopathy resulting in a basal ganglia pattern of injury. Axial FLAIR image (Fig. 3a, arrows) and axial diffusion weighted image (Fig. 3b, arrows) show hyperintense lesions within bilateral basal ganglia as a screening tool for parasagittal HIE.

DWI data are limited in the pediatric population but evidence exists for imaging changes occurring throughout the course of HIE. Several authors caution that DWI can give false negative results if performed within the first several hours of hypoxic-ischemic injury. A missed HIE diagnosis could yield devastating outcomes for the patient involved. After the first 24 hours, the lesions appear hyperintense. As the HIE lesions evolve from the acute to the chronic phases, the initial decreased diffusion in the acute phase progresses to increased diffusion in the chronic phase. This observed DWI phenomenon is likely attributed to fluid shifts between intracellular and extracellular compartments that occur over the course of cell injury. More data from the neonatal population is needed to determine the reliability of diffusion weighted sequences in the detection and diagnosis of hypoxic-ischemic injury.

As with watershed injury, ultrasound and CT are non-diagnostic for basal ganglia insult in the acute setting. In the experience of Barkovich, conventional MR is the technique of choice for this pattern (Fig. 3). In the acute phase (1-2 days), hypointense foci in the basal ganglia appear on T1-weighted sequences, which correspond to hyperintense lesions found on T2 images. The areas of hypointensity on T1 become hyperintense approximately two to three days after injury. Finally, lesions on T2 eventually assume a hypointense appearance at six to ten days after injury. These changes are typical whether occurring in the thalamus, perirolandic cortex, hippocampal formation, or the dorsal mesencephalic structures. Diffuse damage resulting in multicystic encephalopathy may occur if anoxia is severe or prolonged. The medulla and cerebellum however, are spared in this progression. Proton MR spectroscopy and DWI demonstrate basal ganglia injury earlier than any of the other imaging modalities. Robertson et al has confirmed this advantage of diffusion imaging but warns that initial findings may markedly underestimate the final extent of injury. Moreover, other authors caution that as with parasagittal injury, DWI may yield false negative results within the first few hours. Any changes observed with DWI normalize within the first five to six days.

CEREbral INFARCTION

Cerebral infarction of the neonate is most often idiopathic, but coagulopathy is the most common known etiology in this population. Infarction typically ensues within the first few days of life and is likely associated with complex hemodynamic changes occurring during this time period. Clinical presentations of infarction tend to overlap with those of HIE, but seizures are the most common sign.

Multiple modalities have been studied for their efficacy in detecting infarction. As in HIE, cranial ultrasonography and CT are poorly sensitive for acute ischemia. Conventional MR imaging however has been named by Triulzi and colleagues as the overall tool of choice for evaluating focal infarction (Fig. 4). On T1-weighted and T2-weighted images, infarcts become...
Fig 4. This term newborn presented with a seizure and was found to have an acute left frontal lobe infarct. T2-weighted image (Fig. 4a, arrow) demonstrates subtle loss of gray-white matter differentiation within the left frontal lobe. Axial diffusion weighted image (Fig. 4b) shows striking hyperintensity (arrow) within the left frontal lobe confirming decreased diffusion in an acute infarction.

readily visible after two or three days as areas demonstrating loss of gray-white matter differentiation. Connelly et al reports that changes observed on DWI appear before any abnormalities can be viewed on conventional MR. DWI demonstrates hyperintensity with decreased apparent diffusion coefficients (ADC) as early as 20 minutes after an acute infarction. Preliminary data suggests that DWI is the most effective tool for the detection of acute infarcts. DWI can also better identify infarct boundaries and can pinpoint irreversible lesions.

MR arteriography and MR venography can be used in conjunction with MR imaging of the brain to diagnose causes of arterial and venous infarction. MR arteriography may show occlusion of intracranial vessels as a cause of the infarct. MR venography may demonstrate venous sinus thrombosis as the cause of venous infarction.

INFECTIONS

Bacterial Meningitis

Infants are highly susceptible to bacterial meningitis, which is the most common neonatal CNS bacterial infection. Meningitis can have an early onset with severe systemic symptoms appearing in the first few days of life and a high mortality rate. The pathogen in such cases is likely to have originated in the birth canal. Alternatively, meningitis may first appear after the first week of life as a result of pathogenic exposure in the infant’s environment. Mortality is not as likely in the late-onset form and patients typically present with meningitis in the absence of systemic symptoms. The most common causative bacterial pathogens are group B streptococcus, Escherichia coli, Listeria monocytogenes, Staphylococcus aureas, and Pseudomonas aeruginosa. The pathophysiology of bacterial meningitis is complex. The process begins with irritation of the meninges and the ventricles. Marked cerebral edema occurs early in the infection. Inflammation spreads along cerebral vessels inducing a vasculitis, which in turn gives rise to hemorrhagic infarction. Perivascular inflammation extends to neighboring parenchymal tissue and cerebritis results. Ischemia or cerebral hypoperfusion may occur from severe vasospasm in inflamed vessels. Bacterial meningitis can be complicated by hydrocephalus, cerebral infarction, subdural empyema, or abscess.

The diagnosis of uncomplicated bacterial meningitis is established with clinical evaluation, laboratory data, and lumbar puncture. Neuroimaging is used to evaluate the secondary complications of the disease. Conventional MR is the study of choice for detecting the wide array of
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sequelae that can result. MR is particularly adept at demonstrating small lacunar infarcts in the brainstem, basal ganglia, and white matter. Meningitis can be detected on post-gadolinium T1-weighted images as abnormal leptomeningeal or cranial nerve enhancement. Encephalitis is diagnosed as parenchymal areas of increased signal on T2-weighted images with occasional enhancement on post-contrast T1-weighted images. Infarction related to vasculitis is readily diagnosed using DWI. Post-contrast T1-weighted images are the most sensitive for demonstrating extra-axial empyemas or sterile effusions. Although empyemas and sterile effusions may have overlapping MR characteristics, empyemas usually have an avid enhancing rim.

**PROGNOSTIC VALUE OF NEONATAL MR IMAGING**

Current techniques in neonatal neuroimaging allow for early detection of various neuropathological processes including ischemic, hemorrhagic, metabolic and infectious states. However, the long-term prognostic implications of early radiological disease detection are still under investigation. Woodward and colleagues\(^7\) studied this association in 167 preterm infants (gestational age at birth, 30 weeks or less) as part of a prospective longitudinal design. They performed early cranial ultrasonography within 48 hours of birth, brain MRI at term-equivalent age, cognitive assessment, psychomotor testing, cerebral palsy evaluation, and neurosensory testing, followed by repeat neurodevelopmental evaluation at two years of age. MRI findings were qualitatively assessed according to degree of white matter and gray matter involvement. Moderate to severe white matter abnormalities on MRI at term-equivalent age were found to be statistically strong predictors of cognitive and psychomotor delay, cerebral palsy, and neurosensory impairment by two years of age. Gray matter abnormalities were also correlated with cognitive delay, motor impairment, and cerebral palsy, but these associations were statistically weaker. MRI also proved to be more sensitive than cranial ultrasonography in identifying lesions predictive of long-term neurodevelopmental impairment. These findings suggest that MRI at term-equivalent age can serve as a reliable prognostic guide for physicians and families in the management of preterm infants with neurological injury.

A prospective cohort study by Miller et al\(^7\) at UCSF investigated the prognostic value of specific brain MRI findings on neurodevelopmental outcome in preterm neonates. They specifically assessed the prognostic value of white matter involvement, degree of ventriculomegaly, and IVH severity as independent factors. Serial MRI scans were performed at two distinct time-frames - the first before term-equivalent age (median: 32 weeks GA equivalent) and the second at near term-equivalent age (median: 37 weeks GA equivalent). Outcome measures taken at a follow-up appointment between 12-18 months included neuromotor scores and cognitive performance as measured by the Mental Developmental Index. Results from this study showed significant correlations between

Fig 5a

![Fig 5a](https://example.com/fig5a.png)

Fig. 5a. Neonatal MR imaging of the brain can be used for prognostic evaluation of the infant. This preterm newborn developed massive intraventricular hemorrhage (IVH), severe hydrocephalus and severe periventricular white matter injury which are all independent predictors of a poor neurodevelopmental outcome. Axial T2-weighted image (5a) demonstrates severe hydrocephalus and extensive periventricular white matter injury. Coronal T1-weighted image (Fig. 5b) shows massive IVH (arrow) with severe hydrocephalus.

Fig 5b

![Fig 5b](https://example.com/fig5b.png)
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degree of white matter injury, ventriculomegaly, and IVH found on early and term-equivalent age MRI with severity of neurodevelopmental outcome. In addition, initial MRI findings prior to term-equivalent age were stronger predictors of outcome than were findings at term-equivalent age. The authors confirm the role of MRI as a prognostic tool in preterm neonates and argue that it should not be necessary to wait until term-equivalent age to obtain this valuable information.

Dyet and colleagues further stratified brain MRI findings in preterm neonates (23-30 weeks GA) from both early post-birth and term-equivalent periods and correlated each with prognostic outcome at 18-36 months of corrected age. Early post-birth (median: 2 days of life) scans of their neonatal population (n=119) identified a wide range of abnormalities including major destructive lesions, hemorrhagic parenchymal infarction, extra-axial hemorrhage, basal ganglia and thalamic abnormalities, cerebellar hemorrhage, punctate white matter lesions, germinal layer hemorrhage, intraventricular hemorrhage, and ventricular dilatation. Findings on later (term-equivalent: 36 weeks postmenstrual age) scans included diffuse excessive high signal intensity, hemorrhagic parenchymal infarction, widened extra-axial space, basal ganglia and thalamic abnormalities, punctate white matter lesions, germinal matrix hemorrhage, ventricular dilatation, and periventricular leukomalacia. Clinical outcomes were measured at 18-36 months of corrected age with the Griffiths Mental Developmental Scale, which evaluates locomotor ability, personal-social interaction, hearing, speech, eye-hand coordination, performance, and practical reasoning.

Summative developmental quotients (DQs) were calculated for each patient. DQs were used in comparing patient groups with and without a given MRI abnormality. Patients with at least one abnormality on the early scan happened to have statistically higher DQs than those patients with normal initial scans. Moreover, with the exception of cerebellar hemorrhage and major destructive lesions, individual findings on early MRI showed no clear relationship with DQs. In contrast, lesions found at term-equivalent age including diffuse white matter abnormalities and post-hemorrhagic ventricular dilatation were predictive of lower DQs at 18-36 months of corrected age. These results would appear to contradict the findings of Miller et al., who showed that early MRI findings were more predictive of adverse neurodevelopmental outcome. However, Dyet et al. clarifies that the initial scans of the Miller study were performed at a more mature age (median: 32 weeks GA equivalent) than the initial scans of their own study.

MR imaging is beginning to play an important role in developmental risk stratification in preterm and term neonates. Imaging abnormalities which appear to be most predictive of poor outcome include significant white matter injury and intraventricular hemorrhage with accompanying ventricular dilatation (Fig. 5). The appropriate timing for these screening scans remains controversial. Future studies should address the prognostic weight of screening MRI performed at various time points in the neonatal period as well as the relationship between early MRI findings and long-term functional outcomes beyond two years of age.

CONCLUSION

The advent of MR imaging has contributed significantly to the early diagnosis of neonatal disease. New scanning modalities allow for the detection of a wide array of pathology including injuries of prematurity, infarction, hemorrhage, infection, and other disorders. Information obtained from neonatal MR imaging can effectively assist pediatric teams in planning appropriate treatment and determining long-term neurodevelopmental prognosis.

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