The Current State and Future of Fetal Imaging

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Fetal magnetic resonance imaging (MRI) has emerged as an essential diagnostic tool in recent years. The excellent soft tissue resolution, and the detailed visualization of fetal and extrafetal structures, may add important diagnostic information to prenatal sonography and has the power to confirm or change decisions at critical points in clinical care. Discussions of fetal surgery or termination of pregnancy may follow fetal MRI evaluation.

Ultrasound is the primary diagnostic tool in pregnancy. Indeed, as most fetal pathologies still initially are detected or suspected by ultrasound, prenatal sonography remains the modality of choice for screening examinations. Ultrasound has some advantages over MRI. It is less expensive, faster, and can be done at the bedside. Ultrasound, however, is user-dependent, and results will vary significantly with the skill and experience of the examiner. Despite being more costly, MRI’s high spatial three-dimensional resolution, multiplanar capabilities, large field of view, robust image quality, and its ability to characterize chemical tissue properties are arguments which favor its use as a secondary diagnostic modality in the assessment of fetal pathologies.

MRI has been verified as an important adjunct to ultrasound for clinically serious cases.\textsuperscript{1} One study\textsuperscript{2} explored the premise that prenatal MRI could provide additional information about fetal sacrococcygeal teratoma (SCT) when compared with prenatal sonography. SCT is seen in 1 in every 35,000 live births, and is the most common

\begin{itemize}
  \item Fetal
  \item Magnetic resonance
  \item Tractography
  \item Brain
  \item Morphometry
  \item Volumetry
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tumor presenting in newborns. Depending on its tissue makeup, SCT can be mistaken on ultrasound for spina bifida (Fig. 1). In the study, MRI’s characterization of the intra-pelvic and abdominal extent of the tumor was more accurate, and provided more information about its mass effect on adjacent organs, compared with ultrasound. Discrepancies between prenatal MRI and ultrasound occurred in 8 of the 22 fetuses in the cohort. Four fetuses with a type 1 sacrococcygeal teratoma on sonography were assessed as type 2 on MRI; three fetuses diagnosed with type 2 on sonography were type 1 sacrococcygeal teratomas on MRI, and one fetus diagnosed with type 2 on sonography was a type 3 sacrococcygeal teratoma on MRI. Intrapelvic mass effect was seen with MRI in 9 of 22 fetuses (41%), but only three of nine were assessed correctly with ultrasound. The investigators surmised that the additional anatomic resolution afforded by MRI resulted in better prenatal counseling and improved preoperative planning for surgical resection.1 This study supports the capacity of MRI to change clinical course.

Until recently, magnetic resonance image acquisition had been lengthy, and its image quality depended on a complete lack of fetal motion. Maternal–fetal sedation was required for coherent images. Ultrafast MRI sequences, however, have proven efficacious at suppressing fetal motion artifacts, and they do not require sedation. In early studies, no statistically significant difference between sonography and ultrafast MRI was found for the detection of abnormality in any organ system. One study asserts that on occasion, ultrafast MRI was demonstrably superior to sonography in characterizing cerebral abnormalities.3 Most clinicians, however, still agree that MRI should be limited to clinical situations in which ultrasound findings are ambiguous or impaired.

Relative to ultrasound, MRI has some drawbacks secondary to its recent introduction as an antenatal diagnostic tool. The American College of Obstetrics and Gynecology (ACOG)4 recommends against using MRI in early stages of pregnancy, namely the first trimester, unless specifically indicated. Therefore, fetal MRI usually is performed after 17 gestational weeks (GWs) have passed, ensuring the completion of major organogenesis.5 The diagnostic window is narrowed further by logistical concerns; in the United States, termination of pregnancy is illegal after 24 GWs,6 and in addition, most clinics prefer to perform abortions earlier than 22 weeks, because viability is estimated to drop off to 15% in births earlier than 24 GWs.7

Fig. 1. 28 + 3 gestational weeks sagittal (A) and coronal (B) steady-state free precession sequence. Coronal thick-slab T2-weighted sequence (C), and T1 weighted sagittal z-projection (D): sacrococcygeal teratoma with extra- and intracorporal cystic part. T1 weighted hypointensity of the meconium-filled rectum shows compression and displacement of this part of the large bowels.
As a small number of animal studies have suggested a possibility of teratogenic effects, the safety of higher field strengths (more than 1.5 T) at earlier stages of pregnancy is not clear. Still, when MRI has been used as diagnostic imaging tool after 18 GWs, no ill effects have been reported so far. For example, it has been reported that MRI does not demonstrate effects on fetal heart rate patterns, an important marker of fetal health close to term. In short, most human studies assessing the risk of MRI suggest that there are no ill effects to the mother or fetus.

A PubMed literature search of “magnetic resonance imaging fetus” limited to human studies in core clinical journals in the last 10 years, reveals subtle trends in cohorts and in the fetal MRI studies performed. For example, fetal MRI cohort sizes have been growing (Fig. 2), ostensibly in response to the need for reliable MRI standards, especially compared with the massive numbers of ultrasound studies that form the basis of ultrasound morphometric and clinical reference standards. Also of note is the increase in organ systems studied during the same period. Imaging studies of the fetal central nervous system (CNS) always have comprised a significant part of fetal MRI, but in the last 10 years, other fetal organs and organ systems, such as the lung and abdomen, and most recently the heart, have grown in prominence in publications. These trends reflect the growing number of indications for fetal MRI.

RECENT ADVANCES IN FETAL CENTRAL NERVOUS SYSTEM MRI

Cerebral anomalies account for approximately 9% of all isolated anomalies and manifest in 15.9% of multiple malformations, constituting a major impetus for prenatal diagnosis. Of all organ systems in the developing fetus, studies of the developing CNS have benefited most from the image quality and detail that MRI provides. The high resolution of imaging in MRI can identify the critical but extremely small and subtle changes in CNS landmarks, especially at early gestational ages (GA). These changes can manifest in gross MRI morphology, the brain microarchitecture, or the activity of the fetus when assessed in a dynamic sequence. Therefore, MRI has been useful in three regards: (1) the quantification of brain growth and structural

![Fig. 2. Increases in cohort size of fetal magnetic resonance central nervous system studies as a function of date.](image-url)
abnormalities using biometry, (2) the qualitative evaluation of CNS microstructure, and (3) the qualitative assessment of dynamic fetal movements in utero.

Quantification of Brain Growth and Brain Pathology

As an objective method of assessing fetal growth, the clinical implications of morphometric evaluation cannot be underestimated. Willocks and colleagues can be regarded as the pioneers in the field of fetal cephalometry. They introduced the quantification of fetal brain growth by standardized parameters, such as the commonly used biparietal diameter. Since then and to this end, ultrasound parameters were re-evaluated repeatedly, and have been used clinically for decades to evaluate fetal brain or skull structures. They remain the standard screen for normal morphology.

Existing postmortem histologic measurements can help validate standardized measurements of fetal brain parameters for MRI, but with some significant limitations. Correlative studies are subject to postmortem changes in the tissue architecture, both microscopic (e.g., autolysis) and macroscopic (e.g., collapse of ventricular spaces). Dying fetuses tend to bleed in the germinal zone, and thereby provide a dimension of error. The postnatal environment can collapse or distort cerebrospinal fluid (CSF) spaces. Edema makes initial measurements inaccurate and technically challenging. When the brain is fixed postmortem, shrinkage of the tissue is quite pronounced. Because of the high water content of the immature brain, volumetric measurements may be reduced to as much as 70% of their prefixed state, affecting linear dimensions. Despite these setbacks, however, MRI has made a significant impact on the morphometry of structures in the fetal CNS in recent years. This is supported by multiple studies, as detailed next. One study examined the effect of MRI on changes in diagnosis and clinical management of fetuses suspected of having CNS anomalies with ultrasound. In 31.7% (46 of 145) of fetuses with abnormal ultrasound findings, MRI findings changed the diagnosis. Additionally, they found their results were GA-dependent. The mean GA of the 46 fetuses with changes in diagnosis (26.3 weeks) was significantly greater than that of the 99 fetuses with no major change in diagnosis (23.3 weeks, \( P < .01 \)). This finding may suggest that the pathology becomes more apparent with age in both ultrasound and MRI, but does not refute that MRI is a powerful diagnostic adjunct to ultrasound, particularly in earlier weeks, when it would appear that ultrasound is less sensitive. Further contribution of MRI to prenatal CNS assessment is reflected in its diagnostic utility in the evaluation of ventriculomegaly in utero.

A large university study examined 167 cases of isolated mild ventriculomegaly (IMV) (i.e., unilateral or bilateral ventriculomegaly with no associated anomaly at time of diagnosis). In this study, IMV was diagnosed around 26.5 GWs. In addition to associated anomalies, MRI studies identified three criteria that were associated with an unfavorable outcome: atrial width greater than 12 mm, progressive ventricular enlargement, and asymmetrical and bilateral ventriculomegaly (Fig. 3).

Extensive MR templates of gyration and sulcation of the developing fetal brain have been researched, best seen in an extensive 2004 study of both normal and pathologic fetal brains in utero. This study assessed data only after GW 22. Additionally, the standard parameters in 22 to 25 GWs in the previous literature were derived from a very small number of cases. As aforementioned, standardized measurements of brain parameters in fetuses less than 25 GWs previously were extrapolated from ultrasound and histologic measurements. Thus, the MRI morphometry in less than 24 weeks had been significantly lacking until further exploration of fetal brain parameters from 18 to 25 GWs was undertaken recently.

Measurements of fetal brain parameters before 24 GWs present some specific imaging difficulties. The structures themselves are very small. For example, between
18 and 24 GWs, the width of the third ventricle can range from 2 to 3 mm, and the length of the corpus callosum can range between 12 and 18 mm. Additionally, the plane of acquisition can be very sensitive to rotation, and certain structures, because of their size, may be subject to high error due to changes in the plane alone.

As technology has enabled thinner and thinner slices (2 mm generally is considered the lower end of slice thickness range), reassessment of the definition of the parameters is important. The fronto-occipital diameter (FOD) used to be a standard measurement in the sagittal midline of the fetal brain that measured the longest distance between the occipital and frontal lobe poles. As the slices have become thinner, a perfectly midline sagittal slice can avoid the frontal and occipital lobes completely, remaining instead mostly within the interhemispheric fissure (Fig. 4). Therefore, this study suggested that FOD—an important parameter to assess fetal CNS health—might be measured axially, in a plane perpendicular to the brain stem that reflects the longest length between frontal and occipital poles (Fig. 5).

This study \(^{18}\) evaluated the same brain parameters as Garel's study \(^{17}\), but focused on GA between 18 and 25 GWs with a much larger study sample. Additionally, it

Fig. 3. 36 + 6 gestational weeks; axial (A) steady-state free precession sequence, corresponding axial T1 weighted sequence (B), and coronal T2 weighted (C) and T1 weighted (D) sequences depicting blood degradation products in a fetus with an intraventricular hemorrhage. In this case, the etiology of bilateral ventriculomegaly could be explained by obstructions of the Foramen of Monro and at the level of the aqueduct.

Fig. 4. 24 + 3 gestational weeks; sagittal T2 weighted midline plane exhibiting measurement of corpus callosum in oligohydramnios. Note that a midline sagittal slice does not capture the frontal and occipital poles completely.
re-evaluated the morphometric definition of certain brain parameters, such as the aforementioned FOD, to take advantage of recent advances in technology and thinner slices. Many parenchymal brain parameter measurements, such as the length of the corpus callosum (Fig. 6), cranial and bone biparietal diameter, and the transverse cerebral diameter, were found to have a linear rate of growth through the period 18 to 25 GWs, a rate of growth consistent with the trends seen in earlier studies. These previous studies corroborated the trends, although they themselves did not attempt to set down standardized measurements for each GW.

Some structures, like the corpus callosum (see Fig. 4), are easy to define and measure. Their morphology is such that its measurement is not sensitive to variations

![Fig. 5. 22 + 4 gestational weeks; T2 weighted axial plane in which the lateral ventricles are largest. Anteroposterior interopercular distance (APIPD) customarily is measured between the most extreme anterior and posterior edges of the Sylvian fissure (measuring 56.52 mm and 57.16 mm). Note that the right APIPD (measuring 23.20 mm) is significantly greater than the left (17.75 mm). In this plane, fronto-occipital diameter also can be measured between the extreme poles of the frontal and occipital lobes.](image)

![Fig. 6. Measurement of corpus callosum from gestational weeks 19 to 25.](image)
in the acquisition plane, and their regular trends reflected this. Generally speaking, the clinical morphometric definition must be easy for practitioners to use, yet also reflect the expected trends in growth for clinical use. Some structures in the CNS, however, can be difficult to define for repeated weekly measurements by clinicians for a few reasons. The structures can change drastically between GWs. For example, the shape and axis of the lateral ventricles change quite dramatically over the course of brain development, from large rounded spaces until approximately 24 GWs, to thin angled slits nearing term.

In the aforementioned study, it was found that certain brain parameters could be assessed better volumetrically. Measurements of brain spaces, such as diameter of the lateral ventricles, diameters of the third and fourth ventricles, and the interhemicpallamic diameter, were found to show high intrasample variability (Fig. 7). This, too, reflected the variability found within earlier studies. This variability in nonparenchymal brain measurements could be attributed to two factors. First, the high error of measuring such small structures contributes significantly, being comprised of smaller intrinsic errors. These errors include motion artifacts, error intrinsic to the pulse sequences, slice thickness, and screen pixels (in-plane resolution of 0.7 mm results in an inaccuracy of up to 10% of a structure with a length of 7 mm). But secondly, the variability in measurements may reflect the three-dimensional variability of spaces, and suggest that volumetric measurement may be superior. The lateral ventricles, for example, varied significantly in diameter as slices progressed through the brain in all three orthogonal planes. So although the trend in Fig. 7 is linear for the average width of the lateral ventricles, high variability also is found to be present.

A parameter that shows this much variability reflects the difficulty in defining the parameter itself, or reflects the variability between fetuses at the exact same location. Difficulties with the lateral ventricles may not be limited to those measurements made earlier than 24 GWs. Another study compared contemporaneous ultrasound and three-dimensional MRI reconstructions in uncomplicated nulliparous term (37 to 40 GWs) pregnancies. This study showed acceptable correlation between both

![Width of lateral ventricle (right)](image)

**Width of lateral ventricle (right)**

- **Average**
- **Maximum**
- **Minimum**

**Fig. 7.** Measurement of width of right lateral ventricles from gestational weeks 19 to 25.
modalities for head circumference, abdominal circumference, and biparietal diameter, but poor correlation with ultrasound for both right and left ventricular atrial diameters. Regardless of the source of error, the data suggest that simple two-dimensional measurements of spaces in the developing fetal brain may not be as reliable as three-dimensional volumetric analysis and that further exploration of three-dimensional volumetrics may prove that it is a more dependable way to achieve nonparenchymal measurements. Fetal brain volumetry has been validated further with a study examining 50 consecutive fetuses at 17 to 37 weeks of GA referred for MRI for ventriculomegaly. As suggested by the previous data, lateral ventricular volumes (and the supratentorial parenchyma) were deemed to be reliably measured with fetal brain volumetry. Inter- and intraobserver variability were low, and the effect of the imaging plane was considered negligible.

Volumetric analysis of the parenchyma also may prove to have clinical applications. Fetal brain volumetry additionally was used to study fetal posterior fossa volume (PFV). The study suggested that fetal PFV could be a measurable parameter for second and third trimester fetuses with anomalies that manifest in the posterior fossa, such as Chiari II and Dandy-Walker. The standard two-dimensional ultrasound transverse cerebellar diameters cannot quantify PFV and are only an indirect measure of the fossa size. In the study, the authors found that the relationship between PFV (in cubic centimeters) and EGA (estimated gestational age in weeks) was described well by a single exponential function (PFV = 0.689 \exp [EGA/9.10]), and may prove to be another parameter with clinical application. Volumetric measurements, however, do present some difficulties and inefficiencies that must be overcome to be clinically useful and accessible. Difficulties with partial volume averaging, given the slice thickness at early GAs, add another dimension of error. Additionally, volumetric measurements take longer to process than a normal two-dimensional measurement, a single plane taking as long as 19 minutes in this study. Although this time may be adequately short for particular cases that require attention, it may not be sufficiently quick to screen fetal health (eg, for ventriculomegaly). Therefore, certain advances in the computer programs may be necessary before fetal brain volumetry can be implemented effectively.

The discussion of fetal brain morphometry should include recent work on hemispheric asymmetry. Aside from the problem of interindividual variability in brain structure and in brain growth dynamics, significant hemispheric asymmetry already exists at early stages of fetal development. The degree of fetal brain asymmetry depends on the actual developmental stage and on the brain region examined. After the initial descriptions of hemispheric asymmetry in the adult brain by Geschwind and Levitsky, postmortem studies of fetal brains reported an asymmetrical development of sulci and gyri most pronounced at the end of the second trimester and in the perisylvian cortex regions. An ultrasound study revealed significant hemispheric differences in ventricular size in a series of fetuses with normal neurodevelopmental outcome. Ongoing analysis of fetal brain asymmetry moreover has revealed size differences between the right and left fetal temporal lobes. This hemispheric asymmetry was corroborated further in the 2008 study of fetal brains between 19 and 25 GWs, as the measured right anteroposterior interopercular distances (APIPD) were consistently larger than the left between 19 and 25 GWs (see Fig. 5). Advanced computerized fetal MRI and shape analysis is currently performed to assess and quantify the degree of fetal brain asymmetry in vivo. These data require corroboration but raise intriguing questions; it is likely that the normal and potentially abnormal development of lateralization in the human brain will provide important insights into neurodevelopmental outcome.
Qualitative Assessment of Fetal Brain Parenchyma and Microstructure

MRI’s ability to assess fetal brain microstructure has proven to be a significant diagnostic advantage for cases in which abnormalities of the underlying tissue architecture are important. The underlying architecture of fetal brain tissue does not display enough impedance differences to be identified with ultrasound.\textsuperscript{5} Therefore, qualitative assessment of the fetal brain microstructure has depended upon histology, and more recently on MRI.

A review in 2006\textsuperscript{26} correlated histologic and MRI findings of the transient cerebral zones that manifest during different GWs. The studies assessed in the review further validate the clinical utility of the visually detailed imaging found in MRI, stating that transient zones in the fetal brain parenchyma can be seen in MRI as early as 10 GWs. In addition, several histologically correlated transient features in earlier studies are possible to detect that previously had gone unnoticed (Fig. 8), suggesting that the capabilities of MRI to assess fetal brain microstructure have not been exhausted. Although Fig. 8 only shows three distinct neuroarchitectural laminae in an in vivo fetus, in vitro MRI studies\textsuperscript{26} have shown that it is theoretically possible for MRI to detect the seven neuroarchitectural laminae demonstrated histologically between 17 and 28 GWs.

Diffusion Tensor Imaging and Tractography

An important and promising development in the field of diagnostic fetal MRI is diffusion tensor imaging (DTI) and tractography. DTI makes use of diffusion weighted imaging (DWI) technology. Anisotropic (hindered) and isotropic (nonhindered) diffusion of protons generate the image contrast in DWI. In addition, DWI has high diagnostic sensitivity for identifying acute hypoxic ischemic fetal brain lesions.\textsuperscript{5} The technology used in DWI has been used to evaluate in utero normal and pathologic brain tissue architecture in two dimensions.

Fig. 8. The fetal brain parenchyma is well organized and shows three transient neuroarchitectural zones in (A) axial T2 weighted and (B) diffusion weighted images of a fetus with atypical holoprosencephaly at 24 GW. The outermost layer is the cortical plate, which is hypointense in T2 weighted images, and hyperintense in diffusion weighted images. The subplate is the middle layer, and it has signals opposite from the cortical plate (hyperintense in T2 weighted, hypointense in diffusion weighted). The innermost third layer is the ventricular/subventricular zone with ganglionic eminences, and it has the same signals as the cortical plate.
Taking DWI a step further, DTI uses different electromagnetic field gradients to measure the anisotropy and directionality of Brownian motion in more than six orientations. The degree of anisotropic diffusion depends on the microstructural composition of a certain tissue. Anisotropy is increased when diffusion is hindered by microstructural obstacles, such as cell membranes and organelles, myelin, or axonal elements. This allows a noninvasive characterization of a certain tissue component and the three-dimensional reconstruction of the tissue microstructure such as the architecture of the developing fetal brain. In the postmortem and laboratory setting, high-resolution DTI already has been applied in embryonic and fetal brains. Correlation with histology proved that high-resolution postmortem DTI is able to visualize even subtle structures of the fetal brain.

Currently, the greatest challenge in translating postmortem DTI for use in in vivo fetal MRI is the persistent occurrence of fetal and maternal motion. After sequence optimization (greater slice thickness, lower resolution), however, and by the use of acceleration factors, it is possible to acquire in utero DTI data that can be postprocessed further. As a recent study shows, this technique allows the visualization of corticospinal and callosal pathways in 40% of the examined cases. Especially in situations where fetal motion typically is restricted (cephalic presentation, premature rupture of membranes, advanced GA), these major pathways of the fetal brain may be depicted successfully (Fig. 9). This study also provided further evidence for the asymmetrical development of the human brain in utero. Fractional anisotropy (FA) and axial \( \lambda_1 \) and transverse \( \lambda_2, \lambda_3 \) eigenvalues are diffusion parameters used to assess the microstructure and maturity of specific white matter regions. This study reported that higher FA and \( \lambda_1 \) of the right sensorimotor pathway structures led to significant differences in the length of the right and left corticospinal and thalamocortical connectivity, further supporting asymmetrical maturation of fetal white matter.

Ultrasound does not have the capability to evaluate the evolution and development of fetal white matter. Thus, DTI may further underscore the importance of fetal MRI in the in vivo examination of fetal brain parenchyma and contribute an additional dimension of antenatal imaging. Further technical improvements and a more liberal use of sedation in cases with pending severe brain abnormalities may establish DTI as part

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**Fig. 9.** In utero diffusion tensor imaging and tractography at 37 + 6 gestational weeks: two-dimensional projection of the trajectories of the genu and splenium of the corpus callosum (A) and three-dimensional appearance of the bilateral corticospinal tracts and the corpus callosum (B).
of the standard sequence repertoire in the MRI assessment of normal and abnormal fetal brain morphology and function.

Assessment of Fetal Dynamic States: Function and Movement

Early in the second trimester, cortical folding patterns have not yet emerged in the fetal brain, and quantitative morphometry alone can prove insufficient. MRI dynamic sequences investigate qualitative dimensions of fetal health, namely, the assessment of general movements and movement abnormalities that often are found in cases of brainstem pathologies.

As fetal MRI usually is performed after 17 GWs, earlier patterns of activity such as startles, well documented in ultrasound studies, are seen only rarely. From 18 GWs onwards, general movements and primitive reflexes, as well as small intrinsic movements (eg, those involving the diaphragm, eyes, and tongue) and details of general movements (eg, those involving the hands and fingers) may be observed. Seizures may be identified during the study. Dynamic studies presenting repeatedly abnormal movement patterns can be correlated with structural morphologic findings to confirm a suspected diagnosis. A 2006 study using cine MRI (this study’s term for dynamic studies) and two-dimensional fast imaging employing steady-state acquisition (FIESTA) MRI reached the following conclusions. The implementation of parallel imaging with two-dimensional FIESTA has obviated fetal motion as a limitation for prenatal imaging, and cine MRI can illustrate fetal motion with high clinical reliability. The information provided by cine MRI can give critical information for postnatal prognosis, especially in the case of severe CNS abnormalities.

Currently, it is not clear whether fetal behavioral patterns result from the expression of certain genes, or if epigenetic factors (eg, the intrauterine environment) influence fetal activity and lead to individual postnatal variations of movement patterns. Of note, a complete absence of movement during the 30- to 45-minute MRI examination does not assure fetal pathology. Only in the case of abnormally fixed fetal posture (usually characterized by carpopedal positioning of the hands and clubfeet) can a diagnosis of akinesia be made.

In short, dynamic sequences manage to give three-dimensional information about the fetus by displaying two-dimensional images in real time. Watching a fetus move in utero provides much information regarding the neurologic and musculoskeletal function of the fetus, and thereby supplies prognostic information.

ADVANCES IN MRI ASSESSMENT OF PLACENTAL STRUCTURE

Given the dependence on normal placental transfer of oxygen and energy substrate, the ability to assess placental structure and function using MRI would constitute a major advance. The placenta is vascularized heavily, and utero-placental infarction is a significant risk factor for interuterine growth restriction. Determination of an intact placenta and sufficient utero-placental circulation is an essential component of every antenatal examination. The placenta goes through morphologic changes during gestation, well documented with ultrasound imaging and Doppler ultrasound. Ultrasound studies remain the primary imaging modality for macroscopic abnormalities, but MRI can serve as an adjunct modality for antenatal examinations that are difficult to visualize secondary to disorders or disadvantageous anatomic structures or alignment of the mother or fetus.

One study of 100 normal singleton pregnancies examined the placentas to determine an MRI standard of reference, and was able to confirm the clear morphologic changes documented by ultrasound. That said, adverse fetal positions
and certain antepartum pathologies (e.g., oligohydramnios and obesity) can limit ultrasound image resolution of the placenta. In cases like these, where ultrasound cannot give a clear diagnosis, MRI is an excellent adjunct imaging modality. In addition, MRI findings have been correlated well with histology. A retrospective study\textsuperscript{34} examined 45 singleton pregnancies from 19 to 35 GWs with placental pathologies on MRI scans. Placental hemorrhages (retroplacental hematoma, intervillous thrombi, subchorionic hematoma) and ischemic lesions were visualized with fetal MRI (Fig. 11).

**Fig. 10.** Steady-state free precession sequence of a placenta at 20 + 1 gestational weeks (GWs) with regular homogenous signals (A). At 33 GWs (B), the signal characteristics are physiological rather inhomogeneous, showing delineable placentomes.

**Fig. 11.** Echoplanar sequence of a placenta with subchorionic hematoma (black arrowhead, hypointense signals on the placental surface) at 19 gestational weeks.
Chorioamnionitis and perivillous fibrin deposition, however, showed few signal changes, which likely reflected small changes in the placenta. The study concluded that fetal MRI could be a promising tool for assessing placental insufficiency.

**SUMMARY: THE FUTURE**

Relative to other imaging modalities, fetal MRI remains in the early stages of evolution. Certain anatomically defined parameters that have been established for decades in ultrasound and postmortem histology are still being defined to satisfaction in MRI, even as advances in technology (increases in field strength, new pulse sequences) continue. The advantages of MRI include its notable soft tissue detail, high spatial resolution, planar capabilities, and large field of view. Evidence accumulates from in vivo human studies that MRI does not contribute to fetal anomalies and disorders, but fetal MRI still is used sparingly. As MRI becomes less costly, and the acquisition time of images decreases, expanding the use of fetal MRI clinically may be appropriate. Three categories in fetal MRI warrant further exploration to expand on current fetal assessment: volumetric measurement, DTI and tractography, and motion degradation technology.

**Volumetric Measurements**

Currently, volumetric measurements have proven too expensive and time-intensive for everyday screening and diagnostic measurements. Regarding the CNS, two-dimensional ventricular space measurements in early GWs are unreliable diagnostic parameters because of their highly variable nature and inherent error. Further research is warranted to verify three-dimensional and volumetric measurements and to further streamline the process, because early diagnosis of ventricular pathology (eg, hydrocephalus) has such significant clinical implications that two-dimensional measurements in both ultrasound and MRI do not suffice. Three-dimensional reconstruction of fetal brains may not be feasible as everyday clinical adjuncts today, but as the algorithms advance, this method likely will prove an exceptional means of morphometric analysis.

**Diffusion Tensor Imaging and Tractography**

Although in its very early stages, DTI and tractography deserve further exploration. The noninvasive characterization of CNS tissue and the three-dimensional reconstruction of the tissue architecture may lead to identification of the most subtle structures and pathologies of the fetal brain. DTI and tractography currently are used only in postmortem and laboratory settings, but their application in fetal brain pathology has been corroborated by histology. This imaging technique will benefit from technological advances that reduce fetal motion in MRI.

**Motion Degradation Technology**

High-quality MRI depends on a minimization of motion. One study has evaluated the use of snapshot MRI with volume reconstruction and reported a higher signal-to-noise ratio. This technology images the target volume repeatedly and uses a slice-to-volume registration method that achieves alignment of each slice within 0.3 mm. Fetal MRI has a particular interest in this minimization, as sedation of fetuses currently is avoided. Follow-up studies in these areas will contribute to prenatal diagnosis, in hopes of further discerning postnatal neurodevelopmental consequences. In doing so, one can elucidate further the complex interactions between nature and nurture in shaping the human brain, mind, and behavior.
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