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ADVANCES IN CLINICAL RADIOLOGY

Fetal Neuroimaging

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KEYWORDS
• Fetal neuroimaging • Malformation • Disruption • Destruction • Functional sequences • Syndromes

KEY POINTS
- Fetal MRI of the brain allows detailed evaluation of anomalies of the fetal central nervous system, in particular neuronal migration, sulcation, and various maturational processes.
- Fetal MRI progressively serves as a preoperative imaging tool for fetal surgery, especially for spinal dysgraphia.
- Fetal anomalies may involve multiple anatomic structures; a comprehensive review of the entire fetus is essential.
- Translation of postnatally well-established functional MRI sequences into fetal imaging will further enhance the significance of fetal neuroimaging.

INTRODUCTION

Over the past 20 years, many original reports and review articles have been published on fetal MRI. Many of these have evaluated the diagnostic sensitivity and specificity of fetal MRI, often in comparison with prenatal ultrasonography. Some of them have primarily focused on listing and describing the characteristic imaging findings of widely accepted indications for fetal MRI following a systematic case- and category-based approach [1–11]. This article will take a somewhat different approach, focusing on and discussing the unique features and value of fetal MRI with respect to obstetric management, concepts of disruption versus malformation versus destruction, understanding of combined/interacting multilevel malformations, significance of a comprehensive evaluation of the entire feto-maternal unit, value of functional, objective imaging scalars for evaluation of brain maturation, necessity of follow-up imaging, and the value of the uterus as a kind of maternal incubator. This discussion will offer the author's accumulated experience of 25 years of fetal MRI focusing on multiple practical and important conceptual aspects of fetal MRI that are only infrequently presented in the literature in a systematic fashion.

SIGNIFICANCE

Initially, fetal MRI focused primarily on the diagnosis of abnormalities of the fetal central nervous system (CNS).Later the use of fetal MRI was expanded to multiple cardiothoracic (eg, congenital high airway obstruction [CHAOS], esophageal atresia) and abdominal indications (eg, congenital diaphragmatic hernia, omphalocele). The value of fetal MRI, however, is especially evident for CNS abnormalities. Fetal MRI adds diagnostic accuracy and confidence for fetal brain malformations compared with prenatal ultrasound. A recent prospective multicenter cohort study focusing on the diagnosis of fetal brain abnormalities concluded that if fetal MRI is added to prenatal ultrasound, overall diagnostic accuracy increases by 23% for fetuses between 18 and 24 weeks gestational age, while a 29% increase in diagnostic confidence is seen for fetuses 24 weeks and older [8]. This typically impacts patient counseling and/or management, especially for fetuses suspected of brain abnormalities. Fetal MRI of the CNS may be used to confirm, correct, or complete prenatal ultrasound findings. In addition, fetal MRI may guide mode and timing of delivery as well as pre-, peri- and postnatal care.

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ANATOMIC AND ADVANCED FETAL MAGNETIC RESONANCE IMAGING SEQUENCES

The ultrafast, single-shot T2-weighted fetal MRI sequence has proven to be a perfect match for the developing fetal brain. Consequently T2-weighted imaging serves as the backbone of fetal MRI. The signal-to-noise ratio and contrast-to-noise ratio allow one to study the various anatomic structures with ease, consequently allowing one to study multiple developmental processes that are difficult to evaluate in detail by prenatal ultrasonography, such as neuronal migration, white matter myelination, sulcation, and commiseration. Ongoing hardware and software developments have added a plethora of functional imaging techniques that now complement anatomic fetal MRI. These new functional developments may provide objective metrics/scalars to further improve the diagnostic accuracy and specificity of fetal MRI.

Diffusion weighted and diffusion tensor imaging are being used to collect objective quantitative scalars of brain development, allowing for comparison of abnormal brains to normative data. Furthermore, next to the objective diffusion scalars, fiber tractography may be used to better study the internal neuroarchitecture of complex brain malformations. For example, Joubert syndrome, a postnatally well-explored essential ciliopathy characterized by a molar tooth appearance of the malformed brainstem is lacking the classic red dot of crossing white matter tracts of the middle cerebellar peduncle. Fetal diffusion tensor imaging may reveal these aberrant fiber courses, solidifying the accurate prenatal diagnosis of a fetus with Joubert syndrome. Tractography has also been used to explore more apparent brain malformations like a corpus callosum agenesis, diffusion tensor imaging/tractography may help to differentiate between partial or complete corpus callosum agenesis, syntencephaly, or fused brains as part of the holoprosencephaly spectrum.

^{1}H-magnetic resonance spectroscopy (MRS) remains challenging, but in advanced pregnancy the progressive locking-in of the fetal head in the maternal pelvis allows for collection of reliable MRS data. Early and reliable recognition of inborn errors of metabolism may prevent irreversible injury to the newborn brain by the progressive accumulation of toxic metabolites within the first days after delivery. Several inborn errors of metabolism may be suspected based upon an unfavorable outcome of previous pregnancies, unexplained sudden deaths of a newborn after a symptom-free early postnatal time period, or in case of a positive family history. The toxic metabolites may be discovered by fetal MRS, initiating an early and aggressive treatment after delivery to prevent deleterious accumulation of toxic metabolites.

Compared with prenatal ultrasound, fetal MRI has proven especially helpful in the evaluation of cortical development, neuronal migration, and white matter maturation. The developing overlying skull typically limits the diagnostic accuracy of prenatal ultrasound. Acoustic shadowing may obscure subtle, but clinically important disorders of cortical development. In addition, white matter hypo/dysmyelination may suggest various inborn errors of metabolism such as Zellweger syndrome.

Brain pathologies are often complex and may involve multiple developmental processes. An incomplete recognition of the pathology may result in an incorrect or inaccurate estimation of prognosis. For example, an isolated corpus callosum agenesis has a much better functional/cognitive prognosis compared to a fetus with a corpus callosum hypo/agenesis as part of an Aicardi syndrome. The additional findings that make the final prenatal diagnosis may be subtle during early pregnancy and may consequently be missed by prenatal ultrasound.

FETO-MATERNAL UNIT

Fetal MRI should include a detailed evaluation of the entire feto-maternal unit. This should include the fetus from head to toe, the umbilical cord, amniotic fluid, placenta, uterus, and maternal pelvis. Fetal abnormalities may be isolated involving only one anatomic structure or a single developmental process. In complex cases, multiple anatomic structures may be affected simultaneously. Identifying the complete fetal abnormality will facilitate diagnosis, determine fetal care, and allow for better parent counseling. A subtle focal lesion within the brain may be overlooked (eg, a subcortical tuber or subependymal nodules in tuberous sclerosis complex); however, evaluating the entire fetus allows for the identification of more readily identifiable lesions outside of the CNS, such as a cardiac rhabdomyomas and renal angiolipomas, which aid in making the correct final diagnosis. Consequently, it is the opinion of the author that fetal MRI specialists should aim to combine the expertise of a neuroradiologist and a body radiologist, either by a dedicated multisystem fetal training, a combined pediatric body and neuroradiology training, or by having the study evaluated by a team of experts. The brain should not be evaluated in isolation (Fig. 1).

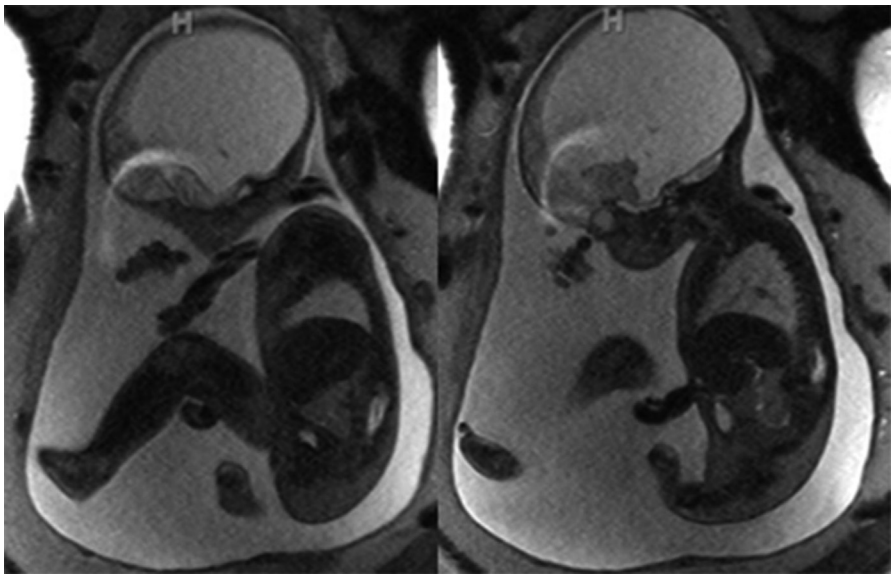

FIG. 1 Sagittal T2-weighted MR images of a fetus with high-grade supratentorial hydrocephalus secondary to an aqueductal stenosis. This case illustrates that the entire fetus should be evaluated. Next to the obvious CNS abnormality, 1 leg is severely hypoplastic/deformed. The contralateral leg was unremarkable.

A comprehensive evaluation should also include the amount and quality of amniotic fluid. An oligohydramnios suggests fetal renal failure (Fig. 2). This may be secondary to isolated renal agenesis or may be part of a syndrome such as Meckel Gruber syndrome (Fig. 3), which is characterized by a combination of an occipital encephalocele, bilateral polycystic kidneys, and hypoplastic/small lungs. Polyhydramnios may be secondary to an obstruction of the gastrointestinal (GI) tract as seen in esophageal atresia, but may also result from a neck teratoma or lymphatic malformation (Fig. 4) obstructing the upper GI tract.

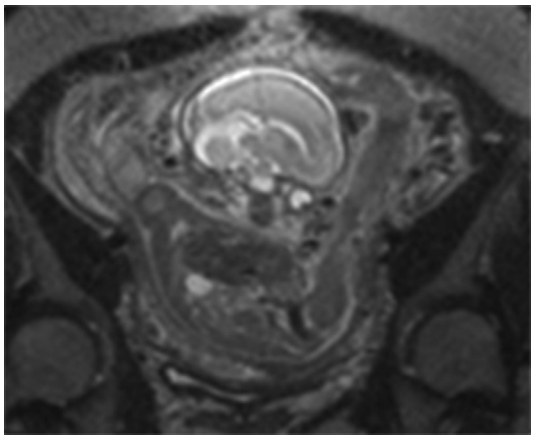

FIG. 2 Sagittal T2-weighted MRI of a fetus with bilateral renal agenesis. No amniotic fluid is noted outlining the fetus. The lungs are hypoplastic and appear T2-hypointense; the lower extremities are angled upwards in front of the fetus, and the facial skeleton is hypoplastic compatible with a Potter sequence.

The umbilical cord and placenta should also be carefully analyzed. An anomalous number of umbilical cord vessels, in particular a 2-vessel umbilical cord (Fig. 5), is linked to a higher incidence of fetal abnormalities. A herniating umbilical cord, a villamentous insertion, a nuchal cord (Fig. 6), an umbilical cord knot, and an umbilical cord varix also increase the risk of fetal abnormalities or complications toward the end of pregnancy or delivery.

Furthermore, uterine malformations or pathologies may increase the risk for fetal injuries during pregnancy or delivery. The uterus should be studied for anatomic variants, including a bicornuate or septated uterus (see Fig. 6), which may impact fetal presentation (eg, breech position) and consequently negatively impact delivery. Uterine myomas/fibroids (Fig. 7) can increase the risk for premature contractions or mimic or induce catastrophic uterine ruptures.

Finally, evaluating the maternal structures that are included in the field of view may show important, surprising findings. For example, if the fetus is suspected

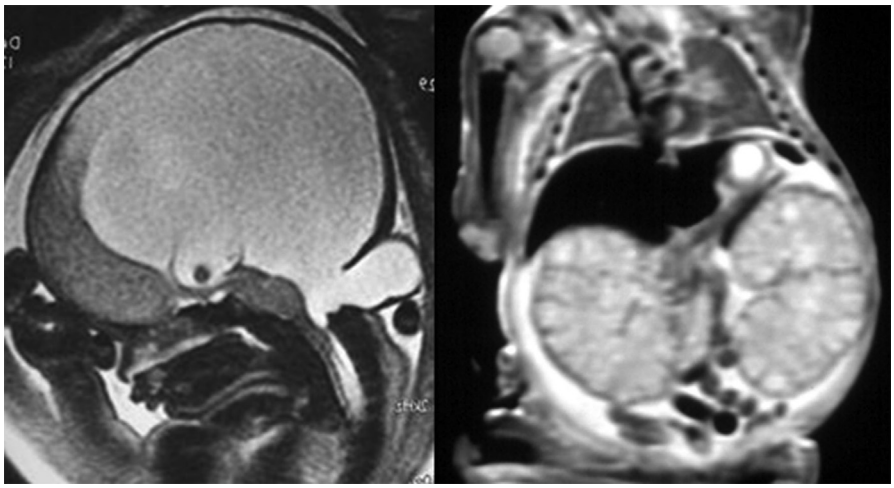

FIG. 3 Sagittal T2-weighted MR images of a fetus with Meckel Gruber syndrome. A moderate-sized midline occipital meningo-encephalocele is seen with simultaneous anterior displacement and compression of the brainstem. Furthermore a high-grade supratentorial hydrocephalus is noted. Postmortem MRI reveals the additional findings typically noted in Meckel Gruber syndrome, which include bilateral pulmonary hypoplasia related to oligohydramnios secondary to bilateral cystic renal dysplasia. Final diagnosis is established by identifying the combination of CNS and extra-CNS anomalies.

for tuberous sclerosis complex, evaluation of the maternal kidneys may show renal angiolipomas and cysts, supporting the final diagnosis of this inherited neurologic disease (Fig. 8). In addition, important incidental maternal findings may be seen including an obstructed kidney, a focal ovarian lesion (eg, teratomas, malignancies) (Fig. 9), or inflammatory bowel disease or appendicitis.

In summary, if an intracranial fetal abnormality is suspected, the remainder of the fetus or, even better,

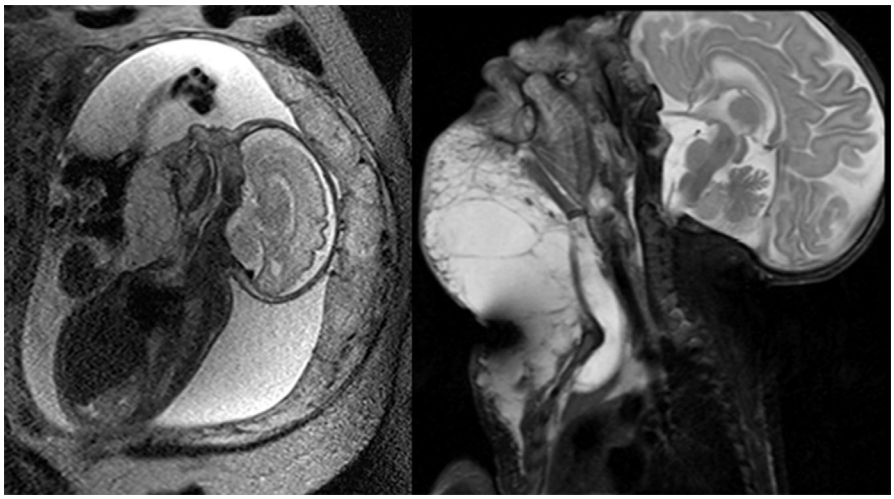

FIG. 4 Sagittal pre- and postnatal T2-weighted MR images of a fetus with a large neck region lymphatic malformation. The malformation is extending from the neck into the upper mediastinum with compression of the trachea and esophagus resulting in a polyhydramnios and mild pulmonary hypoplasia. The polyhydramnios is a leading imaging sign for an upper GI obstruction.

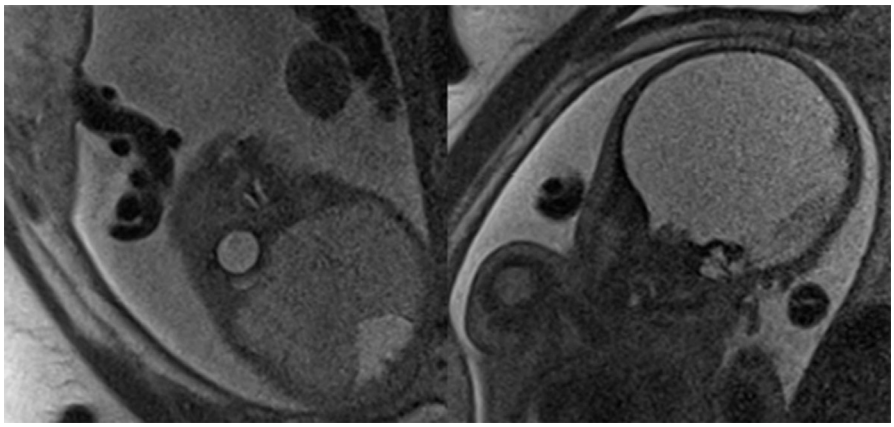

FIG. 5 Coronal T2-weighted MR images of a fetus with a severe and complex brain malformation. The umbilical cord is anomalous with only 2 vessels. A 2-vessel umbilical cord is linked to an increased incidence of fetal anomalies and should always be studied.

the entire feto-maternal unit, should receive the same attention as the central nervous system.

SIGNIFICANCE OF SERIAL OR FOLLOW-UP FETAL MRI EXAMINATIONS

One of the major advantages of prenatal ultrasound is the ease of performing serial follow-up examinations for suspected fetal pathologies. If a pathology is suspected, a follow-up examination may benefit from the increasing fetal size, possible more collaborative phases of relative fetal immobility secondary to progressive engagement of the fetal head within the maternal pelvis, and a more image favorable relative size of the fetus to the amount of amniotic fluid.

In addition, multiple fetal brain abnormalities may become more apparent secondary to progressive maturation of the pathology. For example, a TORCH infection (Fig. 10) typically impacts many aspects of fetal brain maturation, and the interference with the migration of precursor cells from the germinal matrix to the cortical ribbon typically becomes more apparent later during pregnancy. In addition, the impact of migrational abnormalities to the tightly linked subsequent processes of sulcation, myelination, and commissuration benefit from a dynamic imaging approach with follow-up imaging. Consequently similar to serial prenatal ultrasound examination, follow-up/serial fetal MRI should also be considered in select cases.

From a technical point of view, the larger size of the growing fetal brain enhances MR image quality, in particular signal- and contrast-to-noise ratios, eventually benefitting lesion conspicuity and detection rate. For example, in cases of suspected Zellwegers syndrome (Fig. 11), in which the peroxisomal deficiency typically results in a bilateral, perisylvian polymicrogyria and/or pachygyria in combination with white matter hypomyelination and periventricular pseudocysts, early fetal MRI may fail to show the pathognomonic cortical anomaly. Follow-up imaging at a later stage of pregnancy will easily reveal the characteristic imaging findings, establishing final diagnosis. The additional dynamic information provided by serial fetal MRI should not be underestimated and should be considered in select cases, especially if there is suspicion for abnormalities involving brain maturational processes that are known to be underestimated or missed by prenatal ultrasound examinations.

Finally, several fetal pathologies may be characterized by progressive injury to brain structures that were initially well developed. Identification of these secondary complications is essential for prognosis, parental counseling, and pre-, peri- and postnatal management or interventions. For example, in a subset of fetuses with a vein of Galen malformation (Fig. 12) [12], the progressive shunting at the level of the arterio-venous fistula with resultant arterial hypoperfusion of the brain parenchyma, systemic hypercirculation, cerebral venous hypertension and venous stasis as well as secondary hydrocephalus may progressively injure the brain. This entity has been quoted as a melting brain. The concept of a melting brain has

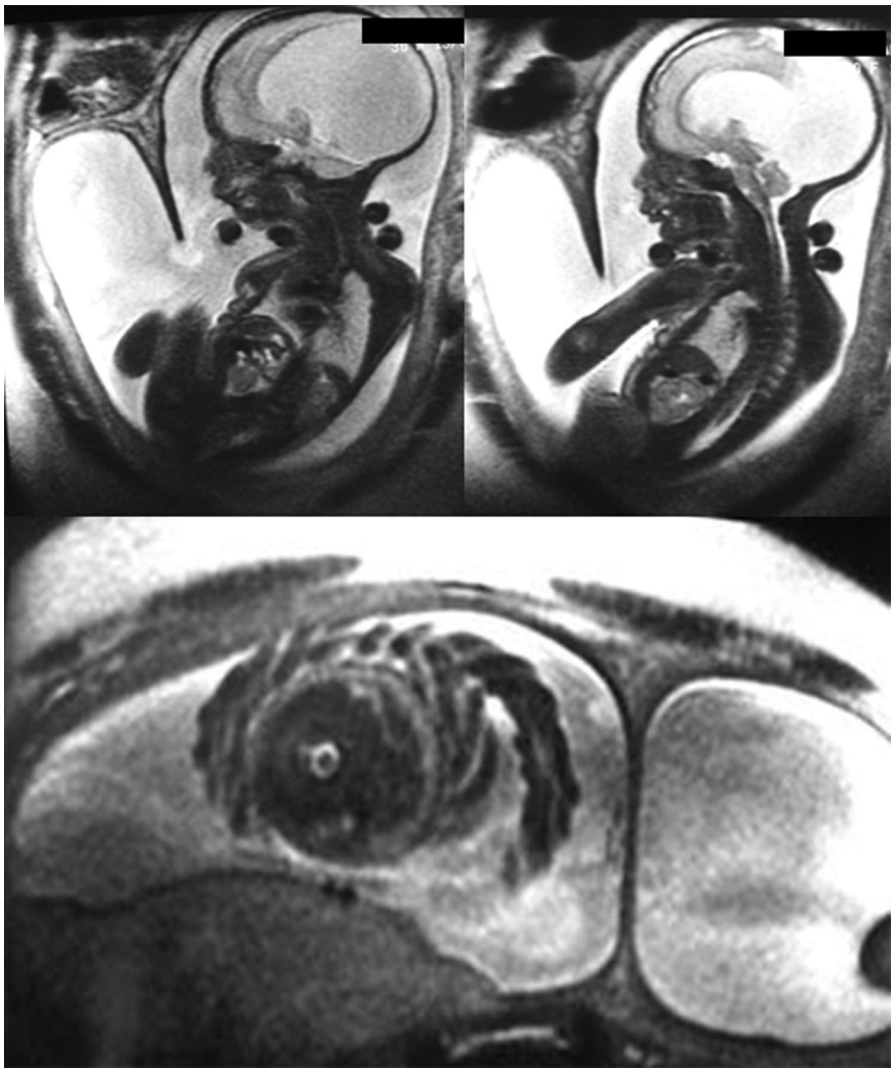

FIG. 6 T2-weighted MR images of a fetus with a high-grade supratentorial hydrocephalus secondary to an aqueductal stenosis. In addition, a septated uterus is noted ,resulting in a fetus stuck in a breech position. Furthermore the umbilical cord is wrapped 2 times around the fetal neck. Identification of the additional findings including septated uterus and nuchal umbilical cord is important for management of delivery next to the obvious CNS anomaly.

been well described for the postnatal period; however, fetal MRI may identify the progressive brain injury already during fetal life and often earlier and in better detail compared with prenatal ultrasound.

In conclusion, serial ultrasound is the typical standard of care for complex fetal pathologies; serial fetal MRI should, however, be considered only in a select group of fetal brain abnormalities, especially in those where a dynamic evolution of the fetal abnormalities may be expected, as well as in those cases where the small size of the fetus may prevent identification of the full extent of fetal brain pathology.

ISOLATED FINDING OR PART OF A SYNDROME, QUO VADIS?

Recognition of the entirety of the fetal brain anomaly is a sine qua non for fetal management. Prenatal

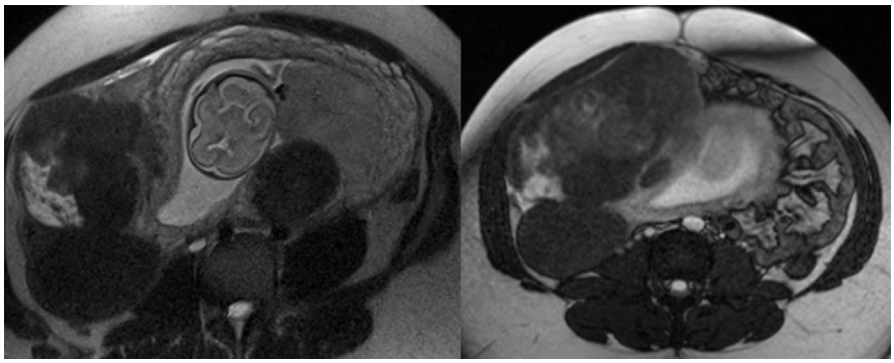

FIG. 7 Axial T2-weighted MR images of this normal fetus reveals multiple partially necrotic, hemorrhagic predominant T2-hypointense uterine fibroids. Hemorrhaging fibroids may be painful and mimic uterine complications like impeding uterine ruptures. Adequate evaluation of the uterus next to fetus is essential.

ultrasound may pick up the most obvious finding with ease; however, this may only be the tip of the iceberg. Fetal ventriculomegaly and a corpus callosum anomaly are frequent indications for fetal MRI. Neurocognitive and functional prognosis depend on the associated findings. Isolated mild ventriculomegaly or partial corpus callosum agenesis has significantly better prognoses than when found as part of a syndrome. Fetal MRI should always search for additional possibly subtle findings. Correlation with the observed prenatal ultrasound findings, gender of the fetus, family history, and clinical signs may help to further narrow down the differential diagnosis.

Fetal ventriculomegaly may be isolated but may also be seen in various anomalies including inborn errors of metabolism (muscle eye brain disease) or syndromal (Chiari 2 malformation or rhombencephalosynapsis) or acquired (postinfection or postintraventricular hemorrhage) etiologies (Fig. 13). Ventriculomegaly secondary to an aqueductal stenosis is still being debated to be either a malformation or acquired. Finally, in rare cases, the ventriculomegaly may resolve spontaneously over the duration of pregnancy.

Anomalies of the corpus callosum face similar challenges. It may be an isolated finding, possibly secondary to an interhemispheric lipoma, or may be part of a syndrome. Aicardi syndrome is a classic example. The hallmark imaging finding is a callosal dysgenesis; however, multiple additional findings including migrational abnormalities, cortical malformations, and possible eye abnormalities including colobomas are part of the Aicardi syndrome (Fig. 14). The corpus callosum agenesis may easily be noted on prenatal ultrasound. The remainder of findings may, however, require fetal MRI in order to establish the final diagnosis. In addition, these findings should be correlated with the gender of the fetus, because Aicardi syndrome is typically lethal in most fetuses of male gender.

CONCEPT OF FETAL MALFORMATION, DISRUPTION, AND DESTRUCTION AND TIMING OF INJURY

Differentiation between a fetal CNS malformation, disruption, and destruction is essential for management of pregnancy, delivery, and parental counseling related to risk of recurrence in future pregnancy and prognosis [9]. A true malformation is best described as a congenital morphologic anomaly of a single organ or body part caused by an alteration of the primary developmental program caused by a genetic defect (eg, holoprosencephaly). A disruption refers to a congenital morphologic anomaly caused by the breakdown of a structure that had normal developmental potential (eg, early infection or stroke). A destructive abnormality is a morphologic finding secondary to the injury of a structure that had already developed normally (eg, third trimester hemorrhage or stroke from a placental infarction) (Fig. 15).

The quintessential relevant difference between these 3 entities is the recurrence risk for future pregnancies. A true malformation like Joubert syndrome may be linked to an increased risk for recurrence, while a disruption or destruction typically has no increased recurrence risk. However, in fetal medicine, there are exceptions to these rules. A disruptive

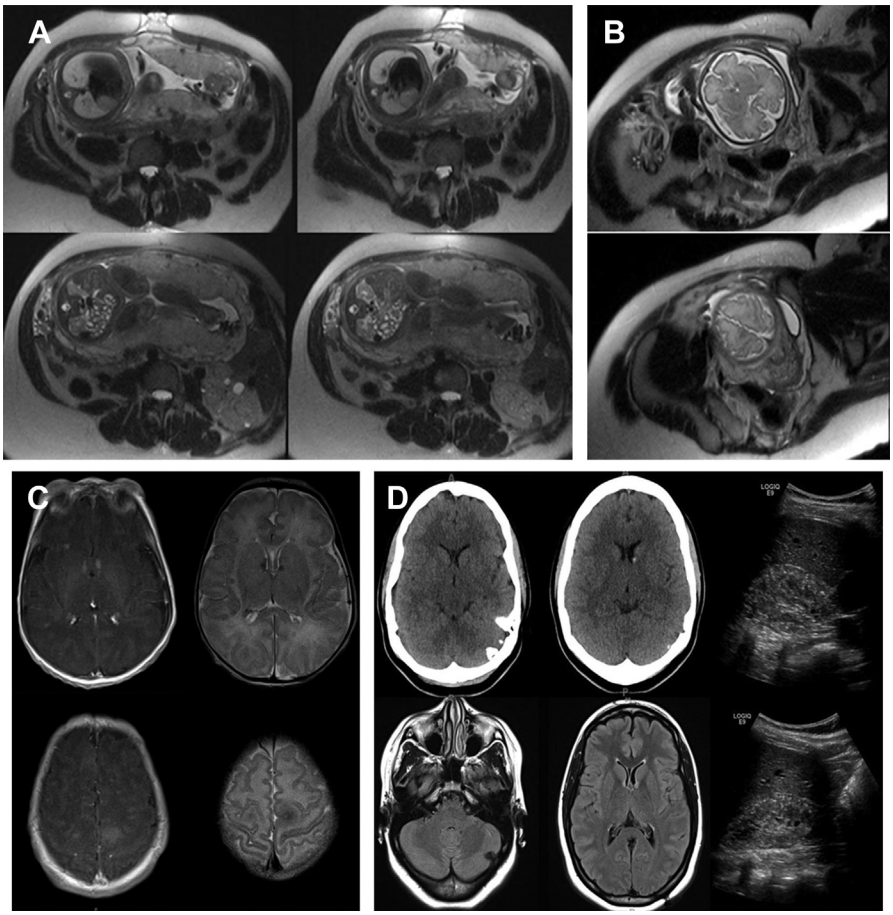

FIG. 8 (**A**) Axial T2-weighted MR images of a fetus with a focal T2-hyperintense mass lesion within the fetal heart compatible with a cardiac myoma. The maternal kidneys that were imaged within the overall field of view reveal multiple angiomyolipomas and cysts within the kidneys. (**B**) Dedicated fetal neuroimaging reveals T2-hypointense nodules along the region of the foramina Monro and a T2-hypointense subcortical tuber along the mesial peri-rolandic region. Identifying the renal lesions in the mother increased the sensitivity and specificity of the fetal MRI evaluation. (**C**) Postnatal contrast-enhanced T1-weighted and T2-weighetd MRI confirm all cerebral lesions as noted on the previous fetal MRI, solidifying the diagnosis of a tuberous sclerosis complex (TSC). (**D**) Axial noncontrast-enhanced CT and matching FLAIR MR images of the mother's brain and ultrasound images of her kidneys show a calcified tuber in the left cerebellar hemisphere with focal partially calcified lesions along the foramina Monro and the classic multiple renal lesions compatible with a maternal TSC diagnosis.

or destructive process may be secondary to a genetic predisposition for systemic entities (eg, COL4A1 mutations). Furthermore, certain triggers may induce or accelerate a disruptive or destructive sequence. For example, vascular malformations may be clinically silent; however, a change in the fetal hemodynamics, possibly because of maternal factors, may result in the evolution or transformation of the fetal anomaly. In addition, an event that impacted the early development of the fetal brain may be compensated later during fetal life, resulting in a normal end product.

An additional concept that has to be considered is the timing of injury in relation to the gestational age. Similar qualities of injury may result in a wide spectrum of fetal abnormalities. An infectious or ischemic injury

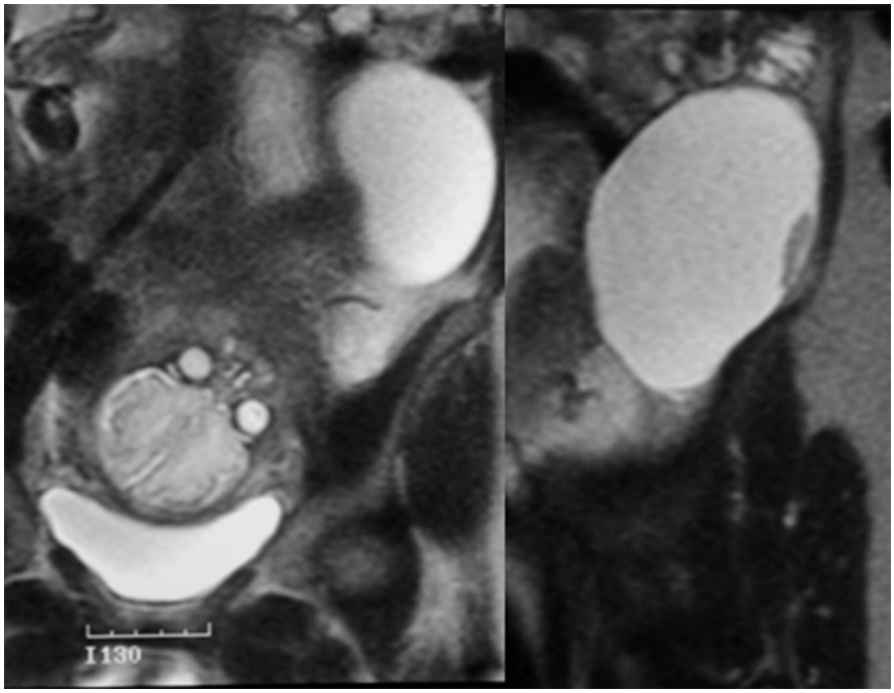

FIG. 9 Coronal and sagittal T2-weighted MR images show a large predominant cystic mass lesion within the left maternal ovary adjacent to the pregnant uterus. The small solid intramural component is compatible with the final diagnosis of a borderline ovarian carcinoma.

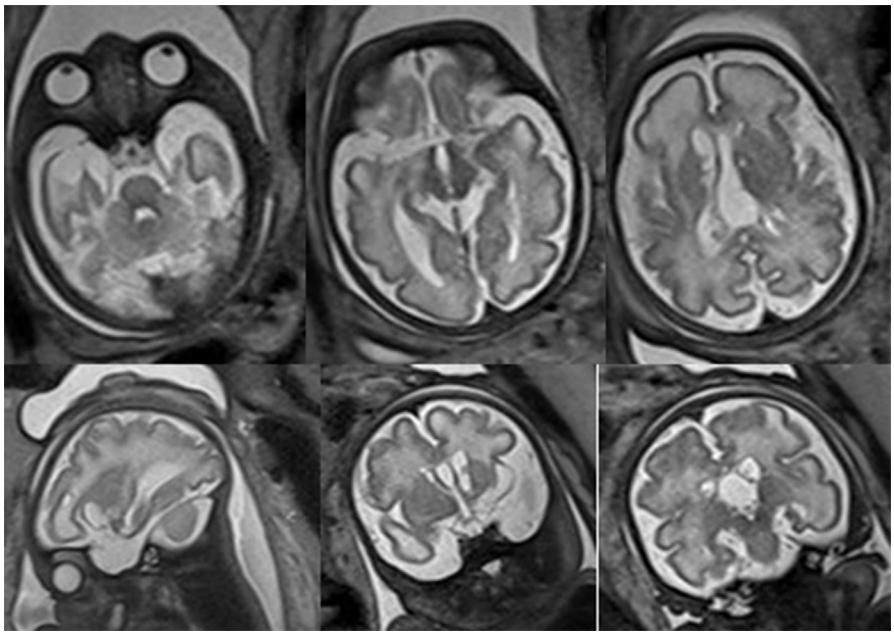

FIG. 10 Axial, sagittal and coronal MR images show multiple subcortical cysts within the temporal-polar region as well as several small cysts within the germinal matrix bilaterally. The white matter signals intensity and is elevated for gestational age. Constellation of imaging findings is concerning for a TORCH infection; cytomegalovirus was subsequently isolated. The cerebellum and most of the supratentorial macroanatomy are intact and compatible with a late second trimester infection.

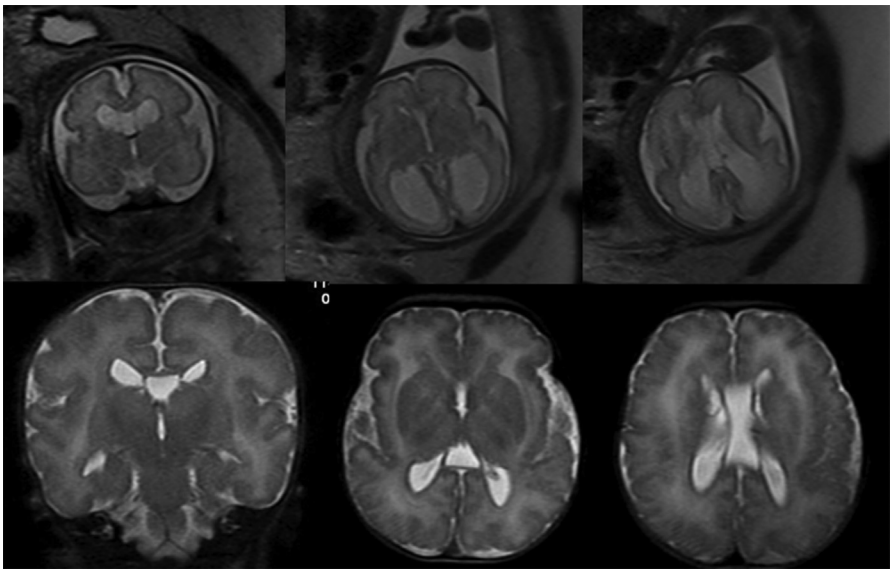

FIG. 11 Coronal and axial prenatal (*upper row*) and matching postnatal (*lower row*) T2-weighted MR images in a fetus/neonate with confirmed Zellweger syndrome. A characteristic bilateral perisylvian poly-/pachygyria and diffuse T2-hyperintensity of the cerebral white matter are noted.

early during gestation is more likely to result in a disruption, while the same kind of injury toward the end of gestation more likely results in a destructive lesion.

In conclusion, familiarity with neurogenetics, patterns of inheritance, syndromes, timing of injury, and the various acquired pathologies is essential for every fetal neuroradiologist.

MULTILEVEL FETAL ABNORMALITY BENEFITS FROM A LARGE FIELD OF VIEW

In contrast to prenatal ultrasound, fetal MRI typically allows one to evaluate the entire fetus in 1 single field of view. This enhances the identification of multiregion or multilevel fetal abnormalities. On prenatal ultrasound, especially in advanced pregnancy, the larger size of the fetus prevents visualizing the fetus in 1 single view or image. The sonographer has to puzzle the various anatomic regions together, which may limit evaluation of abnormalities that may involve multiple organs or regions. For example, in cloacal malformations, there is an increased incidence of spinal anomalies. The simultaneous visualization of the urogenital and spinal anomalies typically enhances lesion detection and allows for a comprehensive diagnosis. A large field of view has also proven to be helpful in the identification of a Chiari 2 malformation in combination with a nonskin-covered, open spinal dysraphism. Furthermore, the large field of view helps to identify the exact positioning of the fetus within the uterus, while specialized sequences, like the previously published MR-fetography, allow ultrafast acquisition of fetal presentation.

FETAL/MATERNAL INCUBATOR

The progressive immobilization of the fetus toward the end of pregnancy secondary to the larger size of the fetus, the smaller amount of amniotic fluid relative to the fetus, and possible progressive engagement of the fetal head into the maternal pelvis (cephalic presentation) enhance the sensitivity and specificity of fetal neuroimaging. Consequently in severe or possibly life-threatening conditions, one should consider imaging the fetus within the last weeks of pregnancy as an alternative to postnatal imaging. Basically the uterus can be considered as one of the safest incubators nature can offer. A critically sick neonate may require sedation for the study; is at risk for hypothermia; may be dependent on a ventilator, multiple perfusors, or even extracorporeal membrane oxygenation (ECMO); and require multiple monitoring devices. The image quality of late pregnancy fetal neuro-MRI is similar to early postnatal neuro-MRI.

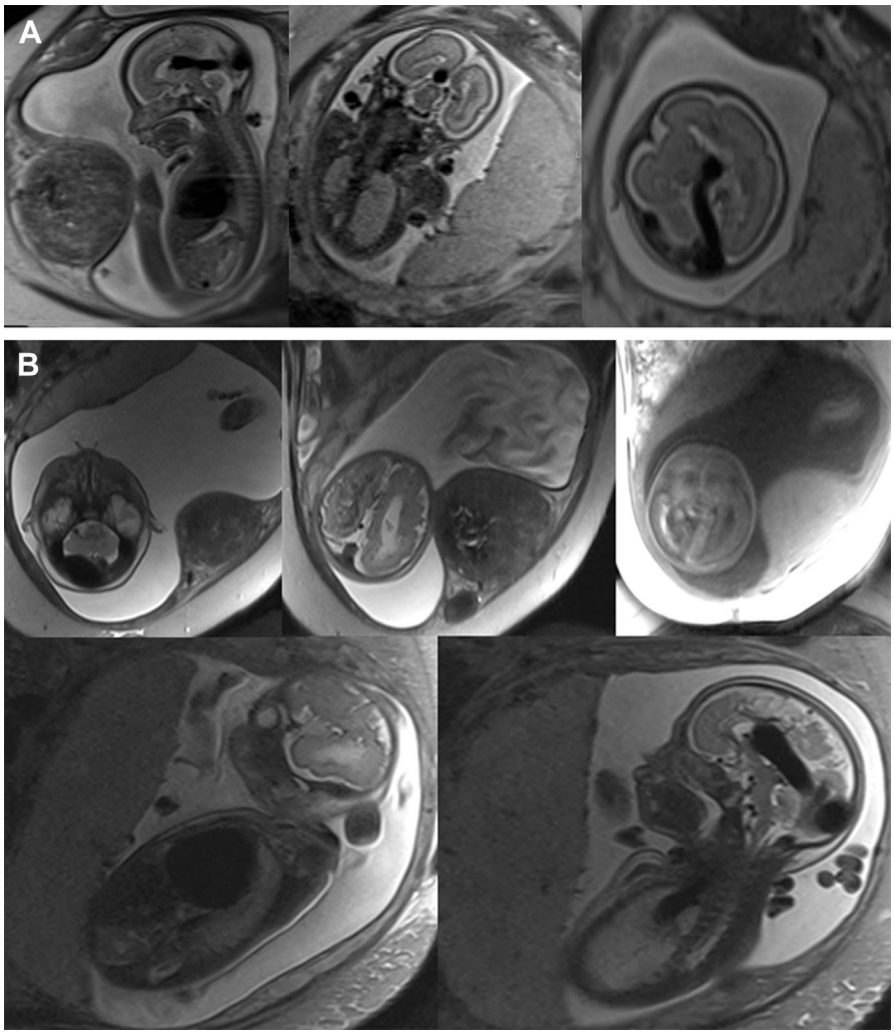

FIG. 12 (**A**) Sagittal, coronal and axial T2-weighetd MR images of a fetus with a vein of Galen aneurysmal malformation (VGAM). The enlarged vein of Galen is noted in the midline; the cerebral gray matter and white matter appear intact. No significant ventriculomegaly. Incidental note is made of a large uterine fibroid. (**B**) Follow-up axial and sagittal T2- and T1-weghted MR images show a progressive hemispheric white and gray matter injury as a complication of the VGAM. This progressive injury is also known as a melting brain. In addition, a progressive cardiomegaly and subcutaneous edema are noted. The dural sinuses, in particular the transverse sinuses, are progressively dilated. This case shows the value of serial fetal MRI to identify progression of disease/destruction.

MAGNETIC RESONANCE PELVIMETRY AND FETAL MRI

In addition to imaging the fetus, MRI also allows one to measure the osseous birth canal in the same session. This may be of special benefit in cases of suspected feto-maternal pelvic disproportion. T1-weighted imaging of the maternal pelvis allows for direct measurement of the birth canal diameter, in particular the entrance and the outlet, assessing for detection of a mismatch between the fetal head and the birth canal. These measurements help guide the physician in deciding whether vaginal birth is possible or a cesarean section should be performed.

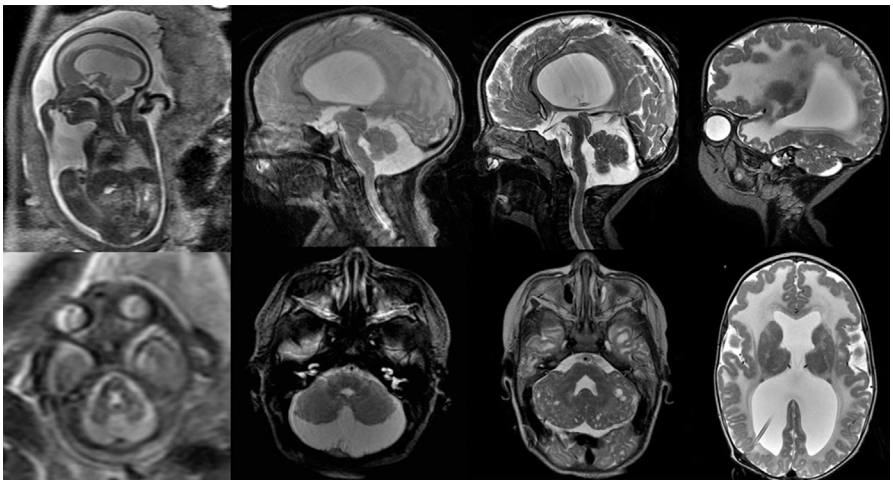

FIG. 13 Initial sagittal and axial T2-weighted fetal MR images with matching serial postnatal follow-up imaging of a fetus and neonate with a muscle eye brain disease: a form of a dystro-glyconopathy. The initial fetal MRI shows a marked hydrocephalus and a mild cerebellar hypoplasia and possible malformed brainstem. The follow-up postnatal MRI shows the characteristic imaging findings with an elongated and swan-like deformed brainstem, hypoplastic pons, high-grade hydrocephalus and progressively prominent cerebellar cysts, and an extensive cortical malformation with white matter hypo/dysmyelination. This sequence of imaging studies shows that findings may become more obvious on follow-up. In addition, findings may be absent on initial imaging and develop with progressive maturation. Serial imaging may be necessary.

CHIARI 2 AND OPEN SPINAL DYSRAPHIA, FETAL INTERVENTIONS

Fetal MRI has not only evolved into a valuable complementary diagnostic tool to prenatal ultrasound but is progressively being used for preoperative and postoperative fetal interventions [10–16].

Fetal MRI has become especially helpful in the preoperative work-up of fetuses with an open, nonskin-covered spinal dysraphism. The recognition of the link between an open neural tube defect and a Chiari 2 malformation has been known for many decades. The so-called unified theory has recognized the leakage of cerebrospinal fluid out of the open neural tube at the level of the spinal dysraphia into the amniotic fluid as a key etiologic factor for the delayed or ineffective expansion of the rhombencephalic vesicle [10–16]. Consequently, the osseous posterior fossa is too small for its contents, which constitutes the hallmark of a Chiari 2 malformation. On prenatal ultrasound, the Chiari 2 malformation can easily be detected by the lemon-shaped skull configuration as well as the banana-shaped cerebellum on axial imaging. High-resolution ultrasound will usually also depict the tonsillar herniation into the upper spinal canal and associated findings including supratentorial hydrocephalus. Fetal MRI is, however, superior to ultrasound to recognize associated findings such as migrational abnormalities or callosal anomalies. As mentioned previously, these additional findings may significantly impact functional and neurocognitive prognosis.

Fetal MRI also allows for detailed evaluation of spinal dysgraphia, including the superior-inferior and left-to-right extension of the osseous defect, the degree of herniation and integrity of the neural placode, the possible associated hydromyelia, and the hypoplasia of the adjacent soft tissues, all of which will guide the possible fetal intervention. Multiple studies have shown that an early closure of the spinal dysraphia may significantly improve the functional outcome. Not only will an early intrauterine closure of the defect protect the neural placode from progressive injury because of amniotic fluid exposure, but it has also been shown that the Chiari 2 malformation may be reversed with improved ventriculomegaly. In many cases the child will not require shunting in the postnatal period (Fig. 16). Furthermore in many cases, the protection of the neural placode from the amniotic fluid typically

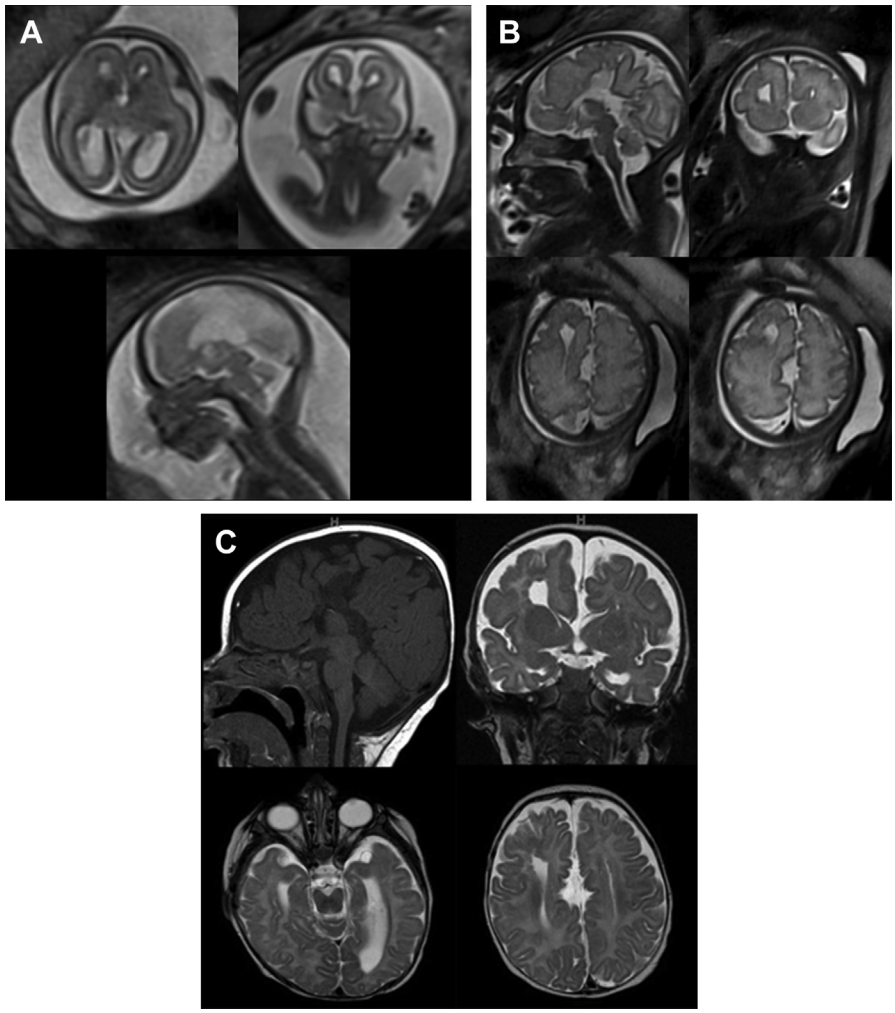

FIG. 14 (**A**) Axial, coronal, and sagittal T2-weighted fetal MR images show a classic complete corpus callosum agenesis. The right frontal horn appears asymmetrically wide and deformed with a suggestion of a subependymal heterotopia. (**B**) Follow-up sagittal, coronal, and axial T2-weighted fetal MR images confirm the imaging findings seen on the previous MRI. The progressive brain development shows the right frontal lesion in better detail. A closed lip schizencephaly is lined by T2-hypointense malformed cortical ribbon. Constellation of findings is consistent with an Aicardi syndrome. (**C**) Sagittal T1-weighted MRI and coronal and axial T2-weighetd postnatal MR images confirm all prenatally identified findings. Aicardi syndrome was confirmed in this young girl. This imaging sequence shows the significance of serial imaging if a finding on initial fetal imaging is be too subtle to allow final diagnosis.

improves the motor control of the lower extremities and the bowel and bladder function. In most institutions, these interventions are done by a multidisciplinary team using a fetoscopic approach. Fetal MRI plays a key role in the preoperative planning and postoperative follow-up.

Fetal MRI has also advanced the understanding of this complex multilevel malformation, which should possibly be reclassified as a fetal disruption rather than a malformation. Further investigations are, however, necessary, because the unified theory may explain the combination of the spinal

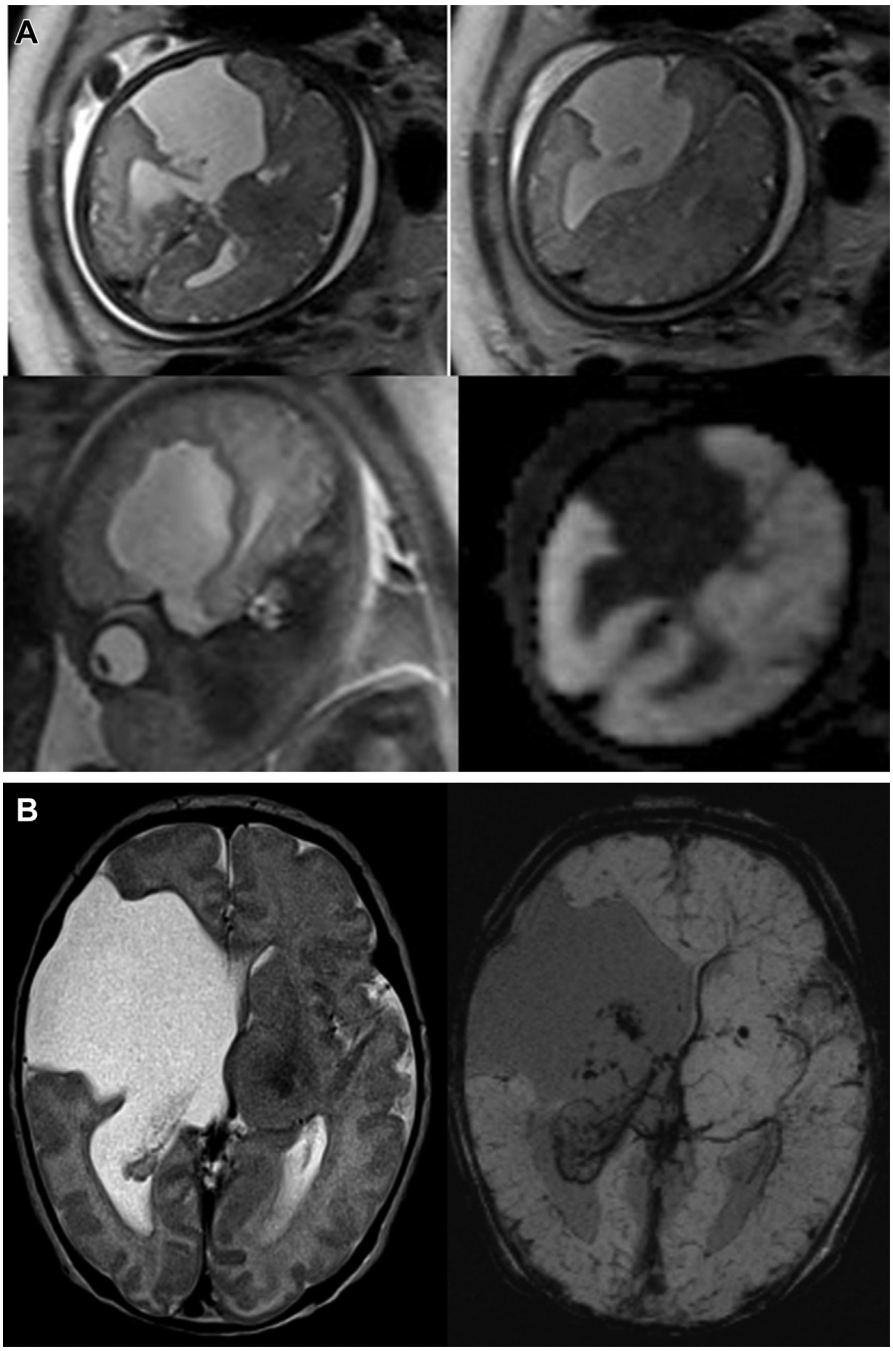

FIG. 15 (**A**) Axial and sagittal T2-weighted and axial diffusion-weighted fetal MR images show a large CSF-filled periventricular porencephalic cyst within the right frontal lobe. DWI confirms the chronic character of this ischemic lesion. (**B**) Postnatal T2-weighted and susceptibility weighted MR images confirm the prenatal diagnosis. A small sliver of cortical gray matter is seen along the periphery of the porencephalic cyst. SWI images show old blood products within the defect, indicating that this lesion likely represented a partially hemorrhagic ischemic lesion.

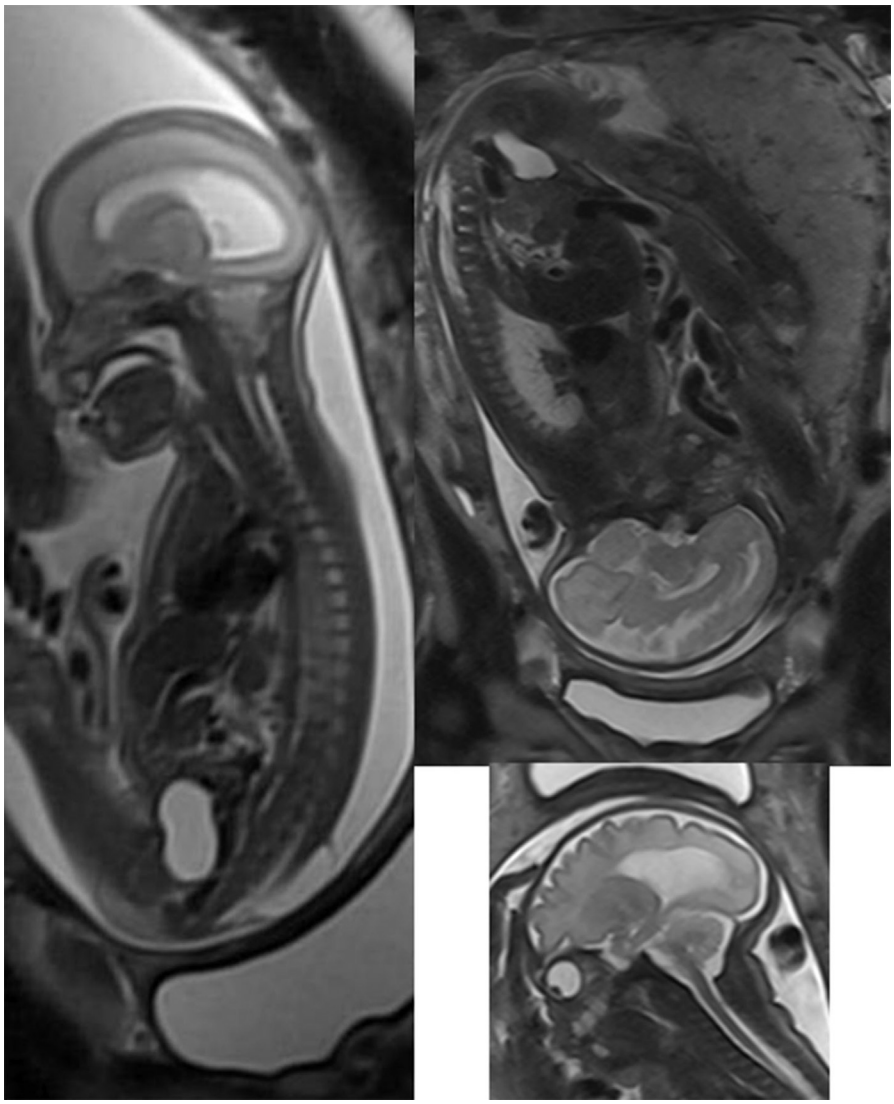

FIG. 16 Serial sagittal MR images of a fetus prior to and after repair of an open lumbar myelomeningocele. On the preoperative imaging, a large cystic defect is seen along the caudal, dorsal contour of the fetus. An associated Chiari 2 malformation is seen within the posterior fossa with significant downward herniation of the cerebellar tonsils. The child is in breach position. Follow-up imaging after fetoscopic repair of the lumbosacral defect shows a complete reversal of the downward displacement of the cerebellar tonsils. The posterior fossa is of normal size. In addition, the fetus is now in a cephalic presentation, which may be secondary to a better lower extremity function. This case exemplifies that preoperative fetal MRI may guide fetal treatment; follow-up fetal MRI can be used to evaluate the success of fetal surgery.

dysraphia and the Chiari 2 malformation, but does not explain the increased incidence of additional cerebral findings like migrational abnormalities, the prominent interthalamic adhesion, or callosal malformations. Advanced fetal MRI including diffusion tensor imaging with tractography may shed more light on this intriguing fetal abnormality.

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