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Review Article

Fetal MRI imaging protocols: current standards, optimization strategies and emerging techniques

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ABSTRACT

Prenatal Magnetic resonance imaging helps to assess the fetus and the pregnancy structures. Maternal obesity, fetal position, or oligohydramnios do not significantly affect MRI image visibility of the fetus, and the ossified skull does not interfere with visualisation of the brain. Many authors have mentioned practical approaches and imaging applications for diagnosis, but there is a lack of a complete standardised imaging protocol for fetal MRI. Different diagnostic centres or hospitals use different sequences, slice thickness, field strength or motion correction methods. This variability in protocol reduces reproducibility and comparison across studies. Thus, there is a need for a standardised fetal MRI protocol. The objective of this review is to provide an overview of fetal Magnetic resonance imaging sequences (SSFSE, SSFP, IVIM, DWI), their applications and parameters, limitations, and safety of fetal magnetic resonance imaging. Magnetic resonance imaging using a T2-weighted sequence of a gravid uterus shows the fetus and pregnancy structures (umbilical cord, placenta and amniotic fluid). T1-weighted sequences are mostly used to demonstrate haemorrhage, calcification, and obesity. The assessment is done in a system-oriented approach that involves the fetal brain, spine, face, neck, chest, abdomen, pelvis, extremities and pregnancy structures. It is an interesting choice of investigation for indications such as congenital anomalies (holoprosencephaly, encephalocele), vascular anomalies (malformations, infarction, twin pregnancy complications), mass (hemangioma, teratoma), etc. Fetal Magnetic resonance imaging is said to be completed when the evaluation of the fetus, placenta, umbilical cord and amniotic cavity is carefully completed.

Keywords: Magnetic resonance imaging, Standardised imaging Protocols, Fetal MRI, Anomalies, Sequences, Pregnancy

INTRODUCTION

Fetal Magnetic resonance imaging is a complementary second-line imaging study usually performed after the routinely obtained anatomic ultrasonography, which provides important information in the evaluation of the fetus and the placenta.[1] It has numerous advantages, including safety, and it can overcome the limits of ultrasound examination. Indications for fetal magnetic resonance imaging are for both the central nervous system and the fetal body, as given in Table 1.[2] Fetal magnetic resonance imaging emerged as a clinical tool in the late

1980s and early 1990s.[3] Magnetic resonance imaging of women during pregnancy was first described in 1983, which was done primarily for maternal and placental abnormalities.[4] Fetal Magnetic resonance imaging was revolutionised by the development of the single-shot rapid acquisition sequence with refocused echoes. Single-shot rapid acquisition with refocused echoes is a high-quality T2-weighted sequence that has a slice acquisition time of less than a second, effectively "freezing" fetal motion.[5] 3T field strength offers higher spatial resolution; still, 1.5T MRI remains the standard and preferred field strength for fetal MRI.[6] The reasons for 1.5T as the standard field of strength for fetal MRI include reduced dielectric artifacts, lower specific absorption rate and less heat tolerance. Acquisition parameters slightly differ according to field of strength.[7] Initially, Fetal Magnetic resonance imaging was used primarily for neuroimaging. Later, Fetal Magnetic resonance imaging started gaining popularity due to some of its advantages, like high-resolution imaging, nonionizing radiation, multiplanar capabilities, Superior soft tissue contrast and greater accuracy.[2] Its applications then expanded to include detailed assessment of fetal thoracic, abdominal, and musculoskeletal structures.[8] Some abnormalities can only be diagnosed via Fetal magnetic resonance imaging, such as degenerative disorders, sensor conditions and metabolic disorders.[9] Prenatal testing, such as ultrasonography, is unable to diagnose these conditions.

A standardised fetal MRI protocol is critical for ensuring diagnostic accuracy, minimising motion artifact, and producing high-resolution, reproducible imaging. The standardisation of the protocol is also beneficial for comparison across different studies, especially for the same fetus, to build growth curves for brain, placenta, lung or body maturation. The fetal growth curve helps in evaluating whether a fetus is developing normally throughout pregnancy.[10]

This review paper aims to provide a complete standardised imaging protocol, including imaging sequences, their applications, parameters, limitations, and safety of fetal magnetic resonance imaging. For improved diagnostic accuracy, research and cross-study comparison, a standardised fetal MRI acquisition technique and reporting requirements would be beneficial.

Indications of fetal magnetic resonance imaging

Fetal magnetic resonance imaging (fetal MRI) is a highly useful supplemental technology, especially for diagnosing the central nervous system (CNS).[11] The indications for fetal Magnetic resonance imaging are mentioned in a categorised way according to body part in Table 1. Sonography and MRI are often used to identify fetal abnormalities between weeks 18 and 24 of pregnancy. It is difficult to diagnose prenatal abnormalities at or before 20 weeks due to the fetus's tiny size, increasing movements, and continuous organ development.[12]

Table 1: The indications of fetal magnetic resonance imaging are according to the American College of Radiology (ACR).[2]

Fetal Organs	Indication category	Indication
Brain	Congenital anomalies	Ventriculomegaly, corpus callosal dysgenesis, holoprosencephaly, posterior fossa anomalies
	Vascular abnormalities	Vascular malformations, hydranencephaly, infarctions, monochorionic twin pregnancy complications
	Screening fetuses with a family risk for brain anomalies	E.g. tuberous sclerosis, corpus callosal dysgenesis.
Spine	Congenital anomalies	Neural tube defects (Encephalocele), sacrococcygeal teratomas, caudal regression, sirenomelia
Skull, face and neck	Masses of the face and neck	Veno-lymphatic malformations, hemangiomas, goitre, teratomas, facial clefts
	Airway obstruction	Conditions that may impact parental counselling, prenatal management, delivery planning
Thorax	Masses	Congenital pulmonary airway malformations (congenital cystic adenomatoid malformation; sequestration, and congenital lobar emphysema);
	Volumetric assessment of lung	Cases at risk for pulmonary hypoplasia secondary to oligohydramnios, chest mass, or skeletal dysplasia
Abdomen and pelvis	Mass	Abdominal–pelvic cyst.; tumours (e.g. hemangiomas, neuroblastomas, teratomas, and renal masses); complex genitourinary anomalies (e.g. cloaca); renal anomalies in cases of severe oligohydramnios and bowel anomalies such as megacystis

STANDARDISED FETAL MRI PROTOCOL

For high-resolution, repeatable imaging, motion artifact minimization, and diagnostic accuracy, a standardised fetal MRI technique is necessary.[13] It helps to create development curves for the brain, placenta, lungs, or body maturation. The protocol's standardisation is also helpful for comparison across multiple studies, particularly for the same fetus. A fetus's proper development during pregnancy may be assessed using the fetal growth curve (Figure. 1).[14]

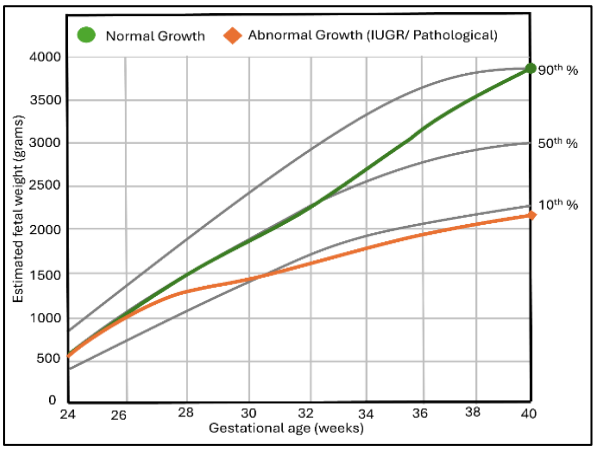


Figure 1: Conceptual illustration of Fetal growth curve. (A) Normal Growth- it follows a consistent, predictable curve appropriate for gestational age. The fetus is meeting its genetic potential. (B) Abnormal Growth/IUGR (Intrauterine growth restriction)- The fetus fails to achieve its growth potential due to pathology.

STANDARD SEQUENCES

Fetal MRI uses ultrafast pulse sequences to freeze maternal and fetal motion. The standard diagnostic protocol relies on a combination of some main sequences, typically acquired in axial, coronal, and sagittal planes relative to the fetus.[2] The main sequences that should be used for fetal MRI include firstly the single-shot fast spin-echo (SSFSE) T2-weighted imaging [HASTE], followed by T1-weighted imaging (fat, calcification, haemorrhage) and finally the steady-state free-precession (SSFP) [TRUFI]

T2 HASTE

HASTE is a single-shot T2-weighted imaging sequence which primarily a T2 W sequence.[15] It is the mainstay tool for fetal Magnetic resonance imaging. It acquires images in seconds. TR (time of repetition) should range between 2000 and 5000 ms; a longer TR gives a heavier T2-weighted image; it can be reduced upto1500 if required. TE remains 60 to 140 ms, which creates excellent contrast between high water content and fetal tissues.[16] To prevent partial volume averaging, slice thickness needs to be 3.0 to 4.0 mm. A 256x256 matrix provides isotropic or near-isotropic voxels for high-resolution anatomical rendering.[17] FOV (field of view) is adjusted according to the patient. The average FOV remains 280 to 350 mm. Low flip angles are used in hyper echo capture to limit SAR; therefore, they should be between 120° and 180°.[18] High echo train length (ETL) of about 128 to 256 is utilised to sample less than half of k-space and synthesise the rest.[19] High ETL reduces the scan time, which helps in fetal movement compensation. All the parameters are summarised in Table 2. Compared to rapid low-angle shot or turbo spin-echo sequences, vision of the fetal brain, visceral organs (lung, heart, liver, kidney, and bladder), extremities, and umbilical cord was much improved. The HASTE sequence provided a clear picture of the brain's myelination, gyrus creation, and white matter-grey matter differentiation (Figure 2).[20]

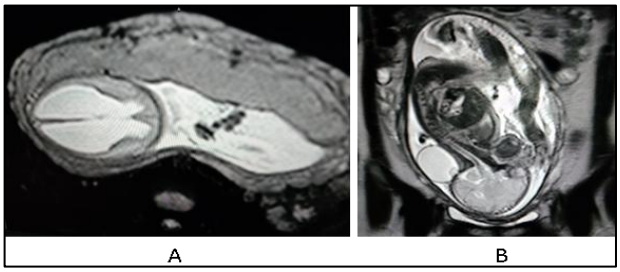


Figure 2: (A) HASTE axial of fetal brain- shows dilated ventricles. (B) HASTE sagittal of fetal brain– shows encephalocele at occipital lobe.

T1-weighted imaging

T1 W image in fetal MRI is usually acquired with fast gradient echo (GRE) during brief maternal breath holds.[21] It is primarily used to identify fat, calcification, and blood products (such as detecting recent and old haemorrhages). It is highly effective for confirming the presence of meconium in fetal bowel.[22] This sequence is well known as the anatomical sequence. Fluid appears dark and fat appears bright on a T1 W image, making the sequence useful for evaluating anatomical structures.[23,24] TR should be kept extremely short to reduce total acquisition time; thus, it should be greater than 180ms for a 2D GRE sequence. Flip angle typically ranges from 10° to 90°.[25] Usually, the slice is maintained at 3 to 4 mm for diagnostic scanning; it can be dropped to 2 mm for 3D sequences. Interslice space should be 0 for 3D GRE but can be 10% (0.3-0.4 mm) in 2D sequences to avoid crosstalk excitation.[26] FL2D is a common fast low-angle sequence acquired in 2D (Table 2). To achieve a compromise between submillimeter in-plane spatial resolution and quick scan progress, a 256x151 or 256x256 matrix should be configured. Using SENSE or GRAPPA with a factor of 2 reduces individual maternal breath-hold segments to 12 to 18-second windows.[27] SPAIR and fat suppression are optional, but it suppresses maternal subcutaneous fat to amplify the dynamic window looking for maternal or fetal bleeding.[28]

Table 2: Fetal magnetic resonance imaging technical parameters for fetal MRI at 1.5 T.

Sequence	TR (ms)	TE (ms)	Flip angle (°)	Slice Thickness (mm)	Matrix/ Resolution	NEX/ Average
T2 SS-FSE (HASTE)	2000-5000	60-140	90°-180°	3.0–4.0	256x256	1
T1W FI2D	>180	5	15° – 90°	3.0 – 4.0	256x151	1
BSSFP (TRUFI)	>500	2 - 3	>30°	3.0 – 4.0	256x192 256x256	1

Balanced steady state free precession

Balanced steady state free precession (bSSFP) is a widely used and highly valuable sequence in routine MRI because of its rapid readout and robustness against motion.[29] It is useful for the evaluation of the heart and vessels because of the bright-blood signal, while in SS-FSE, the blood appears dark. It does not provide pure T1 contrast; instead, it provides a mix of T1 and T2 contrast. TR should be greater than 500ms and TE should range between 2 ms and 3 ms.[31] A high flip angle between 50 and 80 degrees is standard. This configuration maximises signal from structures with a high T2/T1 ratio, making blood and amniotic fluid appear bright. To overcome the overwhelming brightness of fluid and emphasise parenchymal structures, the flip angle can be reduced to 30 – 45 degrees. Slice thickness should be 3-4 mm with no slice interval to maintain spatial resolution. A matrix of 256x192 or 256x256 is configured to yield submillimeter in-plane resolution while matching ultrafast k-space filling.[17]

PROTOCOL

The combination of main sequences like HASTE and TRUFI, usually obtained in axial, coronal, and sagittal planes with respect to the fetus or placenta, provides the foundation of the conventional diagnostic procedure.[33-35] And T1 W is acquired in any one plane, but axial acquisition is preferred.[36-38] Additionally, MEDIC (Multi-echo data combination) can be acquired in the axial plane in case of placental examination for hematoma evaluation.[39]

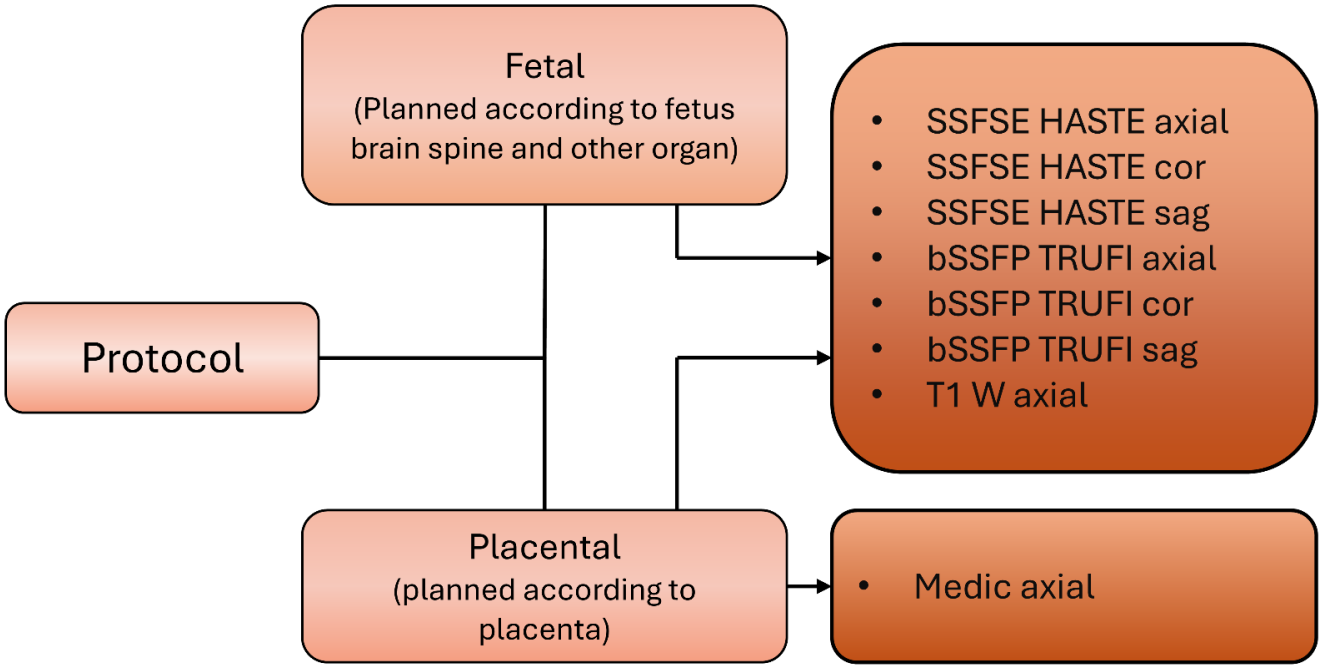


Figure 2: The basic sequences of fetal MRI scan categorised with reference to maternal scanning and fetal scanning.

LIMITATIONS OF FETAL MAGNETIC RESONANCE IMAGING

Fetal mobility, cost, duration, availability, and technical complexity are among the limitations of prenatal magnetic resonance imaging. Due to these limitations, prenatal fetal MRI is not the primary investigative approach and is not recommended for screening.[17,35]

Fetal motion

The unpredictable fetal movements can cause artifact in Magnetic resonance imaging image acquisition. This fetal movement negatively affects overall image quality. Various approaches are used to reduce their negative effect on images, including the adjustment of acquisition parameters. However, such adjustments limit the detail derived from the scan.[5,36]

Costly and time-consuming

Magnetic resonance imaging is much more costly than prenatal ultrasound, which limits its use to some extent. So, fetal Magnetic resonance imaging cannot be used for screening purposes. Due to the affordable cost of ultrasonography, it is generally done first and can be used as a screening modality.[37] A standard fetal MRI procedure takes 30-45 minutes. It is a time-consuming procedure; that's why it cannot be done with uncooperative or uncomfortable patients. It becomes a challenging procedure, especially for claustrophobic patients, and for such patients, sedation is also not an optimal option due to the safety of the fetus.[38]

Availability and technical expertise

The ease of availability of equipment is also an important aspect. Since magnetic resonance imaging is not as available as an ultrasound machine, it is not used primarily. So, for screening purposes of fetal health, the ultrasound modality is preferred due to its ease of availability. Fetal MRI acquires the target anatomy of the fetus by planning on a previously acquired plane.[39] So, it makes it challenging to acquire the target plane before the fetus twists and moves away from the view. MRI involves using the scanners differently than in most other applications. Additionally, because the fetus moves constantly, reduction measures are also necessary, such as motion prevention strategies, motion artefact minimisation methods and motion detection/correction schemes.[40] Fetal MRI acquisition is highly technical, and that's why it demands high expertise to acquire a diagnostic-quality image.[41]

Safety in fetal magnetic resonance imaging (MRI)

Imaging in the first trimester is not recommended. It is recommended to scan the fetus after 18 weeks, as the effects of static magnetic fields, radiofrequency pulses (inherent potential for tissue heating), and rapidly changing gradients are yet to be defined prior to 18 weeks.[42] If fetal magnetic resonance imaging is performed in the first trimester, when fetal cells are implanting, rapidly dividing, and undergoing organogenesis, theoretical risks include disruption of cell proliferation, migration, or differentiation, and damage to cells or organ systems from heating. Depending on the precise week during the first trimester, this cell damage could result in either miscarriage or potentially injury to specific organ systems.[44] Generally, contrast is avoided in Fetal Magnetic resonance imaging. According to Garcia-Bournissen et al, European guidelines state that gadolinium-based contrast agents appear not to be safe in pregnancy, and their use should be considered when the study is important for the health of the mother.[41] Since fetal kidneys are not fully functional, they filter gadolinium poorly, and gadolinium retention increases the risk of fetal nephrogenic systemic fibrosis. Though Gadolinium administration is avoided in fetal magnetic resonance imaging. The aim is not to achieve perfect image quality but sufficient image quality. Because achieving a good-quality image while performing fetal Magnetic resonance imaging may become a cause of discomfort to the patient, as well as to the fetus.[38,44]

DISCUSSION

Initially, to diagnose any fetal abnormality, the USG modality is preferred, but due to some of its limitations, sometimes we need to move on to the MRI modality. Fetal magnetic resonance imaging (MRI) is a complementary second-line imaging examination that offers crucial information for evaluating the baby and placenta.[45] Among its many benefits are safety and the ability to surpass the limitations of ultrasonography evaluation. But still, ultrasonography is the first-line modality because of its ease of availability, ease of operation and cost of examination. So fetal MRI overcomes the limitations of ultrasound but does not replace it. Fetal MRI is indicated for both the fetal body and the central nervous system.[9] Fetal MR imaging is especially valuable to identify CNS abnormalities, including callosal agenesis/hypogenesis, periventricular nodular heterotopia, cerebellar dysplasia, syringohydromyelia, and diastematomyelia, that are often linked to myelomeningoceles/Chiari II malformations.[44] According to Yong-Seok Sohn et al, after a prenatal MRI, the final diagnosis had been changed in 6 out of 30 patients with a verified final diagnosis. So, because of this possibility, fetal MRI becomes more important to be done before concluding any crucial diagnosis.[13] According to Girard et al, the standard protocols include T2WI, T1WI, DWI, T2*WI, or SWI. MRS and DTI (Diffusion tensor imaging) can also be performed.[46] According to Peter et al, the HASTE sequence, which is a T2W sequence, is the mainstay tool for fetal MRI.[42] Every sequence has its own significance. T1W sequence helps in identifying fat, calcifications, and haemorrhages very clearly. The T2W (HASTE) is the most widely used sequence in fetal MRI because of its fast acquisition time. It is highly sensitive to fluid, and the amniotic sac is filled with amniotic fluid, making it optimal for scanning.[20]

CONCLUSION

Fetal Magnetic resonance imaging is a high-grade investigation of fetal and maternal conditions as well, but it cannot be used as a screening tool because of many factors such as cost, longer procedure duration, ease of availability and unpredictable fetal movement. So, considering all these limitations, ultrasonography is preferred as a screening tool for fetal investigations. Fetal Magnetic resonance imaging is far more advanced and a better investigation modality for the fetus than fetal ultrasonography with respect to image quality and thus diagnosis. But even being a far better modality, fetal Magnetic resonance imaging is not a replacement for fetal USG; rather, it is usually performed after the routinely obtained anatomic ultrasonography, and that's why it has been called a complementary second-line imaging study for fetal investigation. When diagnostic doubt remains after prenatal ultrasonography, fetal Magnetic resonance imaging confirms the ultrasound diagnosis and may add significant diagnostic information. In fetal Magnetic resonance imaging, sequences like T2W SSFSE(HASTE), bSSFP(TRUFI) and T1W are used, but the T2W HASTE sequence is known as the mainstay tool for fetal Magnetic resonance imaging because of its advantages. HASTE is a very fast sequence that captures an image in a single shot, avoiding fetal motion artifact. The T2 weighting makes the HASTE sequence fluid-sensitive, which is abundant in fetal tissue and amniotic fluid, aiding in clear imaging of structures. The cine sequence (cine bSSFP), which can be acquired in fetal Magnetic resonance imaging, helps a lot to analyse fetal movements and dynamics of selected segments with good image quality and larger FOV, unlike prenatal ultrasonography. It is really helpful to visualise blood flow in the whole fetal heart, allowing for a comprehensive assessment of fetal circulation.

RECOMMENDATION

Future research should prioritise the development of standardised fetal MRI imaging protocols that include optimised imaging sequences, acquisition parameters and safety recommendations across different gestational ages. Large multicenter studies are needed to validate these protocols and establish consensus guidelines that improve diagnostic accuracy and reproducibility. Integration of advanced MRI techniques and artificial intelligence-based image analysis should be explored to enhance prenatal diagnosis while reducing examination time and motion artifact. Such efforts will support wider clinical implementation and improve maternal and fetal outcomes.

LIMITATIONS

As Fetal MRI technology continues to evolve with advances in faster acquisition techniques and artificial intelligence-assisted imaging, some recommendations presented in this review, such as MRI sequences, may require future revision as higher quality evidence and updated international consensus guidelines become available.

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