Magnetic resonance imaging (MRI) is an alternative modality to evaluate the fetus. It uses no ionizing radiation, has excellent tissue contrast, large field of view, is not limited by obesity or overlying bone, and can image the fetus in multiple planes no matter the fetal lie. Fetal MRI was initially attempted in the 1980s but was limited because of slow sequences requiring fetal and/or maternal sedation. Since then, the development of faster sequences has been fundamental in the success of imaging the moving fetus without the use of sedation.1–3 Faster scanning techniques now allow studies to be performed without sedation in the second and third trimesters with excellent tissue contrast, good signal-to-noise ratio (SNR), and minimal motion artifact.

Utility

With advances in fetal management, there is an increasing need for precise depiction of abnormalities. Ultrasound (US) remains the screening modality of choice in the assessment of the fetus. When additional information is needed, MRI is a useful adjunct in the assessment of complex fetal anomalies. The use of fetal MRI can help confirm or exclude the presence of lesions noted by US. MRI can demonstrate additional subtle anomalies not visualized by US that may alter outcome. These additional findings can aid in the planning of fetal intervention, delivery, and postnatal therapeutic planning as well as in counseling parents regarding long-term prognosis.

MRI has numerous advantages that make it a complementary study in the evaluation of the fetus. MRI, in comparison with US, is not limited by fetal lie, overlying maternal or fetal bone, obesity, or oligohydramnios. MRI offers excellent soft tissue contrast and multiplanar visualization of all organs. Evidence-based data for the performance of fetal MRI is strongest for CNS anomalies and for cases being considered for fetal intervention such as neural tube defects. Advanced techniques are being developed that may provide physiologic information, including fetal spectroscopy and functional MRI (see Chapter 6.3). Much research is currently being performed on the use of MRI to estimate lung volumes, particularly in cases of congenital diaphragmatic hernia as well as lung masses and lung hypoplasia.7,8 With the airway filled with fluid in fetal life, the use of MRI to estimate lung volumes, particularly in cases of congenital diaphragmatic hernia as well as lung masses and lung hypoplasia.7,8 With the airway filled with fluid in fetal life, the use of MRI to estimate lung volumes, particularly in cases of congenital diaphragmatic hernia as well as lung masses and lung hypoplasia.7,8

Motion comes mainly from the fetus, but also from the mother, with the airway filled with fluid in fetal life, MRI can directly visualize the larynx, pharynx, and trachea, assessing the need for ex utero intrapartum treatment (EXIT) procedure when an oral or neck mass is present compressing the airway.2,3 Various T1w, T2w, and echo planar sequences can distinguish blood, fat, meconium, and cartilage, increasing the accuracy of diagnosis. Large field of view with multiplanar capability enables other specialists as well as family members to better visualize and understand the abnormalities. The ability to view images as a team is a powerful tool in counseling families and planning potential interventions.4 Indeed, the ability to view images has pulled many specialists into fetology, including neonatologists, pediatric surgeons, neurosurgeons, neurologists, and urologists who may feel more comfortable reviewing MRI images.9–11 This team approach is particularly useful in planning fetal surgery or complex deliveries in cases of neck masses, sacrococcygeal teratomas, and conjoined twins. In addition, fetal studies can be used for postnatal surgical planning, decreasing the need for emergent studies in the unstable newborn.

Timing

MRI can be a useful adjunct when a targeted sonogram performed by an experienced sonographer raises questions that could benefit from further assessment. MRI may provide additional information when an abnormality is identified by US or when findings are equivocal and require clarification.4,11 The optimal timing of a fetal MRI depends on what questions need to be answered.

As the theoretical risk of MRI is potentially greatest during organogenesis, and the size of the developing fetus is so small early gestation, fetal MRI in the first trimester is not recommended.12–14 At times, owing to maternal indications, MRI has been performed with limited visualization of the embryo. Abnormalities are better visualized by US during this gestation.

From 12 to 16 weeks, fetal MRI remains limited because of the small size of the fetus, increased fetal motion, and the fact that some anomalies may have not yet evolved (such as cortical dysplasias).

MRI between 17 and 24 weeks’ gestation is useful to further evaluate or confirm findings noted on target sonograms that can impact pregnancy planning and intervention.

MRI in the third trimester is optimal for the assessment of anomalies, particularly of the cerebral cortex, owing to improved spatial resolution. Decreased motion, head engagement in the lower pelvis, and larger targets allow for advanced imaging such as spectroscopy, DTI, and fMRI. Later studies, however, risk identifying anomalies too late for optimal intervention. MRI studies performed in the second trimester may, at times, benefit from a follow-up exam in the third trimester, particularly those requiring complex delivery planning such as neck masses.

Limitations

Technical challenges include motion artifact, limited fast sequences, optimizing SNR, and lack of technical expertise. Motion comes mainly from the fetus, but also from the mother, who can be uncomfortable and anxious, making it difficult to obtain adequate images. The moving fetus makes obtaining appropriate planes challenging for the technologist, and repeat sequences are often required to obtain a quality image. If the MRI technologist is inexperienced, the physician will need to
help as complex anatomy can be confusing in a moving fetus, particularly when complex anomalies are distorting normal landmarks.

Fast scanning sequences are limited. T1- and T2-weighted sequences must be optimized to decrease the scanning time and motion artifact. Some sequences require the breath to be held to improve image quality (T1w). This can be difficult for a mother lying uncomfortably with diaphragms elevated by the gravid uterus. Fetal gating is currently not commercially available, limiting evaluation of the fetal heart. When fetal motion is problematic, particularly when polyhydramnios is present, dynamic steady-state free process (SSFP) can be useful.

Interpreting fetal MRIs can be challenging as structures are small and change with fetal maturation. Great care must be made when interpreting as well as performing these studies. Prognosis of abnormalities can be highly varied with limited long-term data available. This can make counseling difficult at times, even when anomalies are well delineated. Additional long-term follow-up studies are necessary to provide more accurate data for improved counseling.

SAFETY

While there is currently no evidence that fetal MRI produces harmful effects to the fetus, long-term safety has not been firmly established. There is a lack of consensus as to whether there are true risks to the fetus.12–16 Saunders16 noted in a review of the literature that while no adverse effects have been consistently demonstrated, the evidence is inconclusive, numbers are small, data variable with potential confounders, and few studies include data obtained at fields greater than 1 T.

Several potential safety issues have been raised. These include acoustic damage and teratogenic effects due to torque, acceleration by the static field, nerve stimulation by the gradient fields, and/or tissue heating by radio frequency (RF) fields.12–18

In terms of acoustic damage, MRI produces a loud tapping noise when coils are exposed to rapidly oscillating electromagnetic currents. Initially, concern was raised regarding potential acoustic damage to the developing ear. A study by Baker et al.19 suggested that hearing was preserved but sample size was small. A study in 1995 simulated the acoustic environment of the gravid uterus by passing a microphone through the esophagus of a volunteer. This demonstrated a sufficient attenuation of sound to an acceptable level not harmful to the developing fetus.20

Some studies have raised the concern for teratogenic effects of MRI when performed early in pregnancy, secondary to the heating effect of MRI gradient changes and a direct nonthermal interaction of the electromagnetic field.16,21,22 Static magnetic fields produce short-term high-field exposure to the patient from 0.2 to 3 T and long-term low-field exposure to MRI staff (0.5 mT to 200 mT). Animal studies have demonstrated effects such as a decrease in crown rump length when mice were exposed to MRI in mid-gestation23; eye malformations in genetically predisposed mice25; and demise of chick embryos when exposed to strong magnetic fields.12 These studies are not applicable to humans and cannot be extrapolated, but they do raise concerns.

RF fields generate heat and are measured by specific absorption rate (SAR). Mathematical models on simulations have identified RF levels that are tolerable to humans; however, fetal dosimetry is only now being developed.23–25 Fast sequences use high-specification magnetic field gradients. Db/dt exposure needs to be further researched not only in adults but in the fetus as well. Murbach et al.26 investigated whether children and fetuses were at higher risk than adults when current RF regulations were applied. In their limited series, they noted local exposure was smaller for children and fetuses than adults. Local thermal load, however, could be increased to the fetus because of high exposure average of the nonperfused amniotic fluid.17

Effective exposure time during a fetal MRI has not been well studied, making estimation of RF deposition and noise exposure difficult. Brugger and Prayer noted that actual imaging time accounts for only about 33% of total study time. Exposure time is not continuous with the remaining time taken up by repositioning of the coil/mother and planning sequences.20

Kanal et al.27 produced a worker survey on female MRI technologists concerning low-field exposure. There were over 1,900 responses with no statistically significant associations revealed. While several series have described no adverse long-term effects of fetal MRI in children imaged as fetus, the samples have been small, and no long-term studies are currently available regarding higher strength magnets greater than 3 T.19,20,28–32

It is unknown whether higher magnet strengths and prolonged imaging times may have biological effects if applied at sensitive stages of development. The United States’ Food and Drug Administration (US FDA) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommend performing studies with caution, including a close control of SAR values.12–14 In the United Kingdom, the Medical Device Agency (MDA) guidelines require SAR to be a maximum of 10 W per kg.31,32

With no conclusive documentation of deleterious effects of MRI at 1.5 T, no specific recommendations may be required for any trimester in pregnancy.33 Pregnant patients should undergo an MRI, if the attending radiologist determines a need, and benefits outweigh any potential risks. However, with the advent of 3 T and higher Tesla magnets, radiologists should be aware of increased power deposition with high-field studies and make sure established guidelines are not exceeded.34–37

Gadolinium

MRI contrast agents should not be routinely administered to the pregnant patient. While there are no specific fetal indications for the use of MRI contrast, rarely, contrast may be needed for assessing maternal pathology.

The use of intravenous gadolinium and its toxic effects to the fetus has been tested in animals, but not adequately in humans. Gadolinium crosses the placenta and is excreted in urine by the fetus and later reabsorbed/swallowed, prolonging the elimination time.38–44 When excreted into the amniotic fluid, the gadolinium chelate molecules may remain for an indeterminate amount of time before being eliminated. The longer the chelate molecule remains in the amniotic fluid, the greater the potential of dissociation of the gadolinium ion from its chelate molecule. The impact of free gadolinium ion on the human fetus remains unclear.45

In a study with rabbits, a high concentration of gadolinium was noted 5 minutes after its administration, with a subsequent decrease of 50% after 60 minutes.41,43 At high (two to seven times the dose used in humans) and repeated doses, teratogenic effects (including growth retardation, visual problems, and bone and visceral anomalies) have been described in animals.38,41–43 No carcinogenic or mutagenic effects have been
noted.\textsuperscript{38} Other preclinical studies using contrast have not shown negative effects on the fetus, including detectable chromosomal damage, abortions, stillbirth, and grossly detectable anomalies, even at 11 to 16 times the clinical dose.\textsuperscript{38}

In the human fetus, the concentration of gadolinium in different organs is low, except for the kidneys, which show an increase in concentration over the first 60 minutes.\textsuperscript{38,44} A few human clinical studies using contrast have been performed with no adverse effects to the fetus or neonate, even when given during the first trimester.\textsuperscript{38} When clinical doses have been administered, side effects have not been observed.\textsuperscript{46,47} However, as contrast may remain within the amniotic fluid for long periods of time, unless absolutely needed, its use is not recommended during pregnancy, particularly during the early period of organogenesis. Use of gadolinium late in gestation may be appropriate for specific maternal or obstetric indications. The decision to administer MRI contrast to the pregnant patient should be well documented with thoughtful risk to benefit analysis. Benefits should outweigh theoretical risks of fetal exposure to free gadolinium ions.\textsuperscript{38,45}

### TECHNIQUE

#### Patient Positioning (Table 6.1-1)

The patient should go through appropriate metal screening. Heavy clothing should be removed and light gowns offered to increase comfort during the study. The bladder should be emptied just prior to getting on the scanner.

The patient can lie either supine with a pillow under her knees, or in a decubitus position. The left lateral position has been thought to reduce the risk of vena cava compression syndrome. However, a study by Kienzl et al. has suggested that vena cava compression syndrome is actually rare during MRI scanning in the supine position. Despite narrowing of the IVC, there appear to be physiologic compensatory mechanisms.\textsuperscript{48} Nonetheless, the lateral decubitus position can have additional advantages. It can help in patients with back pain or sciatica, or in the third trimester when the mother may have shortness of breath lying supine because of elevation of the diaphragm.

Because of claustrophobia, patients prefer to go into the bore of the magnet feet first. This allows the uterus to be in the center of the bore with their head at the level of the flanged opening so they can see out into the room. Having a family member accompany the mother into the scanning room can be helpful. If the mother is anxious, holding her hand may be calming. An alarm ball or other method of direct communication to the technologist should be offered to the mother. Listening to music or watching a movie is a useful distraction technique. If a patient is extremely claustrophobic or anxious, oral sedation and/or oxygen supplementation may be required.

#### Coils

Depending on the size of the mother and fetal gestation, either a torso or cardiac-phased array surface coil is placed over the gravid uterus. One or two flexible phased array surface coils can be wrapped over the patient sandwiching the uterus between the table-top coils and surface coils.\textsuperscript{49} Elements closest to the uterus can then be selected, which can increase the SNR ratio. If the patient is too large to fit into the magnet with a surface coil, the coil intrinsic to the magnet may be used. Large bore magnets are particularly advantageous when the BMI is high or there are multiple gestations.

#### Imaging Protocol (Table 6.1-2)

The development of single-shot rapid acquisition with relaxation enhancement sequences has been key to decreasing fetal and maternal movement artifact. A series of images can be performed in as little as 15 to 20 seconds. Slices are acquired one at a time, each slice produced in less than 400 milliseconds by a single excitation pulse. Examination times overall average 20 to 40 minutes, depending on how many sequences have to be repeated owing to fetal movement and protocol.

An initial three-plane localizer sequence should be performed. This will demonstrate the cranial and caudal extent of the uterus, and can be followed with T2-weighted Half Fourier Single-Shot Echo (SSFSE/Haste/ssTSE/Fast FE) (Table 6.1-2), large FOV,\textsuperscript{36–48} thick (5 to 10 mm) sections through the entire uterus, coronal to the mother. This can be followed by T2w SSFSE or SSFP sagittal and/or axial planes of the maternal pelvis. These sequences will allow assessment of fetal lie, placental position and signal, cervix, and fetal situs. These sequences also help determine whether the surface coils need to be repositioned to get the best signal from the fetal anatomy in question.

At this point, there are several ways to get into a fetal orthogonal plane. Advanced technology allows user selection of three points within the images that will appear on the same plane in the next sequence. For example, two points can be selected in the lumbar spinal canal, and one at the umbilicus, which would result in a perfect sagittal stack. If this technology is not available, it is possible to pick two points that are symmetric on either side of the body, for example, the orbits and place the center “eye” of the stack on the one point, then page through the images until the second point is visible and rotate the stack so that the center line passes through the second point. This will result in images between axial and coronal, from which a perfect sagittal can then be obtained.\textsuperscript{50}

#### Table 6.1-1 Fetal MR Technique Tips

- USE the largest bore magnet available.
- POSITION the patient so she is comfortable, feet first.
- USE distracting techniques. Have a family member accompany the patient in the scanner.
- PLACE a surface coil when possible. Multichannel better, more elements better. Two surface coils work well in series, especially with larger patients.
- LOCALIZE to the uterus with a large field of view. Check cervical length and placental location.
- REDUCE field of view.
- 3-Point PLAN a standard plane in the fetus.
- HAVE a protocol planned, but remain flexible with order of sequences. Acquire the sequences most likely to answer the question first. Consider leaving the lowest sequences and breath-hold sequences until last. If there is significant fetal motion, consider repeating a key sequence until the fetus rests, or use dynamic SSPE.
- OBTAIN images of the entire fetus.
- REVIEW images with the technologist before ending the exam.
Because the fetus continues to move throughout the study, each sequence is typically planned using a plane perpendicular to the prior sequence. Images of the head then body or vice versa should be protocolled depending on which anomaly needs to be evaluated first. In the sagittal and coronal planes, the entire head, chest, and abdomen can often be included particularly in earlier gestation. Dedicated axial sequences of the fetal brain and abdomen, however, are typically needed for optimal image interpretation. At times, the fetus will move but then quickly return to its initial position. Therefore, it can be helpful to simply repeat the sequence without changing parameters. If the fetus truly has moved into another position, the above techniques can be used to rapidly get another appropriate orthogonal plane.

Quiet maternal breathing is typically adequate; however, breath-hold techniques are needed for certain series, particularly T1w gradient-echo (GRE) sequences. Breath-holding can be useful if the fetus is breech, when the maternal diaphragmatic motion is more readily transmitted to the fetus. Breath-holding is successful only if the length of the sequence is relatively short, less than 20 seconds. Allowing the mother to gently release the breath-hold toward the end of the series can help if the sequence is longer than this.

Phase oversampling is often used in fetal MRI. It has the advantages of reducing the field of view to include just the fetus and exclude maternal anatomy by eliminating phase-wrap, and it also increases the SNR, which can be particularly important early in gestation when the fetus is small. The disadvantage is that it increases the scan time according to the number of phase-encoding steps. If this is problematic, the phase oversampling ratio can be reduced or turned off completely. This will result in phase-wrap, but with careful positioning and sizing of the field of view, often the maternal structures will only phase-wrap into the maternal structures on the opposite side of the body, and not overlie onto the fetal anatomy.

When scanning the fetus, a smaller 24- to 30-cm FOV should be used. Slices as thin as 2 to 3 mm can be obtained; however, the smaller the slice thickness, the lower the SNR. In larger fetuses, slice thicknesses of 4 to 6 mm work well, decreasing time per series and improving signal.

A typical matrix size is 256 px. Counterintuitively, increasing the matrix size in the attempt to increase in-plane resolution will typically have the opposite effect because of loss of signal from smaller voxels. This can be partly countered by increasing the slice thickness but results in more volume-averaging.

T2-weighted half Fourier single-shot echo sequences (SSFSE/HASTE/ssTSE/ssFSE/FASE) (Table 6.1-2) provide the highest SNR and resolution, and are fast. Slices as thin as 2 to 3 mm with no skip can be obtained; however, the smaller the slice thickness, the lower the SNR. In larger fetuses, slice thicknesses of 4 to 6 mm work well, decreasing time per series and improving signal.

A typical matrix size is 256 px. Counterintuitively, increasing the matrix size in the attempt to increase in-plane resolution will typically have the opposite effect because of loss of signal from smaller voxels. This can be partly countered by increasing the slice thickness but results in more volume-averaging.

**Table 6.1-2**  
**Vendor Sequences Used in Fetal MRI**

<table>
<thead>
<tr>
<th>Sequence Type</th>
<th>GE (Milwaukee, WI)</th>
<th>Siemens (Erlangen, Germany)</th>
<th>Philips (Eindhoven, The Netherlands)</th>
<th>Hitachi (Twinsburg, OH)</th>
<th>Toshiba (Otawara, Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Fourier single-shot echo (T2w)</td>
<td>SSFSE</td>
<td>HASTE</td>
<td>SSTSE</td>
<td>SSFSE</td>
<td>FASE</td>
</tr>
<tr>
<td>Steady-state free precess (SSFP) (T2w)</td>
<td>FIESTA</td>
<td>TruFISP</td>
<td>Balanced FFE</td>
<td>Balanced SARGE</td>
<td>True SSFP</td>
</tr>
<tr>
<td>Spoiled gradient echo (T1w)</td>
<td>SPGR</td>
<td>FLASH</td>
<td>T1-FFE</td>
<td>RF spoiled SARGE, RSSG</td>
<td>FastFE</td>
</tr>
<tr>
<td>3D ultrafast (T1w)</td>
<td>3D FGRE, 3D Fast SPGR</td>
<td>MPRAGE</td>
<td>3D TFE</td>
<td>MPRAGE</td>
<td>3D Fast FE</td>
</tr>
<tr>
<td>Ultrafast gradient echo</td>
<td>Fast GRE, Fast SPGR</td>
<td>Turbo FLASH</td>
<td>TSE</td>
<td>RGE</td>
<td>FastFE</td>
</tr>
<tr>
<td>Rapid acquisition relaxation enhancement</td>
<td>FSE</td>
<td>TSE</td>
<td>TSE</td>
<td>FSE</td>
<td>FSE</td>
</tr>
<tr>
<td>Diffusion-weighted imaging</td>
<td>DWI</td>
<td>DWI</td>
<td>DWI</td>
<td>DWI</td>
<td>DWI</td>
</tr>
<tr>
<td>Diffusion tensor imaging</td>
<td>Diffusion tensor imaging</td>
<td>DTI</td>
<td>Diffusion tensor imaging</td>
<td>DTI</td>
<td></td>
</tr>
<tr>
<td>Echo-planar imaging</td>
<td>EPI</td>
<td>EPI</td>
<td>EPI</td>
<td>EPI</td>
<td>EPI</td>
</tr>
<tr>
<td>Susceptibility-weighted imaging</td>
<td>SWAN</td>
<td>SWI</td>
<td>SENSE</td>
<td>RAPID</td>
<td>SPEEDER</td>
</tr>
<tr>
<td>Parallel imaging</td>
<td>ASSET</td>
<td>iPAT, mSENSE</td>
<td>SENSE</td>
<td></td>
<td></td>
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</tbody>
</table>

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Steady-state free precession (SSFP/FIESTA/True FISP/Balanced FFE/Balanced SARF/True SSFP) images demonstrate bright blood imaging. The cardiac chambers and great vessels may be discreetly identified. Images can be obtained in all three planes at 3- to 4-mm increments. This sequence is also quite useful for the assessment of fluid-filled structures such as dilated renal collecting systems or cystic masses. Because of its high contrast, inner ear anatomy, clefts of the palate, and fluid surrounding the spinal cord are particularly well demonstrated. Extremities are outlined by the amniotic fluid with fingers and toes often visualized. There is less contrast between gray and white matter in the brain and meconium in the abdomen due to lower flip angles and banding artifacts.

Thick slab T2w are useful for assessing fetal surface contours. Thick slab acquisitions of 40 to 60 mm give an overall three-dimensional (3D) effect. Transparency is increased using shorter echo times or by using SSFP sequences that can similarly be acquired with thick slices. To maximize SNR, overlapping slices of 5- to 6-mm thickness can be used; however, this approach typically makes this sequence less useful for volumetry. These images can be useful for parents and health care workers not used to evaluation of two-dimensional (2D) anatomy.54

T1-weighted sequences are fast multiplanar spoiled gradient recall acquisitions in the steady state (SPGR/FLASH/T1-FFE/Fast FE) sequences (Table 6.1-2) require breath-hold with thicker slices (5-7 skip 0) for sufficient SNR. It can be useful to perform a T1 sequence immediately after a T2 sequence with the same slice parameters so they can be directly compared. T1-weighted images are particularly useful for detecting hemorrhage, calcification, meconium, thyroid tissue, and fat.

Dynamic SSFP sequences (Cine, real time) can be used to assess fetal movements. Multiple frames per second can be obtained at each slice with slice thicknesses ranging from 7 to 50 mm. Assessment of fetal breathing, swallowing, cardiac motion, and gastrointestinal activity is possible. When there is a burst of fetal activity that precludes use of other imaging sequences, it can be a useful backup sequence. When the fetus settles down, other sequences can then be acquired.

Echoplanar imaging (EPI) is useful in assessment of the musculoskeletal system with high-signal cartilage and low-signal bone. The fetal liver has significant hypointense signal, while other organs are intermediate in signal. Flow voids make vessels and heart hypointense. Susceptibility-weighted imaging can be used to detect hemorrhage and calcification.

Long-Tau inversion recovery sequences can be useful to further characterize fluid that appears high-intensity on T2-weighted imaging, but that may contain proteinaceous fluid such as hemorrhage.

Diffusion-weighted sequences (DWI) can be acquired with three phase-encoding directions. The area of interest should be as centered as possible. DWI can demonstrate ischemic lesions in white matter. It can be used in the identification of renal tissue, particularly if kidneys are not visible sonographically or by routine MRI. Advanced imaging with spectroscopy and diffusion tensor imaging is becoming available and is discussed in Chapter 6.3.

Whatever the indication for the fetal MRI, the entire fetus from head to toe should be examined. Fetal pathologies and malformations frequently involve multiple organs. Thus, identification of other anomalies can further elucidate an underlying genetic or chromosomal syndrome.

Because of the risk of maternal fatigue, anxiety, or discomfort, it is important to complete the study as quickly and efficiently as possible. Protocols should be well thought out prior to placing the mother on the scanner. If a brain anomaly is present, planes angled to the brain should first be obtained, then sequences angled to the chest and abdomen. Most protocols benefit from a combination of T2-weighted sequences (SSFSE and/or SSFP) in all three planes and T1-weighted imaging in at least one plane.

Postprocessing

Volumetry of fetal organs by MRI has become a useful tool, particularly in the determination of fetal lung volumes (see Chapter 17). A region of interest can be manually segmented and its total area multiplied by the slice thickness to calculate volumes. Continuous motion-free images are needed for accurate volumetry. Sequences may need to be repeated to ensure continuity of images if volumes are to be obtained. Spatial resolution of reformatted images can be limited owing to large slice thickness. Advanced methods to develop 3D volume images are being developed so that even when motion occurs, accurate data can be generated (see Chapter 6.3).6

Three-dimensional virtual model reconstruction using techniques such as stereolithography or fused deposition modeling can create life-size physical models using T2w MRI data.55,56

3 Tesla MRI

As the push for improved resolution and increased signal continues, and more 3 T scanners become available for use, centers have begun to address the use of 3 T scanners for fetal imaging. The use of 3 T magnets, however, represents another technical challenge with its increased susceptibility to motion artifact and the need to closely follow SAR limits.35,37

The US FDA approved the use of 3 T for human use in 2002. Advantages include improved SNR at higher strengths as more protons are available to increase magnetization. The gain of SNR may be up to 1.7 to 1.8 times that of 1.5 T.37,57 Image quality, temporal and/or special resolution can thus be improved. With greater SNR, parallel imaging can be implemented to speed SSFSE protocols, reduce echo time, and potentially decrease RF heating by decreasing the number of pulses required.37

With 3 T, unfortunately, more artifacts are encountered. RF field inhomogeneity is a major challenge, with the larger field of view, the worse the artifact. RF shielding artifact “conductivity effect” from amniotic fluid results in blackout areas often where the fetus is lying. Dielectric pads, RF cushions, or saline pads can help decrease these dielectric resonance artifacts.57,58 Multichannel transmission coils, RF shimming with parallel imaging may also help decrease RF field inhomogeneity.

Magnetic susceptibility artifacts and chemical shift artifacts are also accentuated with 3 T requiring additional modifications. Changing the field of view, scan orientation, frequency, or bandwidth may move the artifact away from the fetal area of interest.

The US FDA limits of exposure to changing magnetic fields are independent of magnetic field strength. FDA safety limits prevent exposure to changing magnetic fields (dB/dt) of more than 60 T per second with failsafe software limiting scanners from exposures above these limits. With the fetus near the center of the FOV exposure, dB/dt changes are usually low with slew rates similar at both 1.5 and 3 T.37-39
RF pulses deposit energy into the imaged subject. The energy deposition is measured by the SAR reported in Watts per kilogram. The amplitude of applied RF fields increases with increasing magnetic field strength and quadruples from 1.5 to 3 T. Decreasing number of slices, lowering flip angles, increasing repetition time, and shorter echo train length can decrease SAR. The FDA safety limits are set at 4 W per kg independent of magnetic field strength with failsafe controls prohibiting additional exposure. Studies by Victoria et al.37 have demonstrated SAR well below whole body exposure limits for both 1.5 and 3 T. Focal SAR hotspots are of concern because of RF field inhomogeneity, dielectric, and standing wave effects. Modeling of fetal environment by Hand et al.25,59 suggests that maximum energy deposited to the fetus is a fraction of that received by the mother. The fetus may be exposed to a peak of 50% to 70% of maternal SAR at 3 T. In their study, average temperature of the fetus remained below 38°C. However, they noted that continuous exposures over 7.5 minutes can exceed the 38°C limit, so long continuous exposures should be avoided.59 While 3 T has inherent artifact issues and potential increased safety risks, limiting SAR levels to those associated with 1.5 T and developing methods to decrease inhomogeneity appear to be feasible and will likely continue to progress.

**Indications (Table 6.1-3)**

Fetal MRI is a valuable complement to prenatal US. Because of higher contrast resolution, large field of view, and ability to image both sides of the fetus at once, fetal MRI can be more precise than US for anatomic evaluation. There are multiple indications for performing a fetal MRI, some of which are listed in Table 6.1-3. As MRI technology advances, additional indications will continue to develop, many described in the chapters in this book.

<table>
<thead>
<tr>
<th>Table 6.1-3 Fetal MRI Indications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brain</strong></td>
</tr>
<tr>
<td>Congenital anomalies such as ventriculomegalgy, agenesis of the corpus callosum, holoprosencephaly, posterior fossa anomalies, cortical dysplasias, tuberous sclerosis, lissencephaly, microcephaly, family history</td>
</tr>
<tr>
<td>Vascular abnormalities such as malformations, infarctions, hydranencephaly, twin-to-twin complications</td>
</tr>
<tr>
<td>Craniosynostosis</td>
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<tr>
<td>Tumors</td>
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<tr>
<td>Infection</td>
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<tr>
<td><strong>Spine</strong></td>
</tr>
<tr>
<td>Neural tube defects/vertebral anomalies</td>
</tr>
<tr>
<td>Sacrococcygeal teratoma</td>
</tr>
<tr>
<td>Caudal regression/sirenomelia</td>
</tr>
<tr>
<td><strong>Face and neck</strong></td>
</tr>
<tr>
<td>Facial and palatal clefts, micrognathia, dacroccystocele, anophthalmia</td>
</tr>
<tr>
<td>Masses—lymphatic malformations, hemangioma, teratoma, goiter</td>
</tr>
<tr>
<td>Airway obstruction</td>
</tr>
<tr>
<td><strong>Thorax</strong></td>
</tr>
<tr>
<td>Masses—congenital pulmonary airway malformations, congenital diaphragmatic hernia, effusions</td>
</tr>
<tr>
<td>Lung hypoplasia—oligohydramnios, skeletal dysplasia</td>
</tr>
<tr>
<td>Cardiac—heterotaxy</td>
</tr>
<tr>
<td><strong>Abdomen</strong></td>
</tr>
<tr>
<td>Masses/cysts</td>
</tr>
<tr>
<td>Complex ventral wall defects</td>
</tr>
<tr>
<td>Genitourinary anomalies/cloaca</td>
</tr>
<tr>
<td>Bowel anomalies</td>
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<tr>
<td><strong>Musculoskeletal</strong></td>
</tr>
<tr>
<td>Limb anomalies</td>
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<tr>
<td>Muscle abnormalities</td>
</tr>
<tr>
<td>Soft tissue masses—lymphangiommas, hemangiomas</td>
</tr>
<tr>
<td>Skeletal dysplasia</td>
</tr>
<tr>
<td><strong>Twins</strong></td>
</tr>
<tr>
<td>Monochorionic, twin-to-twin complications</td>
</tr>
<tr>
<td>Conjoined</td>
</tr>
<tr>
<td><strong>Fetal intervention/surgery</strong></td>
</tr>
<tr>
<td>EXIT procedures for airway obstruction</td>
</tr>
<tr>
<td><strong>Delivery planning</strong></td>
</tr>
<tr>
<td>Congenital diaphragmatic hernia repair</td>
</tr>
<tr>
<td><strong>Postnatal surgical planning</strong></td>
</tr>
<tr>
<td>Myelomeningocele repair</td>
</tr>
<tr>
<td>Complex lesions requiring immediate neonatal surgery</td>
</tr>
<tr>
<td><strong>Maternal</strong></td>
</tr>
<tr>
<td>Placenta implantation abnormalities</td>
</tr>
<tr>
<td>Poor evaluation due to obesity/oligohydramnios</td>
</tr>
</tbody>
</table>
MRI features include uterine bulging, heterogeneous placental signal, and dark intraplacental bands. Some studies have used intravenous gadolinium contrast to assess for accreta, though the use remains controversial due to safety concerns. If contrast is being considered, the study should be timed as close to delivery as possible.

Cervical length can be measured in the sagittal plane with location of placenta in relation to the cervix best noted on this view. While MRI volumetry of amniotic fluid can be calculated, simple estimation of amniotic fluid is usually adequate. Uterine synechia and amniotic sheets may be well visualized in all three planes (Figs. 6.1-4 and 6.1-5).

The number of umbilical vessels is best determined in a transverse plane either by SSFSP or SSFP. The two umbilical arteries can be followed as they course along the fetal bladder. Placental cord insertion as well as fetal cord insertion should be identified with note made of length and configuration of the umbilical cord (Fig. 6.1-6).

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The sagittal midline plane is important for assessing the facial profile, including the nose, chin, and soft palate (Fig. 6.1-7). Fluid motion may be seen because of fetal exhalation. Coronal planes of the face are useful in assessing symmetry of the face, lips (for clefts), orbits, and nose (Fig. 6.1-8). External ears should be evaluated for their presence, location, and shape. Axial plane of the maxilla demonstrates tooth buds as a continuous arc (Fig. 6.1-9). The primary palate is triangular and includes the alveolar ridge. The secondary palate includes the remaining hard and soft palates.

Table 6.1-4  Fetal Face

<table>
<thead>
<tr>
<th>Anatomy</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craniofacial ratio, profile</td>
<td>Sagittal T2w SSFSE, SSFP</td>
</tr>
<tr>
<td>Nose</td>
<td>Sagittal, coronal T2w SSFSE, SSFP</td>
</tr>
<tr>
<td>Lips, palate, teeth</td>
<td>Coronal, axial T2w SSFSE, SSFP</td>
</tr>
<tr>
<td>Pharynx</td>
<td>Sagittal T2w SSFSE, SSFP</td>
</tr>
<tr>
<td>Swallow, breathing</td>
<td>Sagittal dynamic SSFP</td>
</tr>
</tbody>
</table>

SSFSE, single-shot fast spin-echo sequences; SSFP, steady-state free precession sequences.

**Face (Table 6.1-4)**

Situs
Fetal orientation should be evaluated on the basis of fetal and maternal anatomy using the initial large FOV sequences. Identifying the location of the fetal heart and stomach may not automatically identify the left side of the fetus in cases of heterotaxy.

Brain (see Chapters 6.2 and 6.3)
Coronal, axial, and sagittal orthogonal planes should be acquired with T2-weighted sequences. T1-weighted and diffusion-weighted sequences may provide additional information. Long-Tau inversion recovery, spectroscopy, volumetric data, and DTI are advanced techniques that may be useful in cranial assessment and are described further in Chapter 6.3.

**FIGURE 6.1-5:** Amniotic bands. Numerous thin sheets *(curved arrow)* are adjacent to the fetal face. There were limb deformities, but no facial cleft was noted.

**FIGURE 6.1-6:** Placental cord insertion. Sagittal SSFP image of a gravid uterus demonstrates an anterior placenta with central cord insertion *(black arrow)*. Note the closed cervix *(curved white arrow)*.

**FIGURE 6.1-7:** Fetal profile: Sagittal SSFP midline image demonstrates fetal lips, chin, soft palate, and pharynx: 21 weeks GA *(A)*, 32 weeks GA *(B)*.

**FIGURE 6.1-8:** Fetal face coronal SSFSE. A: 21-week gestation demonstrates orbits, nose, and mouth. B: Slightly more superficial coronal section at 29 weeks' gestation demonstrates intact lip and nares.
Fetal Magnetic Resonance Imaging

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**Table 6.1-5**  Fetal Neck

<table>
<thead>
<tr>
<th>Anatomy</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larynx, trachea</td>
<td>Sagittal, coronal, axial T2w SSFSE, SSFP</td>
</tr>
<tr>
<td>Thyroid</td>
<td>Axial, coronal T1w GRE</td>
</tr>
<tr>
<td>Vessels</td>
<td>Axial, coronal, sagittal SSFP, GRE</td>
</tr>
</tbody>
</table>

SSFSE, single-shot fast spin-echo sequences; SSFP, steady-state free precession sequences; GRE, gradient echo sequences.


Neck (Table 6.1-5)

Axial and sagittal T2w best detect the fluid-filled larynx and trachea. Epiglottis and laryngeal folds are typically noted only in the late second and third trimester (Fig. 6.1-10). The cervical esophagus is usually not seen unless caught during a swallow. The thyroid gland is poorly seen on T2w, but is high signal on T1w imaging from 18 weeks GA onward (Fig. 6.1-11). Cervical vessels can be identified on all three planes using SSPE sequences (Fig. 6.1-12).

**Thorax (Table 6.1-6)**

Fetal lungs increase in volume throughout gestation and can be measured with MRI volumetry. Normal lung volumes have been documented by MRI as demonstrating growth proportionate to fetal body size.

**Figure 6.1-9:** Fetal face axial SSFSE at 29 weeks’ gestation demonstrates the maxilla with tooth buds in a continuous arc.

**Figure 6.1-10:** Sagittal SSFP at 32 weeks’ gestation demonstrates the larynx, epiglottis, and trachea.

**Figure 6.1-11:** Coronal T1w at 29 weeks’ gestation demonstrates high-signal thyroid glands (*curved arrow*), high-signal meconium in the transverse colon, and intermediate signal liver.

**Figure 6.1-12:** Coronal SSFP at 32 weeks’ gestation demonstrates bilateral subclavian and jugular veins as well as superior vena cava.
The trachea, carina, and bronchi are often seen filled with fluid on T2w. Repeating sequences with thinner slices may be required for adequate evaluation as needed (Fig. 6.1-13).

Lung parenchyma is homogeneously brighter than muscle on T2w and increases in signal after 24 weeks’ gestation, while T1w signal decreases with gestational age (Fig. 6.1-14). Apparent diffusion coefficient has been used in addition to T2w signal to assess lung maturation.71

The diaphragms are dome-shaped bands between the lungs and the abdomen. They have low signal on T2w, slightly lower than adjacent liver. Breathing may be noted on dynamic SSFP sequences. The esophagus is rarely seen unless caught during a swallow (Fig. 6.1-15). If an atresia is present, fluid may be identified proximal to the obstruction, but is not a constant finding. Thick dynamic SSFP sequences in the sagittal midline plane may best demonstrate transient dilatation of a proximal esophageal pouch.

The thymus is homogeneous, intermediate signal in the anterior mediastinum. It is best seen in the third trimester and should not have any mass effect on adjacent vessels or the trachea (Fig. 6.1-16).
The heart is low signal on T2w SSFSE due to flowing blood. This sequence is limited to identification of the position and size of the heart. SSFP sequences are more useful in delineating the myocardium, septum, and valves (Fig. 6.1-17). Dynamic SSFP sequences can demonstrate cardiac motion. These sequences may be particularly useful in cases of oligohydramnios and maternal obesity when fetal echocardiography may be limited. While ultrasound remains the primary method of assessing fetal heart dynamics, Chapter 6.4 describes advances in cardiac MRI that may provide additional information.

**Abdomen (Tables 6.1-7 and 6.1-8)**

The fetal abdomen is well visualized by MRI with progressive changes as gestation advances. The dominant fluid-filled abdominal structures throughout the second and third trimesters include the stomach, gallbladder, and bladder (Fig. 6.1-18). The stomach is a fluid-filled structure in the left upper quadrant, high signal on T2w, and low signal on T1w. While the stomach may be transiently small, it should always be seen during a 30-minute scan.
Before 25 weeks' gestation, small bowel is typically collapsed containing minimal fluid. In the third trimester, small bowel becomes fluid-filled, high signal on T2w and low signal on T1w (Fig. 6.1-19). Meconium, which is typically low signal on T2w and high signal on T1w likely because of protein and/or paramagnetic minerals, initially fills the rectum at 19 to 20 weeks' gestation. There is progression from the rectum to the descending colon by 22 to 23 weeks. Meconium will variably extend to the transverse and ascending colon during the third trimester with continuous colonic filling closer to term (Fig. 6.1-20) (see Chapter 18.1). MRI can provide information regarding level of bowel obstruction if present and assess size of colon in later gestation.

The liver is homogeneous low to intermediate signal on T2w, slightly high signal on T1w (Fig. 6.1-21) (Table 6.1-8). Iron causes low signal on T2w. Thus, early in gestation when there is a large amount of iron bound to fetal hemoglobin in the liver, parenchyma is relatively low in signal best assessed by echoplanar sequences. By the third trimester, there is less iron, a change that can help assess fetal physiology. Splenic signal changes may also be noted on echoplanar sequences, possibly due to red pulp volume in the third trimester. The spleen is noted posterior to the stomach, best seen on sagittal and axial images. The two hepatic lobes are equal in size with the ductus venosus and portal vein noted best on SSFP sequences.

MRI appearance of the fetal gallbladder is variable. Signal intensity changes over time, likely due to accumulation
an otherwise normal gallbladder. When the gallbladder is not visualized in the second trimester, diagnosis of biliary atresia, particularly in cases of heterotaxy, should be considered. Cystic fibrosis should also be included in the differential.

The cord insertion is best visualized by axial or sagittal SSFSE or SSFP sequences (Fig. 6.1-22). In the third trimester, the cord insertion may be difficult to identify owing to overlying limbs.

Table 6.1-8 T1 and T2 Appearance of Organs

<table>
<thead>
<tr>
<th>T2w</th>
<th>T1w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbits (vitreous)</td>
<td>High signal</td>
</tr>
<tr>
<td>Nasopharynx, oropharynx, trachea</td>
<td>High-signal lumen, low-signal wall</td>
</tr>
<tr>
<td>Thyroid gland</td>
<td>Intermediate signal</td>
</tr>
<tr>
<td>Thymus</td>
<td>Intermediate signal</td>
</tr>
<tr>
<td>Lungs</td>
<td>Intermediate signal, increasing with GA</td>
</tr>
<tr>
<td>Aorta, heart, vessels</td>
<td>Low signal (flow void)</td>
</tr>
<tr>
<td>Stomach</td>
<td>High signal</td>
</tr>
<tr>
<td>Fluid-filled bowel</td>
<td>High signal</td>
</tr>
<tr>
<td>Meconium</td>
<td>Low signal</td>
</tr>
<tr>
<td>Liver, spleen, gallbladder</td>
<td>Low or high signal second trimester, intermediate or high signal third trimester</td>
</tr>
<tr>
<td>Kidneys</td>
<td>Cortex = intermediate signal</td>
</tr>
<tr>
<td></td>
<td>Medulla = slightly high signal</td>
</tr>
<tr>
<td>Bladder</td>
<td>High signal</td>
</tr>
<tr>
<td>Bone, cartilage</td>
<td>Low signal/high signal—EPI</td>
</tr>
</tbody>
</table>

Brugger et al. described T2w high signal exclusively in fetuses younger than 27 weeks' gestation. Lower signal gallbladders were noted only after 30 weeks' gestation and may cause nonvisualization of an otherwise normal gallbladder. When the gallbladder is not visualized in the second trimester, diagnosis of biliary atresia, particularly in cases of heterotaxy, should be considered. Cystic fibrosis should also be included in the differential.

The cord insertion is best visualized by axial or sagittal SSFSE or SSFP sequences (Fig. 6.1-22). In the third trimester, the cord insertion may be difficult to identify owing to overlying limbs.
Figure 6.1-20: T1w bowel. Coronal (A) and sagittal (B) images at 30 weeks’ gestation demonstrate high-signal meconium in the rectum, sigmoid, and descending colon.

Figure 6.1-21: Liver. Coronal SSFSE images of the liver and spleen at 17 weeks’ (A), 21 weeks’ (B), and 29 weeks’ (C) gestation.

Figure 6.1-22: Cord insertion. A: Axial SSFSE at 20 weeks demonstrates cord insertion (black arrow) at the ventral abdomen. B: Sagittal SSFP image at 32 weeks demonstrates cord insertion (straight arrow), inferior vena cava draining into the right atrium (white curved arrow) as well as the fluid-filled trachea and partially filled proximal esophagus (black arrow).
The genitourinary track requires assessment of the kidneys, adrenal glands, ureters, bladder, and genitalia. The fetal kidneys are relatively well seen early in the second trimester, intermediate in signal on T2w. Perinephric fat is high signal on T2w and can be mistaken for perirenal fluid. Fluid in the renal pelvis is well depicted separate from the renal tissue. With maturation, the renal cortex and the medulla become more differentiated (Fig. 6.1-23). Diffusion-weighted imaging is useful in identifying renal parenchyma, particularly if not in the expected location (Fig. 6.1-24). Apparent diffusion coefficient of the kidneys increases with advancing gestation. The adrenal glands are noted above the kidneys. In the early second trimester, the adrenal are hypointense on T2w and relatively well seen because of surrounding hyperintense perirenal fat (Fig. 6.1-23). They can be triradiate or lambda-shaped. As they grow becoming pyramidal in shape, they become higher in signal, becoming more difficult to visualize in the third trimester.

The ureters are typically not visualized. When dilated, sagittal and coronal SSFSE T2w and SSPE sequences help document level of ureteral insertion. Thick slab coronal imaging can simulate MRI urography (Fig. 6.1-25).

The bladder should always contain high-signal fluid on T2w sequences and should be identified some time during a 30-minute exam.

The uterus, vagina, ovaries, and prostate are not well separated from surrounding tissues. If ascites or an anomaly such as an ovarian cyst or hydrometrocolpos is present, they can be.
Genitalia. A: Axial SSFSE demonstrates labia at 33 weeks gestation. B: Oblique SSFP image of testes within the scrotal sacs (curved arrow) in this 32-week male fetus.

Musculoskeletal (Table 6.1-9)

While US remains the cornerstone of fetal skeletal assessment, MRI has become an important adjunct. Large FOV can help assess configuration of limbs, with thick slab delineating fetal surface contours (Figs. 6.1-27 and 6.1-28). Dynamic SSFP images may characterize extremity movement.

T2w sequences demonstrate skin and muscle. Muscle is relatively homogeneous hypointense on T2w so discreet muscles cannot be delineated. High signal or thin musculature may suggest an abnormality (Fig. 6.1-29). The subcutaneous tissue layer becomes more prominent as subcutaneous fat develops in the third trimester; high signal on T1w (Fig. 6.1-30). EPI sequences provide a way of evaluating bone (low signal) and cartilage (high signal) maturation (Fig. 6.1-31). With US only moderately accurate in the diagnosis of specific skeletal

Table 6.1-9  Fetal Musculoskeletal

<table>
<thead>
<tr>
<th>Anatomy</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hands, feet</td>
<td>Coronal, sagittal SSFP; dynamic SSFP; thick slab SSFP; EPI</td>
</tr>
<tr>
<td>Arms, legs</td>
<td>Sagittal, coronal EPI, SSFP; dynamic SSFP</td>
</tr>
<tr>
<td>Spine</td>
<td>Axial, sagittal T2w SSFSE; EPI; T1w GRE to look for fat</td>
</tr>
</tbody>
</table>

Single-shot fast spin-echo sequences (SSFSE), steady-state free precession sequences (SSFP), gradient echo sequences (GRE).


Lymphangioma. Large field of view SSFSE sagittal image at 24 weeks gestation demonstrates large subcutaneous cysts along the femur, loculated septated cysts within the abdomen (straight arrow) as well as swelling of the foot (curved arrow) in this fetus with extensive lymphangioma.
dysplasias, fetal MRI may become a useful adjunct in arriving at a more definitive diagnosis (see Chapter 21).82

Normal Measurements

Reference values of fetal organs are available from numerous US studies. Various studies evaluating measurements by either fetal MRI alone or by comparison with US have been performed. MRI measurements have shown good correlation with US.83-87 Volumetric data for lung, fetal weight may be more accurate by MRI than US.88-90 MRI measures continue to be established, including brain, lungs, liver, and kidney.

CONCLUSION

MRI has been increasingly used as a problem-solving tool in the assessment of the fetus. It is important when using this modality to be aware of potential safety risks, know how to optimize protocols, and understand how fetal anatomy develops over gestation. With appropriate use, this exciting modality will continue to evolve, further advancing the care of the fetus.

FIGURE 6.1-29: Amyoplasia. SSFSE sagittal image at 34 weeks gestation demonstrates abnormal high signal of the muscles of the thigh (curved arrow). Amyoplasia is characterized by absence of limb muscles that are replaced by fibrous and fatty tissue. Fetal activity was decreased.


FIGURE 6.1-31: Skeleton. A: Sagittal EPI of a 21-week fetus demonstrates hyperintense cartilage and hypointense bone that is well delineated against the adjacent high-signal muscle. B: Axial EPI of both femurs at 33-week GA demonstrates less contrast between muscle and bone.
69. Zaretksy MV, McIntire DD, Reichel TE, et al. Correlation of measured amniotic
indication of fetal lung maturation using echo planar imaging at 0.5 T. Magn
73. Gotstein O, Eshet Y, Hoffmann C, et al. Fetal liver T2* values: defining a stan-
78. Nemec SF, Nemec U, Gragger PC, et al. Skeletal development on fetal MRI. Top