Dynamic motion analysis of fetuses with central nervous system disorders by cine magnetic resonance imaging using fast imaging employing steady-state acquisition and parallel imaging: a preliminary result

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Objective. The authors present a novel cine magnetic resonance (MR) imaging, two-dimensional (2D) fast imaging employing steady-state acquisition (FIESTA) technique with parallel imaging. It achieves temporal resolution at less than half a second as well as high spatial resolution cine imaging free of motion artifacts for evaluating the dynamic motion of fetuses in utero. The information obtained is used to predict postnatal outcome.

Methods. Twenty-five fetuses with anomalies were studied. Ultrasonography demonstrated severe abnormalities in five of the fetuses; the other 20 fetuses constituted a control group. The cine fetal MR imaging demonstrated fetal head, neck, trunk, extremity, and finger as well as swallowing motions. Imaging findings were evaluated and compared in fetuses with major central nervous system (CNS) anomalies in five cases and minor CNS, non-CNS, or no anomalies in 20 cases. Normal motility was observed in the latter group. For fetuses in the former group, those with abnormal motility failed to survive after delivery, whereas those with normal motility survived with functioning preserved. The power deposition of radiofrequency, presented as specific absorption rate (SAR), was calculated. The SAR of FIESTA was approximately 13 times lower than that of conventional MR imaging of fetuses obtained using single-shot fast spin echo sequences.

Conclusions. The following conclusions are drawn: 1) Fetal motion is no longer a limitation for prenatal imaging after the implementation of parallel imaging with 2D FIESTA, 2) Cine MR imaging illustrates fetal motion in utero with high clinical reliability, 3) For cases involving major CNS anomalies, cine MR imaging provides information on extremity motility in fetuses and serves as a prognostic indicator of postnatal outcome, and 4) The cine MR used to observe fetal activity is technically 2D and conceptually three-dimensional. It provides four-dimensional information for making proper and timely obstetrical and/or postnatal management decisions.

Keywords: • central nervous system anomaly • fetal imaging • magnetic resonance imaging • parallel imaging • cine imaging • pediatric neurosurgery

Anomalies in the CNS of fetuses are sometimes fatal and often have a significant impact not only on infants’ lives but also on those of their families. Many studies based on the use of modern imaging techniques have been devoted to prenatal care for earlier diagnosis of CNS abnormalities in fetuses.1,4,6,8–10,14–24,26–30,32,35,36,40,41,43–45,47–51,53,54 For several decades, ultrasonography has been the imaging modality used routinely to screen for fetal anomalies. In recent years, since the clinical implementation of single-shot FSE pulse sequences, half-Fourier acquisition single-shot turbo spin echo imaging studies,24,33 fast imaging with steady-state precession,14 and FIESTA, MR imaging has become the standard prenatal imaging modality. These advanced MR imaging techniques offer high signal contrast not only between the body surface of the fetus and the amniotic fluid but also between the fetal internal organs (for example, the cortical sulci and gyri, spinal cord, lung, and other visceral organs). The morphological information provided by MR imaging of a fetus is almost as reliable as postmortem studies52 and such studies have become routine.
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when a complicated pregnancy is encountered. Nevertheless, it takes these imaging techniques approximately 1.5 to 2 seconds to obtain a slice and approximately 30 to 40 seconds to cover the entire fetal brain or body trunk with a slice thickness of 4 to 5 mm. During the imaging acquisition, fetal movement can hamper the quality of the images. This is particularly problematic in the second trimester, when the uterine space is relatively large for a fetus. In clinical practice, fetal motion remains one of the limitations of prenatal MR imaging.

Recently, with the improvement of radiofrequency and computer technology, parallel imaging techniques have become the major trend in MR imaging data acquisition. With parallel imaging, the scanning time is significantly reduced yet the imaging quality remains above the minimum clinical requirements. In addition, cine MR imaging using fast imaging techniques is already an established method for evaluating cardiac function. A moving fetus is, however, more complicated to scan compared with a beating heart, the primary reasons being that 1) fetal motion is arrhythmic, 2) fetuses move freely and unpredictably, and 3) a large field of view is mandatory for an overview of fetal motion.

In this study we used the cine technique and combined the parallel MR imaging technique with FIESTA to obtain images of fetuses, anticipating that we could thereby evaluate fetal motion and use our findings to predict postnatal outcome.

Clinical Material and Methods

Patient Selection and Chronological Observation

Between February and October 2004, a total of 25 fetuses in whom abnormalities were detected in utero by ultrasonography were further evaluated using MR imaging. The study group was composed of fetuses whose MR images revealed major CNS anomalies that were confirmed postnatally, whereas fetuses who had minor CNS, non-CNS, or no anomalies were the control group for motion evaluation. These MR images were assessed according to the chronological order in which they were obtained. We focused on head position, brain abnormalities (including dysgenesis of the cortex), hydrocephalus, spinal abnormalities, the motion of swallowing, and motion of the jaw, neck, trunk, arms, legs, and fingers. The findings regarding these two groups of fetuses were compared and evaluated.

Magnetic Resonance Imaging

The imaging was performed with a 1.5-tesla unit (Twin Excite; General Electric Medical Systems, Milwaukee, WI) that had an eight-channel, phase-arrayed body coil. In addition to routine single-shot FSE, 2D FIESTA with the cine technique was used (imaging parameters: TR/TE 3.5–4.5/1.6–2.1 msec, field of view 40 cm, matrix 256 × 224 with interpolation to 512 × 512, flip angle 50°, slice thickness 10 mm, number of excitations 1, bandwidth 100 kHz). The temporal resolution of the 2D imaging, using parallel imaging with an acceleration factor of 2, was 0.4 to 0.48 second. Three planes (midline sagittal and 10 mm off midline sagittal on right and left) were routinely used. An additional plane for target organs was used if clinically indicated. Forty or 80 image frames for each plane were usually acquired.

Cine Imaging

For cine display, the 2D FIESTA images were converted to an audio video interleaved file on a workstation (Advantage Window, Version 4.2; General Electric Medical Systems) and played at 10 frames per second (approximately five times faster than the original speed).

Results

The control group contained 20 fetuses. In the other five, the following anomalies were found: torticollis (one fetus), CM-II (three fetuses), and occipital meningoencephalocele (one fetus). The findings are summarized in Table 1.

Morphological imaging of the fetus who had torticollis (Case 1) revealed a hypoplastic, osseous thorax, especially on the right side, and a left-tilted neck. Her cine MR images demonstrated impaired movement of her neck, which was fixed and tilted to the left, but the motility of her extremities did not differ from that of control fetuses. She failed to survive after delivery. The postmortem x-ray fetogram films showed a C-3 hemivertebra and a radiolucent split in the midportion of the C-4 vertebral body (Fig. 1). Torticollis due to a combination of sternocleidomastoid contracture and congenital vertebral anomalies is rarely reported. It may be associated with scoliosis and chest deformity and has been diagnosed postnatally. To our knowledge, no prenatal imaging diagnosis such as the one in this case has ever been reported.

The other four fetuses (Cases 2–5) had lumbosacral myelomeningoceles (three fetuses) and an occult spinal meningoencephalocele (one fetus). The patient in Case 2 had a myelomeningocele at the lumbosacral level that caused high lumbar nerve anomalies, extension deformities of the lower extremities, and club-shaped feet (Fig. 2). His lower extremities did not move actively for 30 minutes during the scanning. In contrast, the legs and even the fingers of the fetuses in the control group moved actively and frequently. After a thorough discussion with the patient’s family members that gave them information on probable clinical outcome, preterm delivery was induced. No comprehensive management was undertaken, and the infant failed to survive. The other two fetuses who had lumbosacral myelomeningoceles (Cases 3 and 4) had low lumbar lesions. Contrary to the patient in Case 2, their lower-extremity motility was well preserved and showed no obvious difference compared with that of control fetuses (Fig. 3). The patient in Case 3 received primary repair of her myelomeningocele 1 day after delivery. Preserved lumbar nerve functions were observed at the postnatal follow-up examination. Induction delivery for termination was performed at 24 weeks for the patient in Case 4. In the patient in Case 5, cine MR imaging demonstrated motion of the neural contents and CSF in the occipital meningoencephalocele but freely and normally moving extremities, head, and trunk.

Discussion

In this study, we applied cine MR imaging using FIESTA and parallel imaging to assess fetuses. Technically, this is 2D imaging; however, it shows 3D and 4D information and demonstrates differences of motility between fetuses who have major CNS anomalies and those who do not. Clinical-
ly, the information is an important reference point for prenatal obstetrical decision making, and postnatal outcomes have been found to be compatible with those predicted prenatally. The imaging is supplementary to and an advancement beyond the conventional MR imaging modalities of single-shot FSE or half-Fourier acquisition single-shot turbo spin echo used to assess fetuses. It may also provide a potential role for future studies in the physiology of CSF hydrodynamics or eye movement and in functional analyses of other fetal organ systems such as the gastrointestinal, genitourinary, and cardiovascular systems.

Anomalies in the CNS are the major disease category among various congenital disorders that draw the attention of clinicians. Of them, hydrocephalus, myelomeningoceles, meningoencephaloceles, Dandy–Walker syndrome, craniofacial synostosis, holoprosencephaly, congenital brain tumors, and infections and hemorrhages in the CNS are the primary anomalies that lead to severe consequences, threatening fetal or early postnatal life.\(^2,10,25,30,37,38,42,51,52\) For children thus afflicted who survive postnatally, these anomalies can impede their ability to lead an independent life free of severe handicaps.\(^2,13,39,40,42,43\) Many obstetricians and pediatric neurosurgeons have longed for more accurate and clear diagnostic methods to use in detecting these abnormalities in the fetal period as early as possible.\(^43\) This crucial clinical demand has obviously been accomplished in part by recent marked technical advances in imaging. In utero high-resolution MR imaging using heavily T\(_2\)-weighted FSE sequences and 3D or 4D ultrasonography are examples.\(^1,4,6,8–10,15–18,20–24,26–30,32,35,36,40,41,43–45,47–51,53,54\) Ultrasonography has been used broadly as an imaging modality for routine prenatal screening, mainly because it is relatively inexpensive, free of motion artifacts, and easy to handle and perform repeatedly. The capability of studying blood flow by using Doppler imaging is the unique feature of ultrasonography,\(^4,10,17,26,35,43,48\) and the recent advance in 3D imaging has further extended its scope in enabling observation of fetal body surfaces and visceral organs.\(^7,42\) However, the low tissue contrast and

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Gestational Age (wks) at MRI, Sex</th>
<th>Major Ultrasonographic Findings/ Clinical Obstetrical Data</th>
<th>Major MRI Findings</th>
<th>Prenatal Diagnosis</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33, F</td>
<td>multiple anomalies &amp; hypertelorhinostation of neck</td>
<td>multiple anomalies &amp; torticollis</td>
<td>torticollis, VB anomalies, hypoplastic osseous thorax</td>
<td>C/S, failure to survive</td>
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<tr>
<td>2</td>
<td>31, M</td>
<td>lumbosacral MMC</td>
<td>lumbosacral MMC, tonsillar herniation, &amp; ventriculodilatation</td>
<td>CM-II</td>
<td>C/S, failure to survive</td>
</tr>
<tr>
<td>3</td>
<td>32, F</td>
<td>lumbosacral MMC</td>
<td>lumbosacral MMC, tonsillar herniation, ventriculodilatation, ACC</td>
<td>CM-II, ACC</td>
<td>C/S, good outcome</td>
</tr>
<tr>
<td>4</td>
<td>23, M</td>
<td>mild ventriculomegaly, DCC, cerebellar hypoplasia</td>
<td>lumbosacral MMC, tonsillar herniation, ventriculodilatation, ACC</td>
<td>CM-II, ACC</td>
<td>termination</td>
</tr>
<tr>
<td>5</td>
<td>18, F</td>
<td>occipital meningocele</td>
<td>occipital MEC</td>
<td>occipital MEC</td>
<td>termination</td>
</tr>
<tr>
<td>6</td>
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<td>ventriculomegaly</td>
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<td>none</td>
<td>NSD, healthy</td>
</tr>
<tr>
<td>7</td>
<td>24, M</td>
<td>ventriculomegaly</td>
<td>none</td>
<td>none</td>
<td>NSD, healthy</td>
</tr>
<tr>
<td>8</td>
<td>19, M</td>
<td>trisomy 13</td>
<td>none</td>
<td>none</td>
<td>termination</td>
</tr>
<tr>
<td>9</td>
<td>27, M</td>
<td>intrauterine growth retardation, polyhydramnios, multiple anomalies</td>
<td>cleft palate, hydronephrosis, postural valve</td>
<td>multiple anomalies</td>
<td>termination</td>
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<td>10</td>
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<td>none</td>
<td>C/S, healthy</td>
</tr>
<tr>
<td>11</td>
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<td>none</td>
<td>C/S, healthy</td>
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<tr>
<td>12</td>
<td>37, F</td>
<td>coronal artery fistulas</td>
<td>none</td>
<td>none</td>
<td>C/S, healthy</td>
</tr>
<tr>
<td>13</td>
<td>20, F</td>
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<td>mild ventriculomegaly</td>
<td>ventriculomegaly</td>
<td>NSD, —</td>
</tr>
<tr>
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<td>20, F</td>
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<td>mild ventriculomegaly</td>
<td>ventriculomegaly</td>
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</tr>
<tr>
<td>15</td>
<td>31, F</td>
<td>ventriculomegaly &amp; choroid plexus cysts</td>
<td>choroid plexus cysts</td>
<td>choroid plexus cysts</td>
<td>NSD, —</td>
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<tr>
<td>16</td>
<td>22, M</td>
<td>mega cisterna magna</td>
<td>none</td>
<td>none</td>
<td>NSD, healthy</td>
</tr>
<tr>
<td>17</td>
<td>33, F</td>
<td>ventriculomegaly</td>
<td>unilateral ventriculomegaly</td>
<td>ventriculomegaly</td>
<td>NSD, —</td>
</tr>
<tr>
<td>18</td>
<td>35, F</td>
<td>microcephaly</td>
<td>none</td>
<td>none</td>
<td>C/S, healthy</td>
</tr>
<tr>
<td>19</td>
<td>33, M</td>
<td>ventriculomegaly</td>
<td>ACC</td>
<td>ACC, ventriculomegaly</td>
<td>NSD, —</td>
</tr>
<tr>
<td>20</td>
<td>32, M</td>
<td>ventriculomegaly</td>
<td>none</td>
<td>none</td>
<td>NSD, healthy</td>
</tr>
<tr>
<td>21</td>
<td>35, F</td>
<td>ventriculomegaly</td>
<td>mild ventriculomegaly</td>
<td>ventriculomegaly</td>
<td>NSD, —</td>
</tr>
<tr>
<td>22</td>
<td>26, M</td>
<td>ventriculomegaly</td>
<td>none</td>
<td>none</td>
<td>C/S, healthy</td>
</tr>
<tr>
<td>23</td>
<td>29, M</td>
<td>large CSF space in pst fossa</td>
<td>mega cisterna magna</td>
<td>none</td>
<td>C/S, healthy</td>
</tr>
<tr>
<td>24</td>
<td>30, M</td>
<td>pleural effusion, intrauterine growth retardation, polyhydramnios</td>
<td>polyhydramnios, rt pleural effusion, duodenal stenosis</td>
<td>multiple anomalies</td>
<td>C/S, postnatal op</td>
</tr>
<tr>
<td>25</td>
<td>24, F</td>
<td>ventriculomegaly</td>
<td>bilater hydrocephalus &amp; ACC</td>
<td>ACC</td>
<td>termination</td>
</tr>
</tbody>
</table>

* ACC = agenesis of corpus callosum; C/S = Cesarean section; DCC = dysgenesis of corpus callosum; MEC = meningoencephalocele; MMC = myelomeningocele; NSD = normal spontaneous delivery; pst = posterior; VB = vertebral body; — = pending for long-term follow up.
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FIG. 1. Case 1. a: Coronal single-shot FSE MR image demonstrating the fetus’ left-tilted neck and the rest of the body. b: Sagittal single-shot FSE MR image of the fetus’ head and neck showing a hyperextended cervical spine and stretched spinal cord. c: Part of a series of cine 2D FIESTA images demonstrating the fetus’ fixed, left-tilted neck and the normal motility of the extremities, which are compatible with congenital torticollis. d: A postmortem x-ray fetogram showing the C-3 hemivertebra body and a radiolucent split in the midportion of the C-4 vertebral body (short arrow). The thoracic spine is scoliotic and the thoracic rib cage is hypoplastic (long arrow).

FIG. 2. Case 2. a: Midline sagittal single-shot FSE MR image demonstrating a myelomeningocele (short white arrow) in the fetus’ lumbosacral region. The posterior fossa is small and the hindbrain has herniated into the dorsal cervical spine (long white arrow). The knee joints are extended and deformed (arrowhead) and the feet are club-shaped (black arrow). b: Transaxial image of the fetus’ brain demonstrating the colpocephalic occipital horns (long arrow) of both lateral ventricles and the rudimentary frontal horns of both lateral ventricles (short arrow). c: Part of a series of images from the fetus’ cine MR study revealing no active movement of the lower extremities during the scanning session.
small viewing field available with ultrasonography limit it as a definitive prenatal diagnostic tool, particularly for clinical conditions such as complicated fetal CNS anomalies, maternal obesity, oligohydramnios, and pregnancies with multiple fetuses. Thus, MR imaging remains an important modality for further evaluation. For prenatal evaluation of fetal CNS anomalies, the advantage of MR imaging and its impact on clinical management have been well documented.\(^8,10,24,32,35\) Traditionally, the use of routine heavily T\(_2\)-weighted FSE sequences in MR imaging has provided anatomical information only. With the application of FIESTA and the parallel imaging technique, observation of fetuses in cine mode is now possible. Cine imaging of fetuses offers the unique property of MR imaging, namely, its ability to provide an overview of the entire body of a fetus and of its relationship to the mother, free of dead space and penetration limits. It presents information on the movement of other body parts in a field of view—including fingers, extremities, trunk, eyeballs, and throat—that are not obtained by ultrasonography. The movements indicate neurological function in the fetus and can serve as prognostic indicators. For example, as shown in the patient in Case 2 (who had a lumbar myelomeningocele and CM-II), a lack of movement in the extended, deformed legs and the clubbed feet may suggest severe lumbar nerve impairment. Although it was not demonstrated in this particular case, we speculate that the emptying of the urinary bladder can also be observed in a fetus and used for functional evaluation. The ability to observe CSF and its hydrodynamics is also unique in cine MR imaging of fetuses. It may also play a role in future study concerning the pathophysiology and chronology of fetal hydrocephalus, craniofacial synostosis, and neural tube defects. To date, the initial experience of using cine MR imaging may not have changed much about obstetric management because the number of cases in which it has been used has been limited. At the current stage, it provides supplementary information to reinforce decision making. More cases are definitely needed so that the impact of this imaging technique can be evaluated and its significance quantified.

Of major concern in the application of MR imaging to fetuses is the power deposition, presented as the SAR of radiofrequency. For single-slice acquisition at an identical matrix size and similar echo spacing, the SAR of FIESTA, with a 50° flip angle, is approximately 13 times lower than that of single-shot FSE, which uses a train of 180° radiofrequency pulses, that is, \((180/50)^2 = 12.96\).\(^{14}\) With multichannel imaging using phase-arrayed coils at an acceleration factor of two, as in the current study, the SAR of FIESTA can be further reduced by 50%. Consequently, continuous data acquisition of 80 frames using 2D FIESTA is equivalent to a maximum of three slices using nonparallel single-shot FSE, that is, \(80/(12.96 \times 2) = 3.09\). Therefore, 80-frame 2D FIESTA imaging is a safe and relatively conservative approach with regard to SAR.

**Conclusions**

On the basis of this initial experience in which we obtained 25 cine MR imaging studies of fetuses, we suggest that this type of MR imaging—when used as an adjunct to routine high-resolution T\(_2\)-weighted single-shot FSE sequences—provides information on fetal motility for fetuses who have CNS anomalies and may serve as a clinically reliable prognostic indicator of postnatal outcome. Since the implementation of parallel-imaging 2D FIESTA, fetal motion is no longer a limitation in prenatal imaging. This novel MR imaging modality is technically 2D and conceptually 3D. It provides 4D information that is useful for
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making proper and timely obstetrical and/or postnatal surgical management decisions.

References


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