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Contrast-Enhanced Abdominal MRI for Suspected Appendicitis: How We Do It

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Abstract

OBJECTIVE—The purpose of this article is to describe our approach to contrast-enhanced abdominal MRI in patients with nontraumatic abdominal pain and suspected appendicitis. We aim to share our experience on the advantages, pearls, and pitfalls of MRI in this clinical setting, in comparison with CT and ultrasound.

CONCLUSION—We present some typical cases of appendicitis and alternative diagnoses in patients presenting with acute nontraumatic abdominal pain.

Keywords

abdominal imaging; appendicitis; CT; imaging protocols; MRI

Acute appendicitis is a common clinical condition that affects both children and adults. Current data show that the frequency of acute appendicitis is increasing and that the lifetime risk may reach as high as 9% [1]. The clinical diagnosis of appendicitis, however, remains challenging because only half of patients present with the classic symptoms of periumbilical pain migrating to the right lower quadrant and nausea with vomiting [2]. In fact, localization of pain may occur anywhere in the abdomen, particularly in children and pregnant women. Patients may experience worsened pain with leg flexion, increased abdominal pressure with palpation, and rebound peritoneal tenderness. Other clinical signs and symptoms include fever, chills, vomiting, nausea, and loss of appetite.

On clinical examination, moderate-to-severe tenderness in the right lower quadrant is typical but is often not well defined. This is particularly true when inflammation has spread to the peritoneum, leading to diffuse abdominal tenderness with guarding and rebound. Unfortunately, many other acute abdominal diseases present with similar signs and symptoms, hindering the specificity of clinical features that contribute to a confident diagnosis of appendicitis. Serum tests may show increased C-reactive protein levels and leukocytosis [3], but normal levels of inflammatory markers do not exclude appendicitis.

To provide a more objective structured approach to the diagnosis of appendicitis, a number of scoring systems have been developed, including the Alvarado Score and Pediatric Appendicitis Score [4, 5]. However, subjective clinical judgment has been shown to be equivalent to or even more accurate than formal scoring systems [6]. Early surgery based on clinical findings alone leads to a significantly higher negative laparotomy rate than when cross-sectional imaging is used to evaluate the patient [7].

For these reasons, imaging has played a central role in the diagnosis of appendicitis. Ultrasound is a rapid and inexpensive test that can be performed at the bedside and has no known safety-related contraindications. Given its lack of ionizing radiation, it is particularly well suited for children and pregnant patients. Unfortunately, ultrasound is highly operator, system, and patient dependent, particularly in patients with a larger habitus [8]. Furthermore, the anatomic location of the appendix (e.g., retrocecal) may limit the utility of ultrasound in many patients. In expert hands, the accuracy of ultrasound may reach 96% and may result in fewer follow-up CT scans and negative laparotomies [9]. However, the number of inconclusive cases using ultrasound is nonnegligible and frequently necessitates a second imaging study for many patients, thus negating the cost benefits of this modality [10, 11]. Finally, ultrasound is also limited for the diagnosis of alternative conditions, which are more frequent than appendicitis [12].

CT does not have the aforementioned limitations and has become the modality of choice for the workup of most patients with suspected appendicitis. It is widely available, rapid, moderate in cost, operator independent, and has high interreader agreement [13]. At many institutions, CT is the first-line imaging modality. CT is also highly effective for the evaluation of alternative diagnoses other than appendicitis [12, 14]. However, CT requires the use of ionizing radiation, raising concerns about its use in children and pregnant patients [15, 16]. Furthermore, most institutions use IV iodinated contrast agents, which carry a low but finite risk of nephrotoxicity and allergic reactions [17–21]. The American College of Radiology Appropriateness Criteria for Right Lower Quadrant Pain/Suspected Appendicitis generally favor the use of contrast-enhanced CT in the general population but advocate for dose-reduction strategies [22]. Historically, ultrasound has been the preferred initial examination for children. For pregnant women, recent data support the use of MRI after an equivocal or inconclusive ultrasound [23].

The increasing prevalence of and access to MRI have allowed emergency departments to shift toward it as a primary cross-sectional imaging tool for appendicitis. As with CT, MRI is an inherently 3D cross-sectional imaging method. Improvements in MRI techniques, sequences, coils, and imaging protocols render it an increasingly attractive imaging method.

Higher temporal and spatial resolutions can be achieved, and motion-related artifacts have been reduced. With modern techniques, such as parallel imaging, rapid gradients, and rapid 3D T1- and T2-weighted imaging methods, examination times have decreased and image quality has improved. Furthermore, the overall cost of MRI has decreased considerably over the past decade and now approaches that of CT or combined CT and ultrasound in many regions and institutions. Finally, the safety profile of gadolinium-based contrast agents is excellent and exceeds that of iodinated contrast agents, with lower rates of allergic reactions and no contrast-induced nephrotoxicity.

For these reasons, MRI is increasingly attractive as a safe and effective imaging alternative for suspected appendicitis, especially for children, young adults, and pregnant women, but potentially also in the future for the general adult population. MRI combines the advantages of ultrasound (i.e., it is noninvasive and lacks ionizing radiation) with the high-resolution 3D cross-sectional information of CT [24]. A recent systematic review and meta-analysis of all published studies since 2005 that evaluated the accuracy of MRI for the diagnosis of acute appendicitis in the general population presenting to emergency departments concluded that MRI has a high sensitivity and specificity for the diagnosis of appendicitis, similar to that reported previously for CT [25].

Protocol Overview

Our protocol for suspected appendicitis is summarized in Table 1. Like other abdominal MRI protocols designed to evaluate the small and large bowels, our protocol for acute appendicitis includes multiple planes of T2-weighted single-shot fast spin-echo (SSFSE) imaging without and with fat saturation. Our protocol includes axial, sagittal, and coronal planes, but two planes, preferably axial and coronal, may suffice. Unenhanced and contrast-enhanced 3D spoiled gradient-echo T1-weighted images are acquired at multiple times and in different orientations. Finally, we obtain axial DW images, which are often helpful for visualization of an inflamed appendix, as well other abnormalities. Below, we review these sequences in more detail, including a description of the imaging appearance and relative advantages of each sequence.

Anatomic coverage should include the peritoneal cavity, kidneys, and gallbladder, where most abnormalities that cause acute abdominal pain are found. In our opinion, it is not necessary to cover the entire perineum or liver, which may require undesirable tradeoffs in spatial resolution or scan time through the use of multiple imaging stations. However, in certain circumstances, such extended coverage may be needed. Volumetric coverage is feasible within a single breath-hold while maintaining high spatial resolution through the use of 2D auto calibrated parallel imaging techniques [26].

Imaging should be performed on highfield magnets (1.5 or 3 T) using a standard phased-array coil capable of parallel imaging acceleration. To our knowledge, there are no specific studies comparing the quality or diagnostic accuracy of MRI of suspected acute appendicitis on 3- versus 1.5-T MRI systems. Studies of inflammatory bowel disorders comparing both field strengths have shown that 1.5-T MRI has a high diagnostic accuracy and that 3-T MRI can be considered equivalent but not superior [27, 28]. In general, we have the greatest

amount of experience at 1.5 T, where MRI has very high performance. Evaluation of MRI for appendicitis at 3 T is of great interest. Patients are generally imaged in the supine position, although there are no contraindications to prone or decubitus positioning, which may be needed for pregnant patients.

Whenever possible, breath-holding should be used to minimize motion-related artifacts, although respiratory gating is an effective way to avoid slice misregistration for 2D SSFSE methods. SSFSE is remarkably motion insensitive, and, for this reason, the inability to breath-hold is not a contraindication for MRI to evaluate for appendicitis. We recommend that breath-holding be performed at end-tidal volume using the instructions, “breathe in, breathe out, stop breathing.” Imaging at end-inspiration is also effective, but the position of the diaphragm is less reproducible and can lead to misregistration of slices or sequences acquired in different breath-holds [29, 30].

For contrast-enhanced imaging, a standard or high relaxivity or extracellular contrast agent can be used. We use a gadobenate dimeglumine (0.1 mmol/kg of body weight; MultiHance, Bracco Diagnostics) bolus injected at 2 mL/s. For safety and quality purposes, we use a fixed weight-based dose of gadobenate dimeglumine (0.1 mmol/kg of body weight), rather than a fixed volume of contrast agent. In this way, we make sure that we do not overdose smaller patients or underdose larger patients. The rate of injection is 2.0 mL/s in all patients, followed by a 20-mL saline flush injected at the same rate. There are currently insufficient data on whether IV contrast agent is necessary. Recent studies have shown that unenhanced MRI is accurate for the diagnosis of equivocal appendicitis in nonsedated pediatric patients [31], but the use of contrast agent increased the confidence of readers [32]. In our experience, contrast agent is very helpful, including in the confirmation of alternative diagnoses. Gadolinium-based contrast agents are contraindicated for pregnant patients and may be contraindicated for some patients with renal failure because of concerns for nephrogenic systemic fibrosis.

Apart from IV access, no other prerequisites are necessary. In particular, oral contrast agent is not necessary and is a major advantage over CT with regard to the patient experience and throughput [33]. For pregnant patients, for whom IV contrast agent is contraindicated, the use of iron-based negative-contrast oral agents given 1.5 hours before examination may be helpful to differentiate dilated periuterine varices from the appendix [34]. To our knowledge, these agents, such as ferumoxsil (Gastromark, Mallinckrodt Medical), are still available in the United States [35].

The entire protocol can be easily completed in 15–20 minutes of scan time. Figure 1 provides an overview of the proposed sequences as a flowchart.

Multipplanar T2-Weighted Single-Shot Fast Spin-Echo

Localizers should be performed during breath-holding and are used to ensure adequate coverage and coil positioning. If the coil is malpositioned, the technologist should stop and reposition the coil before proceeding. On GE Healthcare systems, we perform multipplanar T2-weighted SSFSE sequences, which are also known as HASTE for Siemens Healthcare systems and ultrafast spin-echo for Philips Healthcare systems. We typically perform T2-

weighted SSFSE in all three orthogonal planes, although at least two planes are recommended. T2-weighted SSFSE provides an excellent motion-insensitive overview of the abdomen and appendix and depicts abnormal thickening, mucosal edema, and periappendiceal inflammation. This sequence is extraordinarily robust and, although it is best acquired during a breath-hold, it can be acquired during free breathing. In patients who are unable to hold their breath, the free-breathing acquisition is very robust (i.e., motion insensitive), although slices may be misaligned. The use of respiratory triggering is a useful means to facilitate free-breathing SSFSE and achieve well-aligned slices.

The use of SSFSE in multiple imaging planes is essential, because there are multiple variations in the position and length of the appendix [36]. Depending on the orientation of the appendix, multiple orthogonal planes are often complementary in displaying the appendix in both the short and long axes. Figure 2 shows an imaging example of acute appendicitis with abnormal wall thickening and enhancement in two different planes. We routinely use 1D self-calibrated parallel imaging for all SSFSE acquisitions to reduce the effects of blurring from T2 signal decay [37, 38].

An alternative sequence is the balanced steady-state free precession. This is a rapid sequence with high signal-to-noise ratio performance and contrast dependent on the T2-to-T1 ratio, and it is commonly available as a 2D or 3D acquisition, with or without fat suppression. The balanced steady-state free precession sequence is known as fast imaging employment steady-state acquisition on GE Healthcare systems, true fast imaging with steady-state precession on Siemens Healthcare systems, and balanced fast-field echo on Philips Healthcare systems. We do not routinely use balanced steady-state free precession, but it can be an effective method for depiction of appendiceal edema and extraintestinal findings, such as mesenteric lymphadenopathy, inflammatory changes, and abscess formation. This sequence is also relatively insensitive to motion and can thus be used as a primary sequence in patients with reduced compliance, such as pediatric patients and patients in severe pain.

Axial Fat-Saturated Single-Shot Fast Spin-Echo

The use of fat suppression with SSFSE imaging is important for the depiction of submucosal edema, periappendiceal fluid collections, and periappendiceal inflammatory changes. Fat suppression leads to a low-signal-intensity appearance of the fat with clear delineation of adjacent edema or even abscess formation next to the appendix. The use of fat suppression also plays a critical role in the identification and characterization of other pathologic abnormalities, including the presence of intraperitoneal blood, which can have the same signal intensity as fat on non-fat-saturated sequences.

Dynamic Axial Fat-Saturated T1-Weighted Imaging and Coronal Fat-Saturated T1-Weighted Contrast-Enhanced Imaging

Axial T1-weighted fat-saturated rapid spoiled gradient-echo sequences are routinely performed for dynamic contrast-enhanced acquisition. This is typically performed using a rapid 3D spoiled gradient-echo acquisition with intermittent spectrally selective inversion recovery fat suppression [39]. These methods are widely used for liver imaging and are known as liver acquisition with volume acquisition on GE Healthcare systems, volume-

interpolated breath-hold examination on Siemens Healthcare systems, and enhanced T1 high-resolution isotropic volume excitation on Philips Healthcare systems. We routinely use self-calibrated parallel imaging with all T1-weighted acquisitions to perform 2D acceleration for improved spatial resolution and reduced scan time [37].

Unenhanced fat-suppressed T1-weighted acquisitions are important for characterizing tissues of intrinsic high T1 signal, such as blood products and other structures or fluid with high protein content. As such, the sequence can be used to characterize abnormalities such as hemorrhagic ovarian cysts, which are a common diagnostic consideration in premenopausal female patients with acute abdominal pain.

After the administration of gadolinium-based contrast agent, dynamic contrast-enhanced T1-weighted acquisitions are helpful to show abnormal enhancement of an inflamed appendix, as well as depiction of mucosal discontinuity with appendiceal rupture. Late ruptures and abscesses can be seen easily without contrast agent, but we have found the use of contrast agent to be extremely helpful for the depiction of mucosal disruption in the setting of early rupture. This can actually be seen better on contrast-enhanced MRI compared with CT. We typically acquire T1-weighted imaging in alternating axial and coronal volumes to provide broad coverage of the abdomen and pelvis. However, with advanced parallel imaging and the use of isotropic spatial resolution, any variation of the following approach is likely adequate. Furthermore, we acquire an enteric phase at approximately 40 seconds after the administration of IV contrast agent. The 40-second delay was based on the work of Schindera et al. [40], who found peak small bowel enhancement at approximately 50 seconds. Given the delay between the start of the MRI acquisition in the center of k-space (center of the acquisition using standard k-space ordering), a fixed delay of 40 seconds is optimal to ensure that peak enhancement occurs at approximately 50 seconds. We then acquire multiple additional T1-weighted acquisitions over the course of 2–3 minutes. In our protocol, we acquire a coronal T1-weighted sequence approximately 90 seconds after contrast agent injection as part of the series of dynamic contrast-enhanced sequences. We find that at least one acquisition in an orthogonal plane is helpful to visualize the abdominal structures in this second orientation. Coronal contrast-enhanced sequences are also invaluable for evaluation of the arteries and veins of the abdomen and pelvis, to evaluate for aortoiliac pathologic abnormalities and for deep venous thrombosis. When fat suppression is used, these sequences are ideal for visualization of mesenteric and paraaortic lymphadenopathy, and they provide visualization of the gastrointestinal tract and other organs in a manner that is complementary to T2-weighted SSFSE acquisitions. In general, inflammatory changes and abnormal mucosal enhancement seen with appendicitis are best visualized at the later time points.

DWI

DWI takes advantage of the restricted diffusion (random thermal motion) of water molecules in tissue that occurs in the setting of ischemia or inflammation as well as in malignant tumors, where cells are densely packed with a high cellularity that inhibits the free diffusion of water. Active inflammatory processes, such as swelling or edematous changes in the cellular structure, also lead to a reduction in the normal diffusivity of water in tissue. In

addition, DWI methods that use echoplanar techniques are fat suppressed and also T2 weighted, with relatively long TEs. Thus, acute pathologic abnormalities, such as acute appendicitis, have high signal intensity on fat-suppressed DW images because of the combination of restricted diffusion and edema that has high signal intensity with T2 weighting.

DWI has been successfully exploited for small-bowel imaging to improve the diagnostic confidence for identifying acute changes seen with inflammatory bowel disease [41–43]. For abdominal DWI, we use a respiratory-triggered echo-planar imaging acquisition. At least two b values, which relate the degree of diffusion weighting and are used to generate DW images, are used. We typically use b values of 0 and 500 s/mm². Images acquired with a b value of 0 are effectively fat-suppressed T2-weighted images and are effective for visualizing periappendiceal fluid. Although higher b values (e.g., 800–1000 s/mm²) can be used for higher diffusion weighting, this comes at the cost of lower signal-to-noise ratio performance.

Because DWI is a relatively new technique for bowel imaging, originating from neuroradiology, the optimal combination of b values for acute abdominal abnormalities has not been firmly established. Anecdotally, we have found that a b value of 500 s/mm² is a good compromise for imaging of acute appendicitis, balancing adequate diffusion weighting and good signal-to-noise ratio performance. DWI with this b value improves the conspicuity for detection of acute appendicitis, and we are not attempting to generate pure diffusion weighting in these images. Figure 2 shows a case of acute appendicitis with clear depiction on DWI. The apparent diffusion coefficient map can be calculated from two DWI datasets at different b values, where reduced diffusion can be found as a signal drop and can thus distinguish restricted diffusion from long T2 signal decay (i.e., T2 shine-through) [44]. In general, we have not found the quantitative apparent diffusion coefficient maps particularly useful for the diagnosis of acute appendicitis because of small spatial misregistrations between images acquired with different b values, although we have found images acquired with a b value of 500 s/mm² to be very helpful for qualitative detection of edema and inflammatory changes (Figs. 2 and 3). Finally, we routinely use externally calibrated parallel imaging with all DWI acquisitions to reduce distortion in the phase-encoding direction due to the sensitivity of echo-planar methods to magnetic field inhomogeneities [45].

Case Examples

Appendicitis

A normal noninflamed appendix is a slender blind-ending tubular structure typically found in the right lower quadrant, but it may be in many different orientations and locations. The diameter of the normal appendix should generally be less than 7 mm, although use of this threshold is questionable, especially in the pediatric population [46]. The wall thickness of the appendix should not exceed 2–3 mm. When the appendix is inflamed, wall thickness increases because of edema, which is easily visualized as hyperintensity on T2-weighted images, high signal intensity on DW images, and wall enhancement on dynamic contrast-enhanced T1-weighted images. Figures 2 and 3 show typical cases of appendicitis with CT correlation.

Pregnant patients often show an even wider variety of appendiceal localization, which increases along with the progression of pregnancy [47]. As discussed already, imaging should be performed without contrast agent in pregnant patients. T2-weighted and unenhanced T1-weighted images are helpful to depict the appendix, as shown in Figure 4.

Other Causes of Acute Nontraumatic Abdominal Pain

In patients with acute nontraumatic abdominal pain in whom appendicitis is suspected, the frequency of proven appendicitis is typically 25–30% [48]. Apart from acute appendicitis, there are a wide variety of causes that can mimic appendicitis that can also be diagnosed with MRI. Although more data exist on the diagnostic performance of CT for these alternative diagnoses [12], in our experience, the performance of MRI is comparable to that of CT for the diagnosis of alternative causes of abdominal pain. Examples of alternative diagnoses include inflammation and infection of the remaining gastrointestinal tract (enteritis, colitis, or diverticulitis). Other, less frequent, bowel pathologic abnormalities including malignancy can be found on MRI as well. Figure 5 shows a case of a patient with acute small-bowel angioedema induced by recently starting an angiotensin-converting enzyme inhibitor. A wide variety of genitourinary abnormalities can also mimic the clinical presentation of appendicitis, such as obstructing urolithiasis and ovarian abnormalities. MRI may be particularly effective in the setting of pelvic pain in women, for which both CT and endovaginal ultrasound images are frequently obtained. In such cases, MRI may be an effective single test that can reduce cost and overall time in the emergency department. Figure 6 shows an example of a hemorrhagic ovarian cyst, (i.e., mittelschmerz), a common cause of acute nontraumatic pain in young women. Figure 7 shows a case of acute nontraumatic abdominal pain due to an obstructing right ureteral calculus with associated hydronephrosis. Because of the coverage from above the kidneys down to the symphysis, this differential diagnosis can easily be detected. In Figure 8, we present an additional cause of nontraumatic abdominal pain that is not rare: acute calculous cholecystitis.

Conclusion

In conclusion, we have developed and tested a focused, yet comprehensive, contrast-enhanced MRI protocol for suspected acute appendicitis at our institution. This imaging protocol has been studied and directly compared against contrast-enhanced CT in nonpregnant patients, showing robust performance to date (our unpublished data). With this approach, it is feasible to diagnose appendicitis and accurately differentiate acute appendicitis from other causes of abdominal or pelvic pain. This technique may be particularly appealing for women with acute pelvic pain, for whom sequential CT and endovaginal ultrasound are often performed in the emergency department setting. A similar argument could be made for cholecystitis, where MRI could replace the CT-ultrasound combination.

With the continued concern over ionizing radiation exposure inherent to CT, MRI for patients with acute abdominal pain with suspected acute appendicitis will emerge as a viable, safe, and effective imaging alternative. As the use of MRI for this indication matures,

additional important considerations including the interpretation learning curve [49], cost-effectiveness, and access to the technology must be investigated.

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Fig. 1.

Flowchart for proposed MRI protocol for suspected appendicitis. SSFSE = single-shot fast spin-echo, FS = fat saturated.

Fig. 2.

34-year-old woman with appendicitis. Comprehensive MRI protocol to rule out or diagnose appendicitis should include all these imaging sequences.

A–F, Appendicitis (*arrows*) is seen on non-fat-saturated (**A**) and fat-saturated (**D**) T2-weighted images, T1-weighted contrast-enhanced MR image (**B**), and DW image (**E**; $b = 500 \text{ s/mm}^2$). Note exact correlation of this appendicitis case on MR images with coronal (**C**) and axial (**F**) CT images. Bowel wall edema can be nicely depicted on fatsaturated T2-weighted image (**D**).

Fig. 3. 24-year-old man with acute nontraumatic right lower quadrant pain. **A** and **B**, Sagittal T2-weighted MR image (**A**) reveals long appendix (*arrow*), with only slight contrast enhancement seen on contrast-enhanced image (*arrow*, **B**). **C** and **D**, DW image (**C**; $b = 500 \text{ s/mm}^2$) shows restricted diffusion (*arrow*), leading to confident diagnosis of appendicitis, which is seen on corresponding axial CT image (*arrow*, **D**).

Fig. 4. 31-year-old pregnant woman with acute right lower quadrant pain. Diagnosis of acute appendicitis can be easily made with T2-weighted single-shot fast spin-echo image because of appendiceal wall thickening, edema, and periappendiceal fluid collection (*arrow*).

Fig. 5. 24-year-old man with acute nontraumatic abdominal pain. History revealed recent initiation of angiotensin-converting enzyme inhibitor therapy, which caused small-bowel angioedema. **A–D**, Small-bowel angioedema is depicted equally well on coronal T1-weighted contrast-enhanced (**A**) and axial T2-weighted (**C**) MR images, compared with coronal (**B**) and axial (**D**) CT images.

Fig. 6. 22-year-old woman with acute nontraumatic abdominal pain in right lower quadrant. **A–F**, Imaging reveals multiple ovarian cysts on right side (*arrows*), one of which is hemorrhagic, as seen on unenhanced T1-weighted MR image (**D**), with fluid-fluid level seen on fat-saturated T2-weighted MR image (**E**). Coronal T2-weighted (**A**) and T1-weighted contrast-enhanced (**B**) MR images show hemorrhagic cyst contents better than do coronal (**C**) and axial (**F**) CT images.

Fig. 7. 43-year-old man with acute right abdominal pain. **A–D**, Coverage from above kidneys to symphysis (coronal images, **A** and **B**) allows overview of whole peritoneal cavity. Right hydronephrosis and perirenal edema due to obstructive ureteral stone can be seen. Tip of appendix is found to be normal (*arrows*, **C** and **D**). Coronal (**A**) and axial (**C**) single-shot fast spin-echo images without fat saturation are shown. Coronal (**B**) and axial (**D**) CT images are also shown.

Fig. 8.

65-year-old man with right abdominal pain.

A–D, Because of extended coverage, reason for pain can be found on imaging and attributed to acute cholecystitis. Sludge and stone can be seen in wall-thickened gallbladder on all imaging methods, including coronal 2D single-shot fast spin-echo (SSFSE) without fat saturation (*arrow*, **A**), ultrasound (**B**), axial 2D SSFSE with fat saturation (*arrow*, **C**), and CT (*arrow*, **D**).

TABLE 1

Imaging Parameters for MRI of Suspected Appendicitis

Parameter	2D SSFSE Without Fat Suppression			Axial 2D SSFSE With Fat Suppression	3D T1-Weighted Imaging With Fat Suppression		Axial 2D DWI With Fat Suppression (b = 0 and 500 s/mm ²)
	Axial	Coronal	Sagittal		Axial	Coronal	
TR/TE	≈ 1000/90 ms	≈ 1000/90 ms	≈ 1000/90 ms	≈ 1000/90 ms	3.6/1.7 ms	3.6/1.7 ms	> 5 s/70 ms
FOV (cm)	36–38×27	36–38×36	36–38×27	36–38×27	36–38×30	36–38×36	36 × 36
Matrix	320×256	320×256	320×256	384×224	256 × 192	256×192	128×128
Bandwidth (kHz)	63–83	63–83	63–83	63–83	63	63	250
Scan time	20–25s	20–25s	20–25s	25 s	22 s	25 s	1 min 30 s to 2 min
Slice (mm)	4	4	4	4–6	3	3	4–6
Flip angle (°)	90	90	90	90	12–15	12–15	90
No. of signal averages	1	1	1	1	1	1	4
Parallel imaging	Self-calibrated, R = $\frac{2}{2}$	Self-calibrated, R = $\frac{2}{2}$	Self-calibrated, R = $\frac{2}{2}$	Self-calibrated, R = $\frac{2}{2}$	Self-calibrated, R = $\frac{2}{2} \times 2$	Self-calibrated, R = $\frac{2}{2} \times 2$	Externally calibrated, R = 2
Method of respiratory control	Breath-hold	Breath-hold	Breath-hold	Breath-hold	Breath-hold	Breath-hold	Respiratory triggering

Note—SSFSE = single-shot fast spin-echo, R = acceleration factor.