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Appendicitis is the most common indication for acute abdominal surgery in children. In the United States, >70,000 children aged ≤18 years are diagnosed with appendicitis annually. The incidence is highest in boys aged 10 to 14 years and in girls aged 15 to 19 years. Accurate diagnosis is crucial to avoid unnecessary operations and complications of delayed diagnosis, such as perforation. History and physical examination in children with suspected appendicitis are highly variable, and currently children are rarely operated on without previous imaging.

Computed tomography (CT) has been considered the gold standard for diagnosis of appendicitis with high sensitivity and specificity. Use of ultrasonography for the diagnosis of appendicitis is growing and does not expose patients to radiation. However, ultrasonography is highly operator dependent, with a consequently wide reported sensitivity range (44%–100%). Advantages of CT include less operator dependence, easier visualization of retrocecal appendix, less interference of bowel gas, obesity, or patient’s pain, and tenderness with image quality. Perhaps for these reasons, CT remains the most common primary imaging modality before appendectomy in children. To increase sensitivity of diagnosis but decrease radiation exposure, CT used in conjunction with equivocal ultrasonography has been recommended as the most judicious diagnostic imaging pathway. A major disadvantage of CT is radiation exposure. As CT use for diagnostic imaging has increased, so has the associated radiation exposure. Decreasing radiation exposure is therefore important, particularly in the pediatric population, and lower-radiation CT protocols have been described. MRI has been used in combination with ultrasonography for the diagnosis of appendicitis in adults, maintaining a high sensitivity and specificity without effect on negative appendectomy or perforation rate. In children, MRI has been shown to be feasible and effective in diagnosing acute appendicitis, but reports of clinical outcomes are lacking.

In November 2010, our children’s hospital initiated a new algorithm for the diagnostic imaging of appendicitis. In place of CT, ultrasonography became the initial imaging modality. Children who were capable of cooperating (typically >6 years of age) with inconclusive findings after ultrasonography were then studied by MRI. CT was used only in patients not able to cooperate with MRI. We hypothesized that this radiation-free imaging strategy of ultrasonography selectively followed by MRI would not change clinical endpoints (eg, negative appendectomy or perforation rates) compared with CT for diagnosing appendicitis in children.

METHODS

We retrospectively reviewed a cohort of pediatric patients (aged <18 years), who presented to our emergency department (ED) from November 1, 2008 until October 31, 2012. All patients who had a CT, ultrasonography, or MRI ordered in the ED for abdominal pain were identified using a query of the electronic medical record and a Radiology Department database. All charts of patients undergoing appendectomy during the same period were obtained from operating room case logs. We excluded patients who were aged ≥18 years; who had imaging performed for specific questions, based on chart review, that did not include appendicitis; or who had initial diagnostic imaging performed elsewhere. We designated group A as including patients from November 2008 through October 2010, when CT was the primary imaging modality, and group B as including patients from November 2010 through October 2012, when ultrasonography followed by MRI for equivocal ultrasonography findings became the standard approach.

CT scans were performed after the administration of oral and intravenous contrast material on a 16-slice General Electric Lightspeed scanner (General Electric, Fairfield, CT) using a weight-based technique (Table 1). Each patient drank a weight-based amount of a 2% diatrizoate meglumine solution 1 hour before the scan. Standard dose of 2 mL/kg Omnipaque 200 was administered intravenously. Imaging parameters included 25-cm field of view, slice thickness of 2.5 mm, interval of 1.5 mm, and pitch of 1.3 with a rotation time of 0.5 seconds. Ultrasounds of the right lower quadrant were performed on a GE LOGIQ E9 scanner using graded compression technique with a linear transducer (ML8-15 for smaller children and 9L for larger children) by both pediatric and general sonographers. The sonographers’ experience varied from newly hired generalists with minimal experience to those with many years of dedicated pediatric experience. All MRI was carried out on nonsedated patients on a 1.5-T MRI system using an 8-channel array torso coil (Signa HDxt, GE Healthcare, Milwaukee, WI). T2-weighted single-shot fast spin echo in the axial, sagittal, and coronal planes, axial and coronal balanced steady-state free precession, axial T1-weighted fat-suppressed precontrast, and axial

<table>
<thead>
<tr>
<th>Wt, kg</th>
<th>Voltage, kV</th>
<th>Current, mA</th>
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<tr>
<td>&lt;15</td>
<td>120</td>
<td>50–65</td>
</tr>
<tr>
<td>15–24</td>
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<td>25–34</td>
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<td>35–44</td>
<td>120</td>
<td>120–140</td>
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<tr>
<td>45–55</td>
<td>120</td>
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</table>
and coronal T1-weighted fat-suppressed postcontrast sequences were obtained (see Table 2). Post contrast images were acquired using intravenous gadobenate dimeglumine with a weight-based dose of 0.2 mL/kg. All imaging was carried out in supine positioning without the use of oral contrast or bowel motility stasis agent. All patients received intravenous contrast as per protocol. The total scan time was ~30 minutes. Age range of patients successfully scanned was CT 2 to 18 years, ultrasonography 1 to 18 years, and MRI 5 to 18 years (MRI was not attempted in any patients aged <5 years). We did not identify any patients who were unable to complete an MRI after beginning examination.

For each patient, attending radiologist imaging interpretation was reviewed for acute appendicitis (inflamed appendix) or complicated appendicitis (associated phlegmon or abscess) on CT, MRI, and ultrasonography. CT and MRI were read as negative if there were no signs of appendicitis (visualization of normal appendix or no secondary signs of inflammation in region of cecum and terminal ileum). Ultrasonography was read as negative only if a normal appendix was seen. Ultrasonography studies were defined as equivocal if the appendix was not visualized or the study showed a phlegmon or abscess indicating complicated appendicitis. CT and MRI were defined as either positive or negative but not as equivocal. Alternate diagnoses were documented.

Patients underwent treatment with appendectomy, percutaneous drainage, or antibiotics. Diagnosis for patients who underwent appendectomy was determined by the surgeon's documentation as acute appendicitis, normal appendix, or complicated appendicitis (perforated, purulent, or gangrenous appendix) and by pathologic evaluation of specimens as acute appendicitis, normal/noninflamed appendix, or complicated appendicitis (perforated, purulent, or gangrenous appendix). Additional data collected included demographics and time from ED triage to imaging, antibiotic administration, operation, and discharge. Of patients with imaging studies negative for appendicitis who were discharged from the ED, follow-up by telephone occurred for 225 (group A = 65, group B = 160). Another 66 patients with negative imaging had alternate diagnoses (group A = 42, group B = 24). These 291 of 365 with negative studies were true-negatives. The remaining 74 patients (74 of 662 = 11%) did not return to our hospital; we considered them true-negative, but we cannot exclude that they went elsewhere.

The study aims were to evaluate clinical end points. Negative appendectomy rate, delineated by appendiceal pathologic evaluation without signs of appendicitis, and perforation rate, defined as complicated appendicitis by pathology among those who underwent appendectomy, were primary outcomes. Perforation rate was also assessed by surgeon's intraoperative impression. Secondary outcomes included the time from ED triage to diagnostic imaging, antibiotic administration, appendectomy incision, and hospital discharge.

Descriptive analysis was performed. Data are reported as frequencies and percentages, mean (SD). Statistical analysis was conducted with Fisher's exact and Mann-Whitney U tests by using Stata 11.0 (StataCorp, 2009, College Station, TX). Significance was considered at P < .05. Sensitivity, specificity, and negative and positive predictive values of each imaging pathway (groups A and B) for diagnosis of appendicitis were determined by using contingency tables, and 95% confidence intervals were calculated. The institutional review board of Columbia University approved this study (IRB-AAA1250).

**RESULTS**

We initially reviewed 1245 patients’ charts. We excluded 583 patients for the following reasons: aged ≥18 years, imaging performed for specific questions not including appendicitis, or imaging performed at another hospital. Thus, 662 patients were included who had imaging ordered from the ED for abdominal pain to rule out appendicitis; group A = 265, November 1, 2008 to October 31, 2010, when CT was the primary imaging modality; and group B = 397, November 1, 2010 to October 31, 2012, when ultrasonography selectively followed by MRI was the primary imaging pathway.

In group A, 224 of 265 (84.5%) patients underwent CT as the first imaging

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**TABLE 2 MRI Parameters by Sequences**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Echo Time</th>
<th>Flip Angle</th>
<th>Bandwidth</th>
<th>FOV</th>
<th>Slice Thickness, mm</th>
<th>Spacing</th>
<th>Frequency</th>
<th>Phase</th>
<th>Phase FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal T2 SSFSE</td>
<td>90</td>
<td>62.5</td>
<td>44</td>
<td>5</td>
<td>0</td>
<td>384</td>
<td>224</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Axial T2 SSFSE</td>
<td>90</td>
<td>62.5</td>
<td>40</td>
<td>8</td>
<td>0</td>
<td>384</td>
<td>224</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sagittal T2 SSFSE</td>
<td>100</td>
<td>62.5</td>
<td>44</td>
<td>5</td>
<td>0</td>
<td>256</td>
<td>224</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Coronal bSSFP</td>
<td>1.7</td>
<td>&lt;75</td>
<td>83.33</td>
<td>44</td>
<td>0.4</td>
<td>256</td>
<td>192</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Axial bSSFP</td>
<td>1.7</td>
<td>70</td>
<td>83.33</td>
<td>40</td>
<td>0.4</td>
<td>224</td>
<td>192</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Axial T1-weighted post contrast fat-sat dynamic</td>
<td>2.1</td>
<td>12</td>
<td>83.33</td>
<td>30</td>
<td>4</td>
<td>320</td>
<td>192</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Coronal T1 fat-sat post single phase</td>
<td>2.1</td>
<td>12</td>
<td>125</td>
<td>40</td>
<td>4</td>
<td>320</td>
<td>160</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

bSSFP, balanced steady-state free precession; fat-sat, fat saturated; FOV, field of view; SSFSE, single-shot fast spin echo.
modality (Fig 1). CT was positive for appendicitis in 124 (55.4%), 24 (19.4%) of which were complicated. All 100 patients with acute appendicitis had an appendectomy. Eighteen of 24 patients with complicated appendicitis were treated nonoperatively. In group A, 40 (15.1%) patients had ultrasonography, and 1 patient had an MRI as the initial imaging test.

In group B, 365 (91.9%) patients had ultrasonography initially (Fig 2). Ultrasonography was interpreted as positive for acute appendicitis in 72 cases (19.7%). All 72 patients had an appendectomy. Ultrasonography findings were equivocal in 206: in 171 (46.8%) because the appendix could not be seen and in 35 because complicated appendicitis could not be ruled out (findings of free fluid, possible phlegmon, or abscess). Of the 206, 31 had no additional imaging or intervention, 142 had an MRI, 1 of which had a subsequent CT, and CT was performed in 34 patients. MRI was positive for appendicitis in 62 cases (43.7%), 7 (11.3%) of which were complicated. All patients with findings of acute appendicitis had an appendectomy. Two of 7 patients with complicated appendicitis on MRI were treated nonoperatively. Of the 34 CT scans done after ultrasonography, 20 showed appendicitis, 10 of which were complicated. In group B, 20 (5%) patients had a CT and 12 (3%) had an MRI as their initial imaging test.

Table 3 shows demographics and differences in frequency of imaging modality used to diagnose appendicitis for the 2 study periods. The total number of patients who had imaging was higher in group B than group A. There was significant difference between the groups when comparing the proportion of positive imaging and the proportion of patients who underwent an operation, with more negative imaging in group B (ultrasonography and MRI). Rate of negative appendectomy (false-negative imaging) was similar between groups (group A = 2.5%, group B = 1.4%). The rate of complicated appendicitis both by operative findings and pathology was similar between groups. We did not identify any missed appendicitis (false-negative imaging), but 74 patients (74 of 662 = 11%), 22 in group A and 52 in group B, did not have follow-up after discharge from the ED with negative imaging. Sensitivity, specificity, and positive and negative predictive value of the imaging pathways for the diagnosis of appendicitis was similar between study periods (groups A and B; Table 4).

Table 5 shows results of imaging over the 2 study periods. As expected, the most common initial imaging test in group A was a CT (224 of 265 = 84.5%), but 91.9% (365 of 397) in group B initially had ultrasonography. Roughly half of the ultrasonography studies obtained were equivocal or non-diagnostic and warranted follow-up cross-sectional imaging. In group B, most equivocal ultrasonography studies were followed by an MRI, and roughly half of those were negative for appendicitis (see Fig 2). Among patients in group B with suspicion of
complicated appendicitis by ultrasonography findings, a higher proportion underwent a subsequent CT than MRI. Table 6 shows time from ED triage to imaging, antibiotics, and appendectomy for image-positive appendicitis as well as length of stay. Time to CT was presumably longer in group B; more than half of CTs in group B were preceded by ultrasonography, but in group A, only a few CTs were preceded by ultrasonography. MRIs were similarly preceded by ultrasonography in most cases. However, despite different imaging pathways and longer average time to imaging for group B than group A, there was no difference in time from ED triage to treatment with antibiotics or appendectomy or length of stay between group A and group B. There was also no difference in time to antibiotics for complicated appendicitis between group A (8.8 [SD 4.1] hours) and group B (9.3 [SD 6.2] hours; P = .13). Mean overall length of stay was 52.2 (SD 79.9) hours and 43.4 (SD 63) hours for group A and B, respectively (P = .18). There was no difference in length of stay for patients with image-positive appendicitis between group A (82.2 [SD 102.5] hours) and group B (76.6 [SD 82.7] hours; P = .9). Mean length of stay for image-negative patients was 24.8 (SD 32.2) hours for group A and 20.3 (SD 25.1) hours for group B (P = .36). Almost all appendectomies were laparoscopic (264 of 265, 99.6%); 1 patient in group A underwent conversion to open (0.4% conversion rate).

**DISCUSSION**

Our study shows that imaging with ultrasonography selectively followed by MRI for diagnosis of acute appendicitis in children does not increase perforation rate or negative appendectomy rate. Furthermore, time to treatment and length of hospital stay was similar between the 2 imaging pathways. Use of ultrasonography and MRI is possible and effective for diagnosis in most cases of pediatric appendicitis. These
TABLE 4 Performance of Diagnostic Imaging Pathways

<table>
<thead>
<tr>
<th></th>
<th>Group A (n = 265)</th>
<th>Group B (n = 397)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>100% (133 of 133)</td>
<td>100% (159 of 159)</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>97–100</td>
<td>97–100</td>
<td></td>
</tr>
<tr>
<td>Specificity</td>
<td>98% (129 of 132)</td>
<td>99% (236 of 238)</td>
<td>.0001</td>
</tr>
<tr>
<td>95% CI</td>
<td>93–99</td>
<td>97–100</td>
<td></td>
</tr>
<tr>
<td>Positive predictive value</td>
<td>98% (133 of 136)</td>
<td>99% (159 of 161)</td>
<td>.0001</td>
</tr>
<tr>
<td>95% CI</td>
<td>93–99</td>
<td>95–100</td>
<td></td>
</tr>
<tr>
<td>Negative predictive value</td>
<td>100% (129 of 129)</td>
<td>100% (236 of 236)</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>96–100</td>
<td>98–100</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5 Results of Imaging for Group A (n = 265) and Group B (n = 397), n (%)

<table>
<thead>
<tr>
<th></th>
<th>Ultrasonography</th>
<th>CT</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of studies</td>
<td>40 (15.1)</td>
<td>245 (92.5)</td>
<td>54 (13.6)</td>
</tr>
<tr>
<td>Negative for appendicitis</td>
<td>10 (25)</td>
<td>87 (23.8)</td>
<td>116 (47.3)</td>
</tr>
<tr>
<td>Equivocal*</td>
<td>24 (60)</td>
<td>171 (46.8)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Positive for simple appendicitis</td>
<td>6 (15)</td>
<td>72 (19.7)</td>
<td>105 (42.9)</td>
</tr>
<tr>
<td>Positive for complicated appendicitis</td>
<td>0 (0)</td>
<td>24 (6.8)</td>
<td>11 (20.4)</td>
</tr>
</tbody>
</table>

* CT and MRI were not coded as equivocal but only as negative or positive for appendicitis (simple or complicated).

TABLE 6 Time to Imaging, Antibiotics, Operation, and Length of Stay, Mean Hours (SD)

<table>
<thead>
<tr>
<th></th>
<th>Group A (n = 265)</th>
<th>Group B (n = 397)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to ultrasonography</td>
<td>4.4 (1.7)</td>
<td>5.5 (3.3)</td>
<td>.07</td>
</tr>
<tr>
<td>Time to CT</td>
<td>6.7 (3.5)</td>
<td>10.9 (4.9)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Time to MRI</td>
<td>9.3 (3.5)</td>
<td>12.6 (5.5)</td>
<td>.23</td>
</tr>
<tr>
<td>Time to antibiotics*</td>
<td>8.7 (4.1)</td>
<td>8.2 (4.8)</td>
<td>.14</td>
</tr>
<tr>
<td>Time to appendectomy*</td>
<td>13.2 (7.2)</td>
<td>13.9 (6.7)</td>
<td>.41</td>
</tr>
<tr>
<td>Length of stay</td>
<td>32.2 (73.7)</td>
<td>43.4 (63)</td>
<td>.18</td>
</tr>
</tbody>
</table>

* For image positive appendicitis.

data support the notion that use of CT could be limited.

An imaging protocol of ultrasonography followed selectively by MRI eliminates radiation exposure. Although CT might still be used as needed for younger children who cannot cooperate with the need to lay still for an MRI (in our experience, <6 years of age) the overall reduction in radiation exposure should be substantial. The incidence of appendicitis in preschool-aged children is low (<5% of all children with appendicitis).19 Our results showed that ultrasonography findings consistent with complicated appendicitis resulted in preference of a subsequent CT rather than MRI, which perhaps reflects surgeon’s perception that CT scan is superior to MRI in the evaluation of an associated abscess. With increased experience and usage of MRI, this perception and practice might change.20 The use of CT in pediatric patients in the ED has steeply increased in the United States over the past decade, without change in the proportion of patients presenting with abdominal pain or diagnosis of appendicitis.21,22 Population-based studies have also shown significant increases in advanced diagnostic imaging use in recent years, including use of CT, with associated increased radiation exposure.12 Although CT use seems to be higher for pediatric patients in non–children’s hospitals compared with children’s hospitals, CT alone remains the most common imaging modality to diagnose appendicitis in both types of practice settings.3,4 In response to increased CT use, pediatrict radiologists have been leaders in increasing awareness of the issue of radiation and in advocating for changing practices to decrease radiation.23 Ultrasonography is an alternative imaging method for diagnosis of acute appendicitis that does not involve radiation. However, this imaging modality is more operator-dependent than CT or MRI and is less effective in patients with complicated intraabdominal pathology (eg, abscess) or obesity. Perhaps as a result, several studies have shown significantly lower sensitivity and specificity for ultrasonography compared with CT scan.24,25 Yet the concerns regarding the association between radiation from CT and malignancy are valid. Data from a large retrospective cohort study estimated radiation doses and indicated that repeated CT scans in childhood could triple the risk of brain cancer and leukemia.26 Alternative imaging, which does not involve radiation, should be considered.

Our results did not show a significant difference in important clinical outcomes such as perforation and negative appendectomy rates or length of stay between CT and ultrasonography/MRI use. Perforation rate is high in children, reported anywhere from 20% to 60%.27,28 In our appendectomy patients, the perforation rate was not different between the 2 groups. In addition, a similar proportion of patients in each group was treated nonoperatively based on imaging findings of complicated appendicitis.

The difference in the proportion of positive imaging and the proportion of patients who underwent an operation (higher in group A) may indicate increased use of imaging to rule out appendicitis in the latter period with an increased number of negative imaging results. However, this did not lead to an increased negative appendectomy rate. Negative appendectomy rates are
reported from 1% to 15% in recent studies.\(^3,5,28\) We had a negative appendectomy rate of 2% to 3%, indicating a low rate of false-positive results for both imaging pathways. Others have shown that decreased negative appendectomy rate does not result in increased perforation rate.\(^28\) Using a large pediatric database, Bacher et al found that increased use of diagnostic imaging was correlated with lower negative appendectomy rate, with the exception of boys <5 years of age.\(^26\) In a study of adults and children, Wagner et al found that use of CT before appendectomy between 2 study periods (1995–1999 and 2000–2007) increased from 40% to >90% in a single institution, concurrent with a decrease in negative appendectomy rates from 16% in the earlier period to 5% in 2006 without change in perforation rate (~30%).\(^30\) Other studies have shown a similar decrease in negative appendectomy rates with increased CT use, without increase in perforation rate for both adults\(^31,32\) and children.\(^32\) A delay of appendectomy from diagnosis for up to 12 hours while patients receive antibiotics does not seem to increase perforation rate or operative time.\(^33\) For these reasons, appendectomy is no longer treated as an operative emergency.

There are several limitations to this study. First, although we reported on performance of each imaging pathway, our main study question was not of diagnostic accuracy. This has been reported previously in the 95% to 100% range,\(^15,17,18\) but our results indicated similarly high sensitivity, specificity, and negative and positive predictive value of ultrasonography-MRI as for CT. Our MRIs were usually performed after an equivocal ultrasonography, and patients with positive ultrasonography for acute appendicitis usually did not undergo additional imaging. Therefore, the true sensitivity and specificity of MRI could not be determined; However, the specificity of the ultrasonography-MRI pathway was high (99%), and the sensitivity was 100% because we did not identify any missed appendicitis. We had follow-up for 80% of patients after negative imaging but cannot exclude that some had missed appendicitis and sought care elsewhere after discharge. A follow-up telephone survey of discharged ED patients with negative imaging at another New York City institution did not find any patients who went elsewhere than the initial institution.\(^34\) That approximately half of ultrasonography studies were equivocal is consistent with other reports.\(^3\) Our data suggest that this is precisely the setting in which cross-sectional imaging may best be used. Second, the radiologists were not blinded to the clinical presentation or the ultrasonography findings. However, it is unlikely that this resulted in significant bias because the diagnosis of appendicitis on MRI is based purely on radiographic findings. Third, because of the retrospective nature of the data collection, some patients might have been missed, although by reviewing all ultrasonography, MRI, and CT studies ordered from the ED for abdominal pain during the study period as well as all patients who had an appendectomy, this should be negligible. Fourth, we did not analyze cost or charges, but we did find an increase in the number of imaging studies in the ultrasonography-MRI period compared with the CT period. Increased use of imaging may be associated with increased cost; however, the associated decrease in cost from limiting radiation is difficult to quantify.\(^4\) The increased imaging use in the latter period (group B) might be because of lower threshold for imaging when there is no radiation risk, or it might reflect a known recent trend in increased imaging use in the ED possibly related to easier access or a change in culture.\(^22\) Finally, our results are limited to a single tertiary care–level children’s hospital, and the clinical applicability to other centers is unknown.

**CONCLUSIONS**

In children with suspected acute appendicitis, a radiation-free diagnostic imaging of ultrasonography selectively followed by MRI is comparable to CT with no difference in time to treatment, negative appendectomy rate, perforation rate, or performance.

**REFERENCES**

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Ultrasonography/MRI Versus CT for Diagnosing Appendicitis
Gudrun Aspelund, Abbey Fingeret, Erica Gross, David Kessler, Connie Keung, Arul Thirumoorthi, Pilyung Stephen Oh, Gerald Behr, Susie Chen, Brooke Lampl, William Middlesworth, Jessica Kandel and Carrie Ruzal-Shapiro
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