Diagnostic performance of CUBE MRI sequences of the knee compared with conventional MRI

T. Ai, W. Zhang, N.K. Priddy, X. Li

AIM: To evaluate the efficacy and efficiency of three-dimensional (3D) fast spin-echo (FSE) with variable flip angle (“CUBE”) magnetic resonance imaging (MRI) in knee imaging as compared with conventional MRI.

MATERIALS AND METHODS: Twenty-nine patients (single knee) with joint injuries of varying degrees were enrolled in this study between January, 2011 and December, 2011. All patients underwent conventional MRI and a fat-suppressed CUBE MRI sequence. All patients subsequently underwent knee arthroscopic surgery performed by an experienced orthopaedic surgeon within 2 weeks after the MRI examinations. With standard reference provided by arthroscopic results, the sensitivity, specificity, and accuracy of both the CUBE and conventional MRI techniques were calculated for detecting cartilage lesions, meniscus tears, and anterior cruciate ligament injuries, respectively. A chi-square test was used for statistical analysis with a level of significance of p < 0.05.

RESULTS: For the evaluation of articular cartilage lesions, the CUBE sequence had higher sensitivity (70.9% versus 50.6%, p < 0.01), higher specificity (72.6% versus 58.9%, p < 0.05), and higher accuracy (71.8% versus 55.2%, p = 0.001) than conventional MRI. For the evaluation of meniscus tears, CUBE and conventional MRI had similar sensitivity, specificity, and accuracy (p = 0.20–0.55). Similarly, there was no significant difference in sensitivity, specificity, or accuracy between CUBE imaging and conventional imaging in the detection of anterior cruciate ligament injuries (p = 0.13–0.65).

CONCLUSION: CUBE MRI has similar or superior sensitivity, specificity, and accuracy to a conventional imaging protocol in the comprehensive evaluation of knee joint injuries.

Introduction

The knee joint is the largest weight-bearing joint and is vulnerable to a wide variety of acute and chronic injuries. Knee injury usually involves bone injuries, meniscus tears, ligament tears, and articular cartilage injuries, and presents a challenge to imaging assessment because of its complex anatomical structures. With superior soft-tissue contrast and high spatial resolution, magnetic resonance imaging (MRI) is the most widely used imaging method for the evaluation of knee injuries. MRI can clearly depict complex anatomical structures and show varying degrees of injury to the menisci, ligaments, and articular cartilage. However, conventional MRI protocols are usually performed using repeated two-dimensional (2D) fast spin-echo (FSE) sequences. Aside from being time-consuming, 2D imaging also suffers from the partial volume effects caused by thick sections and gaps, which may result in missed diagnosis and misdiagnosis of some small lesions. Recently three-dimensional (3D) FSE (or TSE) imaging sequences with...
variable flip angle (“CUBE” or “SPACE”) have been developed to overcome the drawbacks of 2D imaging. They can acquire isotropic images with high quality, high spatial resolution, and relatively short scan time. These sequences have shown some unique advantages in the evaluation of the knee injuries. However, additional studies with surgical correlation are still needed to determine whether these new sequences can replace current conventional MRI protocols used in knee imaging.

In the present study, patients with knee injuries were evaluated with CUBE and conventional 2D imaging and the respective sensitivity, specificity, and accuracy were calculated. In this way, the aim of the study was to evaluate the efficacy and efficiency of CUBE MRI over conventional 2D imaging for the comprehensive evaluation of knee joint imaging.

Materials and methods

Patients and imaging

Written consent forms were obtained in accordance with institutional review board (IRB), 29 patients with knee injuries of varying degrees (single knee, total 29 knees) were enrolled from January 2011 to December 2011. Of the total patients, there were 17 men and 12 women. The age ranged from 18–53 years (average age = 32.6 years).

All patients were imaged with a 1.5 T MRI unit (HDxt 1.5 T, GE Healthcare, Waukesha, WI, USA) equipped by an eight-channel phased-array extremity coil. 2D conventional MRI was acquired with coronal spin-echo (SE) T1-weighted imaging (T1WI), coronal fat-suppressed (FS) fast-recovery FSE proton density (PD)/T2-weighted imaging (FSE PDWI/T2WI) and sagittal FS FR FSE PDWI/T2WI. Then a FS CUBE MRI sequence was performed.

The MRI parameters included: coronal SE T1WI [360 ms repetition time (TR)/9 ms echo time (TE); 320 × 256 matrix; 18 cm field of view (FOV); 4 mm section thickness]; coronal FS PDWI/T2WI [3060 ms TR, 12.4/99.7 ms TE (PD/T2WI); 320 × 192 matrix; 18 cm FOV; 4 mm section thickness]; sagittal PDWI/T2WI [3700 ms TR; 13.3/110.3 ms TE (PD/T2WI); 320 × 192 matrix; 18 cm FOV; 4 mm section thickness]; FS CUBE [2000 ms TR, 48 ms TE; 320 × 320 matrix; 18 cm FOV; 1 mm section thickness; ±31.35 kHz bandwidth; echo train length = 44]. Scan times were approximately 5 min 40 s for CUBE imaging and 10 min for conventional 2D imaging.

Arthroscopic knee surgery

An experienced orthopaedic surgeon performed arthroscopic knee surgery on all 29 patients within 2 weeks (duration range 3–14 days; mean duration 6.7 days) of the MRI examinations. The arthroscopist was blinded to the preceding MRI results. The articular cartilage, menisci, and anterior cruciate ligament were carefully visualized. The positive findings were recorded as a standard reference.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grading criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Normal, normal signal, and homogeneous thickness for articular cartilage</td>
</tr>
<tr>
<td>1</td>
<td>Local abnormal signals in articular cartilage, but normal cartilage surface</td>
</tr>
<tr>
<td>2</td>
<td>Superficial ulcers or fissure, &lt;50% of entire layer of cartilage</td>
</tr>
<tr>
<td>3</td>
<td>Deep ulcers or fissure, &gt;50% but less than of entire layer of cartilage</td>
</tr>
<tr>
<td>4</td>
<td>Entire layer of cartilage defects, with or without subchondral bone oedema or damage</td>
</tr>
</tbody>
</table>

Image analysis

All MRI images were analysed retrospectively by two experienced musculoskeletal radiologists. The radiologists were blinded to the history and arthroscopic findings of each patient when they reviewed the MRI studies. A dedicated off-line workstation (ADW4.4, GE Healthcare, Waukesha, WI, USA) was used in image analysis, which allowed reviewers to reformat the original image data for both the CUBE and conventional MRI protocols. The analysis included: (1) grade of cartilage lesions; (2) grade of meniscus tears; (3) evaluation of anterior cruciate ligament tears.

Grade of cartilage lesions

The entire articular surface of the knee joint was divided into six segments: (1) lateral femoral condyle, (2) medial femoral condyle, (3) lateral tibia plateau, (4) medial tibia plateau, (5) trochlea, and (6) patella. A modified Noyes Scoring System was used to evaluate the cartilage injuries (Table 1). If there were different grades in the same region, the highest grade was adopted.

Grade of meniscus tears

Each meniscus (medial and lateral) of the knee was divided into three regions: (1) anterior horn, (2) posterior horn, and (3) body. A total number of six regions were counted. The MRI classification of meniscus tears is given in Table 2. Meniscus tears of grade 2 or below, as diagnosed by MRI, do not reach the articular surface and therefore demonstrate negative arthroscopy results. So in the case with meniscus tears up to grade 2, MRI images were analysed alone without comparative analysis related to arthroscopic results.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grading criteria</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Normal</td>
</tr>
<tr>
<td>1</td>
<td>Focal globular or elliptic high signal within meniscus, but not extending to the articular surface of meniscus</td>
</tr>
<tr>
<td>2</td>
<td>Linear high signal within meniscus, extending to the meniscus rim, but not reaching the articular surface of meniscus</td>
</tr>
<tr>
<td>3</td>
<td>Abnormal high signal reaches the articular surface of meniscus</td>
</tr>
</tbody>
</table>
Evaluation of anterior cruciate ligament tears

The classification of anterior cruciate ligaments injuries included: (1) complete tear, demonstrating interrupted ligament continuity, thickened stump, and increased signal within the ligament; (2) partial tear, demonstrating persisting continuity, swollen ligament, and increased signal within the ligament.

Statistical analysis

Taking the arthroscopic results as the reference standard, the sensitivity, specificity, and accuracy of the CUBE and conventional MRI protocols were calculated for detecting cartilage lesions, meniscus tears, and anterior cruciate ligament injuries. The statistical analysis was performed using SPSS (Version 18, SPSS, Chicago, IL, USA). A chi-square test was used to compare differences between the CUBE and conventional MRI protocols (when \( n < 40 \) or actual frequency <5, Fisher’s exact probability test was used). The level of significance for statistical tests was set to \( p < 0.05 \).

Results

A total of 174 segments of articular cartilages in 29 patients were confirmed to be articular cartilage injuries by arthroscopic knee surgery. The results included: grade 0, 95 segments; grade 1, 38 segments; grade 2, 29 segments; grade 3, 5 segments; grade 4, 7 segments. As shown in Table 3, the sensitivity, specificity, and accuracy for the detection of articular cartilage lesions were 70.9, 72.6, and 71.8%, respectively, for the CUBE sequence and 50.6, 58.9, and 55.2%, respectively, for conventional 2D imaging. CUBE imaging had significantly higher sensitivity \((p = 0.009)\), specificity \((p = 0.047)\), and accuracy \((p = 0.001)\) compared with conventional 2D imaging (Figs 1 and 2).

<table>
<thead>
<tr>
<th>Cartilage lesions</th>
<th>Sensitivity CUBE</th>
<th>Conventional 2D</th>
<th>p-Value</th>
<th>Specificity CUBE</th>
<th>Conventional 2D</th>
<th>p-Value</th>
<th>Accuracy CUBE</th>
<th>Conventional 2D</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1</td>
<td>68.4% (26/38)</td>
<td>52.6% (20/38)</td>
<td>0.159</td>
<td>72.6% (69/95)</td>
<td>58.9% (56/95)</td>
<td>0.047</td>
<td>71.4% (95/133)</td>
<td>57.1% (76/133)</td>
<td>0.015</td>
</tr>
<tr>
<td>Grade 2</td>
<td>72.4% (21/29)</td>
<td>48.3% (14/29)</td>
<td>0.06</td>
<td>72.6% (69/95)</td>
<td>58.9% (56/95)</td>
<td>0.047</td>
<td>72.5% (90/124)</td>
<td>56.5% (70/124)</td>
<td>0.008</td>
</tr>
<tr>
<td>Grade 3</td>
<td>80% (4/5)</td>
<td>60% (3/5)</td>
<td>0.49</td>
<td>72.6% (69/95)</td>
<td>58.9% (56/95)</td>
<td>0.047</td>
<td>73.0% (73/100)</td>
<td>59% (59/100)</td>
<td>0.037</td>
</tr>
<tr>
<td>Grade 4</td>
<td>71.4% (5/7)</td>
<td>42.9% (3/7)</td>
<td>0.28</td>
<td>72.6% (69/95)</td>
<td>58.9% (56/95)</td>
<td>0.047</td>
<td>72.5% (74/102)</td>
<td>57.8% (59/102)</td>
<td>0.02</td>
</tr>
<tr>
<td>All lesions</td>
<td>70.9% (56/79)</td>
<td>50.6% (40/79)</td>
<td>0.009</td>
<td>72.6% (69/95)</td>
<td>58.9% (56/95)</td>
<td>0.047</td>
<td>71.8% (125/174)</td>
<td>55.2% (96/174)</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Figure 1 Sagittal MRI images in a 43-year-old woman with a surgically confirmed grade 1 cartilage lesion on the lateral femoral condyle. It was detected by neither reader with the conventional MRI imaging protocol, but detected by both readers using CUBE. (a) FS FR FSE PDWI image of left knee joint does not show any abnormal-appearing articular cartilage on the lateral femoral condyle. (b) Corresponding CUBE image shows a high intensity signal in the articular cartilage on the lateral femoral condyle (white arrow), but the surface is still smooth.
One hundred and seventy-four meniscus segments in 29 patients were investigated by arthroscopic knee surgery and 35 segments of meniscus tears were found: six horizontal tears, 11 radial (transverse) tears, two longitudinal tears (bucket-handle tears), 13 oblique tears, and three mixed tears. The sensitivity, specificity, and accuracy in detecting meniscus tears (grade 3) were 82.9%, 95%, and 92.5%, respectively, for CUBE and 77.1%, 91.4%, and 88.5% for conventional 2D imaging. There was no significant difference in sensitivity, specificity, or accuracy for the detection of meniscus tears ($p = 0.55$).

Table 4

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUBE</td>
<td>Conventional 2D</td>
<td>$p$-Value</td>
</tr>
<tr>
<td>Meniscus tear (Grade 3)</td>
<td>82.9% (29/35)</td>
<td>95% (132/139)</td>
</tr>
</tbody>
</table>

The anterior cruciate ligament in 29 patients was also examined by arthroscopy. Four complete tears and nine partial tears were found. The sensitivity, specificity, and accuracy in detecting anterior cruciate ligament injuries were 76.9%, 87.5%, and 82.8% for CUBE and 53.8%, 75%, and 65.5% for conventional 2D imaging. There was no significant difference in sensitivity, specificity, or accuracy for the detection of anterior cruciate ligament injuries ($p = 0.134–0.654$).

Discussion

Multiple recent studies have shown that 3D FSE sequences can be used for comprehensive joint assessment similar to 3D gradient-echo sequences initially used for cartilage imaging. So far, the preliminary results from these studies have shown 3D FSE imaging has a lower or similar diagnostic performance compared with conventional 2D imaging. In this study, the sensitivity, specificity, and accuracy of CUBE and conventional 2D imaging in evaluating knee joint injuries were compared. The experimental results showed that the CUBE sequence had significantly higher sensitivity, specificity, and accuracy compared with conventional 2D imaging in detecting articular cartilage lesions, showing encouraging results. Although CUBE suffers from image

Figure 2 Sagittal images in a 50-year-old man with a surgically confirmed grade 3 cartilage lesion on the medial femoral condyle. With FS FR FSE PDWI image, both readers ranked the lesion as grade 4 due to poor cartilage–subchondral interface (a, arrowheads). However, the corresponding CUBE image clearly demonstrated that the inner articular cartilage layer was intact (b, arrowheads). In addition, a grade 1 cartilage lesion was detected on the anteromedial femoral condyle (arrows) and an enchondroma was incidentally found in the proximal tibia (asterisks).
blurring effect and reduced magnetization transfer effect, both effects potentially reducing the visualization of superficial cartilage lesions, more cartilage lesions were detected with CUBE compared with conventional 2D imaging in the present study. Ristow et al.\(^{15}\) used an animal model and also demonstrated that 3D FSE sequences had better performance in depicting and characterizing cartilage abnormalities than the standard 2D FSE sequence.\(^{15}\)

CUBE had similar sensitivity, specificity, and accuracy in assessing meniscus tears as conventional 2D imaging. This result agrees with previous studies.\(^{5,16}\) The CUBE technique applies variable flip angle modulation to restrict T2 decay over the long echo train; however, CUBE images still suffer from blurring effect because of the late acquisition of high spatial frequencies. It is particularly evident with subjective analysis of image quality. This blurring can be reduced by increasing readout bandwidth or decreasing echo train length at the cost of the signal-to-noise ratio and examination time. Further studies should be performed to optimize the trade-off between these factors.

The capsule of the knee joint is thin, and its stability relies principally on adjacent muscles and ligaments. CUBE sequences obtain thinner, continuous sections through the whole joint, which will most likely reduce the partial-volumetric effects possibly resulting in fewer diagnostic mistakes. CUBE also allows multiplanar reformatting (including a curve reformat) of volumetric data, which will improve detection of abnormalities of the knee joint and evaluation of the relationship between the cruciate ligaments and the rivets after reconstruction surgeries. Yoon et al.\(^{17}\) demonstrated that 3D FSE sequences had high diagnostic values for cruciate tears. However, the present study showed that CUBE and conventional 2D imaging actually had similar sensitivity, specificity, and accuracy in evaluating anterior cruciate ligament injuries, which is consistent with the study from Kijowski et al.\(^5\) This may indicate that both techniques have an inherent, highly consistent diagnostic performance.

The main limitation in the present study is the small patient population. Many statistical results (\(p\)-values) between CUBE and conventional 2D imaging are not significant because of the small sample of positive findings, such as the sensitivity, specificity, and accuracy for detecting anterior cruciate ligament injuries and tears. For this reason, additional clinical studies with a larger patient population need to be performed for a thorough evaluation of diagnostic values for the CUBE technique. In addition,
only cartilage lesions, meniscus tears, and anterior cruciate ligament injuries were assessed in this study. Further evaluation should be done for more comprehensive joint assessment, including both collateral ligaments and bone marrow lesions. Besides, a comparison between 3D FSE sequences and 3D GRE sequences for knee joint imaging will also be useful for clinical practice.

In conclusion, the present study demonstrated that CUBE has a superior diagnostic performance in detecting cartilage lesions, and a comparable diagnostic performance in meniscus tears and anterior cruciate ligament injuries as compared to conventional 2D sequences. Results show that CUBE is comparable if not superior to conventional 2D imaging for the comprehensive joint assessment of the knee injuries, and is likely to replace the currently used 2D imaging protocols for knee evaluation.

Acknowledgements

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References