Three-dimensional turbo spin-echo magnetic resonance imaging (MRI) and semiquantitative assessment of knee osteoarthritis: comparison with two-dimensional routine MRI

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Purpose: The aim of this study was to evaluate three-dimensional (3D) turbo spin-echo (TSE) magnetic resonance imaging (MRI) for semiquantitative assessment of knee OA.

Materials and method: Twenty subjects fulfilling the American College of Rheumatology clinical criteria of knee OA underwent both two-dimensional (2D) and 3D MRIs on the same day. The 2D MRI protocol included triplanar fat-suppressed (FS) intermediate-weighted (Iw) TSE. For the 3D TSE technique, a sagittal FS Iw sequence was acquired and triplanar reformations were constructed. 2D and 3D MRIs were read separately by two radiologists using the Whole-Organ Magnetic Resonance Imaging Score (WORMS) system. Agreement was determined using weighted kappa statistics and percentage of overall agreement. The diagnostic performance of WORMS readings using 3D TSE MRI to detect the presence or absence of features was assessed using readings from 2D TSE images as a reference.

Results: Agreement for the scored features ranged between 0.62 (osteophytes (OS)) and 0.94 (meniscal extrusion). The sensitivity of WORMS readings using the 3D TSE technique ranged between 80% (peri-articular cysts) and 100% (several features), the specificity ranged between 62.3% (OS) and 100% (several features), and accuracy ranged between 77.2% (OS) and 99.3% (subchondral cysts).

Conclusions: Semiquantitative assessment of knee OA can be reliably performed using 3D TSE MRI, showing substantial to almost perfect agreement and high accuracy when compared to routine 2D TSE MRI. 3D TSE MRI also takes less time, which is important for large OA studies.

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Introduction

Magnetic resonance imaging (MRI) is the most important imaging tool for assessing knee osteoarthritis (OA) in both clinical and research environments1,2. Validated MRI-based semiquantitative scoring systems are used to assess the whole knee joint3–6 and have been applied to many OA studies. These scoring systems were based on routine two-dimensional (2D) MRI sequences, using different fluid sensitive spin-echo (SE) techniques such as proton density-weighted (PDw), T2-weighted (T2w), or short tau inversion recovery (STIR), acquired in different planes. Routine 2D SE MRI techniques are widely applied in observational studies and clinical trials in knee OA, are recommended in MRI protocols in the Osteoarthritis Research Society International (OARSI)/Outcome Measures in Rheumatology Clinical Trials (OMERACT) consensus5, and are being applied in the largest ongoing observational knee OA study, the Osteoarthritis Initiative (OAI)5.

Although 2D MRI sequences have high in-plane spatial resolution, they are acquired with relatively thick sections and gaps between sections, which can lead to partial-volume artifacts. Such
drawbacks especially affect assessment of articular cartilage in knee OA. It is also impossible to reconstruct a 2D MRI sequence in multiple planes without significant loss of image quality, and time-consuming multiple acquisitions are required.

To compensate for partial-volume artifacts, many MRI protocols in OA research, including the OAI, have added cartilage-specific three-dimensional (3D) techniques. Currently, most of the 3D MRI techniques in OA research are gradient recalled-echo (GRE) sequences that can be acquired with isotropic or nearly isotropic resolution, reducing partial-volume artifacts while acquiring very thin continuous sections through the joint. This technique has improved detection of cartilage abnormalities in the knee. However, 3D GRE-type sequences are also time consuming, and while it is possible to reconstruct the source acquisition in multiple planes, 3D GRE-type sequences cannot replace routine 2D SE MRI sequences because they do not allow accurate assessment of other important joint structures such as the menisci, ligaments, and subchondral bone.

3D turbo spin-echo (TSE) MRI techniques have been recently used to obtain images of the knee joint with high SE contrast resolution and isotropic spatial resolution. Such techniques can produce images with SE intermediate-weighted (Iw) contrast, which is a widely used tissue contrast in musculoskeletal imaging. Recent studies have demonstrated that 3D TSE MRI is as good for assessing cartilage, menisci, and cruciate ligaments as routine 2D TSE techniques. Further, unlike 3D GRE-type sequences, 3D TSE MRI depicts bone marrow abnormalities equally well. Thus, it seems possible that a single-acquisition of the 3D TSE technique with multiplanar reformatting could replace routine 2D TSE imaging in clinical practice, as well as in clinical research. 3D TSE MRI is also faster compared to the acquisition time of the whole 2D TSE protocol, which is important in large studies. So far, no one has reported on semiquantitative whole joint assessment of knee OA using 3D TSE MRI.

The aim of this study was to evaluate semiquantitative assessment of knee OA using 3D TSE MRI, by comparing it to the current standard 2D TSE MRI protocol.

**Methods**

**Participants**

A total of 20 subjects (one knee per subject) were examined. Mean age was 56.7 (range 46–70) and 60% (12) were women. All subjects met the American College of Rheumatology (ACR) clinical criteria for knee OA. None of the knees had typical features of acute trauma on MRI, or typical features of inflammatory or infectious disease. The study protocol was approved by the institutional review board at the University of São Paulo at Ribeirão Preto, Brazil, and we obtained signed informed consent from all
subjects. Subjects were offered an MRI of the symptomatic knee (one knee per subject); if both knees were symptomatic, the more symptomatic knee was chosen; if symptoms were identical in both knees, the knee from the dominant leg was selected.

### MRI acquisition

All knees were imaged with the same 1.5-T MRI unit (Philips Achieva 1.5-T MRI System, Philips Medical Systems, Best, The Netherlands) using an 8-channel SENSE knee coil. Both routine 2D and 3D TSE images were acquired on the same day.

The routine 2D TSE MRI sequences were acquired with SPAIR (spectral attenuated inversion recovery), a high uniform fat saturation method that uses adiabatic spectral saturation pulses. Three sequences were used: (1) sagittal lw TSE (repetition time (TR) 2342 ms, echo time (TE) 50 ms, 224 × 176 matrix, 16 × 16 cm field of view (FOV), 4 mm slice thickness, 4 number of excitations (NEX), echo train length (ETL) 14, bandwidth 395 Hz/pixel, acquisition time 2 min 43 s); (2) coronal lw TSE (TR 2342 ms, TE 50 ms, 224 × 176 matrix, 16 × 16 cm FOV, 4 mm slice thickness, 4 NEX, ETL 14, bandwidth 386 Hz/pixel, acquisition time 2 min 30 s); and (3) axial lw TSE (TR 3045 ms, TE 50 ms, 224 × 176 matrix, 16 × 16 cm FOV, 4 mm slice thickness, 4 NEX, ETL 14, bandwidth 429 Hz/pixel, acquisition time 3 min). The total acquisition time for routine 2D TSE MRI was 8 min 13 s.

The 3D TSE sequence was also acquired with the SPAIR technique in the sagittal plane (source images), with lw contrast and nearly isotropic voxels (0.6 × 0.6 × 0.7 mm), and the following parameters: TR 2500 ms, TE 35 ms, 300 × 258 matrix, 18 × 18 cm FOV, 1 NEX, ETL 65, and bandwidth 255 Hz/pixel. The total time acquisition for the 3D sagittal sequence (source images) was 5 min.

The source images were used to create sagittal, coronal, and axial reformatted images of the knee joint with 1.5 mm slice thickness, which were used for the 3D TSE MRI assessment of the knee (Fig. 1). Post-processing of source sagittal 3D TSE MRI was performed by a fellow in musculoskeletal radiology (FACN) on the imaging workstation immediately after the MRI examination.

### MRI assessment

Two musculoskeletal radiologists (MDC, MDM) each with 5 years of experience in standardized semiquantitative assessment of knee OA, blinded to clinical data, read both 2D and 3D TSE MRIs separately and independently. Knees were assessed for both techniques using the Whole-Organ Magnetic Resonance Imaging Score (WORMS) method. In WORMS, the knee is subdivided into 15 subregions: five subregions in each tibiofemoral compartment (central and posterior femur; anterior, central, and posterior tibia), five subregions in the patellofemoral compartment (medial and lateral patella, anterior medial femur, and anterior lateral femur), and the subspinous region. The MRI features evaluated according to WORMS were cartilage morphology (CM), subchondral bone marrow lesions (BMLs), subchondral cysts (SC), meniscal morphology (MT), osteophytes (OS), bone attrition (BA), joint effusion (EF), and periarticular cysts (PC).

CM was scored semiquantitatively from 0 to 6 in each subregion: 0 = normal thickness and signal; 1 = partial thickness focal defect <1 cm in greatest width; 2 = full thickness focal defect <1 cm in greatest width; 3 = multiple areas of partial-thickness defects intermixed with areas of normal thickness, or a grade 2.0 defect wider than 1 cm but <75% of the region; 4 = diffuse (≥75% of the region) partial-thickness loss; 5 = multiple areas of full-thickness loss or a grade 2.5 lesion wider than 1 cm but <75% of the region; 6 = diffuse (≥75% of the region) full-thickness loss. BMLs and SC were scored from 0 to 3 based on the extent of regional involvement: 0 = none; 1 = 25% of the subregion; 2 = 25–50% of the subregion; 3 = >50% of the subregion.

The anterior horn, body, and posterior horn of the medial and lateral menisci were graded separately from 0 to 4: 0 = intact; 1 = minor radial tear or parrot-beak tear; 2 = non-displaced tears including horizontal and vertical tears or prior surgical repair; 3 = displaced tears including displaced flap tears and bucket-handle tears, or partial resection or maceration; 4 = complete maceration/destruction or complete resection.

OS were graded from 0 to 7 along 14 different margins of the knee according to WORMS, using the following scale: 0 = none; 1 = equivocal; 2 = small; 3 = small-moderate; 4 = moderate; 5 = moderate-large; 6 = large; and 7 = very large. BA represented flattening or depression of the articular surfaces and was graded from 0 to 3 on the subjective degree of deviation from the normal articular surface contour: 0 = normal; 1 = mild; 2 = moderate; and 3 = severe.

Joint EF was scored semiquantitatively from 0 to 3 in terms of maximal distention of the synovial cavity: 0 = absence of EF;
Table I
Comparing agreement of WORMS scoring of 2D TSE and 3D TSE MRI: analysis per subregion.

<table>
<thead>
<tr>
<th>MRI features</th>
<th>N</th>
<th>Reader 1</th>
<th>Reader 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weighted kappa [95% confidence intervals]</td>
<td>Agreement %</td>
</tr>
<tr>
<td>BA (14 subregions)</td>
<td>280</td>
<td>0.85 [0.75, 0.96]</td>
<td>97.9</td>
</tr>
<tr>
<td>BMLs (15 subregions)</td>
<td>300</td>
<td>0.92 [0.86, 0.98]</td>
<td>97.7</td>
</tr>
<tr>
<td>CM (14 subregions)</td>
<td>300</td>
<td>0.81 [0.75, 0.87]</td>
<td>87.5</td>
</tr>
<tr>
<td>EF (one subregion)</td>
<td>20</td>
<td>0.81 [0.59, 1.00]</td>
<td>85.0</td>
</tr>
<tr>
<td>MT (six subregions)</td>
<td>120</td>
<td>0.89 [0.82, 0.97]</td>
<td>93.3</td>
</tr>
<tr>
<td>MX (two subregions)</td>
<td>40</td>
<td>0.89 [0.78, 0.99]</td>
<td>90.0</td>
</tr>
<tr>
<td>OS (16 subregions)</td>
<td>320</td>
<td>0.63 [0.57, 0.69]</td>
<td>65.0</td>
</tr>
<tr>
<td>PC (seven subregions)</td>
<td>140</td>
<td>0.82 [0.64, 1.00]</td>
<td>97.1</td>
</tr>
<tr>
<td>SC (15 subregions)</td>
<td>300</td>
<td>0.83 [0.60, 1.00]</td>
<td>99.3</td>
</tr>
</tbody>
</table>

1 = <33% of maximal potential distention; 2 = 33–66% of maximal potential distention; 3 = >66% of maximal potential distention. In WORMS, joint EF and synovial thickening are scored together. PC (popliteal, prepatellar bursitis, anserine bursitis, meniscal cysts, infrapatellar bursitis, bicipital cysts, etc.) were evaluated and graded from 0 to 3 based subjectively on size (popliteal cyst); all other cysts were graded present or absent.

In addition to the WORMS system, extrusion of the medial and lateral meniscal body was assessed using coronal STIR images. The reference slice in which the medial tibial spine had the greatest lateral meniscal body was assessed using coronal STIR images. The lateral cyst); all other cysts were graded present or absent.

The agreement for scoring of the different MRI features based on a subregional assessment, comparing 2D and 3D MRI readings, is presented in Table I with weighted kappas ranging between 0.63 (OS) and 0.92 (BMLs) for reader 1, and between 0.62 (OS) and 0.94 (MX) for reader 2. Overall percent agreement ranged between 65.0% (OS) and 99.3% (SC) for reader 1, and between 53.8% (OS) and 99.3% (SC) for reader 2 (Table I).

Table II
Diagnostic performance of WORMS scoring using 3D TSE MRI with 2D TSE MRI as the reference standard: analysis per subregional basis using weighted kappa statistics and percentage of overall agreement. We further assessed the inter-reader agreement between the 3D readings of both readers on a subregional basis using weighted kappa statistics and percentage of overall agreement. All statistical calculations were performed using SAS® software (Version 9.1 for Windows; SAS Institute; Cary, NC).

Results
The agreement for scoring of the different MRI features based on a subregional assessment, comparing 2D and 3D MRI readings, is presented in Table I with weighted kappas ranging between 0.63 (OS) and 0.92 (BMLs) for reader 1, and between 0.62 (OS) and 0.94 (MX) for reader 2. Overall percent agreement ranged between 65.0% (OS) and 99.3% (SC) for reader 1, and between 53.8% (OS) and 99.3% (SC) for reader 2 (Table I).

The values of sensitivity, specificity, and accuracy of semiquantitative assessment with 3D TSE considering the readings of 2D TSE as the reference standard are presented in Table II. Sensitivity ranged between 80% (PC) and 100% (MX and SC) for reader 1 and between 80% (BA) and 100% (several features) for reader 2. Specificity ranged between 85.2% (OS) and 100% (EF) for reader 1 and between 62.3% (OS) and 100% (EF and MX) for reader 2. Accuracy ranged between 85.6% (OS) and 99.3% (SC) for reader 1 and between 77.2% (OS) and 99.3% (SC) for reader 2.

The inter-reader agreement between the 2D MRI readings of both readers is presented in Table III and ranged between 0.42 for BA and 0.83 for MX (weighted kappa). The overall inter-reader percent agreement ranged between 55% for OS and 98.7% for SC. The inter-reader agreement between the 3D MRI readings of both readers is presented in Table IV and ranged between 0.52 for OS and 0.85 for MX (weighted kappa). The overall inter-reader percent agreement ranged between 51.9% for OS and 98% for SC.

Discussion
We compared the results of semiquantitative assessment of 3D TSE images to the results of semiquantitative assessment of routine
2D TSE sequences. We found that the scores for the 3D and 2D images were very close with substantial to almost perfect agreement for all features assessed, and were comparable to the results obtained by trained readers assessing routine 2D TSE sequences acquired on 1.5 and 3.0 T MRI systems. We further could show that inter-reader agreement using 3D readings achieved quite similar results when compared to the inter-reader exercise using 2D readings.

The 3D VISTA (Philips Medical Systems) MRI technique used in this study provides high-resolution volumetric 3D images acquired with TSE. Acquisition time and inter-echo spacing are optimized by applying reduced flip angles in combination with non-selective refocusing pulses. Combining parallel acquisitions using robust techniques, which are acquired with gradient-echo contrast and are limited in the assessment of other joint tissues, 3D TSE MRI is acquired with SE contrast, which allows high-resolution assessment of other articular structures such as the menisci, ligaments, and subchondral bone as well as articular cartilage. Previous studies have found that 3D TSE and 2D TSE MRI performed almost equally well when assessing pathology in such as cartilage, ligaments, and subchondral bone as well as articular cartilage (Fig. 2). Some limitations of this study need mentioning. First, we did not compare the diagnostic performance of the semiquantitative readings using the 3D TSE technique to arthroscopic, surgical or histologic data. Thus, it was not possible to assess the absolute accuracy of 3D TSE readings in this study. As mentioned before, many studies have already tested similar techniques against arthroscopy with promising results comparable to routine 2D sequences. Large OA studies and clinical trials are unlikely to have arthroscopic or histologic data, and comparison to arthroscopic or histological data was not the purpose of this study. Second, we did not test intra-observer results for the two MRI protocols. Images from both techniques were read by the same persons independently, and we assume that the intra-observer variability would be similar for the 2D and 3D images. Finally, although we demonstrated that semiquantitative assessment of knee OA using the 3D TSE technique cross-sectionally is reliable, it is not known if such reliability would extend to longitudinal assessment, especially detecting changes of scoring of different features over time. Longitudinal OA studies with 3D TSE MRI will be necessary to answer such question.

In conclusion, we demonstrated that 3D TSE MRI is a reliable technique for semiquantitative assessment of knee OA, with substantial to almost perfect agreement and high accuracy when compared to routine 2D TSE techniques. 3D TSE MRI has the advantage of faster time acquisition, which would be important in large OA studies and clinical trials.
Authors’ contributions

Conception and design: all authors; Analysis and interpretation of the data: MDC, MDM, JN; Drafting of the article: all authors; Critical revision of the article for important intellectual content: all authors; Final approval of the article: all authors; Provision of study materials or patients: MDC, MHNB, FACION; Statistical expertise: JN.

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Conflict of interest

Michel D. Crema, Frank W. Roemer, and Monica D. Marra are stockholders of Boston Imaging Core Lab (BICL), LLC. Ali Guermazi is president of BICL, LLC. He is also a consultant for MerckSerono, Genzyme, Novartis, Stryker, and AstraZeneca.

References