Magnetic Resonance Imaging of Knee Cartilage Using a Water Selective Balanced Steady-State Free Precession Sequence

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Purpose: To compare an optimized water selective balanced steady-state free precession sequence (WS-bSSFP) with conventional magnetic resonance (MR) sequences in imaging cartilage of osteoarthritic knees.

Materials and Methods: Flip angles of sagittal and axial WS-bSSFP sequences were optimized in three volunteers. Subsequently, the knees of 10 patients with generalized osteoarthritis were imaged using sagittal and axial WS-bSSFP and conventional MR imaging techniques. We calculated contrast-to-noise ratios (CNR) between cartilage and its surrounding tissues to quantitatively analyze the various sequences. Using dedicated software we compared, in two other patients, the accuracy of cartilage volume measurements with anatomic sections of the tibial plateau.

Results: CNRtotal eff (CNR efficiency between cartilage and its surrounding tissue) using WS-bSSFP was maximal with a 20 –25° flip angle. CNRtotal eff was higher in WS-bSSFP than in conventional images: 6.1 times higher compared to T1-weighted gradient echo (GE) images, 5.1 compared to proton-density (PD) fast spin echo (FSE) images, and 4.8 compared to T2-weighted FSE images. The mean difference of cartilage volume measurement on WS-bSSFP and anatomic sections was 0.06 mL compared to 0.24 mL for T1-GE and anatomic sections.

Conclusion: A WS-bSSFP sequence is superior to conventional MR imaging sequences in imaging cartilage of the knee in patients with osteoarthritis.

Key Words: cartilage; MRI; knee imaging; SSFP; osteoarthritis
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MAGNETIC RESONANCE (MR) imaging has been used successfully to visualize cartilage (1). Currently, the techniques most widely used for imaging cartilage are fat suppressed proton-density weighted fast spin-echo (PD-FSE), fat suppressed T2-weighted fast spin-echo (T2-FSE), and fat suppressed T1-weighted gradient-echo (T1-GE) sequences (2,3).

Recently, several other MR imaging pulse sequences have attracted attention with regard to their optimal visualization of cartilage (4,5). These sequences include steady-state free precession (SSFP) techniques such as fluctuating equilibrium MR (FEMR) (6), fat suppressed steady-state free precession (FS-SSFP) (7), linear combination steady state free precession (LC-SSFP) (8), Dixon SSFP imaging (9), and dual-echo steady-state (DESS) (10). Other imaging techniques successfully used for cartilage imaging are driven equilibrium Fourier transform (DEFT) (11), three-dimensional fat-suppressed echo planar imaging (EPI) (12,13), magnetization-transfer contrast (MTC) (14), and selective water excitation (15–18).

Our purpose was to optimize a three-dimensional balanced SSFP imaging sequence in combination with water excitation for MR imaging of articular cartilage of the knee, and to compare this sequence with conventional MR imaging sequences in patients with osteoarthritis. The other sequences included were T1-GE, PD-FSE, and T2-FSE, all in combination with fat-suppression.

MATERIALS AND METHODS

Patients

The study was approved by our institution’s medical ethical review board. Written informed consent was obtained from the patients before the study and permission was given by the patients, who underwent total...
knee arthroplasty, to use the tibial plateau for the purpose of this study.

Twelve patients and three normal volunteers were included in this study. Images of the three volunteers were used to optimize MR image contrast. Subsequently, knees of 10 patients with radiographic characteristics of osteoarthritis were imaged using the optimized sequences. Osteoarthritides of the knee was defined as a Kellgren and Lawrence score on conventional radiographs of the knee of more than 1 (19). The 10 patients aged between 54 to 74 years (median 61 years). Anatomic sections of the tibial plateau were obtained in two patients (64 and 70 years old) who underwent total knee arthroplasty because of severe osteoarthritis.

**Optimization in Three Volunteers**

The flip angle of the WS-bSSFP sequence was optimized in three volunteers. Each volunteer was scanned 11 times using the WS-bSSFP sequence, with stepwise increase of the flip angle. Flip angles used were 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, and 80°. The optimal flip angle for articular cartilage imaging was defined as the maximal contrast-to-noise ratio (CNR) between cartilage and its surrounding tissues. This was performed both in the sagittal and axial orientated WS-bSSFP images.

**MR Acquisition in 12 Patients**

All MR images were acquired with a 1.5-T superconducting MRI-system (Gyroscan Intera, Philips Medical Systems, Best, The Netherlands) using a dedicated knee coil. Each examination consisted of the following sequences: sagittal three-dimensional fat suppressed T1-GE sequence (repetition time [TR] 46 msec; echo time [TE] 2.5 msec; flip angle 40°; 3.0-mm slice thickness; slice overlap 1.5 mm; 75 slices; 140 mm field of view [FOV]; voxel size 0.51 × 0.51 × 2.00 mm; bandwidth/pixel: 98.6; acquisition time five minutes and five seconds). Total acquisition time of the four sequences (including the initial survey sequence) was 27 minutes.

**Quantitative Analysis**

For quantitative analyses, not only signal intensities (SI) of cartilage and synovial fluid, but also other surrounding tissues including bone, menisci, muscles, and fat, were measured on axial and sagittal WS-bSSFP, T1-GE, and PD/T2-FSE images. The regions of interest (ROI) used to measure SI were placed at identical positions on matching sections in each patient. We selected a single slice displaying all above mentioned tissue types in each patient (Fig. 2). The mean SI over the ROIs was used to represent the tissue’s signal. The minimal surface area of a ROI was 15 mm², and the mean surface area of a ROI was 163 mm². We calculated CNR between cartilage (ca) and fluid using the following formula:

\[
\text{CNR}_{ca, \text{fluid}} = \frac{|SI_{\text{cartilage}} - SI_{\text{fluid}}|}{SI_{\text{noise}}}
\]

Because cartilage is only in contact with synovial fluid for a small percentage of the total cartilage perimeter, we are also interested in a sequence with good contrast between cartilage and other surrounding tissue. Therefore, we calculated CNR between cartilage and all of the cartilage surrounding tissues (n) using the formula:

\[
\text{CNR}_{\text{total}} = \frac{\sum |SI_{\text{cartilage}} - SI_{\text{tissue}_{n}}|}{SI_{\text{noise}}} \times \frac{\text{Tissue}_{n} \text{ to cartilage interface (mm)}}{\text{Total cartilage perimeter (mm)}}
\]

In this formula, tissue to cartilage interface is the length in millimeters where bone, fluid, menisci, fat, and muscle, respectively, are in direct contact with cartilage. Tissue-to-cartilage interface divided by the total cartilage perimeter represents the percentage of cartilage that is in direct contact with a specific tissue. For example, for bone this percentage is 50% because half of the cartilage (the non-articular side) is always in direct contact with bone. When calculating CNR_{\text{total}} we used the same slice per sequence in each patient to keep the tissue-to-cartilage interface the same for all compared sequences.

Additionally, we calculated CNR efficiencies for comparison. CNR efficiency is the ratio of CNR to the square root of total imaging time (4). In comparing sequences, the relative CNR efficiency numbers are used. All CNR efficiency calculations are normalized by voxel volume.

Because SSFP techniques are sensitive to magnetic field inhomogeneity, we compared CNRs between bone.
and cartilage that were based on SI measurements of both the most medial and most lateral sections of the axially orientated WS-bSSFP image sequence.

**Cartilage Volume Measurements**

In two patients who underwent total knee arthroplasty, the preoperatively obtained MR images and the anatomic sections of the tibial plateau were used to determine and compare cartilage volume measurements. Immediately after total knee arthroplasty, sagittal anatomic sections of the tibia plateau were obtained with a thickness of 4 mm, using a diamond band saw (Exact Apparatebau, Norderstedt, Germany) that is capable of creating anatomic sections without damaging the cartilage. The anatomic sections were placed next to a ruler and were digitally photographed (Fig. 3). The sagittal WS-bSSFP and T1-GE sequences and the digital photographs were analyzed quantitatively on an IPC workstation (SUN Microsystems Inc., Mountain View, CA), by one observer, using the MASS software package (20). All cartilage contours were drawn manually. Cartilage volumes measured on the anatomic sections of the tibia plateau were compared with the cartilage volumes measured on the two MR sequences.

**RESULTS**

Figure 4 shows the CNR between cartilage and fluid and CNR between cartilage and surrounding tissues as a...
function of the flip angle in axial and sagittal WS-bSSFP images. Maximum CNR between cartilage and fluid and cartilage and all of its surrounding tissues in a WS-bSSFP sequence is displayed at 20° for the axial orientated images and at 25° for the sagittal images. CNRs and acquisition times of the sequences are presented in Table 1. CNR efficiencies between cartilage and synovial fluid, and between cartilage and all its surrounding tissues, obtained with WS-bSSFP sequences are higher than those obtained with conventional sequences. Figure 5 shows an example of cartilage surface detail on WS-bSSFP images and on conventional images.

Field inhomogeneity on the WS-bSSFP sequence is reflected by differences in SI obtained on medial and lateral sides on axial images. Over all 10 patients, the average SI of bone at the medial side was 46.28 and 47.40 at the lateral side of the knee. The average difference of bone signal between medial and lateral side was 1.92 (3.2%).

Table 2 shows the cartilage volume of the medial and lateral tibia plateau in the anatomic sections, WS-bSSFP, and T1-GE images in two patients. The differences between cartilage volumes measured on anatomic sections and on MR images were smallest using WS-bSSFP images in three out of four regions. The mean difference between cartilage volume measurements on anatomic sections and WS-bSSFP images was 0.06 mL. The mean difference between anatomic sections and T1-GE images was 0.24 mL.

**DISCUSSION**

CNR between cartilage and the cartilage surrounding tissues on WS-bSSFP sequence is optimal with a flip angle of 20–25°. Our result is in accordance with theoretical SI curves derived from literature (4,9,21,22). Reeder et al (9) optimized flip angles for SSFP imaging of cartilage with a method that is similar in principle to the method used to optimize the flip angle for SPGR sequences using the Ernst angle. In that study the flip angle that maximized the cartilage signal of an SSFP image was 27°.

CNR between cartilage and surrounding tissue in axial orientated images is somewhat higher than in the sagittal orientated images. The reason for this small difference in CNR is the difference in composition of the tissues surrounding cartilage in axial and sagittal images. In the sagittal images, the cartilage contacts also the menisci and muscle. However, on axial images, car-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Average CNR Efficiencies Between Cartilage and Other Tissues (Interpatient Variation) Over 10 Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>WS-bSSFP</strong></td>
</tr>
<tr>
<td>CNR\textsubscript{ca-fluid} eff</td>
<td>1</td>
</tr>
<tr>
<td>CNR\textsubscript{ca-bone} eff</td>
<td>1</td>
</tr>
<tr>
<td>CNR\textsubscript{ca-meniscus} eff</td>
<td>1</td>
</tr>
<tr>
<td>CNR\textsubscript{ca-muscle} eff</td>
<td>1</td>
</tr>
<tr>
<td>CNR\textsubscript{ca-fat} eff</td>
<td>1</td>
</tr>
<tr>
<td>CNR\textsubscript{total} eff</td>
<td>1</td>
</tr>
<tr>
<td>Tacq (min)</td>
<td>5.05</td>
</tr>
</tbody>
</table>

\textsuperscript{a}All CNR efficiencies and interpatient variation are relative to the WS-bSSFP sequence. 

\textsuperscript{b}Contrast between cartilage and meniscus, cartilage and muscle, and cartilage and fat was not calculated on axial PD-FSE and T2-FSE weighted images. CNR\textsubscript{ca-fluid} eff = contrast to noise ratio efficiency between cartilage and fluid, CNR\textsubscript{ca-bone} eff = contrast to noise ratio efficiency between cartilage and bone, CNR\textsubscript{ca-meniscus} eff = contrast to noise ratio efficiency between cartilage and meniscus, and all of its surrounding tissue, WS-bSSFP = balanced steady-state free precession with water excitation, T1-GE = T1 weighted gradient echo sequence with fat suppression, PD-FSE = proton- density weighted fast spin echo sequence with fat suppression, T2-FSE = T2 weighted fast spin echo sequence with fat suppression, Tacq = acquisition time.
Data does not contact the menisci and muscle. CNR between cartilage and fluid is similar for the sagittal and axially orientated images.

CNR between cartilage and synovial fluid is higher in WS-bSSFP images than in the T1-GE, PD-FSE, and T2-FSE images. More importantly, we found an increased CNR between cartilage and all of its surrounding tissue in WS-bSSFP images compared to conventional images. This is important because techniques for quantifying cartilage volume have been developed (16,23–26). These techniques require segmentation. Segmentation in its turn requires high contrast between cartilage and surrounding tissues combined with a high spatial resolution. Therefore, an optimal imaging technique for automatic or semi-automatic assessment of cartilage volume should have a high CNR between cartilage and all cartilage surrounding tissue, together with an optimal delineation of cartilage surface detail. These requirements make the WS-bSSFP imaging technique ideal for cartilage imaging. Another advantage of WS-bSSFP over the conventional imaging techniques is the excellent cartilage surface detail. Actual sharpness of the cartilage is not quantitated, but the observed sharpness is better because the voxel size used in the WS-bSSFP sequence is smaller than that of the conventional sequences. Decrease of voxel size in the WS-bSSFP sequence was possible because CNRs in the WS-bSSFP sequence are high compared to conventional imaging techniques. This sharp delineation of the tissues (i.e., low blurring) is highly desirable because it makes the process of cartilage segmentation much easier. These advantages can be obtained using clinically acceptable acquisition times. WS-BSSFP sequences have an acquisition time that is two-thirds of the fat suppressed T1-GE, and one minute longer than the PD-FSE and T2-FSE sequences used in this study.

We found less difference between cartilage volumes measured on anatomic sections and WS-bSSFP images than between cartilage volumes measured on anatomic sections and T1-GE images. Because WS-bSSFP images show a more detailed cartilage contour and CNR between cartilage and surrounding tissues is higher, WS-bSSFP images allow a more unequivocal contour tracing of cartilage than T1-GE images because of superior CNR and sharpness.

MR images of articular cartilage acquired with WS-bSSFP sequences have several advantages over those with conventional fat suppressed T1-GE and PD/T2-FSE sequences. WS-bSSFP imaging technique uses water excitation instead of fat saturation techniques in the conventional cartilage imaging sequences. This provides a better fat suppression because the lipid signal is never excited (27). It has been shown that an increased CNR between cartilage and fluid is obtained using SSFP sequences alone (4), or with the use of selective water excitation (15–18) compared to conventional imaging techniques such as FSE and GE sequences. Although

<p>| Table 2 |
| Cartilage Volume in mL of Tibia Plateau in Two Patients Measured on Sagittal MR Images and Sagittal Anatomical Sections |</p>
<table>
<thead>
<tr>
<th>Anatomical sections</th>
<th>WS-bSSFP</th>
<th>T1-GE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1 Medial</td>
<td>0.86</td>
<td>0.90</td>
</tr>
<tr>
<td>Patient 1 Lateral</td>
<td>1.62</td>
<td>1.63</td>
</tr>
<tr>
<td>Patient 2 Medial</td>
<td>0.96</td>
<td>0.84</td>
</tr>
<tr>
<td>Patient 2 Lateral</td>
<td>1.84</td>
<td>1.76</td>
</tr>
</tbody>
</table>

mL = milliliters, WS-bSSFP = balanced steady-state free precession with water excitation, T1-GE = T1 weighted gradient echo with fat suppression.
already described in 1958 by Carr (28), balanced steady-state free precession (commercially also known as True-FISP, FIESTA, or balanced FFE) has become feasible and popular in clinical practice during the past four years (22). The WS-bSSFP sequence, presented in this paper is characterized by time-balanced gradients for all gradient directions (X, Y, Z). Its contrast is related to $T_2/T_1$ ratio, independent of the repetition time. An alternating phase of excitation pulse ensures combined acquisition of echo and free induction decay (FID) signal. Balanced gradient echo sequences are flow compensated and show few flow artifacts. The WS-bSSFP sequence needs field shimming to improve field homogeneity because SSFP techniques are sensitive to magnetic field inhomogeneity. Shimming improves image quality especially in and near Hoffa’s fat pad and subcutaneous fat near the coil. After shimming of the WS-bSSFP sequence, no influence of field inhomogeneity is measured as CNRs are similar at the lateral and medial side of the knee. We measured a difference of only 1.8%.

In the current study we compared WS-bSSFP sequence to conventional SPGR and FSE sequences. Comparing WS-bSSFP sequence with other SSFP based sequences is difficult. In the present study we ran the WS-bSSFP sequence on a Philips 1.5-T system. Most of the other SSFP sequences described in the literature, such as FMER, LC-SSFP, FS-SSFP, and Dixon SSFP sequences, run on a GE or Siemens 1.5-T system (6–9,11). Therefore, we could not directly compare the WS-bSSFP sequence to the other SSFP sequences in the same patients. In theory, the primary difference between WS-bSSFP and other SSFP sequences is the fat suppression technique. Most of the SSFP sequences described in literature use fat suppression as opposed to the water excitation of the WS-bSSFP technique. The contrast achieved, however, should be similar because the sequences all use a SSFP technique. The Dixon SSFP is even more similar to the WS-bSSFP sequence because it acquires water-weighted images. Main advantage of WS-bSSFP above the other SSFP sequences is that it benefits from the homogeneous field of the Philips scanner. A disadvantage of WS-bSSFP compared to the other SSFP sequences is the slightly longer scan time. Other SSFP based techniques show acquisition times of three to four minutes, whereas WS-bSSFP lasts five minutes and five seconds.

A limitation of this study is that the number of patients used for determining the accuracy of the WS-bSSFP sequences to measure cartilage volume is relatively small. However, there is a clear trend in the results, showing that the WS-bSSFP sequence provides higher accuracy in the determination of cartilage volume.

Another limitation of this study is that we compared our sequences with validated conventional T1-GE, PD-FSE, and T2-FSE sequences by means of CNR. We did not correlate our findings with cadaver knees. However, although results of new sequences are correlated sometimes with cadaver knees (12), comparison between SNR and CNR of the sequences is the usual method.

An advantage of this study is that it has been performed in patients with osteoarthritis. When articular cartilage is damaged, the structure of its collagen framework is disorganized leading to abnormal consistency of cartilage (29). Therefore, comparison of cartilage MR sequences developed to image damaged articular cartilage should be performed in patients with this different consistency of cartilage in contrast to control subjects with healthy cartilage.

In conclusion, WS-bSSFP MR imaging sequence allows, relative to conventional MR imaging sequences, optimal imaging of cartilage in the osteoarthritic knee, with clinically acceptable acquisition times.

REFERENCES