

Three-Dimensional Isotropic Fat-Suppressed Proton Density-Weighted MRI at 3 Tesla Using a T/R-Coil Can Replace Multiple Plane Two-Dimensional Sequences in Knee Imaging

Drei-dimensionale isotrope Protonen-gewichtete fettunterdrückte MRT bei 3 Tesla als Substitut multiplanarer zwei-dimensionaler Knie Sequenzen

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Key words

- knee
- 3 D
- MRI
- multiplanar reformation
- proton density-weighted

Zusammenfassung

Ziel: Klärung der Frage, ob eine dreidimensionale (3D) isotrope Protonen-gewichteten fettunterdrückte (PDwFS) Sequenz vom Knie mehrere zwei-dimensionale (2D) Sequenzen ersetzen kann.

Material und Methoden: 52 Patienten (26 Männer, 26 Frauen, mittleres Alter 41,9 ± 14,5 Jahre) erhielten eine magnetresonanztomografische Bildgebung (MRT) vom Knie unter Nutzung einer T/R Spule an einem 3-Tesla-(T)-Magnet. Das Protokoll enthielt 3 Ebenen 2D-PDwFS (Gesamtaufnahmedauer (AD), 6:40 min; Voxelgröße [V], 0,40 – 0,63 × 0,44 – 0,89 × 3 mm³) und eine 3D-PDwFS (AD, 6:31 min; V, 0,63 × 0,68 × 0,63 mm³). Beurteilt wurden die Homogenität der Fettunterdrückung, Artefakte, und die Bildschärfe anhand einer 5-Punkteskala (5[Exzellente] – 1[nicht-diagnostisch]). Die Summe der Parameter diente als ein Maß für die Gesamtbildqualität (GBQ). Zusätzlich wurden Kontrastverhältnisse (KR) für den Meniskus (MEN), das vordere (ACL) und das hintere Kreuzband (PCL) im Vergleich zum Musculus popliteus berechnet. Von den 52 Patienten erfolgte bei 13 Patienten aus klinischer Indikation eine Knie-Arthroskopie. Bei diesen Patienten untersuchten zwei unabhängige Radiologen die 3D- und 2D-Aufnahmen auf das Vorhandensein von Läsionen des Meniskus, der Bänder und des Knorpels. Hierauf basierend wurden die Sensitivität und Spezifität berechnet.

Ergebnisse: Die KR waren für ACL, PCL und MEN in der 3D-PDwFS höher als bei der 2D-PDwFS ($p < 0,01$ für ACL und PCL; $p = 0,07$ für MEN). Verglichen mit den 2D-Bildern, wurde die GBQ aufgrund von weniger Artefakten und einer homogeneren Fettunterdrückung ($p < 0,01$) in den 3D-PDwFS Bildern höher bewertet, trotz einer geringeren Bildschärfe ($p < 0,01$). Sensitivität und Spezifität für die Diagnose einer Knieläsion waren für 3D- und 2D-PDwFS ähnlich.

Abstract

Purpose: To evaluate whether a 3D proton density-weighted fat-suppressed sequence (PDwFS) of the knee is able to replace multiplanar 2D-PDwFS. **Materials and Methods:** 52 patients (26 men, mean age: 41.9 ± 14.5 years) underwent magnetic resonance imaging (MRI) of the knee at 3.0 Tesla using a T/R-coil. The imaging protocol included 3 planes of 2D-PDwFS (acquisition time (AT): 6:40 min; voxel sizes: 0.40 – 0.63 × 0.44 – 0.89 × 3 mm³) and a 3D-PDwFS (AT: 6:31 min; voxel size: 0.63 × 0.68 × 0.63 mm³). Homogeneity of fat suppression (HFS), artifacts, and image sharpness (IS) were evaluated on a 5-point scale (5[excellent] – 1[non-diagnostic]). The sum served as a measure for the overall image quality (OIQ). Contrast ratios (CR) compared to popliteal muscle were calculated for the meniscus (MEN), anterior (ACL) and posterior cruciate ligaments (PCL). In 13 patients who underwent arthroscopic knee surgery, two radiologists evaluated the presence of meniscal, ligamental and cartilage lesions to estimate the sensitivity and specificity of lesion detection.

Results: The CR was higher in the ACL, PCL and MEN in 3D-PDwFS compared to 2D-PDwFS ($p < 0.01$ for ACL and PCL; $p = 0.07$ for MEN). Compared to 2D images, the OIQ was rated higher in 3D-PDwFS images ($p < 0.01$) due to fewer artifacts and HFS despite the lower IS ($p < 0.01$). The sensitivity and specificity of lesion detection in 3D- and 2D-PDwFS were similar.

Conclusion: Compared to standard multiplanar 2D-PDwFS knee imaging, isotropic high spatial resolution 3D-PDwFS of the knee at 3.0T can be acquired with high image quality in a reasonable scan time. Multiplanar reformations in arbitrary planes may serve as an additional benefit of 3D-PDwFS.

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Schlussfolgerung: Verglichen mit dem Standard der multiplanaren 2D-PDwFS Knie-Bildgebung, können isotrope hochaufgelöste 3D-PDwFS-Aufnahmen bei 3.0T mit hoher Bildqualität und ähnlicher Aufnahmedauer akquiriert werden. Ein Vorteil der 3D-PDwFS besteht in der Möglichkeit multiplanarer Reformationen in beliebigen Ebenen.

Kernaussagen:

- ▶ 3D-PDwFS Knie Aufnahmen sind bei hoher Bildqualität möglich
- ▶ 3D-PDwFS Knieaufnahmen können in nur einer Messung in akzeptabler Zeit erzielt werden
- ▶ Im Gegensatz zur Standardbildgebung ermöglicht die 3D-PDwFS zusätzlich die Rekonstruktion multiplanarer Reformationen

Introduction

Three-dimensional (3D) volume data sets with isotropic spatial resolution may be beneficial in magnetic resonance imaging (MRI) of various joints and potentially improve image quality and diagnostic efficiency, especially at high field strengths [1–6].

Currently, multiple 2D sequences in orthogonal slice orientations are required in musculoskeletal MRI in order to fully cover the anatomy and ensure lesion detection. Diagnostic image quality largely depends on ideal planning of imaging planes, which requires the presence of highly trained and dedicated technicians. Imaging may be time-consuming and require additional sequences in specifically angulated orientations to account for lesions that are not well visualized by standard planes. 2D sequences are acquired with relatively thick sections with consecutive partial volume effects. They are mostly used with imaging gaps to avoid cross talk and scan time prolongation that may lead to limited imaging accuracy particularly of small structures. These limitations may be overcome by isotropic voxels that allow for the reconstruction of multiplanar reformats (MPRs) in arbitrary orientations including curved and oblique planes [3, 7–9]. 3D volume data sets with isotropic resolution may be of advantage as they are acquired with thin continuous sections and no interslice gaps. In 3D sequences pulsation as well as motion artifacts are less pronounced compared to 2D sequences due to their inherently thicker slabs.

Proton density-weighted sequences with fat suppression (PDwFS) in multiple planes are currently used as the standard sequences for knee MR imaging in many centers. They provide excellent performance with reduced chemical shift artifacts and an extended range of signal intensities in articular cartilage [10–13].

The purpose of this study was to quantitatively and qualitatively evaluate the image quality of isotropic high spatial resolution 3D-PDwFS-TSE of the knee at 3.0 Tesla (T) using a transmit/receive coil (T/R-coil) and to evaluate whether isotropic 3D-PDwFS may replace multiple 2D-PDwFS planes.

Methods

Patients

52 patients (26 men; mean age: 41.9 ± 14.5 years) with suspected knee injury (22 suspected meniscal tears, 18 suspected ligament tears, 7 unclear knee swellings, and 5 suspected degenerative lesions) were included in a prospective, intra-individual comparative study. The study protocol was approved by the institutional ethics committee and all patients provided informed consent before inclusion in the study. The exclusion criteria were contraindications for MRI (e.g., pacemakers, non-MRI-compatible metallic implants).

Key Points:

- ▶ 3D-PDwFS of the knee is acquired with high image quality
- ▶ 3D-PDwFS can be achieved in only one measurement with a reasonable scan time
- ▶ 3D-PDwFS with the advantage of multiplanar reformation may replace 2D-PD-weighted knee MRI

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Clinical treatment was not delayed for any patient because of study participation. All patients were asked to report any adverse events and to comment on the overall toleration of the procedure.

MR Imaging

All scans were performed on a 3.0-Tesla whole-body scanner equipped with a transmit/receive 16-channel knee coil to cover the entire knee (Ingenia; Philips Healthcare, Best, The Netherlands). Patients were examined feet-first in a supine position. The acquisition parameters for the 3D- and 2D-PDwFS sequences are summarized in **Table 1**. All sequences were obtained without contrast medium and were performed within the same session. 2D-PDwFS sequences were acquired without the use of parallel imaging due to restrictions because of signal loss at short echo times when using long echo trains. 3-mm-thick transverse, sagittal and coronal MPR planes were generated from 3D-PDwFS in corresponding planes to 2D-PDwFS. 2D and 3D-PD sequences were combined with a spectral selective attenuation recovery fat suppression technique (SPAIR) with the following parameters: spectral selective fat saturation with an adiabatic inversion pulse duration of 18 ms and an inversion delay of 85 ms for optimal bone marrow and muscular fat suppression. The water-fat shift

Table 1 Technical parameters of 2D- and 3D-PDwFS.

Tab. 1 Technische Parameter der 2D- und 3D-PDwFS.

parameter	2D-PDwFS	3D-PDwFS
TR/TE (ms)	3387/9.2	1300/176
flip angle (degrees)	90	90
FOV (mm)	160	144
matrix	160 × 89	162 × 160
acquired voxel (mm ³)	0.40 × 0.44 × 3	0.63 × 0.63 × 0.63
slices	27	254
TSE factor	11	63
acquisition time (min:s)	3:04.2 (sagittal) 1:33.2 (coronal) 2:02.9 (transverse) total: 6:40.3	6:31.3
parallel imaging	none	2 × 2.2 (P _x S, SENSE)
NSA	1	2
water-fat shift	2 pixels (220 Hz/pixel)	1.3 pixels (340 Hz/pixel)
fat suppression	SPAIR	SPAIR

PDwFS: proton density-weighted fat-suppressed sequence; NSA: number of signal averages; SPAIR: spectral selective attenuation recovery fat suppression technique.

was 2 pixels (220 Hz/pixel) for 2D-PDwFS and 1.3 pixels (340 Hz/pixel) for 3D-PDwFS.

Arthroscopic Knee Surgery

Clinical evaluation of MR imaging was performed by 2 senior radiologists with more than 10 years of experience in musculoskeletal imaging. Based on these findings, 13 patients (5 men, 8 women; mean age: 46.4 ± 17.0) received arthroscopic knee surgery (AKS) by an experienced orthopedic surgeon within 3–56 days (mean: 28.9 ± 20.5 days) of their MRI examination. Documentation of AKS procedures included evaluation of ligamental (anterior and posterior cruciate ligament [ACL, PCL], collateral ligaments) and meniscal (inner and outer meniscus) structures as well as cartilage lesions. The articular surfaces of knee joints were graded using the Outerbridge classification (grade 0: normal; grade 1: cartilage softening or superficial fissures; grade 2: deepness of cartilage lesions < 50%; grade 3: deepness of cartilage lesions > 50%; grade 4: full-thickness cartilage lesion) [14].

Quantitative Image Analysis

The quantitative analyses consisted of measuring contrast ratios (CR) of (A) the signal of the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL) and the meniscus (MEN) compared to (B) the signal of the popliteal muscle: $CR = (A - B)/(A + B)$. Polygonal regions of interest (ROI) were placed in the respective tissues, with each area being as large as possible to cover the tissue of interest while avoiding inclusion of confounding structures (e.g. blood vessels). The signal intensities (SI) were measured in the medial portion of the ACL and PCL, at the region of the inner meniscus and the adjacent proximal part of the popliteal muscle. To ensure consistency of ROI placement, all ROIs were placed by the same investigator.

Qualitative Image Analysis

Artifacts, image sharpness and homogeneity of fat suppression were rated in consensus by 3 investigators with more than 2 years of experience in musculoskeletal imaging. Image evaluations were done using a picture archiving and communication system (IMPAX 2.0, Agfa Healthcare, Bonn, Germany). Ratings were based on 5-point scales for:

- ▶ Artifacts (1: non-diagnostic; 2: poor = insufficient diagnostic confidence; 3: moderate = some artifacts, not interfering with diagnosis; 4: good = minimal artifacts; 5: excellent = no artifacts),
- ▶ Image sharpness (1: non-diagnostic = blurry; 2: poor = knee structures can be identified, insufficient diagnostic confidence; 3: moderate = sufficient for diagnosis, but low diagnostic confidence; 4: good = diagnostic with high diagnostic confidence; 5: excellent = crispy images) and
- ▶ Homogeneity of fat suppression (1 = non-diagnostic; 2: poor = central and peripheral inhomogeneities; 3: moderate = major inhomogeneities (central); 4: good = minor inhomogeneities (peripheral); 5: excellent = no inhomogeneities).

The sum of the scores (a+b+c) was used as a measure of the overall image quality (13–15 points: excellent; 10–12 points: good; 7–9 points: moderate; 3–6 points = poor).

Diagnostic Accuracy

In the 13 patients who underwent AKS, two radiologists with more than 10 years of experience in musculoskeletal imaging who were blinded to the histories of the patients and the results of AKS independently evaluated the presence or absence (1/0) of the following lesions: ligamental tears and/or degeneration, meniscal tears and/

or degeneration, and cartilage lesions (grade > 2 according to Outerbridge classification; medial/lateral femoral, medial/lateral tibial, retropatellar). Image evaluation was performed with time gaps of 4 weeks between 2D- and 3D-PDwFS readings in a randomized order. Readers were free to reconstruct any desired imaging plane using the integrated MPR software tool of the PACS.

Statistical Analysis

Statistical analysis was performed using SPSS (IBM SPSS Statistics 22.0, Armonk, New York). Data concerning CR measurements were presented as mean scores with standard deviations. To determine the statistical significance of CR measurements and of the qualitative ratings, Student's t-tests were performed. P-values lower than 0.05 were considered significant. Inter-observer agreement for diagnostic efficiency was estimated by Cohen's kappa statistics, where $\kappa = 0.81 - 1.0$ was considered as almost perfect agreement, $\kappa = 0.61 - 0.8$ as substantial agreement, $\kappa = 0.41 - 0.6$ as moderate agreement, $\kappa = 0.21 - 0.4$ as fair agreement, $\kappa = 0 - 0.2$ as slight agreement and $\kappa < 0.2$ as no agreement [15]. With AKS as the standard of reference, the sensitivity, specificity, accuracy, false-positive and false-negative results of 2D- and 3D-PDwFS images for the detection of knee pathologies were calculated.

Results

▼ All examinations were successfully completed by the participants of the study.

Image Contrast

The results of CR measurements revealed higher contrast ratios of all investigated knee structures (ACL, PCL and MEN) in 3D-PDwFS compared to 2D-PDwFS ($p < 0.01$ for ACL/PCL, $p = 0.07$ for MEN). These differences were most pronounced in the ACL. Image contrast was higher in all investigated structures in 3D-PDwFS. However, in 2D-PDwFS the contrast ratio of the ACL was lower than that of the PCL and MEN (▶ Table 2).

Image Quality

The overall image quality was rated significantly higher in 3D-PDwFS compared to 2D-PDwFS with fewer artifacts and a higher homogeneity of fat suppression (▶ Table 3). The most pronounced difference in image quality was observed when analyzing the presence of artifacts comparing sagittal 2D-PDwFS to sagittal MPR reconstructions of 3D-PDwFS. This was due to strong pulsation artifacts in the 2D technique in the phase encoding direction (▶ Fig. 1).

Table 2 Measurements of contrast ratios (CR) in 2D- and 3D-PDwFS. The results of CR measurement were higher for all investigated knee structures (ACL, PCL and MEN) in 3D-PDwFS compared to the 2D technique.

Tab. 2 Messungen des Kontrastverhältnisses (CR) in 2D- und 3D-PDwFS. Verglichen mit der 2D-PDwFS waren die CR-Werte für alle untersuchten Kniestrukturen (ACL, PCL und MEN) höher in der 3D-PDwFS.

	3D-PDwFS	2D-PDwFS	p-value
CR ACL/muscle	0.62 ± 0.24	0.47 ± 0.25	< 0.01
CR PCL/muscle	0.75 ± 0.13	0.68 ± 0.15	< 0.01
CR MEN/muscle	0.73 ± 0.11	0.71 ± 0.11	0.07

CR: contrast ratio; ACL: anterior cruciate ligament; PCL: posterior cruciate ligament; MEN: meniscus; FS: fat suppression; PDwFS: proton density-weighted fat-suppressed sequence.

Though significant, the homogeneity of fat suppression was only somewhat higher in 3D-PDwFS (● Fig. 2). Image sharpness, on the other hand, was rated significantly higher in 2D-PDwFS (● Table 3).

Comparison to arthroscopic knee surgery

In a subgroup of 13 patients who received AKS, 33/182 analyzed regions contained lesions. These included 6 meniscal and 6 ligament tears, 16 cartilage lesions, 4 degenerative lesions of the meniscus and one giant cell tumor. The sensitivity, specificity, false-positive and false-negative results were similarly high for both readers when using 2D- vs. 3D-PDwFS (● Table 4). Substantial inter-observer agreement for lesion detection was found for both readers using either 2D- or 3D-PDwFS (Cohen's kappa coefficients; 3D-PDwFS: 0.75; 2D-PDwFS: 0.62).

Both readers considered the possibility to reconstruct MPR in arbitrary planes out of isotropic 3D-PDwFS data sets advantageous as these allowed for better depiction of small and curved anatomic structures (● Fig. 3) and lesions (● Fig. 4).

Table 3 Parameters of image quality of 2D- and 3D-PDwFS. Overall image quality was higher in 3D-PDwFS with significantly fewer artifacts and (though less pronounced) higher homogeneity of fat suppression. Image sharpness was significantly higher in 2D-PDwFS.

Tab. 3 Parameter der Bildqualität der 2D- und 3D-PDwFS. Die Gesamtbildqualität war höher in der 3D-PDwFS, wobei sich signifikant weniger Artefakte und (etwas geringer ausgeprägt) eine homogenere Fettunterdrückung zeigten. Die Bildschärfe wurde in der 2D-PDwFS signifikant höher bewertet.

	3D-PDwFS	2D-PDwFS	p-value
artifacts	4.5 ± 0.35	3.3 ± 0.17	< 0.01
image sharpness	2.6 ± 0.23	3.6 ± 0.14	< 0.01
homogeneity of FS	3.7 ± 0.21	3.6 ± 0.13	< 0.01
overall image qualitative	10.9 ± 0.63	10.5 ± 0.28	< 0.01

CR: contrast ratio; ACL: anterior cruciate ligament; PCL: posterior cruciate ligament; MEN: meniscus; FS: fat suppression; PDwFS: proton density-weighted fat-suppressed sequence.

Discussion

Recent advances in MRI have led to the introduction of different 3D techniques aiming at improving image quality and diagnostic efficiency and facilitating sequence planning, whereas the routinely used 2D technique needs ideal planning of imaging planes in different orientations [3–6]. Early 3D techniques applied gradient echo sequences, which not only suffered from long acquisition times, but also proved insufficient for accurate evaluation of ligaments, menisci and bone marrow changes. This was only later possible with the introduction of 3D-TSE techniques [7–9, 16, 17]. Further major improvements were achieved at higher field strengths and by using parallel imaging techniques and multi-channel surface coils, which both reduced acquisition times and improved image quality [18–23]. This study shows the feasibility of a 3D proton-weighted fat-suppressed knee MRI sequence at 3.0T. The sequence is shown to provide sufficient image quality to replace multiplanar proton-weighted fat-suppressed 2D sequences in a reasonable scan time.

Both quantitative and qualitative parameters of image quality were equal or superior in 3D-PDwFS compared to 2D-PDwFS. Only in-plane image sharpness was rated superior in 2D-PDwFS. In a subset of patients, who also received both the study imaging protocol and AKS, the single 3D-PDwFS sequence and multiplanar 2D-PDwFS revealed similar diagnostic accuracy in the detection of various knee lesions.

The acquisition of a 3D data set allows for arbitrary multiplanar reformations without the need for additional sequences to obtain specific angulations that may be necessary to visualize small knee structures. 2D sequences are of limited value for multiplanar reformatting due to their inherently non-isotropic voxels resulting from thick slices, imaging gaps and partial-volume artifacts that may negatively affect image quality and obscure small pathologies [5, 7]. In order to overcome these limitations and produce isotropic data sets, the slice thickness of 2D-PDwFS would have to be substantially decreased. However, thinner slices require long scan times and small voxel sizes lead to decreased signal-to-noise [18, 19]. 3D sequences are more suitable for the acquisition of small voxels due to their inherently higher signal level, but they require longer acquisition times than 2D sequences [4, 8, 20, 21].



Fig. 1 Left knee of a 42-year-old female with anterolateral pain at the level of the patella. Note the lack of pulsation artifacts in the sagittal multiplanar reconstruction of the 3D proton density-weighted fat-suppressed image **a** compared to the 2D image **b**.

Abb. 1 Linkes Knie einer 42-jährigen Frau mit Schmerzen anterolateral im Bereich der Patella. Es zeigen sich keine Pulsationsartefakte in der sagittalen multiplanaren Rekonstruktion der 3D-Protonengewichteten fettunterdrückten Aufnahme **a** verglichen mit der 2D-Aufnahme in Bild **b**.

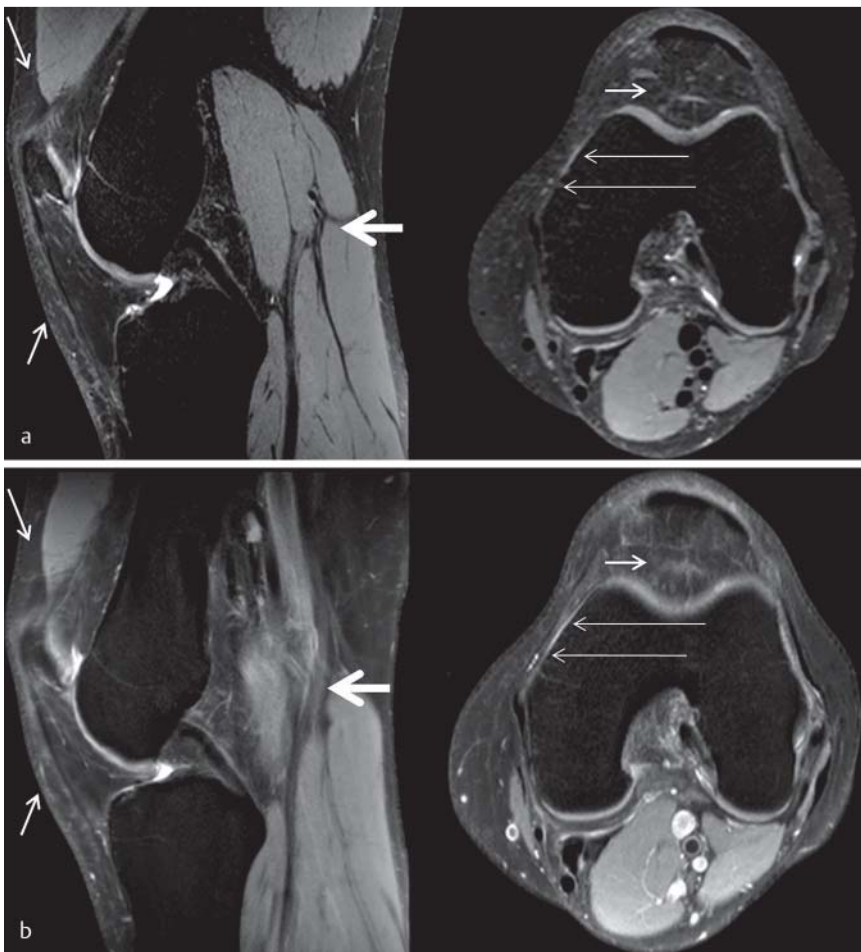


Fig. 2 Sagittal and transverse images in a 35-year-old man with pain of the right medial knee after a soccer game. Note the more homogeneous fat suppression (thin arrows), the reduction of artifacts (thick arrows) and the somewhat lower image sharpness (long arrows in axial slices) in **a** 3D proton density-weighted and fat-suppressed images (PDwFS) compared to **b** 2D-PDwFS.

Abb. 2 Sagittale und transversale Aufnahmen des Knies eines 35-jährigen Mann bei medialen Schmerzen nach einem Fußballspiel. Die 3D-Proton-gewichteten fettunterdrückten Aufnahmen (PDwFS) **a** zeigen eine homogenere Fettunterdrückung (dünne Pfeile), geringere Artefakte (dicke Pfeile) und eine etwas niedrigere Bildschärfe (lange Pfeile in den axialen Schichten) als die 2D-PDwFS **b**.

Table 4 Diagnostic accuracy of 2D- and 3D-PDwFS compared to arthroscopic knee surgery in 13 patients.

Tab. 4 Diagnostische Genauigkeit der 2D- und 3D-PDwFS verglichen zu Arthroskopien bei 13 Patienten.

	reader 1		reader 2	
	2D-PDwFS	3D-PDwFS	2D-PDwFS	3D-PDwFS
sensitivity	81.8%	81.8%	81.8%	78.8%
specificity	85.9%	87.9%	93.3%	92.6%
accuracy	85.2%	86.8%	91.2%	90.1%
false-positive diagnoses	21/149	18/149	10/149	11/149
– ligamental lesions	2	1	1	0
– meniscal lesions	5	5	3	4
– cartilage lesions	3	4	2	0
– meniscal degeneration	11	8	4	7
false-negative (missed lesions)	6/33	6/33	6/33	7/33
– ligamental lesions	0	0	0	0
– meniscal lesions	0	0	2	2
– cartilage lesions	5	6	4	5
– meniscal degeneration	1	0	0	0

PDwFS: proton density-weighted fat-suppressed sequence.

To shorten the scan time, 3D-PDwFS includes a modulation of flip angles by a refocusing radiofrequency angle technique, parallel imaging in both the phase- and slice-encoding direction and partial-Fourier acquisition [18–23]. A T/R-knee coil with high signal-to-noise and multiple elements was used at a field strength of 3.0T to allow for the implementation of these techniques. The T/R-coil allows for a higher B1 amplitude due to the reduced excited field of view and for a reduced overall SAR compared to conventional techniques that use the body coil for excitation [24, 25]. The results are a higher signal-to-noise ratio, sharper pulse profiles and shorter pulse durations. The latter two points are particularly important for fast spin echo sequences with long echo trains where the total echo train length needs to be limited to avoid blurring, signal loss and loss of contrast. The large-slab excitation pulse of 3D-PDwFS allows for high signal-to-noise in spite of small voxel volumes, for a homogenous fat suppression (Fig. 2), for decreased pulsation artifacts, and for high contrasts in proton-weighted imaging.

The increased contrast of anatomic structures in 3D-PDwFS was most pronounced in the ACL. In general, differences in contrast parameters may be a result of excitation-related (e.g.; 2D vs. 3D techniques), sequence-related (e.g.; TR, TE, FA), and field strength-related (e.g.; 1.5T, 3.0T) parameters [22–26].

Another mechanism for markedly lower contrast of the ACL in 2D-PDwFS compared to 3D-PDwFS may be a partial volume effect that results from the small thickness of the ligament and its orientation in space. The latter is difficult to fully account for in sagittally oriented 2D slices and likely leads to partial volume effects that



Fig. 3 Para-coronal MPR along the anterior cruciate ligament in 3D-PDwFS in a 34-year-old man.

Abb. 3 Para-koronare MPR entlang des vorderen Kreuzbandes in der 3D-PDwFS bei einem 34-jährigen.

lower the contrast of the ligament. Overall, the higher contrast of knee structures together with the better delineation of small pathologies, e.g. meniscal tear, in 3D-PDwFS may be regarded as an additional advantage of 3D-PDwFS. Similar observations were made in 3D-TSE intermediate-weighted sequences [5–7].

The significantly lower incidence of artifacts in 3D-PDwFS was mostly related to the decreased pulsation artifacts that are usually observed in 2D-PDwFS, especially in sagittal planes due to AP phase-encoding direction. These were not observed in sagittal MPR of 3D-PDwFS and may be attributed to the excitation pulse that covers a larger slab in 3D-PDwFS [5, 7, 24, 26, 27]. This has certain advantages in the case of preparation pulses, e.g. for fat suppression or inversion. Also the slice profile in 2D stretches over an entire slab in 3D and eliminates cross-talk between slices. Additional artifacts were not observed in 3D-PDwFS.

Image sharpness, on the other hand, was rated higher in 2D-PDwFS than in MPR of 3D-PDwFS in corresponding planes. This may be attributed to a lower in-plane resolution of 3D-PDwFS compared to 2D-PDwFS (0.40×0.44 vs. 0.63×0.63). However, the sensitivity, specificity and accuracy of 2D- and 3D-PDwFS in the subset of 13 patients who received AKS revealed no differences of the two sequences regarding lesion detection. As a result, the overall image quality of 3D-PDwFS was rated higher than that of 2D-PDwFS despite the lower in-plane resolution.

The availability of multiplanar reformats in any desired imaging plane in 3D-PDwFS was considered an advantage of 3D-PDwFS by both readers, particularly when analyzing oblique and curved structures including the cruciate ligaments. The acquisition of a complete 3D data set of the knee allows for reconstruction of arbitrary imaging planes as needed by the radiologist without

acquiring additional carefully angulated sequences. Therefore, even though scan times of 3D-PDwFS and three standard planes of multiplanar 2D-PDwFS are in the same range (6:30 min. vs. 6:40 min.), the total scan time of knee examinations in clinical practice may benefit from the acquisition of a 3D data set. Another advantage of 3D-PDwFS may be reduced planning time of the MR examination for the MR technician due to the fact that careful angulations along small anatomic structures are not required when acquiring large 3D data sets [28, 29].

The fact that the assessment of the image quality including image sharpness, homogeneity of fat suppression and artifacts was performed in consensus reading instead of independent readers may be regarded as a limitation of this study. For instance, a recent study by Pass et al. observed reduced agreement between two independent observers for menisci and articular assessment using a 3D fast spin echo proton density fat-saturated technique compared to the standard 2D technique at 1.5 Tesla. However, the accuracy, sensitivity and specificity in the detection of knee pathologies were calculated using the standard 2D protocol as the reference standard in that particular study [30]. Our study involved both quantitative and qualitative parameters to analyze the performance of both techniques and arthroscopic surgery was taken as the reference standard whenever available in a subgroup of 25% of the patients. The small number of patients who received arthroscopy as a reference standard may be regarded as a limitation of the study and larger follow-up trials will be necessary to validate the preliminary results of the current study as it has been shown earlier regarding pathologies of the articular cartilage [1].

The non-randomized sequence order (first 2D-PDwFS, second 3D-PDwFS) may also be regarded as a limitation of this study. In patients who do not tolerate long acquisition procedures, motion artifacts may be more likely in the sequence acquired second. However, the overall image quality was rated higher in the sequence acquired second in this study, thus supporting the finding of the non-inferiority of 3D-PDwFS.

In 3D-PDwFS, temporary patient movement may affect the entire 3D data set and therefore all reconstructed planes, whereas in 2D-PDwFS the same movement may only affect a single plane. In this case, repeating the 3D-PDwFS sequence is more time-consuming than repeating a single 2D-PDwFS plane that was acquired during the short movement phase. In these particular patients, a prolongation of total scan time may be regarded as a possible drawback of the 3D technique. However, we did not observe any case with impaired diagnostic image quality due to movement artifacts in 52 consecutive patients covering a wide spectrum of knee diseases. Finally, the optimal trade-off between high spatial resolution, sufficient signal-to-noise and scan time was not systematically analyzed in this study and may be further optimized. However, we observed high diagnostic accuracy in a subgroup of patients who received AKS as the standard of reference procedure with good sensitivity, specificity and predictive values for both 3D-PDwFS and 2D-PDwFS. Dedicated future studies will be required to investigate whether a further increase in diagnostic accuracy even beyond that of 2D-PDwFS may be possible using an optimized 3D proton density-weighted fat-suppressed sequence.

Conclusion

▼ The acquisition of a 3D proton density-weighted fat-suppressed data set with high spatial resolution can be realized in a reasonable scan time with high image quality at 3 Tesla. The sensitivity, speci-

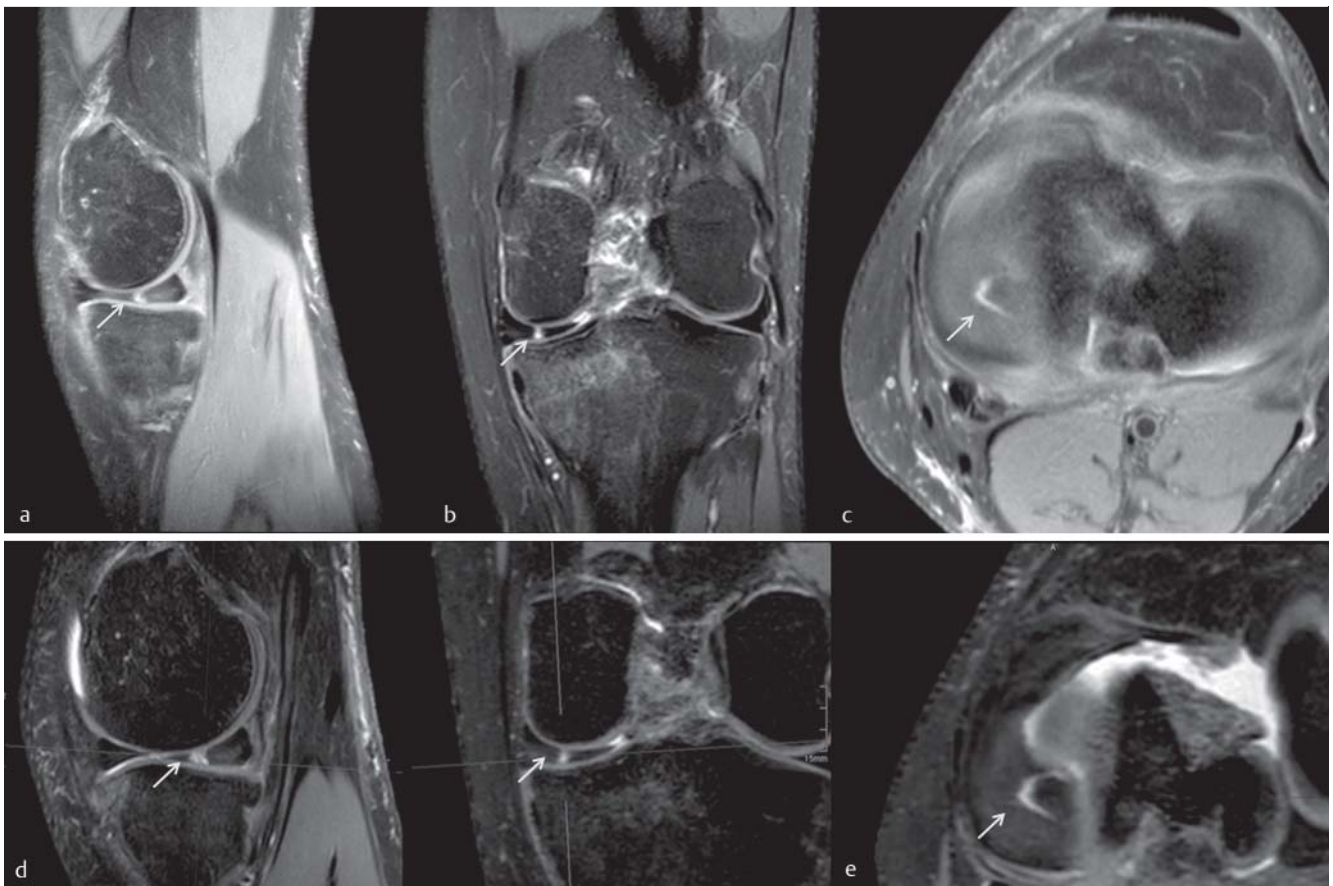


Fig. 4 Sagittal, coronal and transverse 2D-PDwFS knee images **a–c** showing a rupture of the posterior horn of the medial meniscus (arrows) in a 19-year-old male patient. Para-transverse multiplanar reformats along the axis of the posterior horn of the medial meniscus (**d** = planning of optimal plane on a non-angulated coronal MPR of 3D-PDwFS, **e** = angulated multiplanar reconstruction of 3D-PDwFS) lead to optimized visualization of the lesion (arrows).

Abb. 4 Sagittale, koronare und transversale 2D-PDwFS Knie-Aufnahmen **a–c**. Die Aufnahmen zeigen eine Ruptur des Innenmeniskushinterhorns (Pfeile) eines 19-jährigen Patienten. **d** = Planung der optimalen Ebene einer para-transversalen multiplanaren Reformation entlang der Achse des Innenmeniskushinterhorns anhand einer nicht-angulierten koronaren MPR der 3D-PDwFS. Die angulierte multiplanare Rekonstruktion der 3D-PDwFS **e** führt zu einer optimierten Visualisierung der Läsion (Pfeile).

ficiency and diagnostic accuracy were similar to that of standard multiplanar 2D proton density-weighted fat-suppressed images in a subset of 13 patients who received arthroscopic knee surgery. Post-processing by reconstruction of multiplanar reformats in arbitrary planes using isotropic voxels may serve as a diagnostic benefit of 3D data sets.

Clinical relevance of the study

- ▶ Multiplanar 2D imaging is the current standard in knee MRI but suffers from disadvantages such as non-isotropic voxels, thick sections and imaging gaps.
- ▶ Separate sequences for each perpendicular plane may be time-consuming especially when additional regions of interest have to be studied in more detail.
- ▶ 3D volume data sets with isotropic voxels can be acquired in a reasonable scan time at 3.0 T with high image quality and allow for multiplanar reformation.

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