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Research article

Evaluation of an accelerated 3D SPACE sequence with compressed sensing and free-stop scan mode for imaging of the knee

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ABSTRACT

Purpose: To prospectively evaluate a prototypical 3D turbo-spin-echo proton-density-weighted sequence with compressed sensing and free-stop scan mode for preventing motion artefacts (3D-PD-CS-SPACE free-stop) for knee imaging in a clinical setting.

Methods and materials: 80 patients underwent 3T magnetic resonance imaging (MRI) of the knee with our 2D routine protocol and with 3D-PD-CS-SPACE free-stop. In case of a scan-stop caused by motion (images are calculated nevertheless) the sequence was repeated without free-stop mode. All scans were evaluated by 2 radiologists concerning image quality of the 3D-PD-CS-SPACE (with and without free-stop). Important knee structures were further assessed in a lesion based analysis and compared to our reference 2D-PD-fs sequences.

Results: Image quality of the 3D-PD-CS-SPACE free-stop was found optimal in 47/80, slightly compromised in 21/80, moderately in 10/80 and severely in 2/80. In 29/80, the free-stop scan mode stopped the 3D-PD-CS-SPACE due to subject motion with a slight increase of image quality at longer effective acquisition times. Compared to the 3D-PD-CS-SPACE with free-stop, the image quality of the acquired 3D-PD-CS-SPACE without free-stop was found equal in 6/29, slightly improved in 13/29, improved with equal contours in 8/29, and improved with sharper contours in 2/29. The lesion based analysis showed a high agreement between the results from the 3D-PD-CS-SPACE free-stop and our 2D-PD-fs routine protocol (overall agreement 96.25%-100%, Cohen's Kappa 0.883–1, $p < 0.001$).

Conclusion: 3D-PD-CS-SPACE free-stop is a reliable alternative for standard 2D-PD-fs protocols with acceptable acquisition times.

1. Introduction

Magnetic resonance imaging (MRI) of the knee is a standard procedure almost replacing diagnostic arthroscopy [1]. Traditionally, the standard MR protocol comprises mainly 2D sequences in multiple planes with high resolution and a slice thickness of ≥ 3 mm [2–4]. The main limitation of 2D sequences can be seen in the slice thickness: partial-volume effects can occur and therefore small lesions, e.g. of the cartilage, might remain undetected [5].

3D-imaging offers the potential of free 3D multiplanar reconstructions (MPRs). By acquiring only one sequence, it allows the evaluation of the knee in all 3 major anatomic orientations and also the assessment of oblique structures (e.g. the anterior cruciate ligament) by reconstruction along the structures of interest [5].

The isotropic 3D sequences available at present have not reached wide clinical use in MRI of the knee. This is mainly due to their long scan times of up to 9 min [4]. Further, in case of motion artefacts, the obtained sequence may be of limited use, and an additional 2D protocol must be carried out to complete the examination. This leads to an increase of the examination time by at least 10–15 min. It is still uncertain whether 3D sequences offer a real diagnostic benefit in daily clinical routine compared to conventional 2D sequences [6–8]. Nevertheless, the possibility of MPRs, the improved spatial resolution and thinner slice thickness provide potential benefits, especially for imaging the cartilage [4].

Accelerated 3D imaging has evolved over the years with reduced acquisition time that makes an application more practical. Sparse, incoherent undersampling of k-space and a nonlinear iterative reconstruction to correct for sub-sampling artefacts, and therefore preserve image quality, is known as compressed sensing (CS). This technique is now widely recognized as a feasible approach to acceleration and has shown promising results in cardiac imaging but also in imaging of the knee [9–13]. However, it is not yet clear whether CS 3D sequences will provide adequate quality to be suitable for clinical use.

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In addition, also for 3D CS techniques, motion artefacts could be a relevant drawback, as repeating the sequence or acquiring additional sequences would be impractical in a highly scheduled clinical routine. Recently, a 3D turbo spin-echo (TSE) based prototype sequence using "Sampling Perfection with Application optimized Contrasts using different flip angle Evolutions" (SPACE) together with CS was introduced [12–15]. This sequence features a restore pulse (driven equilibrium or fast recovery pulse) and variable refocusing flip angles (FA) allowing large turbo-factors [16–18]. Further, the sequence is equipped with a motion scout that stops the scan in the event of motion (free-stop scan mode) [14]. If a sufficient part of the raw data has already been acquired prior to the occurrence of the scan stop, images will nevertheless be reconstructed.

The purpose of this prospective comparative study was to evaluate this new 3D proton-density (PD) weighted SPACE sequence with CS and free-stop scan mode (3D-PD-CS-SPACE free-stop) in a clinical setting for imaging of the knee. Therefore, we compared it to conventional and routinely used high-resolution 2D-PD-fs sequences to evaluate the potential for replacement of this standard 2D protocol. Further, the free-scan mode was assessed concerning its benefit in daily clinical routine.

2. Materials and methods

This prospective comparative study was approved by our institutional review board (Medical University of Innsbruck). Written informed consent was obtained from each patient prior to MR imaging of the knee. The authors who are employees of Siemens Healthcare had no control of any data and were not involved in the execution of the study.

2.1. Patients

All patients were referred to the Department of Radiology at the Medical University of Innsbruck for MR evaluation of the knee. Patients had to meet the following inclusion criteria: (a) MRI of the knee accomplished with the sequences listed below, (b) age > 18 years, (c) no general contraindication to MRI (e.g. pacemaker, claustrophobia), (d) no history or suspicion of soft-tissue or bone tumour in the knee joint, (e) no indication to administer contrast agent. A total of 80 consecutive patients (39 female, 41 male; age range 18–84 years, mean age 43 years) were evaluated between March 2016 and December 2016. All were scanned with our routine 2D sequence protocol and the 3D-PD-CS-SPACE sequence with free-stop scan mode.

2.2. Imaging protocol

All MRI examinations were performed on a 3 T scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany). A dedicated 15-element transmit/receive knee coil (QED, Mayfield Village, OH, USA) was used. Patients were scanned in supine position, feet first, and carefully instructed not to move their leg during the examination. Our routine 2D protocol is listed in Table 1. A pre-saturation slab was placed over the popliteal vessels to avoid flow and pulsation artefacts. The accelerated 3D-PD-CS-SPACE sequence was performed in sagittal orientation and with spectral fat saturation (TE: 33 ms; TR: 1200 ms; FA: 120°; Matrix: 320 × 320; FOV: 160 mm, number of slices: 144; voxel size: 0.5 × 0.5 × 0.5 mm^3; time of acquisition: 05 min 38 s; slice thickness: 0,5 mm; sampling factor 0.15). In the event of a scan-stop the 3D-PD-CS-SPACE sequence was repeated without the free-stop function. All sequences were acquired in one session without replacement of the patients.

2.3. Visual analysis of the images

Two fully trained radiologists with 9 (reader 1 Henninger B) and 5 (reader 2 Kranewitter C) years of experience in musculoskeletal imaging independently assessed all exams. Diagnosis, gender, age and clinical history were blinded for the reviewers.

Table 1
MR-parameters of the routine 2D protocol.

Parameter	t1_tse	pd_tse_fs	pd_tse_fs	pd_tse_fs
Orientation	Coronal	Sagittal	Coronal	Axial
TE (ms)	13	38	38	37
TR (ms)	522–638	3710–4190	3100–3790	3100–3290
Slice thickness (mm)	3	3	3	3
Matrix	512 × 512	448 × 448	448 × 448	378 × 448
Field of view (mm)	160 × 160	160 × 160	160 × 160	126 × 150
Time of Acquisition	03:13	03:00	02:58	02:34
Number of slices (n)	27	27	27	37
Interslice gap (mm)	0.45	0.3	0.45	0.3
Bandwith (Hz/pixel)	150	245	245	255
PAT factor	–	–	–	2
Number of averages	1	1	1	2

The initial diagnostic reading of the images was based on our routine 2D-PD-fs protocol (Table 1). Thereby, the 2D-PD-fs sequences were rated with respect to the impairment of image quality due to the occurrence of motion artifacts (0 = no motion artefact, optimal image quality; 1 = slight motion artefact, no limitation of image quality; 2 = moderate motion artefact, assessment slightly limited; 3 = severe motion artefact, assessment not possible). In addition, a lesion-based analysis was performed based on standard imaging criteria for the bone, cartilage, cruciate ligaments (anterior and posterior cruciate ligament were analysed separately), collateral ligaments (medial and lateral collateral ligament were analysed separately) and meniscus (medial and lateral menisci were analysed separately). For classification, a Likert type scale with 3–8 levels as shown in Table 2 was used. The presence of a lesion/pathology for the cartilage was only recorded once. For example, even if multiple lesions of the cartilage were noted, the observers recorded one lesion (the most severe and highly rated), regardless of the number and location.

After a waiting time of 6 weeks to avoid memory bias, the image quality of the 3D-PD-CS-SPACE with free-stop was rated (0 = optimal image quality, sharp contours, ideal SNR; 1 = slight decrease of SNR, sharp contours; 2 = moderate decrease of SNR, slightly blurring of contours; 3 = severe decrease of SNR, contours blurred, assessment limited; 4 = severe decrease of SNR, contours blurred, assessment not possible). In addition, also a lesion-based analysis with the same criteria as described above was performed. The obtained results were then compared for all patients with the results of the 2D-PD-fs sequence.

In a final step, after another waiting time of 6 weeks, the images of the 3D-PD-CS-SPACE without free-stop function were evaluated. These images were only available for a subset of patients where the initial run of the 3D-PD-CS-SPACE with free-stop resulted in the occurrence of a scan-stop and the 3D-PD-CS-SPACE was repeated without free-stop function. For this subset of patients, the image quality was rated in comparison to the available 3D-PD-CS-SPACE free-stop images (0 = equal quality; 1 = slight difference of SNR, contours equal; 2 = improved SNR, contours equal; 3 = improved SNR, contours sharper; 4 = assessment is now possible; 5 = free-stop with better quality). Also, here a lesion based analysis was performed which was then compared to the results of the 3D-PD-CS-SPACE with free-stop. The whole analysis procedure is summarized in the flow chart of Fig. 1.

For all results (image quality evaluation and lesion based analysis), in case of discrepancy, a consensus was reached between the two reviewers. Readers were free to use the volumetric data to create MPRs in any orientation and slice thickness for the 3D SPACE CS with and without free-stop. Acquisition times for each of the sequences were documented.

2.4. Statistical analysis

All statistical calculations were performed using the R Project for