Background
Magnetic resonance imaging (MRI) of the knee is justifiably one of the most commonly performed MRI examinations, as it offers excellent direct depiction of cartilage, ligaments, menisci and periar- ticular soft tissue. This can be achieved by standard application of fat-saturated moderately T2-weighted 2D Turbo Spin Echo (TSE)-sequences in three orienta- tions [1, 2]. However, conventional TSE-sequences are not isotropic, hence struc- tures and signal alterations / lesions with a size less than the usual slice thickness of 3 to 6 mm, i.e. meniscal roots, may not be completely detected. A slice thickness below 3 mm is rarely acquired because of its reduced signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) and because of the prolonged acquisition time for complete joint coverage. Fur- thermore post-processing options for 2D-sequences for the assessment of structures, which are captured in an oblique course through several slices, like the anterior cruciate ligament or the fem- oral trochlear cartilage [3] are limited. In this setting the introduction of a highly resolved 3D moderately T2-weighted (3D-T2w-TSE) sequence may be useful. In the literature time effi- cient 3D-T2w-TSE sequences have already been evaluated for the central nervous system [4] and recently for the body trunk [5, 6]. They enable data acquisition with high isotropic spatial resolution and allow for an interactive 3-dimensional visualization. Such post- processing after an initial isotropic data acquisition has been proven successful in many other MR and CT-based applications.

Technical considerations for syngo SPACE
Recently a 3D-TSE-sequence with moder- ate T2-weighting called “Sampling Perfec- tion with Application optimized Contrasts using different flip angle Evolutions” (syngo SPACE), was developed for 3T sys- tems. A restore pulse and variable flip angle distribution enable extremely large turbo factors. The variable flip angles provide a particular evolution of the signal during the echo train resulting in a “pseudo steady-state” with constant signal level neglecting relaxation [7]. Addi- tionally, SAR is reduced by this acquisition scheme. The usage of this technique on a high field 3T system allows integration of parallel imaging with excellent SNR and CNR at reason- able acquisition times [8, 9]. The application of syngo SPACE at 3T might establish a new approach to MRI of the knee. Parallel imaging facilitates blockwise 3D-data acquisition with isotropic spatial resolution for evaluation of the whole knee in a reasonable time window. The acquisition time should be either less or at least comparable to acquisition times of conventional 2D TSE datasets in three planes. The advantage of an isotropic 3D-dataset is the possibil- ity of 3-dimensional multiplanar refor- matting (MPR), which may enhance the evaluation of small delicate or oblique structures like meniscal roots or the fasci- cles of the anterior cruciate ligament. Disadvantages might be slightly decreased in-plane resolution as com- pared to conventional 2D-TSE-fs-sequences and some additionally required time for the 3D reconstructions. Recently our research group evaluated syngo SPACE for isotropic highly resolved MRI of the knee at 3T (MAGNETOM Trio, Siemens Healthcare, Erlangen, Germany) with consecutive 3-dimensional-MPR in comparison to conventional 2D-TSE-fs-sequences in three planes (coronal, sag- ittal, axial) [10]. Sequence parameters for syngo SPACE and for the moderately T2w-2D-TSE-fs- sequence are given in table 1. Fat satura- tion in syngo SPACE was performed with the SPectral selection Attenuated Inver-
Parallel imaging was performed with the k-space based technique syngo GRAPPA with an acceleration factor $R = 2$. For signal reception, a dedicated multichannel knee coil with 8 independent RF-channels was used. Reformation of the datasets was performed on a syngo MultiModality Workstation (Leonardo, software version VB15A, Siemens Healthcare, Erlangen, Germany). Analysis of axial, sagittal and coronal reformations (MPR) of 0.5 mm, 1 mm and 2 mm slice thickness suggest a slice thickness for MPR of 1 mm ($\text{SPACE}_{1\text{mm}}$) to be optimal for the visualization of anatomical structures (Fig. 1). This slice thickness provides significantly higher SNR for ligaments, subchondral bone and menisci and at least equal SNR for cartilage, bone marrow, muscle and fat of syngo SPACE as compared to conventional 2D-TSE-fs. Though identification of anatomical structures was comparable for syngo SPACE and 2D-TSE-fs, the $\text{SPACE}_{1\text{mm}}$ showed significantly better visualization of menisci in axial sections and meniscal roots in coronal sections despite slightly inferior CNR (joint fluid/cartilage, joint fluid/menisci, fat/ligaments and bone marrow/subchondral bone) as compared to 2D-TSE-fs.

**Clinical application**

The reconstruction time for one syngo SPACE dataset was below 30 s, the data acquisition time was 10 min 35 sec with syngo SPACE versus 12 min 48 sec with 2D TSE in three planes (table 1). Thus the overall acquisition time for syngo SPACE was comparable to the acquisition of the 2D-TSE-fs datasets in three

<table>
<thead>
<tr>
<th></th>
<th>TR</th>
<th>TE</th>
<th>FA</th>
<th>Resolution</th>
<th>FOV</th>
<th>Matrix</th>
<th>Parallel Imaging</th>
<th>$T_{\text{acquis}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>syngo SPACE</td>
<td>1200</td>
<td>30</td>
<td>120</td>
<td>0.5</td>
<td>16</td>
<td>320 x 320</td>
<td>GRAPPA $r=2$</td>
<td>10’35”</td>
</tr>
<tr>
<td>T2w-2D-TSE-fs</td>
<td>3200</td>
<td>30</td>
<td>180</td>
<td>0.36 x 0.36 x 3</td>
<td>16</td>
<td>448 x 448</td>
<td>GRAPPA $r=2$</td>
<td>12’34”</td>
</tr>
</tbody>
</table>
planes suggesting that the technique is feasible for daily clinical use. The advantage of syngo SPACE over 2D-TSE-fs is the possibility of free multiplanar isotropic reconstructions at comparable SNR resulting in a slightly improved detection and differentiation of relevant small ligamentous (Fig. 2) and meniscal structures (Figs. 3, 4). Clinical relevance thus might be better visualization of small avulsive ligamentous lesions, e.g., of meniscal roots and of radial or complex meniscal tears whose configuration is challenging to interpret on conventional angulated thick sagittal or coronal sections (Fig. 5). The signal/image characteristics of syngo SPACE appear more similar to TSE image characteristics than to GRE and therefore are unlikely to require a big adjustment of the radiologist’s reading and interpretation habits to the new sequence. Usage of the free 3D-reformation according to the course of oblique anatomical structures as seen for femoral trochlear cartilage (Fig. 6) and the anterior cruciate ligament (Fig. 7) may aid in the evaluation of primarily difficult anatomical sites or a complicated situation after injury.

**Conclusion**

Blockwise acquired syngo SPACE is a new approach to MRI of the knee at 3T. It allows highly-resolved isotropic true 3-dimensional acquisition and subsequent reconstruction. Overall acquisition time is shorter than that of three separate 2-dimensional datasets and SNR for 1 mm reconstructions is similar to con-
Axial sections of the medial meniscus of a healthy individual. syngo SPACE provides more detailed depiction of the meniscus throughout a higher number of slices as compared to 2D-TSE-fs. Both the meniscal body and its attachments (meniscal roots) are clearly visualized in SPACE while in 2D-TSE-fs parts of those are masked by partial volume effects.
Axial reconstructed syngo SPACE\textsubscript{1\,mm} and 2D-TSE-fs of a patient with a bucket handle tear. SPACE provides better visualization of the configuration of the bucket handle tear as compared to T2w-2D-TSE-fs, in which delineation is impaired due to partial volume effects.

Coronal, sagittal and axial reconstructed syngo SPACE\textsubscript{1\,mm} images (row A) show a good delineation of a horizontal tear within the medial meniscus which approach the quality of the T2w-2D-TSE-fs sequence (row B) and provide an even clearer depiction of the lesion’s borders and its extent.
Axial reconstructed syngo SPACE_{1mm} and 2D-TSE-fs of a patient with a trochlear cartilage delamination. In strictly axially acquired 2D-TSE-fs (Topo A/B and series A) the femoral trochlear cartilage is partially blurred because of partial volume effects, whereas depiction in SPACE_{1mm} (B/C) is sharper. Axially reconstructed SPACE_{1mm} (Topo A/B and series B) is able to cover the trochlear cartilage on more slices than 2D-TSE-fs enabling a more detailed depiction. MPR perpendicular to the trochlear cartilage (Topo C and series C) even allows a clearer depiction of cartilage height and the lesion.
ventional 2D-TSE-fs. The identification of anatomical structures at least equals the conventional sequence and allows superior discrimination of relevant small ligamentous structures. These data suggest that a protocol comprising 1 mm syngo SPACE reconstructions in three orientations would be useful for clinical evaluation. The additional possibility of free 3-dimensional reconstruction depending on the specific clinical need may become useful for the diagnosis of difficult anatomical situations and presurgical planning, i.e. for traumatic ligamentous lesions or complex meniscal tears.

References

Contact
Annie Horng, M.D.
Department of Clinical Radiology
University Hospitals Munich – Campus Grosshadern
Marchioninistrasse 15
81377 Munich
Germany
Phone: +49 89 7095 3620
annie.horng@med.uni-muenchen.de