Iterative Denoising Applied to 3D SPACE CAIPIRINHA: An Application to Musculoskeletal Imaging

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Abstract

The purpose of this study was to evaluate the performance of 3D SPACE with CAIPIRINHA acceleration combined with a prototype iterative denoising (ID) algorithm[1] in musculoskeletal imaging at 1.5T, and to qualitatively compare image quality between the conventional sequence and the iteratively denoised sequence.

This prospective study involved a total of 23 patients who underwent a 1.5T knee or ankle MRI. Standard SPACE and SPACE with ID reconstruction were acquired. Two reviewers assessed sequence performance (resolution, signal/noise, contrast, edge sharpness) and clinical criteria (cartilage defect, meniscus, bone marrow edema, ligament) based on a 5-point scale. Qualitative scores were statistically analyzed using Wilcoxon rank tests, and the interobserver reliability was evaluated using Cohen's kappa coefficient.

SPACE with ID demonstrated better image quality than the standard SPACE sequence for all evaluated items (median = 4; $p < 0.05$) apart from signal/noise (median = 3; $p > 0.05$). Once the utilization of ID in MSK was validated in a patient cohort, a second evaluation step focused on contrast-optimized sequences with ID reconstruction in patients. We show that signal and contrast could both be improved in comparison to the standard SPACE sequence and reconstruction.

Introduction

Magnetic resonance imaging (MRI) has been established as a very reliable modality for the evaluation of the musculoskeletal (MSK) system, including the knee and the ankle joints. The standard protocol for MSK MRI usually comprises fat-saturated proton density (PD) or T2-weighted 2D turbo-spin-echo (2D TSE) sequences in three planes and one sagittal T1-weighted TSE sequence. Indeed, an accurate visualization of the cartilage, bone damage, and joint effusion is usually obtained using this contrast combination. The main indications are diverse and depend on the studied joints. These sequences offer excellent image quality and are routinely used. However, due to partial volume effects occurring in the usual slice thickness of ≥ 3 mm at 1.5T and the limited possibilities of postprocessing with 2D sequences, the detection of small lesions and small structures remains difficult with 2D sequences [1].

3D TSE sequences allow covering a whole volume of interest with an isotropic resolution and reduced partial volume effects [2]. 3D TSE sequences have been used in MSK imaging, particularly of the spine, knee, and ankle [3, 4]. The commercially available SPACE sequence, a 3D TSE sequence, uses extended echo trains with flip-angle modulation allowing very high turbo factors and a scan time that is compatible with clinical routine. The SPACE sequence with CAIPIRINHA (controlled aliasing in parallel imaging results in higher acceleration), a parallel imaging technique [5, 6], has been proven to be an advantageous combination in MSK and brain imaging, as an improvement in spatial resolution and a reduction of the acquisi-

[1]*Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

tion time were observed [7]. More recently, the combination of SPACE readout with a prototype iterative denoising (ID) algorithm [8] has been highly encouraging for neurological disease exploration, as shown in previous work by Vaussy et al. [9].

To our knowledge, the ID algorithm has not yet been evaluated in combination with SPACE readout in MSK imaging. In this work, we first seek to provide clinical cases and evidence of the added value of ID in MSK imaging. We then present some contrast-optimized SPACE protocols that are enabled by the time saved using an improved image reconstruction algorithm compared to standard parallel imaging.

Validation of iterative denoising applied to the SPACE CAIPIRINHA sequence in MSK imaging

Materials and methods

Study information

This prospective study was carried out from October 2020 to December 2020 at Groupe du Mail, Grenoble, France. A total of 23 patients (13 female and 10 male) aged 40 ± 14 [15–63] years (mean ± SD [range]) were enrolled for this first study. Knee MR examinations were conducted on 15 patients (laterality: 9 left and 6 right), and ankle MR examinations were performed on 8 patients (laterality: 2 left and 6 right). The main reason for the MR exams was pain in the knee or in the ankle area. Severe motion artifacts in 3D sequences were the exclusion criteria for this population. The images were independently reviewed and evaluated by two musculoskeletal radiologists with over 10 years of experience.

MRI technique

All MR examinations were acquired on a 1.5T MRI system (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany) using a Tx/Rx 15-channel coil for knee examinations and a 16-channel receive-only coil for ankle examinations.

The patients underwent both the conventional SPACE sequence with CAIPIRINHA acceleration (a commercially available sequence), and a SPACE CAIPIRINHA with prototype[1] iterative denoising [8]. The image contrast studied was proton density with SPAIR fat saturation (PD FS).

Different sequence optimization strategies were implemented depending on the anatomical region:

For knee examinations, the aim was to improve spatial resolution while keeping scan time constant at 4 minutes. Therefore, a 3D sagittal SPACE sequence with an interpolated (0.36 mm)^3 isotropic resolution was acquired with a field of view of 187 x 165 mm^2, a parallel imaging acceleration factor of 2 x 2 (3D CAIPIRINHA), weak SPAIR mode, a turbo factor of 35, and TE/TR of 75 ms/1000 ms, combined with ID reconstruction and 85% denoising strength.

For ankle examinations, the aim was to adapt the original 0.7 mm^3 protocol to reduce scan time. Therefore, a 3D sagittal SPACE sequence with a (0.7 mm)^3 isotropic resolution (interpolated to 0.37 x 0.37 x 0.7 mm^3) was acquired with a field of view of 190 x 190 mm^2, a parallel imaging acceleration factor of 3 x 2 (3D CAIPIRINHA), and TE/TR of 77 ms/800 ms, combined with ID reconstruction and 85% denoising strength.

Spatial resolution and scan time of the standard and ID sequences are reported in Table 1 for the different applications. For more information about the sequence parameters, please contact the corresponding authors.

		Spatial resolution (mm^3)	CAIPIRINHA acceleration factor	Scan time
Knee	**Reference** 3D SPACE PD FS	0.8 x 0.8 x 0.8	2 x 2	4:00
	High-resolution 3D SPACE PD FS + ID	0.36 x 0.36 x 0.36i	2 x 2	4:10
Ankle	**Reference** 3D SPACE PD FS	0.7 x 0.7 x 0.7	2 x 2	4:50
	Accelerated 3D SPACE PD FS + ID	0.37 x 0.37 x 0.7i	3 x 2	3:25

Table 1: Principal sequence parameters of the 3D SPACE CAIPI sequences (with and without iterative denoising, ID).

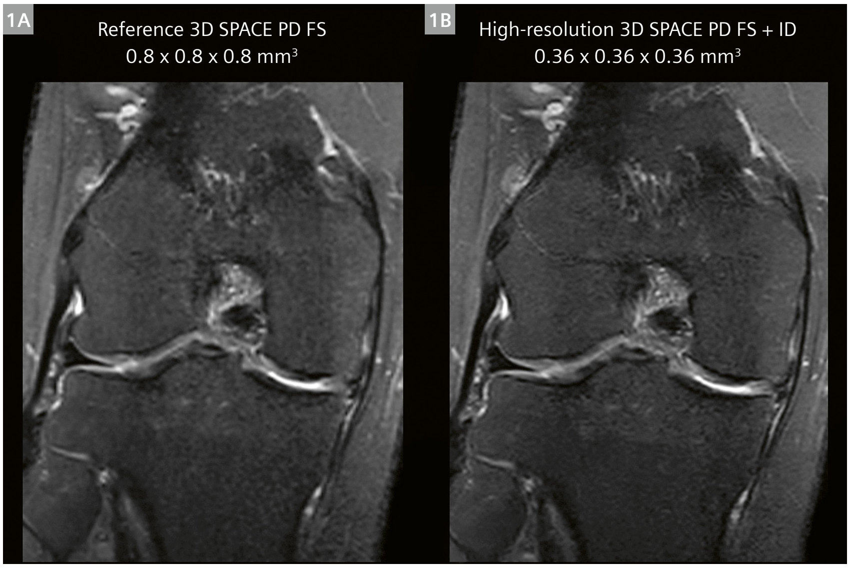
Qualitative assessment

The standard images and the optimized SPACE CAIPIRINHA with ID reconstruction were compared side-by-side for each patient by two reviewers.

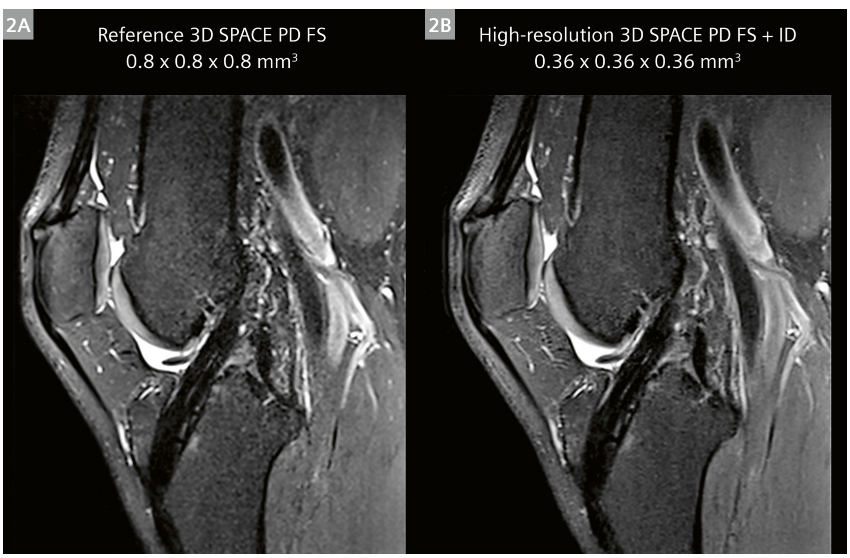
Images were rated by evaluating eight qualitative criteria: four imaging scores (resolution, signal/noise, contrast, and edge sharpness) and four clinical scores (chondropathy, meniscus, bone marrow edema, ligament) that evaluate the capacity of the new sequence to visualize the latter aspects. Scores were based on a scale of 1 to 5 (1 = markedly worse; 2 = worse; 3 = equivalent; 4 = better; 5 = markedly better).

Statistical analysis

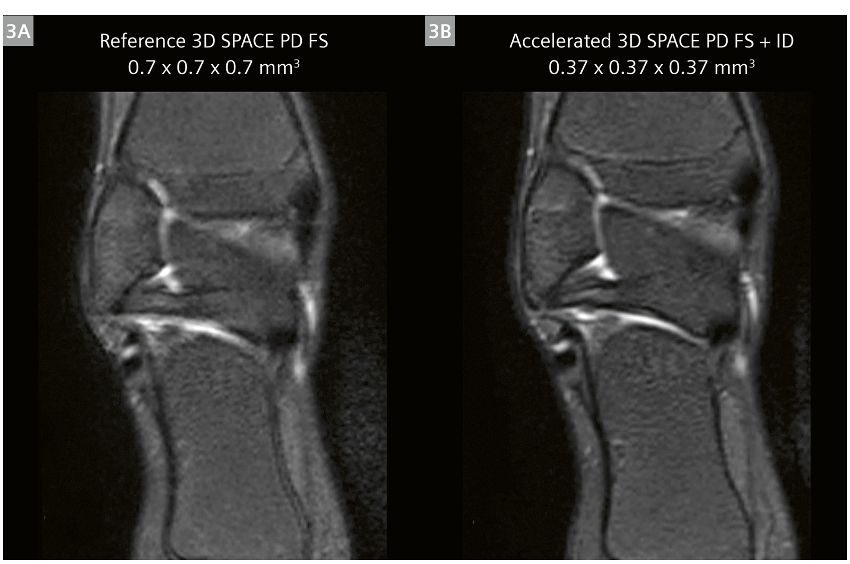
Statistical analyses were performed using the commercially available software R, version 3.6.2 (The R Foundation, Vienna, Austria) [10]. The statistical analyses for the quality scores were performed using Wilcoxon rank tests



1 59-year-old male with a medial meniscal tear, coronal reformat of 3D SPACE PD FS image with ID **(1B)** shows a better outline of the meniscus and the medial femoral condyle abnormalities than the reference 3D SPACE **(1A)**.



2 40-year-old male with a history of anterior cruciate ligament reconstruction, native sagittal 3D SPACE PD FS image with ID **(2B)** shows a significantly better signal-to-noise ratio in the intercondylar notch and the distal femur compared to the standard 3D SPACE **(2A)**.



3 15-year-old female with ankle pain, coronal reconstruction of 3D SPACE PD FS image with ID **(3B)** shows a significantly better signal-to-noise ratio and improved visualization of the calcaneo-fibular and posterior talo-fibular ligaments compared to the standard 3D SPACE **(3A)**, with a scan time reduction of almost 30%.

(one-sided, null hypothesis H_0: $m \leq m_0$ with $m_0 = 3$, which represents the "equivalent" quality score). P-values < 0.05 (α = 5%) were considered as statistically significant and were Bonferroni-corrected for multiple comparisons. The inter-rater agreement for the qualitative scores was assessed using the weighted Cohen's kappa coefficient with 0–0.20 = slight agreement; 0.21–0.40 = fair agreement; 0.41–0.60 = moderate agreement; 0.61–0.80 = substantial agreement; 0.81–1.0 = almost perfect agreement [11].

Results

Image-quality assessment

Our results demonstrate that it was possible to achieve high-quality $(0.36\ mm)^3$ isotropic 3D SPACE PD FS images in a clinically acceptable imaging time of 4 minutes for knee imaging at 1.5T. Figures 1 and 2 present two clinical cases.

While we aimed to improve spatial resolution for knee imaging, our focus for ankle imaging was on optimizing the acquisition time. A 30% reduction in scan time was feasible while maintaining high image quality and radiological confidence, as depicted in the clinical example in Figure 3.

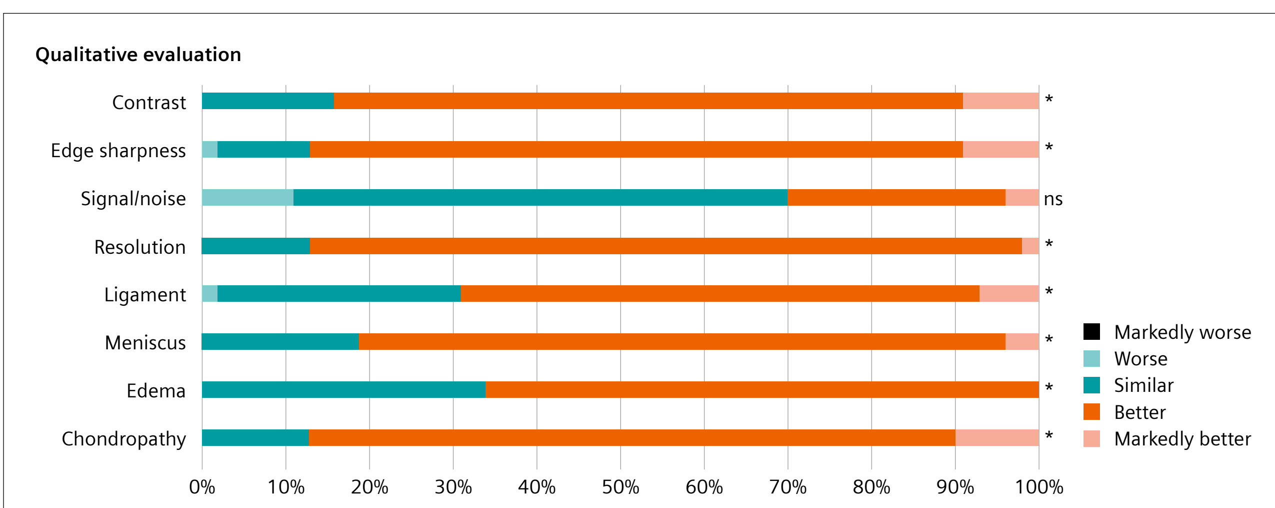
Quality scores and statistical analysis

The quality scores for the high-resolution or accelerated SPACE CAIPIRINHA combined with ID reconstruction were significantly higher than those for the standard SPACE CAIPIRINHA reconstructions without ID. This was true for almost all the quality scores: resolution (median = 4; range = 3 to 5; p-value < 0.001), contrast (median = 4; range = 3 to 5; p-value < 0.001), edge sharpness (median = 4; range = 2 to 5; p-value < 0.001), chondropathy (median = 4; range = 3 to 5; p-value < 0.01), bone marrow edema (median = 4; range = 3 to 4; p-value < 0.05), meniscus (median = 4; range = 3 to 5; p-value < 0.05), ligament (median = 4; range = 2 to 5; p-value < 0.01). Only the signal/noise score was not significantly improved (median = 3; range = 2 to 5; p-value > 0.05). We also noted that neither of the two radiologists ever rated the ID images as being "markedly worse" (score of 1) than the original images. Relative score distributions are displayed in Figure 4.

The average kappa coefficient is 0.55 (p < 0.05) between the two reviewers for all evaluated items, which indicates moderate agreement between the two radiologists. Substantial agreement was observed for the bone marrow edema, ligament, and chondropathy quality scores (κ = 0.75, 0.8, and 0.6 respectively; p-value < 0.05) and fair agreement was seen for the meniscus and edge sharpness scores (κ = 0.35 and 0.3 respectively).

Discussion

This study shows that ID reconstruction, when compared to conventional parallel imaging reconstruction and applied to the 3D SPACE sequence in MSK, achieves an overall improvement in image quality. The sole exception is the signal/noise criterion, which seems to be equivalent for the new and the standard reconstructions, although the spatial resolution or the acquisition time were improved. This can be explained by the fact that the denoising strength was deliberately set at 85% to avoid a synthetic or blurred appearance in the final reconstructed images. Furthermore, in MSK imaging the endpoints of MR examinations are the visualization and radiological confidence of the clinical findings (chondropathy, meniscus, ligament,



4 Results of the two radiologists' ratings based on the comparison of images from the standard and the new sequences (the scores were combined into relative distributions, as a percentage of the total number of cases). Quality scores for the new images with iterative denoising were significantly higher than the original images without ID (*p < 0.05, Wilcoxon rank tests) for all the qualitative criteria except signal/noise (ns = non-significant, p > 0.05).

or edema). The SPACE sequence with ID reconstruction was shown to be superior in all of these clinical aspects, with an improved visualization of the clinical criteria. However, one bias of the present study is that the prototype sequence was always acquired at the end of the exam in order to ensure reliable clinical findings. This might have introduced more variations into the measured metrics, especially signal stability over the successive long SPACE readouts with respect to motion. Figure 5 shows an example in which the ID reconstruction was rated worse than the standard one.

We have demonstrated that improvement of the spatial resolution or reduction of the acquisition time, which undeniably reduces the inherent signal-to-noise ratio, were feasible without visual signal loss using this denoising approach. Therefore, this version of SPACE ID with higher spatial resolution or reduced acquisition time allowed us to address the most important clinical evaluation criteria in MSK imaging while keeping the high signal-to-noise ratio needed for clinical decision-making.

This first cohort study was necessary to validate the ID reconstruction while maintaining clinical confidence. The following part now focuses on improving contrast and signal quality while maintaining the clinical benefits obtained in the first study.

Using iterative denoising to improve image contrast: An MSK imaging case report

Population and MRI technique

A total of 6 patients (4 female and 2 male) aged 43 ± 17 [24–71] years (mean ± SD [range]) were enrolled for this second study. Half of the patients underwent knee MR examinations (laterality: 2 left and 1 right) and half underwent ankle MR examinations (laterality: 2 left and 1 right). The same two radiologists reviewed and evaluated the images.

All MR examinations were acquired on the same scanner and using the same coils as the first study. The patients underwent both the conventional sequence and a contrast-

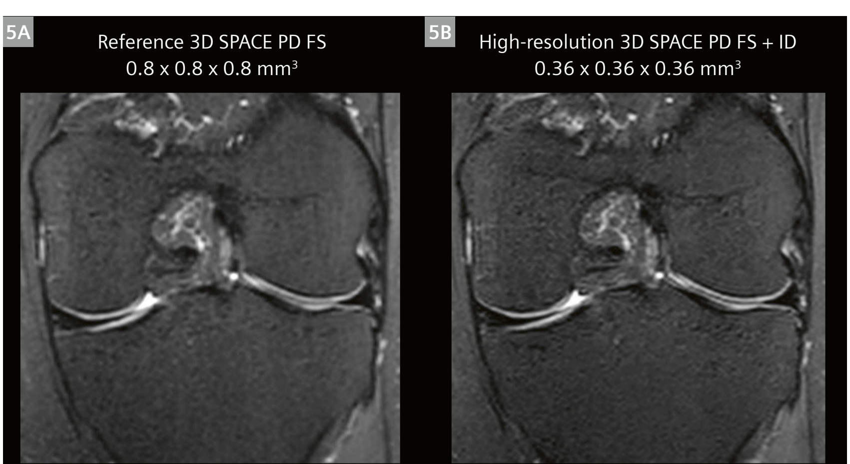
		Spatial resolution (mm^3)	CAIPIRINHA acceleration factor	Scan time
Knee	**Optimized** 3D SPACE PD FS + ID	0.36 x 0.36 x 0.36i	2 x 2	3:58
Ankle	**Optimized** 3D SPACE PD FS + ID	0.37 x 0.37 x 0.37i	3 x 2	3:53

Table 2: Principal sequence parameters of the contrast-optimized 3D SPACE CAIPIRINHA ID sequences.

optimized SPACE CAIPIRINHA with ID reconstruction. Again, the contrast was proton density with SPAIR fat saturation (PD FS).For this second study, some parameters were finely tuned to improve image contrast and signal-to-noise ratio:

For knee imaging the SPACE variable flip angle mode was set to Constant (FA 120°) instead of PDVar, a strong SPAIR FS mode was selected, and a denoising strength of 95% was carefully chosen to accommodate signal loss using strong SPAIR fat saturation.

For ankle imaging the acceleration factor and spatial resolution were kept constant with a final reconstructed isotropic voxel size of $(0.37\ mm)^3$. TE/TR was increased from 77 ms/800 ms to 100 ms/1000 ms, TF was increased from 33 to 44 using T2Var instead of PDVar, and a partial signal average of 1.4 instead of 1 was used. SPAIR mode was also set to Strong, and the denoising strength was slightly increased from 85% to 90% to improve the final image appearance and the signal-to-noise ratio.

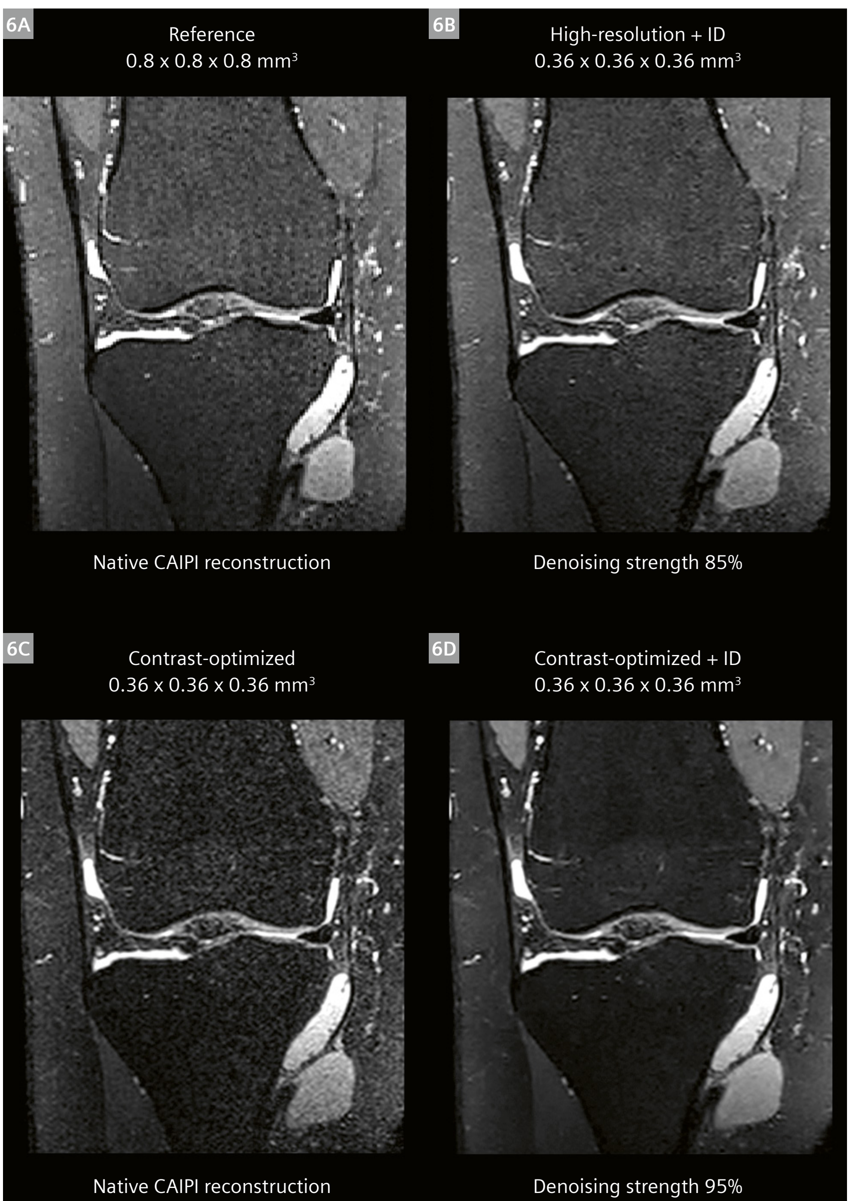


5 26-year-old male referred for a lateral knee pain. Coronal 3D SPACE PD FS image with ID **(5B)** shows a reduced signal-to-noise ratio and signal ripples at the interfaces within the medial femoral cartilage in comparison to the product SPACE reference **(5A)**; this could be attributed to excessive motion during the scan.

Results and discussion

The contrast-optimized SPACE ID sequence allowed us to obtain higher image quality than the standard SPACE sequence without ID for all the quality scores: resolution (median = 4; range = 3 to 5), contrast (median = 4; range = 3 to 5), edge sharpness (median = 4; range = 3 to 5), chondropathy (median = 4; range = 4 to 5), bone marrow edema (median = 4; range = 3 to 5), meniscus (median = 4; range = 4 to 4), ligament (median = 4; range = 3 to 5), and signal/noise (median = 4; range = 3 to 5). We also noticed that none of the quality scores were lower than 3, meaning that all of the new images acquired with the contrast-optimized SPACE ID sequence were at least equivalent to the images from the standard SPACE sequence.

A comparison of the three knee protocols proposed in this article is presented in Figure 6. While the parameter changes for the first study (6A and B) could accommodate a denoising strength of only 85%, by using strong SPAIR fat sat and a constant flip angle readout to improve the contrast, one can easily see that the resulting image using default reconstruction was too noisy for proper interpretation. With stronger denoising of 95%, the final image is drastically improved in terms of contrast, SNR, and radiological confidence. This result demonstrates that iterative denoising is an interesting method for improving signal-to-noise ratio and for gaining more freedom in MR sequence parameter settings to improve

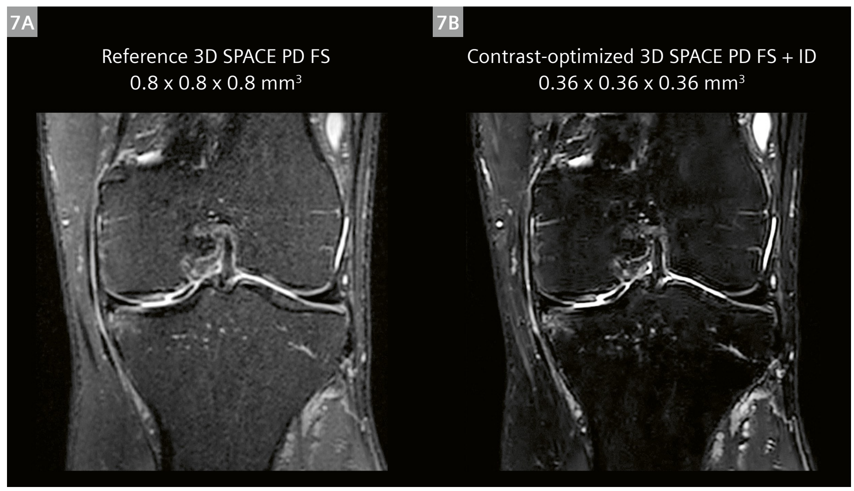


6 Contrast-optimized 3D PD FS SPACE of a 54-year-old female patient referred for a symptomatic medial cyst. The window levels (contrast and width) have been set equally for all sequences to highlight both signal and contrast changes. The contrast-optimized ID image allowed a better homogeneity and contrast within the cyst as well as the bone marrow and subcutaneous fat. Note the higher contrast in **6C** and **6D** between the quadricipital muscle and the adjacent subcutaneous fat compared to **6A** and **6B**.

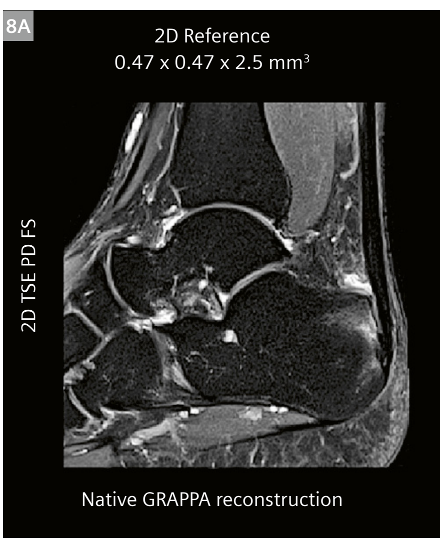
the image contrast and quality, even with the lower SNR produced by a 1.5T magnet.

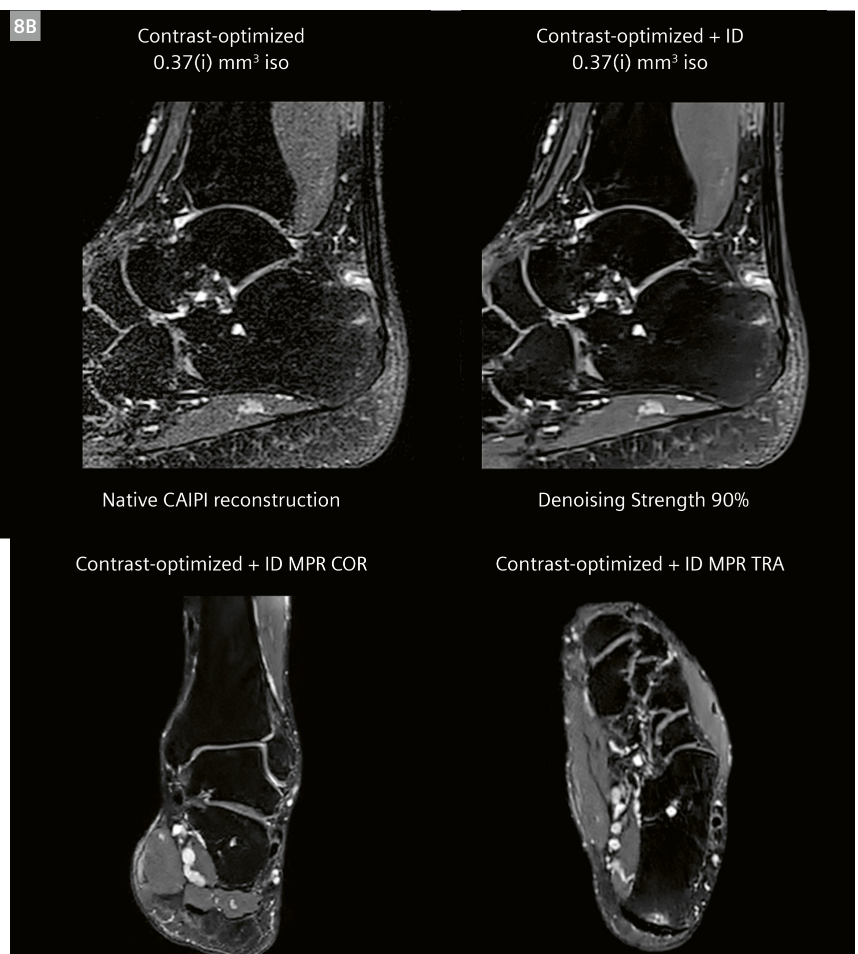
Contrast-optimized SPACE ID yielded high-quality images with an effective fat suppression (allowing more precise detection of the bone marrow edema), along with noise reduction in the final image (Fig. 7). The accuracy of the meniscus and cartilage visualization remained unchanged.

Finally, Figure 8 compares a clinical case of contrast-optimized 3D SPACE ankle with the 2D TSE standard. Interestingly, we were able to reproduce the overall image appearance, which is known to be difficult in MSK imaging when moving from 2D to 3D.



7 71-year-old male with a medial meniscal flap and grade 3 chondropathy. The contrast-enhanced ID image **(7B)** allows better visualization of bone marrow edema in the medial tibial plateau compared to the standard image **(7A)** while preserving high-quality exploration of the meniscus and the weight-bearing cartilage.





8 Comparison of contrast-optimized 3D SPACE PD FS acquired in 3:53 min **(8B)** and the clinical standard 2D TSE PD FS obtained in 2:50 min **(8A)**. Coronal and transversal multiplanar reconstructions of the contrast-optimized denoised SPACE sequence are presented in the bottom row.

Conclusion

Three-dimensional PD FS is a well-established MSK technique mostly used in knee and ankle joints, allowing for isotropic resolution imaging of meniscus and cartilage abnormalities. However, 3D MSK does have some weaknesses, such as lower signal-to-noise ratio and contrast quality compared to conventional 2D PD FS imaging. In this study, we attempted to resolve the insufficiencies of 3D SPACE imaging without altering the time-effectiveness of the sequence. Iterative denoising allowed a significant improvement in the diagnostic confidence of knee and ankle abnormalities. Image quality was assessed in terms of contrast, edge sharpness, signal/noise, and resolution. All these criteria were significantly improved by the ID reconstruction, except for signal/noise, which was maintained at a stable level to emphasize other image parameters.

The clinical value of the ID reconstruction was determined using major criteria such as the evaluation of ligaments, meniscus, cartilage, and subchondral bone changes. Both readers considered the evaluated SPACE variants combined with ID reconstruction to be more accurate, while performing equally on time-effectiveness.

We believe this contrast-optimized SPACE ID to be a promising, time-effective, all-in-one sequence. However, further studies with larger cohorts are needed to objectively evaluate the diagnostic performance of this sequence. Furthermore, multicenter evaluations should be conducted to confirm our findings.

In conclusion, we demonstrated that the iterative denoising reconstruction is a reliable technique for imaging the knee and ankle for internal disruptions, resulting in a better evaluation of the anatomical components of these joints.

Acknowledgments

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