Accelerated 3D T2 SPACE CAIPIRINHA with Iterative Denoising for the Assessment of Deep Infiltrating Endometriosis

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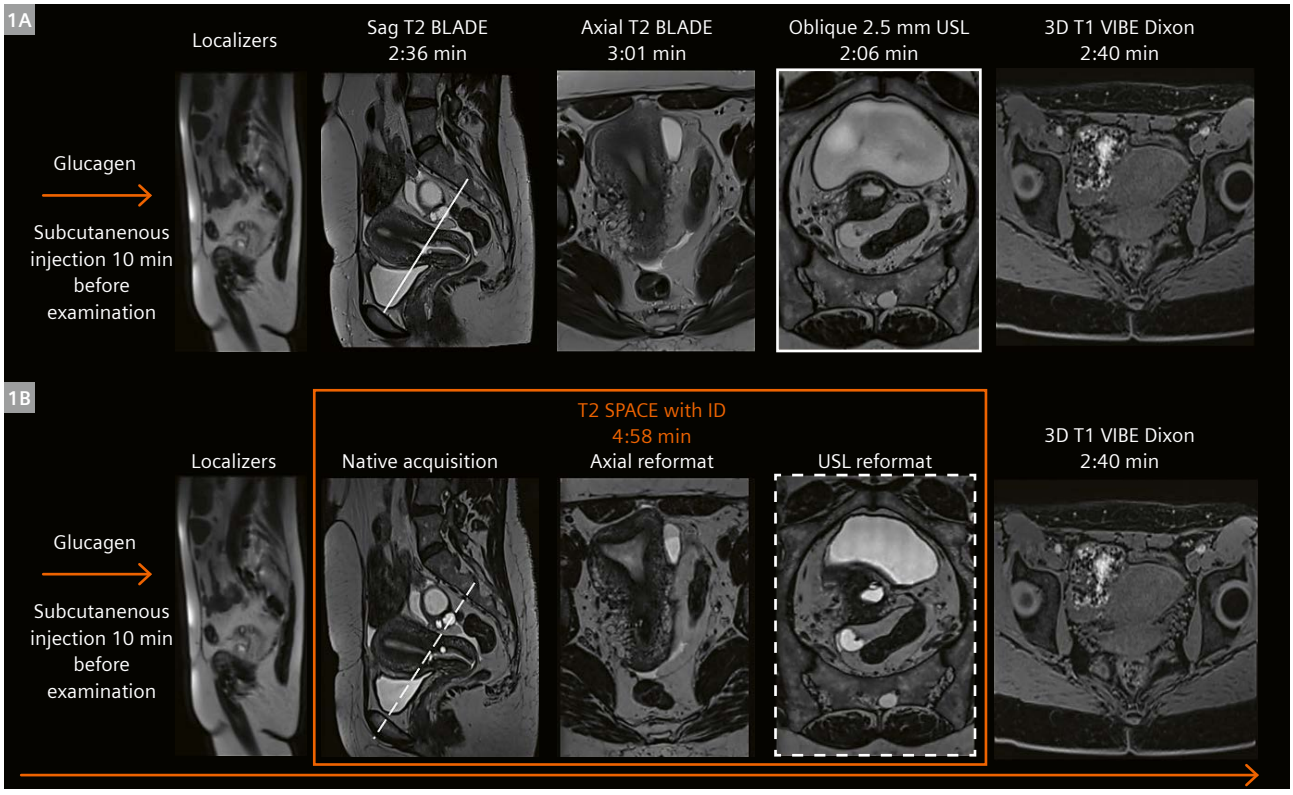
Introduction

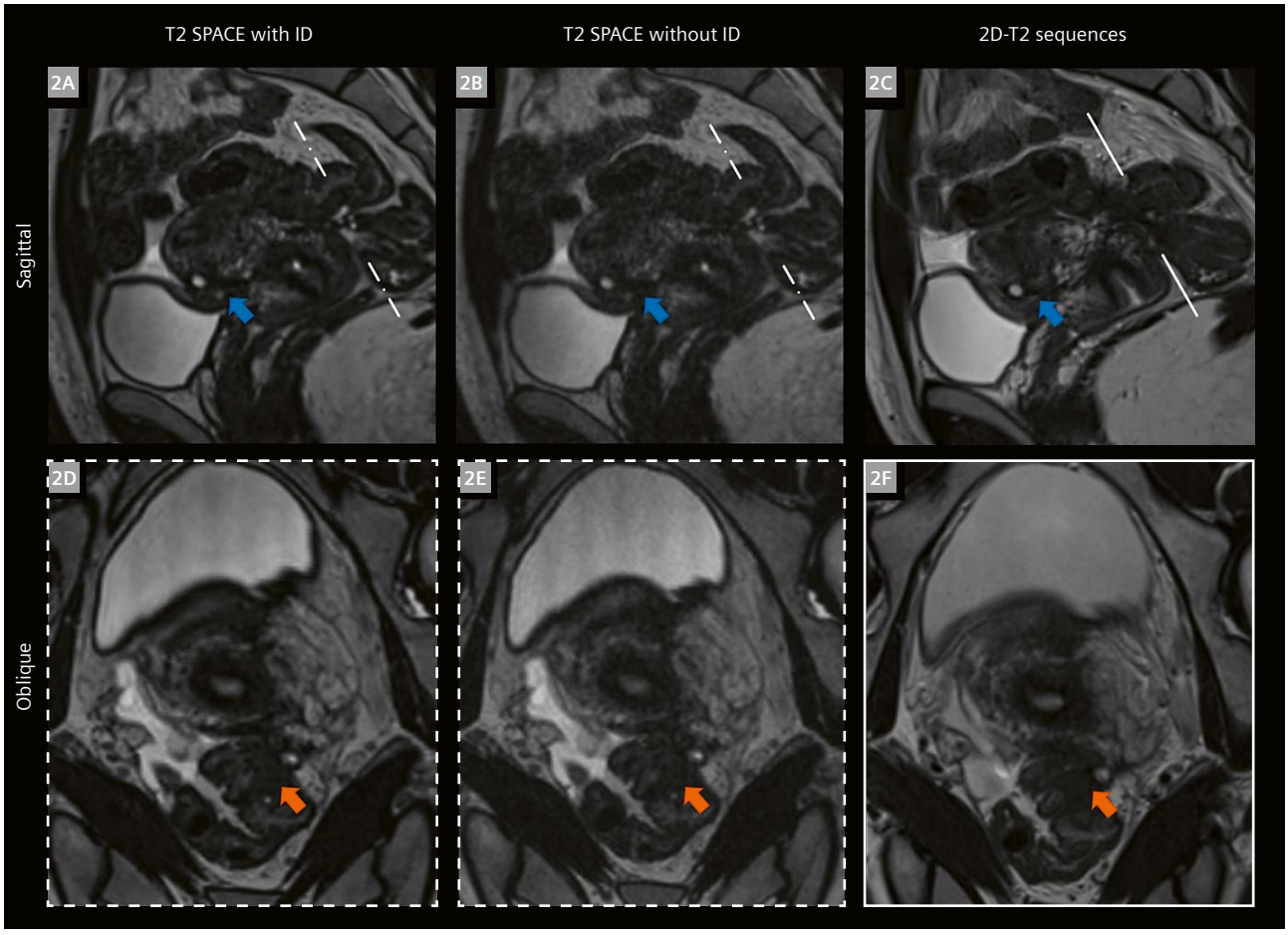
Deep infiltrating endometriosis (DIE) is a common gynecological inflammatory disease that primarily affects women of reproductive age, with a prevalence of 10% [1]. This pathology can be defined as functional ectopic endometrial tissue outside the uterine cavity. The most common locations of DIE include the torus, uterosacral ligaments, rectosigmoid colon, and vagina [2]. According to the European Society of Urogenital Radiology guidelines (ESUR) [3], magnetic resonance imaging (MRI) is considered one of the most effective techniques for the evaluation of pelvic endometriosis with transvaginal ultrasonography. Nowadays, the most commonly used



1 **Illustration of the protocol strategy used for endometriosis assessment. (1A)** First routine protocol used until 2019 for the assessment of endometriosis (scan time = 10 min 23 sec). **(1B)** New optimized protocol from March 2020 using a T2 SPACE with ID reconstruction (scan time = 7 min 38 sec).

MRI protocol for endometriosis includes 2-dimensional turbo spin echo (TSE) T2-weighted (2D T2) sequences in addition to 2D T1-weighted sequences with and without fat suppression. Additional 2.5 mm thin oblique 2D T2 slices can improve the assessment of uterosacral ligaments (USL) and parametrial endometriosis locations [4]. However, the spatial localization of USL is variable and needs to be carefully adapted for each patient. Furthermore, the visualization of small endometriosis lesions remains limited by the thick slice thickness of 2D imaging and the resulting partial volume effect.

For that reason, 3-dimensional (3D) TSE sequences are of high interest as they offer the possibility to reconstruct any multiplanar view from a high-resolution isotropic volume [5, 6]. However, the visualization of small endometriosis lesions would require a sub-millimetre voxel size and complete coverage of the uterine cavity, which would considerably lengthen the scan time. Furthermore, the detection of subtle T2 contrast changes induced by endometriosis lesions may be masked by the extended echo train length used with the Sampling Perfection with Application-optimized Contrasts using different flip angle Evolutions (SPACE) technique [6]. Recently, a suc-



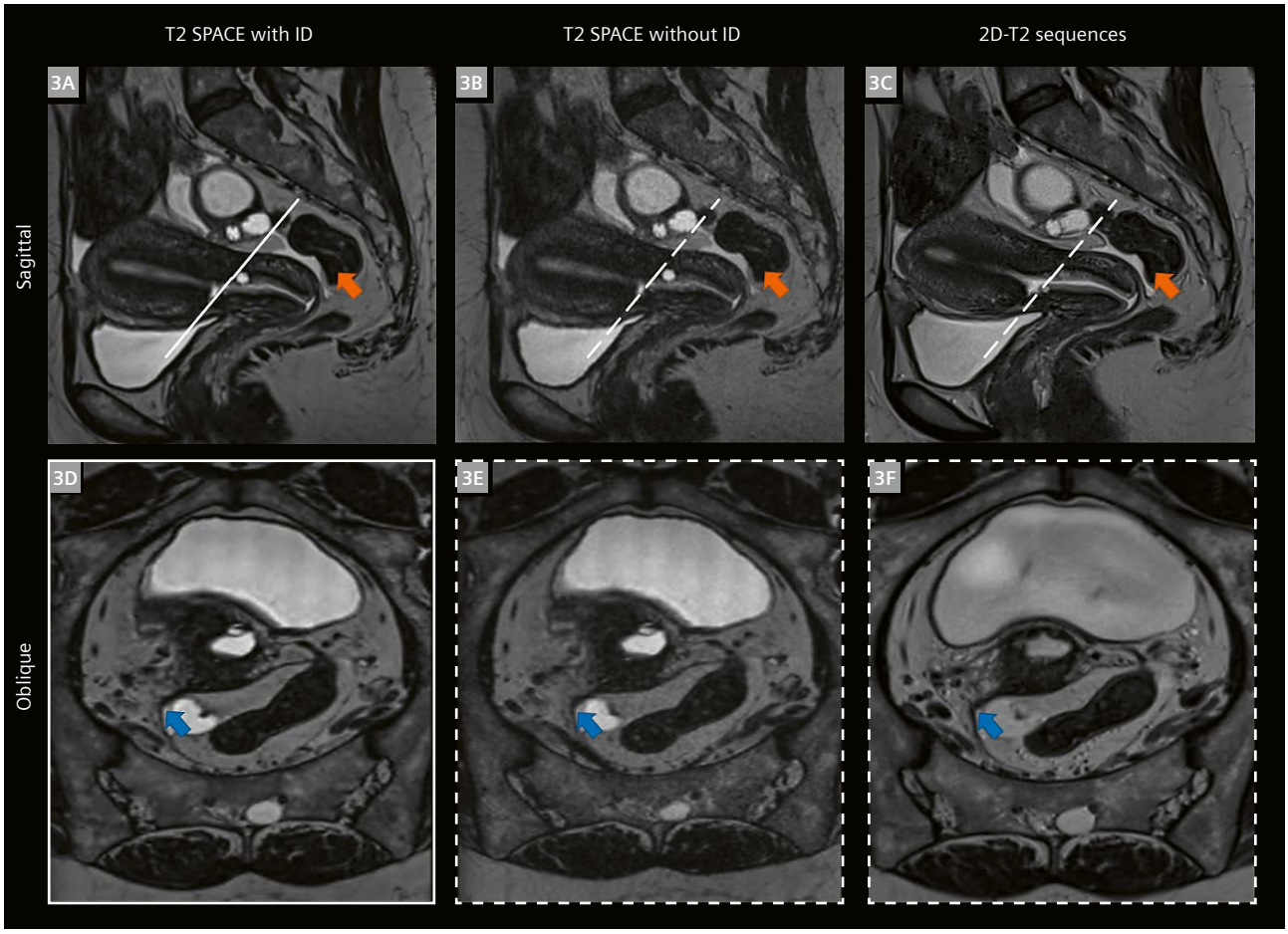
2 **Representative images comparing T2 SPACE with/without ID reconstruction and conventional 2D T2 sequences.** A 28-year-old patient seen for follow-up of known moderate endometriosis after appearance of new symptoms (dyspareunia, dysuria, and dyschezia). Corresponding T2 SPACE acquisition with oblique reformatted plans (dotted line) with ID (2A, 2D) and without ID reconstructions (2B, 2E) and separately acquired sagittal and oblique (full line) 2D T2 sequences (2C, 2F). From **(2A)** to **(2C)**, an endometriosis location is visible on the vesico-uterine pouch (blue arrow), while a digestive location is identified on rectosigmoid area (orange arrow) from **(2D)** to **(2F)**. In both cases, the fibrous endometriosis component is identified as an hyposignal intensity in close contact with anatomical structures. Both endometriosis locations are better depicted with T2 SPACE with ID reconstruction, which displays a sharper image quality and lower partial volume effect. Additionally, the identification of endometriotic cysts visible as hypersignal intensity between dotted lines in **(2A)** and **(2B)** is carried out more easily than on the conventional 2D T2 sequence **(2C)**.

cessful combination of SPACE acquisition with Controlled Aliasing In Parallel Imaging Results IN Higher Acceleration (CAIPIRINHA) acceleration [8–10], reconstructed with a prototype iterative denoising (ID) algorithm [11], demonstrated tremendous results in several applications, such as brain and musculoskeletal imaging [12, 13].

Very recently, the setup, optimization, and evaluation of a 3D T2 SPACE accelerated with CAIPIRINHA parallel imaging with prototypal ID reconstruction (T2 SPACE with ID)[1] was carried out at "Centre d'Imagerie du Landy" by Florin et al. in close collaboration with MR application developers and the local clinical scientist [14]. From December 2019 to March 2020, 90 female patients with suspected endometriosis were prospectively enrolled. We performed a systematic evaluation of the diagnostic performance of the optimized T2 SPACE with ID against conventional 2D T2 sequences. MRI was performed on a 1.5T MAGNETOM Aera scanner (Siemens Healthcare, Erlangen, Germany) using a 30-channel phased array coil in combination with a 32-channel spine coil. In this study, we demonstrated similar intra- and interobserver agreements between T2 SPACE with ID and conventional 2D T2 sequences with a scan time reduction of 36%.

In this article, we propose to share our workflow for patient preparation, sequence parameter optimization, and slab positioning. We also present several clinical cases to demonstrate the diagnostic value of T2 SPACE with ID in the context of deep infiltrating endometriosis.

[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.*



3 **Representative images comparing T2 SPACE with/without ID reconstruction and conventional 2D T2 sequences.** A 47-year-old woman presented with suspected endometriosis. Corresponding T2 SPACE acquisition with oblique reformatted plans (dotted line) with **(3A, 3D)** and without ID reconstructions **(3B, 3E)** and separately acquired sagittal and oblique (full line) 2D T2 sequences **(3C, 3F)**. From **(3A)** to **(3C)**, an endometriosis location is visible on rectosigmoid area (orange arrow), while another location is visible on the right USL from **(3D)** to **(3F)**. Of note, the thinner slice thickness of the T2 SPACE with ID offers a better delineation of the USL structures compared to the conventional oblique 2D T2 sequence.

High-resolution T2 SPACE for female pelvis imaging: How we do it

2D vs. T2 SPACE strategies

The routine protocol used until 2019 for the assessment of endometriosis integrated a manual positioning of each 2D T2 sequences. It included two orthogonal T2 BLADE sequences (sagittal and axial) for the whole uterine cavity and a thin T2 section oblique to the cervix for USL evaluation (total scan time of the three 2D T2 sequences: 7 minutes 43 seconds). However, the spatial localization of USL is variable according to the pelvis anatomy and needs to be carefully adapted for each patient. A 3D gradient-echo T1-weighted sequence with and without fat suppression using a two-point Dixon technique was additionally performed at the end of the examination for the diagnosis of endometriotic cysts and blood identification. The whole protocol lasts 10 minutes 23 seconds (Fig. 1A).

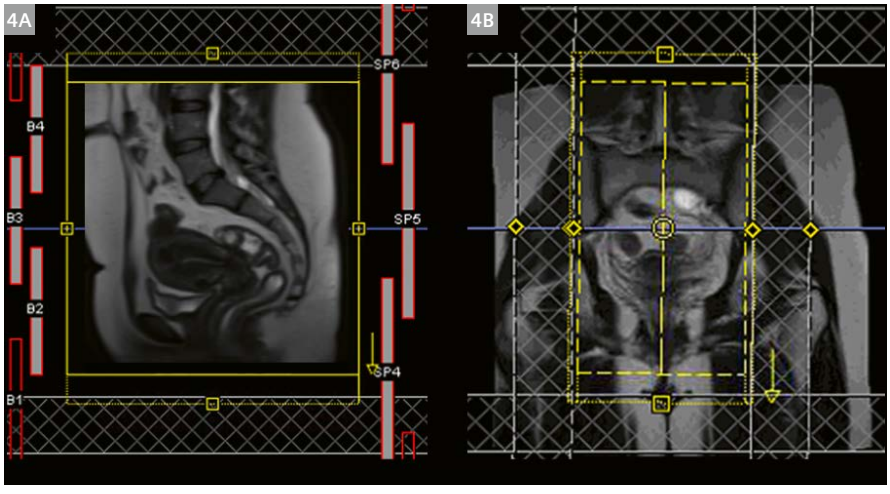
Since March 2020, the new protocol, including the optimized T2 SPACE with ID, has provided a real benefit by allowing the acquisition of a unique set of volumetric T2 images that could be reconstructed in any plane, eliminating the possibility of a suboptimal plane [14]. Furthermore, the scan time of the T2 SPACE with ID is 36% shorter than the separately acquired sagittal, oblique, and axial 2D T2 sequences (Fig. 1B). Figures 2 and 3 present two relevant clinical cases to highlight the advantages of the new T2 SPACE with ID for the assessment of DIE compared to conventional 2D T2 sequences.

3D T2 SPACE settings

The sequence parameters of the T2 SPACE with ID sequence are presented in Table 1. The SPACE technique is an optimized 3D TSE sequence, which allows increasing the duration of the echo train (and thereby reducing the acquisition time) by using short non-spatially selective radiofrequency pulses and variable flip angle schemes. In this study, the scan time of the T2 SPACE with ID sequence was shortened using a 4-fold CAIPIRINHA acceleration factor, while the g-factor penalty and SNR drop were compensated with the ID prototype algorithm. The sequence was set up to cover the whole pelvis cavity using full Fourier sampling and a voxel size of 0.8 × 0.8 × 0.9 mm^3 to ensure the visualization of fine anatomical details and multiplanar reconstruction in any desirable reformats. Finally, the SPACE variable flip angle mode was set to constant, while the echo

T2 SPACE with ID	
Orientation	Sagittal
Field of view	256 × 256 × 176 mm
Matrix	320 × 320 pixels
Acquired voxel size	0.8 × 0.8 × 1.0 mm^3
No. averages	1.4
TR/TE	1360/152 ms
Turbo factor	72
Bandwidth	679 Hz/pixel
Accelerator factor	CAIPIRINHA 2 × 2
Scan time	4:58 min

Table 1: T2 SPACE with ID reconstruction sequence



4 Sequence positioning on the MR console. The volume (yellow box) is positioned in sagittal orientation to cover the whole pelvis cavity on sagittal **(4A)** and coronal **(4B)** localizers. The phase encoding direction is set from head to feet to reduce motion breathing artifacts. Four saturation bands are placed along the phase encoding direction (manual positioning in front of the activated coils) and slice direction (automated positioning) to reduce the fold-over artifact from the upper abdomen, thumbs, and hips. The automated coil selection is set to "Minimize" to prevent any additional risks of folding artifacts.

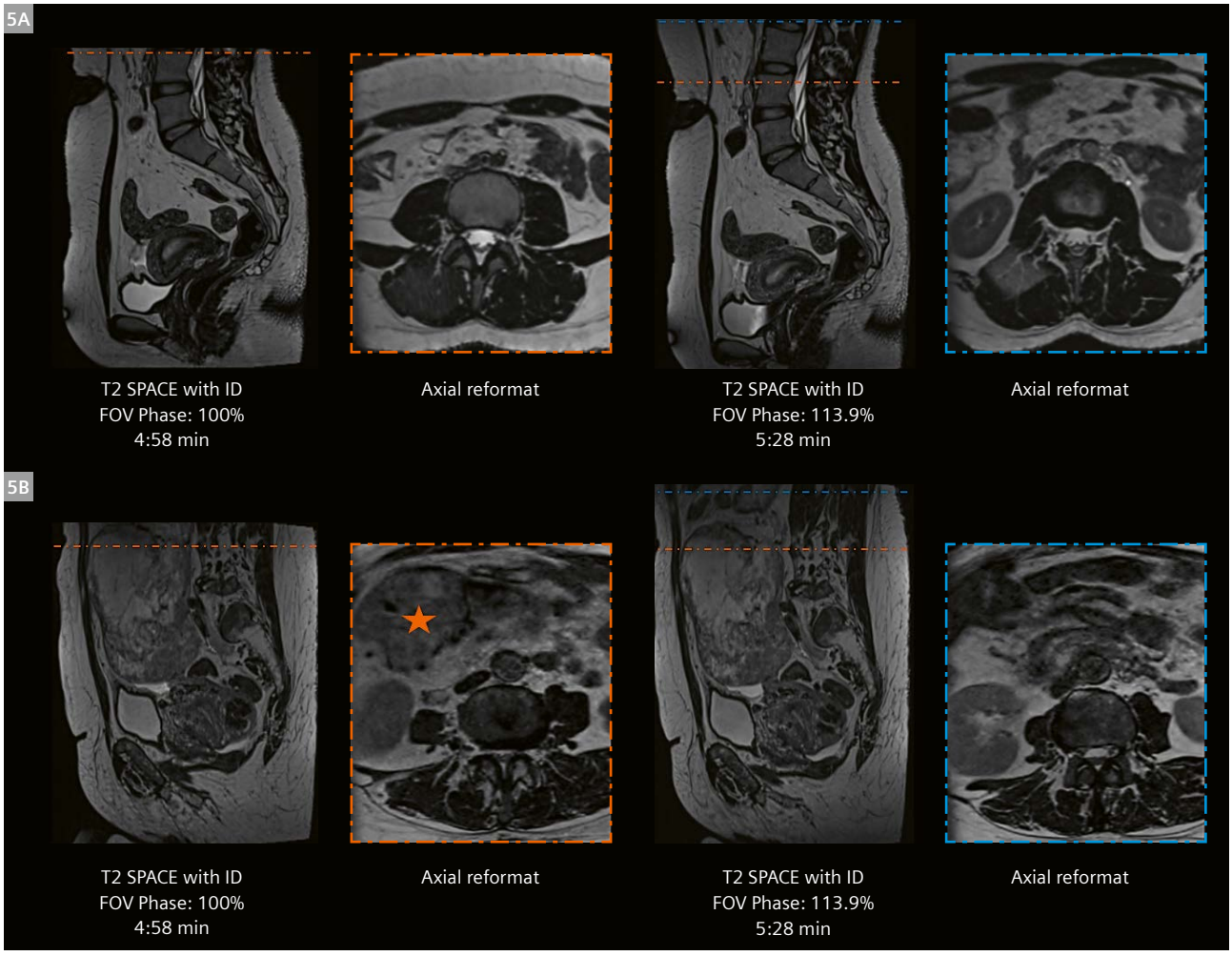
train length was significantly reduced to 265 ms using a low turbo factor of 72 and a high bandwidth of 679 Hz/Px. This setting allowed to reproduce the desired contrast of the conventional 2D T2 sequences.

While this may at first seem counterintuitive, the phase encoding direction is set from head to feet with a phase oversampling of only 20% to maintain a clinically compatible scan time. This choice is made to minimize artifacts caused by breathing and to avoid the saturation band placement on the straight muscle of the abdomen, which could hide an endometriosis location. To reduce the fold-over artifact from the upper abdomen and the thumbs, two saturation bands are positioned in front of the activated coil elements not covered by the phase oversampling (Fig. 4). Two additional parallel sat bands are placed along the slice direction. The automatic coil selection is set to "Minimize" to prevent any additional risks of folding artifacts.

Moreover, an easy adaptation of the phase field of view parameter can be performed, depending on patient anatomy and pathology context (Fig. 5), without compromising voxel size and image quality, at the cost of a slightly increased scan time.

Patient preparation

According to the latest ESUR guidelines, the use of antiperistaltic agent is recommended in the evaluation of DIE to reduce bowel peristalsis [3]. However, there is currently no performance recommendation regarding the best



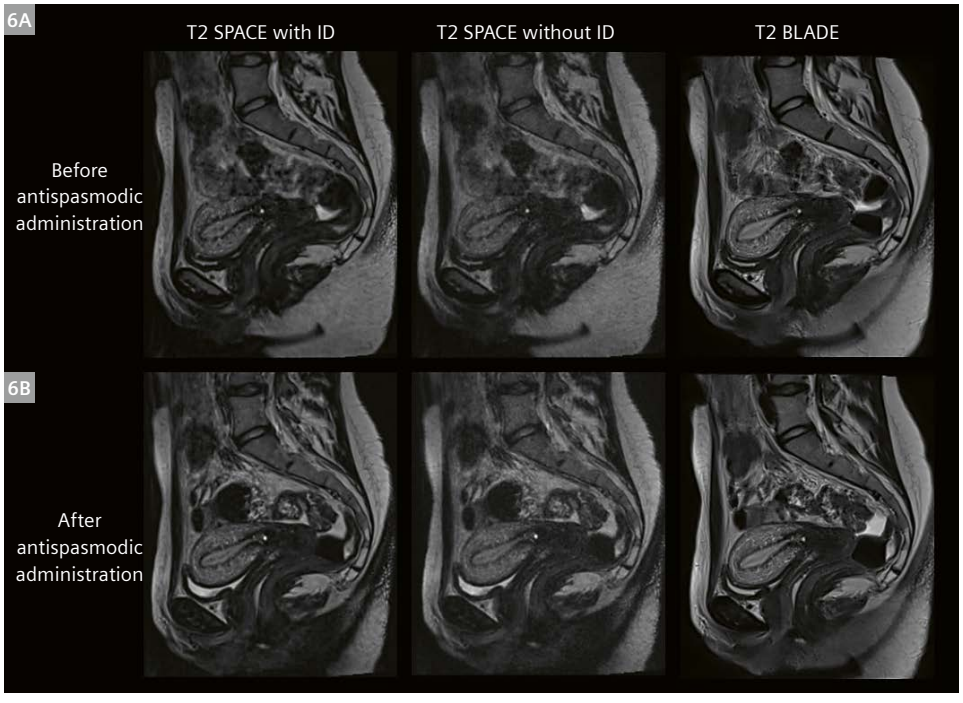
5 **Effect of the phase encoding direction to easily adapt the FOV according to patient anatomy and clinical indications.** In **(5A)**, due to patient height, the FOV phase was increased from 100% to 113.9% to explore the complete pelvis cavity from iliac crest to the pyelo-calyceal cavities in the context of endometriosis. In **(5B)**, the head to feet coverage did not offer a complete visualization of the uterine fibrosis borders (orange star), corrected with the increased FOV. Please note that this operation would slightly increase the scan time without any impact on the acquired voxel size.

administration procedure and timing. Figure 6 shows the impact of the antispasmodic drugs on T2 SPACE with ID image quality, compared to the reduced motion sensitivity of the conventional T2 BLADE. For that reason, precise timing is required between the antispasmodic administration and the acquisition of the T2 SPACE with ID. At our center, a single dose of antispasmodic subcutaneous injection (Glucagen, 1 mg/mL, Novo Nordisk, Paris, France) is administrated in the patient preparation room 10 minutes before MRI examination. Furthermore, before each examination, patients are asked to perform an intestinal toilette (Normacol). Patients are positioned in supine position, arms along the body. An abdominal strapping is used to reduce artifacts caused by respiratory movement, as recommended by ESUR guidelines.

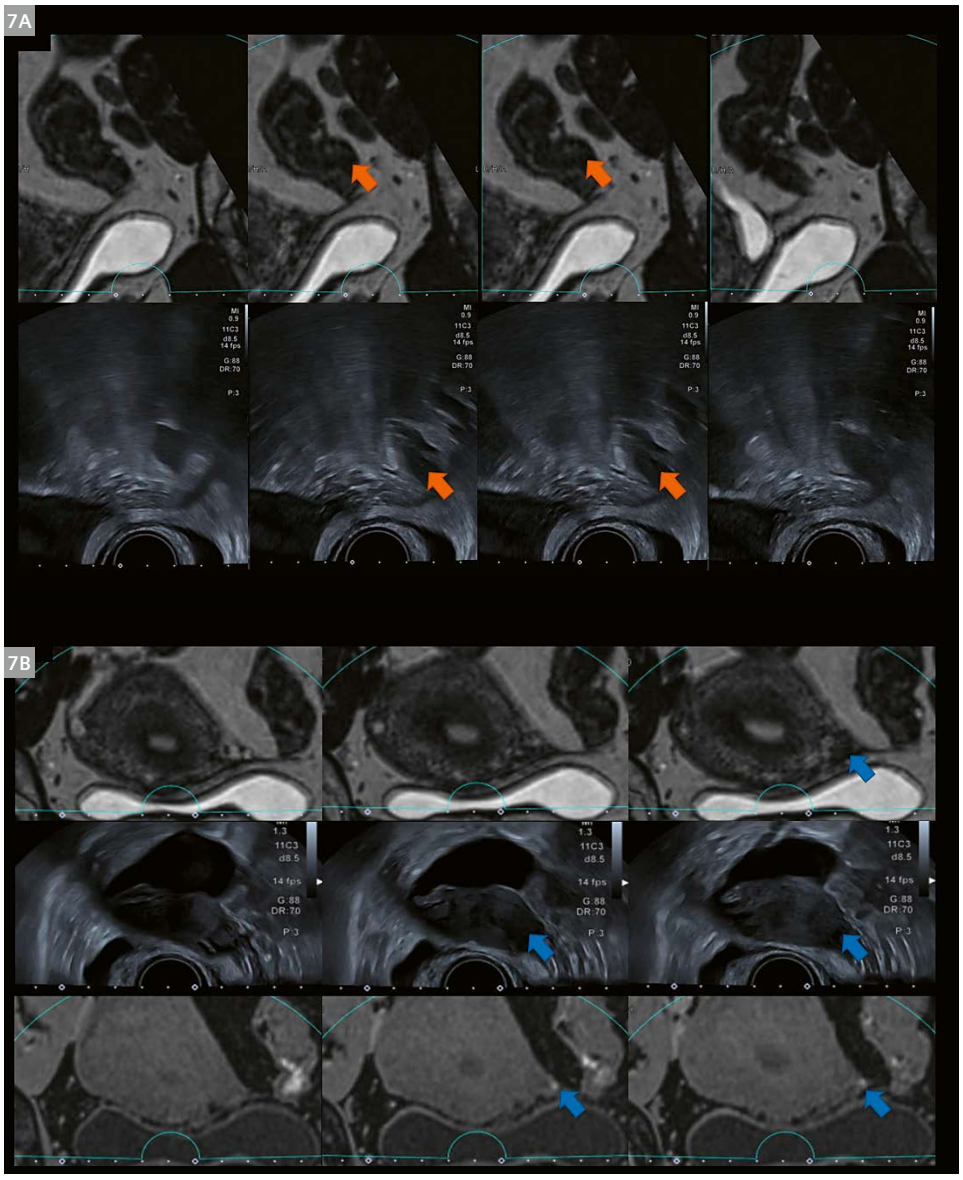
Future perspectives: fusion imaging between MRI and ultrasound

MRI and ultrasound (US) complement each other in the screening and diagnosis of DIE and are considered the best non-invasive techniques for this indication. While US is considered a first-line technique, owing to its widespread availability and cost effectiveness, the modality suffers from higher interobserver variability in the diagnosis of pelvic endometriosis, and its performance is highly dependent on the radiologist's experience [15]. In contrast, MRI provides a visualization of the whole pelvis, an excellent tissue contrast resolution [16], and is also considered less biased and more reproducible than US [17, 18]. Therefore, fusion imaging has great potential in the assessment of endometriosis as it combines the advantages of US and MRI modalities, and overcomes their weaknesses by providing superior spatial, contrast, and temporal resolution to that possible with each modality technique alone. As a result, MRI can be used to locate the targeted structures with US.

Despite the promising and encouraging results of DIE assessment by fusion imaging [19], it was demonstrated that MRI-US fusion imaging could not be readily implemented into daily practice as a routine evaluation of DIE due to the lack of accuracy between both modalities' datasets [20]. However, it must be noted that these studies used standard 2D T2 sequences, and that the sets of images needed to be synchronized manually using only one anatomical plane and reference point. The optimized T2 SPACE with ID proposed in this study may bring useful anatomical information to obtain a perfect fusion calibration independently of the desired reformatted plan required for US exploration. Figure 7 shows some preliminary clinical cases where the T2 SPACE with ID was used and fused with US in the context of DIE. This additional value of the MRI and US fusion using this novel MRI sequence will be further evaluated in a dedicated study.



6 Illustration of the impact of antispasmodic on image quality for T2 SPACE with/without ID and T2 BLADE sequence. (6A) shows the high peristaltic sensitivity and reduced image quality of T2 SPACE with/without ID before antispasmodic administration compared to conventional T2 BLADE. After antispasmodic administration **(6B)**, the image quality of the T2 SPACE with ID is similar to conventional T2 BLADE, while the image quality of T2 SPACE without ID remains unacceptable for clinical examination.



7 Simultaneous fusion imaging between magnetic resonance imaging (MRI) and transvaginal ultrasonography (US). Fusion imaging of intestinal endometriosis (**7A**, orange arrows) and superficial endometriosis (**7B**, blue arrows) with simultaneous display of corresponding planes obtained by MRI (reformatted T2 SPACE, first row) and transvaginal ultrasonography (US, second row). Intestinal endometriosis appears as a thickened structure associated with hypointense and hypoechogenic signals on MRI and US images, respectively. The same structure identification can be performed for superficial endometriosis facilitated by the additional hyperintense signal delineation offered by 3D T1 VIBE Dixon (**7B**, third row).

Conclusion

As outlined in this article, recent advances in 3D T2 SPACE imaging technique have given clinicians powerful tools to diagnose endometriosis pathologies. These tools can range from better MRI identification of endometriosis lesions to the most advanced perspectives, such as MRI and US fusion imaging. In our study, the combination of SPACE acquisition with a CAIPIRINHA sampling pattern and ID reconstruction offered a 36% scan time reduction compared to conventional 2D T2 sequences without compromising image quality. According to the World Health Organization, there is a need to improve early diagnosis of endometriosis as almost 190 million reproductive age women may be affected by this disease. We believe T2 SPACE with ID to be a promising tool to handle the growing challenges of this pathology management by providing all relevant information in only one sequence. Further investigations are needed to validate these results on a larger scale and to confirm the diagnostic performance of this sequence with surgical findings.

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