Rationale and objectives: High-resolution T2-weighted magnetic resonance imaging (MRI) of the pelvis is the main technique used for diagnosing benign and malignant uterine diseases. However, the procedure may be time-consuming and requires training and experience. Therefore, this study was performed to compare the image quality of standard clinical BLADE (stBLADE) with a prototypical accelerated simultaneous multi-slice (SMS) BLADE procedure with either improved temporal resolution (tr) at the same slice thickness (SL) or improved spatial resolution (sr) with the same examination time and a prototypical isotropic 3D SPACE procedure with inner-volume excitation and iterative denoising.

Materials and methods: Patients who underwent clinically indicated MRI of the uterus were included in this prospective study and underwent stBLADE (acquisition time, 2 min 59 s; SL, 4 mm) and SMS BLADE (tr) with the same SL (4 mm) but reduced examination time (1 min 20 s) as well as SMS BLADE (sr) with thinner slices (3 mm) and comparable examination time (3 min 16 s). In addition, 3D SPACE was acquired in a sagittal orientation (5 min 36 s). The short axis of the cervix and the long axis of the corpus uteri were reconstructed in 1-mm and 3-mm SLs, retrospectively. Subjective overall image impression, delineation of anatomy/organs, lesion demarcation, and motion artifacts were assessed using a 5-point Likert scale and compared among the different techniques. The preferred sequence was then selected by three independent assessors.

Results: The analysis was based on 38 women (mean age, 44 ± 15 years). The overall image impression was similar for stBLADE, SMS BLADE (sr), and SMS BLADE (tr) but was significantly lower for 3D SPACE than stBLADE (p = 0.01). SMS BLADE (sr) was considered the preferred sequence because of slightly better performance in terms of overall image impression, organ delineation, and lesion demarcation, but without statistical significance. Both SMS BLADE (tr) and (sr) produced significantly fewer motion artifacts than stBLADE (p < 0.01 and p = 0.01), with no significant difference between SMS BLADE (tr) and (sr), while 3D SPACE had a significantly lower rating than stBLADE (p < 0.01). Image quality was rated as the least diagnostic criterion in all sequences and all cases.

Conclusion: SMS BLADE (sr) was the preferred sequence for MRI of the female pelvis, with higher sr than stBLADE. SMS BLADE (tr) may also be used to reduce the acquisition time without compromising image quality. Despite its lower image quality, 3D SPACE can also reduce the examination time and improve the workflow because of the possibility of retrospective multiplanar reconstructions.

Key Words: Magnetic resonance imaging; Female pelvis; Uterus; Quality improvement.

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INTRODUCTION

Magnetic resonance imaging (MRI) has become an established technique for evaluating benign and malignant diseases of the uterus, such as leiomyomas and uterine cancer, because of its high spatial resolution (sr) and excellent soft tissue contrast (1-4). High-resolution T2-weighted (T2w) sequences of the female genital organs are the mainstay of these examinations. Recent technical advances have improved the sr of MRI, allowing the identification of fine structures such as the uterine and ovarian suspensory ligaments (5). T2w sequences with high temporal resolution (tr) and sr can be obtained using various strategies (6-8). In this context, radial k-space sampling with T2w BLADE sequences is a well-established strategy for reducing motion artifacts (6,7).

The general recommendation is to visualize the uterus in at least two T2w orthogonal oblique planes (2). The sagittal T2w image is usually acquired first and used for planning necessary additional orientations. For example, staging of endometrial carcinoma, characterization of leiomyomas, and classification of congenital uterine malformations require additional T2w axial oblique long-axis views of the uterine corpus parallel to the uterine cavity (1,2). In contrast, an axial oblique plane perpendicular to the cervical canal ("short-axis view") is required for staging cervical carcinoma (4). Moreover, the use of thin-slice oblique 2D T2w imaging improves the assessment of deep infiltrating endometriosis (9).

The current approach, which involves tailored acquisition of supplemental T2w planes, requires additional scan time and accurate anatomic and pathophysiologic knowledge of the female genital organ diseases to precisely define the imaging plane.

Several approaches have been introduced to reduce the time and thus improve the cost efficiency as well as to allow for easier execution of the examination. Simultaneous multi-slice (SMS) imaging speeds up the imaging by enabling the simultaneous excitation/readout of multiple slices, thus reducing the acquisition time and/or improving slice thickness (SL), with limited detrimental effects on image quality (10). Alternatively, isotropic 3D sequences can be used, in which a volume dataset is acquired in a single acquisition similar to computed tomography imaging, allowing retrospective reconstruction of the four endometrial axes and additional oblique planes. In this context, a recent study revealed excellent intraobserver agreements for both denoised 3D Sampling Perfection with Application-optimized Contrasts using different flip angle Evolutions (SPACE) and conventional 2D T2w sequences for the assessment of deep infiltrating endometriosis, while 3D T2w significantly reduced the scan time (11).

Our hypothesis was that both SMS BLADE and 3D SPACE can be acquired with a decreased scan time and/or higher sr compared with the clinical standard. This study was therefore performed to compare the image quality of “standard” clinical BLADE (stBLADE) with prototypical SMS BLADE with either reduced acquisition time at the same SL or reduced SL for a similar examination time and prototypical isotropic 3D SPACE with inner-volume excitation and iterative denoising (ID) to optimize the imaging protocol for the female pelvis in terms of time efficiency and workflow.

METHODS

Ethics statement

This study was approved by the ethics committee of Northwestern and Central Switzerland (2020-00408). All patients received study-specific information and provided written informed consent.

Patient selection

Female patients who underwent a clinically indicated MRI examination of the pelvis from August 2020 to April 2021 were included in this prospective study. The exclusion criteria were basic MRI contraindications, hysterectomy, lack of informed consent, and incomplete examinations (n = 54).

MRI acquisition

All scans were executed using the same 1.5 T MRI scanner (MAGNETOM Aera; Siemens Healthcare, Erlangen, Germany) equipped with a 66-channel coil setup (2 × 18-channel body coil and 30-channel spine coil). The patients were placed in the MRI scanner head-first in the supine position. Each patient fasted for 4 h before MRI as recommended by the literature and were premedicated with glucagon to decrease bowel motility (12,13).

MRI examination protocols

The MRI protocol was compiled according to our clinical protocol, which was based on European Society of Urogenital Radiology guidelines. The protocol involved non-contrast T1w- and T2w-sequences, including stBLADE, SMS BLADE, and 3D SPACE. Depending on the underlying disease, diffusion-weighted imaging and contrast-enhanced sequences were also obtained after intravenous administration of gadopentetate dimeglumine (Dotarem, 1 mmol/kg, 2 mL/s; Guerbet, Paris, France). Detailed information on the protocol parameters of stBLADE and the prototypical study sequences are shown in Table 1.

BLADE and SMS BLADE

In BLADE sequences, data are acquired in radial blades containing parallel phase-encoding lines. The individual blades are rotated in a circle in k-space.
In addition to the routine sagittal stBLADE sequence (30 slices) with an acquisition time of 2 min 59 s (4-mm SL), an accelerated SMS BLADE prototype was also applied (14). SMS imaging uses multi-band radiofrequency pulses to excite and refocus several slices simultaneously, and a slice-generalized autocalibrating partial parallel acquisition method is used to unfold the simultaneously acquired slices (Fig. 1). The blipped-controlled aliasing in parallel imaging (CAIPI) technique is used to reduce noise amplification (15). SMS BLADE was obtained with the same SL (4 mm; SMS BLADE (tr)) and an examination time of 1 min 20 s (30 slices) as well as with thinner slices and a slightly increased acquisition time (3 mm (40 slices); 3 min 16 s; SMS BLADE (sr)). Both were performed using a parallel imaging factor of 2 and SMS acceleration of 2. SMS can reduce the fluid signal intensity because of increased slice crosstalk, which has a greater effect in tissues with long T1 (16). SMS BLADE protocols thus use a longer echo time to keep the contrast similar to that in stBLADE.

3D T2w SPACE

3D SPACE is a 3D imaging technique with reduced acquisition time, achieved by deploying non-spatially selective radiofrequency pulses and extending the echo-train length (17). The acquisition time can be further reduced by using high parallel imaging factors.

To maintain image quality, an ID algorithm to preserve the signal-to-noise ratio and an inner-volume excitation to overcome aliasing artifacts are combined in a prototypic SPACE sequence (18–20). In the present study, 3D SPACE covered the whole uterus (0.8– × 0.8– × 0.9-mm³ voxel size) to visualize small structures in multiplanar reconstructions. The 3D SPACE flip angle was set to constant, and the echo-train length was reduced to 265 ms using a low turbo factor of 72. This setting produced contrast similar to that of conventional T2w sequences. Phase encoding was set from head to foot and phase oversampling was set to 35% to ensure a clinically acceptable acquisition time and to reduce breathing artifacts. To prevent folding, two saturation bands were placed in front of the activated coil elements that were not covered by the oversampling.

3D SPACE was acquired with an examination time of 5 min 26 s (160 slices) in a sagittal orientation. The short axis of the cervix and the long axis of the corpus uteri were then reconstructed in 1-mm and 3-mm SLs. Fig. 2 shows the additional long and short axes tilted toward the uterine cavity and the cervical canal.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Resolution (mm³)</th>
<th>FOV (mm)</th>
<th>TR (ms)</th>
<th>TE (ms)</th>
<th>Scan time (min:s)</th>
<th>Parallel imaging</th>
<th>SMS* factor</th>
<th>TF*</th>
</tr>
</thead>
<tbody>
<tr>
<td>stBLADE</td>
<td>0.7 × 0.7 × 4.0</td>
<td>210</td>
<td>5730</td>
<td>88</td>
<td>02:59</td>
<td>2</td>
<td>n.a.</td>
<td>21</td>
</tr>
<tr>
<td>SMS BLADE (tr)</td>
<td>0.7 × 0.7 × 4.0</td>
<td>210</td>
<td>4000</td>
<td>119</td>
<td>01:20</td>
<td>2</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>SMS BLADE (sr)</td>
<td>0.7 × 0.7 × 3.0</td>
<td>210</td>
<td>5300</td>
<td>119</td>
<td>03:16</td>
<td>2</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>3D SPACE</td>
<td>0.8 × 0.8 × 0.9</td>
<td>256</td>
<td>1360</td>
<td>154</td>
<td>05:26</td>
<td>2 × 2</td>
<td>n.a.</td>
<td>72</td>
</tr>
</tbody>
</table>

* FOV, Field of View; TR, Repetition time; TE, Echo time; SMS, Simultaneous multi-slice; TF, Turbo factor.

MRI assessment

Subjective image assessments were performed independently by three radiologists with 20, 10, and 6 years’ experience in female pelvic MRI (Readers A, B, and C), respectively.

Subjective image quality criteria and scan preference

The patients were evaluated sequentially as part of the read-out. All evaluated sequences were visible to the readers at the same time and side by side. The sequence names and parameters were not visible to the readers. No randomization was performed.

Subjective overall image impressions of the clinically established stBLADE, SMS BLADE (tr), SMS BLADE (sr), and 3D SPACE with ID were assessed using a 5-point Likert scale (1 = non-diagnostic, 2 = acceptable; 3 = diagnostic; 4 = good, 5 = very good). Image quality was considered acceptable if it was just sufficient for a diagnosis. In contrast to “diagnostic,” however, the assessment of the examination was already limited. In addition, delineation of the anatomy/ organs (sharpness of contours) and motion artifacts were assessed using the same 5-point Likert scale.

After the image quality had been read, Reader A randomly selected one lesion among all patients in whom lesions were visible, and the demarcation (i.e., contrast and lesion borders) was scored independently by all three readers in all sequences.

In 3D SPACE, two retrospectively reconstructed axes (cavum long axis; cervix short axis) with 1 mm and 3 mm SLs each, as well as a comparison of the original SPACE and SPACE after ID, were assessed. The overall image quality of 3D SPACE with and without ID and the quality of the short axis of the cervix uteri and the long axis of the corpus uteri reconstructed from 3D SPACE with ID and 1 and 3 mm SLs were evaluated using the same 5-point Likert scale.

Finally, all three readers independently identified the preferred sequence (stBLADE, SMS BLADE (tr), SMS BLADE (sr), or 3D SPACE). The scan preference was thus purely subjective, based on all the above-described criteria.

Agreement among all three readers regarding all parameters was evaluated using Cohen’s κ statistic.

Statistical analyses

All statistical analyses were performed using the R environment for statistical computing (R version 4.0.3 (2020-10-10)) and
(a) Diagram of prototyping simultaneous multi-slice BLADE sequence. An separate turbo spin echo reference scan is performed at the beginning of the sequence, with the same phase-encoding direction as the first blade. Controlled aliasing in parallel imaging blips are combined with the spoiler gradients in the slice-selection direction (blue gradients). (b) Flow chart of the reconstruction showing an example of slice acceleration factor 2, where two slices located in the peripheral region and central region are excited and acquired simultaneously. Kernel training and slice-generalized autocalibrating partial parallel acquisition reconstruction are performed blade-by-blade. The synthetic reference...
dedicated packages. All analyses were carried out using R markdown in Rstudio (Boston, MA) according to the principles of reproducible research (21–23). The obtained data were visualized by bar charts using the ggplot2 package. Two-sided Wilcoxon’s rank sum tests were used to compare data for the following variables: overall image impression, delineation of anatomy/organ, demarcation of lesions, and motion artifacts. Two-sided exact Poisson tests were used to test for differences in sequence preferences. The significance level was set to alpha = 0.05 for all tests. We adjusted alpha for multiple testing using the Bonferroni correction. The adjusted alpha for overall image impression, anatomy/organ delineation, lesion demarcation, motion artifacts, scan preference, and the overall image impression of the 3D SPACE reconstructions was set to

data matching the in-plane blade rotation is interpolated from acquired reference data. A linear fit is performed to generate kernels that are convolved with collapsed blades to produce uncollapsed blades. The standard BLADE reconstruction is then followed to produce the final images. (Color version of figure is available online.)

Figure 2. Image of a 48-year-old patient with a sonographically unclear lesion of the left adnexa and uterine fibroids. (a) One short and one long axis is usually acquired along both the uterine cavity and the cervical canal. (b) In the present study, the 3D SPACE reconstructions included a short and long axis tilted onto the uterine cavity and the cervical canal with 1-mm and 3-mm slice thicknesses. (Color version of figure is available online.)
alpha = 0.01. The adjusted alpha for the scan preference of the 3D SPACE reconstructions was set to 0.03. Cohen’s $\kappa$ was determined using the R package irr.

RESULTS

Patients

In total, 38 eligible patients with a mean age of 44 ± 15 years were finally included. The reasons for exclusion were hysterec- tomy ($n = 11$), refusal to participate ($n = 25$), claustrophobia ($n = 11$), examination using a scanner without installation of prototypical sequences ($n = 17$), and technical failure ($n = 1$). Details of the selection procedure are shown in Fig. 3.

Overall image impression

There was no significant difference in overall image impression between stBLADE and SMS BLADE (tr) ($p = 0.76$) or SMS BLADE (sr) ($p = 0.15$) and no significant difference between SMS BLADE (tr) and SMS BLADE (sr) ($p = 0.08$). The overall image impression rating of 3D SPACE was significantly lower than that of stBLADE ($p = 0.01$). However, overall image impression was rated at least diagnostic in all cases and sequences (Fig. 4a).

Anatomy/organ delineation

There was no significant difference in anatomy/organ delineation between stBLADE and SMS BLADE (tr) ($p = 0.38$), between stBLADE and SMS BLADE (sr) ($p = 0.47$), between stBLADE and 3D SPACE ($p = 0.07$), or between SMS BLADE (tr) and SMS BLADE (sr) ($p = 0.11$) (Fig. 4b).

Lesion demarcation

Lesions were detected and evaluated in 26 patients (leiomyomas: $n = 13$, deep infiltrating endometriosis: $n = 8$, endometrial carcinoma: $n = 2$, post-Caesarean section niche: $n = 1$, nabothian cyst: $n = 1$, scars after resection of cervical carcinoma: $n = 1$).

There was no significant difference in lesion demarcation between stBLADE and SMS BLADE (tr) ($p = 0.93$), between stBLADE and SMS BLADE (sr) ($p = 0.09$), between stBLADE and 3D SPACE ($p = 0.17$), or between SMS BLADE (tr) and SMS BLADE (sr) ($p = 0.12$) (Fig. 4c).

Motion artifacts

Motion artifact ratings were significantly higher in stBLADE than in SMS BLADE (sr) ($p = 0.01$) and SMS BLADE (tr) ($p < 0.01$) and were lower than those in 3D SPACE ($p < 0.01$) (Fig. 4d).

Scan preference

There was a significant difference between stBLADE and SMS BLADE (sr) ($p < 0.01$), but not between stBLADE and SMS BLADE (tr) ($p = 0.31$) or between stBLADE and 3D SPACE ($p = 0.50$). SMS BLADE (sr) was the most preferred sequence (Fig. 5).
Figure 4. Comparison of (a) overall image impression, (b) anatomy/organ delineation, (c) lesion demarcation, and (d) motion artifacts for standard (st) BLADE and the prototypical simultaneous multi-slice (SMS) BLADE (spatial resolution, sr), BLADE (temporal resolution, tr), and 3D SPACE. (a–c) SMS BLADE (sr) received the highest ratings. (d) Motion artifacts were most pronounced for 3D SPACE, and SMS BLADE delivered the best results.
3D SPACE original versus 3D SPACE with ID

3D SPACE with ID showed a significant improvement in overall image impression compared with the original sequence ($p < 0.01$).

3D SPACE reconstructions

There was no significant difference between 1-mm and 3-mm SLs for the cavum ($p = 0.44$) or the cervix regarding overall image impression ($p = 0.40$) or organ delineation (cavum, $p = 0.51$; cervix, $p = 0.21$).

Figure 5. Sequence preferences of sagittally oriented standard (st) BLADE, simultaneous multi-slice (SMS) BLADE (spatial resolution, sr), SMS BLADE (temporal resolution, tr), and 3D SPACE. (a) SMS BLADE (sr) was the most preferred sequence. (b) SMS BLADE (sr) showed better demarcation of the anterior wall of the uterus and no detectable vascular pedicle was seen (arrows), indicating an ovarian mass rather than a subserosal myoma in a 48-year-old patient (same patient as in Fig. 3). (c) In contrast, the bridging vessel sign in a 40-year-old patient with uterus myomatosus who developed a pedunculated myoma (arrowheads) was best detected by SMS BLADE (sr).
However, there was a significant difference in scan preference between 1-mm and 3-mm SLs for the cavum ($p = 0.02$) and cervix ($p < 0.01$), with a 1-mm SL being preferred significantly more often than a 3-mm SL for both the cavum and cervix (Fig. 6).

**Inter-reader agreement**

The pairwise rater reliability (Cohen’s $\kappa$) for the three raters for each sequence was determined (Table 2). Because most of the ratings were “good” or “very good,” the kappa value reflects the agreement of these two levels among the raters. Overall, the agreement was low, which could be explained by the similarity of these two levels. We then investigated the agreement among the raters when “good” and “very good” levels were merged. However, this led to skewed datasets that tended to have kappa values close to zero. This may not necessarily reflect low rates of overall agreement (24).

**DISCUSSION**

The results of the present study show that both prototype SMS BLADE and prototype 3D SPACE with ID can be acquired with clinically satisfactory image quality. SMS BLADE (sr) was the preferred sequence, providing improved sr. SMS BLADE (tr) was at least equivalent in image quality characteristics with lower acquisition time than stBLADE. The image quality of 3D SPACE with ID was also clinically adequate and allowed retrospective multiplanar reconstructions. ID was proven to be very useful for improving image quality ($p < 0.01$).

The MRI protocol for assessing the uterus is time-consuming and technically demanding. In addition to the expertise of the radiologist, 2D sequences require extensive training of technical staff to select the required orientations (longitudinal axis and short axis of uterine cavum and cervix), and correct identification of the different axes often requires the presence of the radiologist at the MRI scanner.

Figure 6. Sagittal (left) and reformatted (cavum short-axis) (right) images of a 24-year-old female patient with uterus didelphys who was examined for verification of the malformation and with the question of additional renal malformations. It was impossible for the technicians to correctly identify the axes for this norm variant. (a) The axes need to be adjusted depending on the question/pathology (e.g., exclusion of a septum in incomplete malformations or in the vagina). These adjustments can best be made retrospectively by the radiologist using 3D SPACE. (b – d) There were no significant differences in overall image impression or anatomy organ delineation between 1-mm and 3-mm 3D SPACE reconstructions. However, a 1-mm slice thickness was preferred more often than a 3-mm slice thickness, independent of the region.
Figure 6 Continued.
3D sequences are less prone to partial volume effects than is 2D imaging, and they enable retrospective multiplanar reconstructions of a single 3D dataset. Compared with standard T2w sequences, however, older 3D sequences produce heterogeneous results in terms of image quality (25). Some cases without image quality limitations have produced promising results for the female pelvis compared with 2D sequences (26). Relatively poor contrast has also been reported in other pelvic organs, such as the rectum, making organ and lesion boundaries difficult to identify (25). However, the currently available sequences have largely eliminated this limitation.

The combination of SPACE acquisition with CAIPIRINHA acceleration (27,28), reconstructed using a prototype, has largely eliminated this limitation. The opportunity for multiplanar reconstructions, thus eradicating the risk of false slice orientation (11). Moreover, the scanner for planning. It would also eliminate the need for dedicated training of technicians. Further improvements of the sequence could even lead to the replacement of 2D sequences with significant time savings.

SMS accelerated sequences have already been proven useful in other areas of the body (10,30–33); however, the technique has not yet been applied to the female pelvis. In the present study, SMS BLADE (sr) was the preferred sequence and provided better overall image quality, although not statistically significant ($p = 0.15$), with a slightly longer acquisition time (3 min 16 s) than stBLADE (2 min 59 s). SMS BLADE (tr) also showed non-significant advantages over stBLADE in terms of image quality despite a significantly reduced acquisition time (1 min 20 s), and it could be used to reduce the examination time. However, compared with 3D SPACE, SMS BLADE still presents challenges for the radiologist or technician performing the examination.

**TABLE 2. Inter-Reader Agreement of Subjective Image Perception (Cohen’s $k$)**

<table>
<thead>
<tr>
<th></th>
<th>A vs B</th>
<th>A vs C</th>
<th>B vs C</th>
</tr>
</thead>
<tbody>
<tr>
<td>stBLADE</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Overall Image Impression</td>
<td>0.31</td>
<td>0.25</td>
<td>0.34</td>
</tr>
<tr>
<td>Anatomy/organ Delineation</td>
<td>0.17</td>
<td>0.38</td>
<td>0.24</td>
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<tr>
<td>Lesion Demarcation</td>
<td>0.37</td>
<td>0.47</td>
<td>0.58</td>
</tr>
<tr>
<td>Motion Artifact</td>
<td>0.38</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>SMS BLADE (sr)</td>
<td>A vs B</td>
<td>A vs C</td>
<td>B vs C</td>
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<tr>
<td>Overall Image Impression</td>
<td>0.46</td>
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<tr>
<td>Anatomy Organ Delineation</td>
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<td>0.29</td>
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<tr>
<td>Lesion Demarcation</td>
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<td>0.33</td>
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<tr>
<td>Motion Artifact</td>
<td>0.32</td>
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<tr>
<td>SMS BLADE (tr)</td>
<td>A vs B</td>
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<td>B vs C</td>
</tr>
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<td>Overall Image Impression</td>
<td>0.44</td>
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<td>Anatomy Organ Delineation</td>
<td>0.50</td>
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<td>3D SPACE (original)</td>
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<td>B vs C</td>
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<td>Overall Image Impression</td>
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<td>Anatomy Organ Delineation</td>
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<tr>
<td>Motion Artifact</td>
<td>0.49</td>
<td>0.42</td>
<td>0.31</td>
</tr>
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</table>

In the current study, the prototypical isotropic 3D SPACE with inner-volume excitation and ID provided diagnostic image quality in all cases. Unfortunately, however, the image quality was significantly poorer than that of stBLADE despite effective ID, and the motion artifacts were significantly more severe. Nevertheless, good to very good image impression, organ delineation, and lesion demarcation were obtained in most cases. 3D SPACE can thus improve the workflow and reduce the workload of radiologists, who would no longer need to be present at the scanner for planning. It would also eliminate the need for dedicated training of technicians. Further improvements of the sequence could even lead to the replacement of 2D sequences with significant time savings.

**LIMITATIONS**

This study had several important limitations. First, it was a subjective analysis without quantifiable and objective data. Second, this was a single-center study with a small sample size, and generalizable statements were therefore not possible. The relatively small number of participants was partly affected by the need to stop the study at times because of COVID restrictions. Third, SMS BLADE and stBLADE were only conducted in the sagittal orientation; the other planes were not analyzed. Fourth, this was a technical study, and the diagnostic performances of the sequences for assessing different diseases were not compared in a clinical setting. This should be investigated in future studies. Finally, the low inter-rater agreement and the inhomogeneity of the data might limit the generalizability of the results.

**CONCLUSIONS**

In summary, SMS BLADE (sr) improved image quality with higher sr and could simultaneously improve examination efficiency by shortening the acquisition time without compromising image quality (SMS BLADE (tr)). 3D SPACE can be clinically useful by allowing retrospective multiplanar reconstruction. However, despite efficient ID, the image
quality was slightly (but not significantly) inferior to that of stBLADE, notably because of motion artifacts. The results of this study need to be verified in larger populations in a clinical setting.

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**ACKNOWLEDGMENTS**

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**REFERENCES**