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Maintaining Image Quality While Reducing Acoustic Noise and Switched Gradient Field Exposure During Lumbar MRI

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Background: MR-generated acoustic noise can contribute to patient discomfort and potentially be harmful. One way to reduce this noise is by altering the gradient output and/or waveform using software optimization. Such modifications might influence image quality and switched gradient field exposure, and different techniques appear to affect sound pressure levels (SPLs) to various degrees.

Purpose: To evaluate SPLs, image quality, switched gradient field exposure, and participants’ perceived noise levels during two different acoustic noise reduction (ANR) techniques, Quiet Suite (QS) and Whisper Mode (WM), and to compare them with conventional T2-weighted turbo spin echo (T2W TSE) of the lumbar spine.

Design: Prospective.

Subjects: Forty adults referred for lumbar MRI.

Field Strength/Sequence: Conventional T2W TSE, T2W TSE with QS, and T2W TSE with WM were acquired at 1.5 T.

Assessment: Peak SPL (A-weighted decibels, dBA), perceived noise levels (Borg CR10®-scale), signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), three radiologists’ qualitative assessments in image quality on an ordinal scale 1–4, switched gradient field exposure (% general public), and gradient currents were measured. Interobserver reliability was reported as percentage agreement.

Statistical Tests: Repeated measures ANOVA, Friedman’s ANOVA, and Wilcoxon’s Signed-Rank Test for acoustic noise measurements and image quality assessments.

Results: Mean peak SPLs were 89.9 dBA, 74.3 dBA, and 78.8 dBA for conventional, QS, and WM, respectively (P < 0.05). Participants perceived QS as the quietest and conventional as the loudest sequence (P < 0.05). No qualitative differences in image quality were seen (P > 0.05), although QS showed significantly improved SNR and CNR (P < 0.05). Switched gradient field exposure was reduced by 66% and 48% for QS and WM, respectively.

Data Conclusion: Without degrading image quality, both QS and WM are viable ANR techniques in lumbar T2W TSE. QS provided the lowest SPL, the lowest gradient field exposure and was perceived as the most silent among the three sequences.

Level of Evidence: 1

Technical Efficacy Stage: 5

MRI scans cause noises that occur due to current alterations feeding the MR system’s gradient coils.1 The gradients are switched on and off rapidly throughout the entire scan, resulting in forceful vibrations in the coils’ mountings.2 These vibrations form airborne pressure waves, which, in turn, are perceived as acoustic noise.3–5 Unfortunately, the noise is a main contributor to patient discomfort, causes distress and anxiety, and it limits communication between the patient and MR radiographer.6–7 Furthermore, acoustic noise exposure during MRI can cause transient hearing threshold shifts8,9 and might even be harmful if not compensated for.10 Sound pressure levels (SPLs) for day-to-day clinical imaging sequences typically exceed the risk for possible hearing impairment—85 decibels (dB)—and at times reach 110–120 dB.11 Therefore, it is considered necessary that anyone who is in the scanning room during an exam wears hearing protection, such as headphones or disposable earplugs.11,12 However, passive hearing protection does not decrease the sound...
level directly from its source. Thus, every effort to reduce sound propagation from within the MR system should be considered an important part of the proactive work in keeping both patients and the work environment safe.

There have mainly been two approaches to restrict sound propagation within an MR system: modifying the hardware and optimizing the software.1,4,13,14 When remodeling the hardware, the focus has been to minimize the mechanical forces, thus reducing vibrations and sound pressure waves (eg embedding the gradient coils in a vacuum chamber or dampening mechanical components).1,4,14,15 However, this is complex, often costly, and, in some cases, even reduces the gradient efficiency.4,15 To circumvent this, software options that alter the gradient waveform in various ways have been developed. The general principle is to modify the current waveform by smoothing steep current alterations and thus reducing the mechanical output on the coil,14,16 as well as avoiding gradient resonant frequencies.2 One of the simplest ways to achieve this is to restrict the maximum slew rate and gradient amplitude. As a result, gradients lose performance rate and put restrictions on parameters such as echo time (TE) and repetition time (TR). Such adjustments can potentially prolong the scan time or restrict the number of available image slices, and have raised concerns as to whether it affects image quality.3 A more recent commercial development uses a Quiet Suite (QS) algorithm that optimizes gradient trajectories to maintain gradient activity as low as possible and only affects gradients that do not interfere with radio-frequency signal or readout activity. This enables removing unnecessary gradient activity while maintaining the net effect on the magnetization, thus optimizing the gradient waveform regardless of timing constraints.4,13,17

The QS algorithm can be applied to spin echo (SE), turbo spin echo (TSE), diffusion weighted imaging, and gradient echo (GRE) with T1 contrast, or susceptibility weighted imaging. Still, several pulse sequences do not have the option, eg T2*-weighted GRE. However, the vendor’s traditional Whisper Mode (WM) technique, which simply restricts the maximum slew rate, is readily available for most sequences. Conversely, there is limited knowledge in the literature about WM. Therefore, it is of interest to compare both QS and WM with respect to image quality and SPLs.

Altering the gradient waveform not only enables acoustic noise reduction (ANR); it can also decrease the time derivative of the switched magnetic gradient field. Consequently, it reduces the induced current that in clinical imaging easily can reach levels where patients can perceive peripheral nerve stimulation (PNS).18,19 Although not dangerous, PNS may feel uncomfortable and even painful, and minimizing the risk is desirable.12,20 Accordingly, the International Electrotechnical Commission (IEC) standard21 sets requirements to reduce the risk for PNS in patients during MRI procedures.

Several authors have studied gradient waveform optimization for noise reduction and its effect on image quality,4,13,14,22–25 yet, there is limited knowledge about gradient field exposure in this context.18

Previous ANR research has been focused on head MRI.3,13,14,17,24,26–28 However, spinal MRI constitutes some of the most common clinical exams29 and the performance of ANR techniques for imaging of the spine is not well known. Therefore, the purpose of our study was to evaluate SPLs, image quality, switched gradient field exposure, and participants’ perceived noise levels during two different ANR techniques, QS and WM, and to compare them with conventional T2-weighted turbo spin echo (T2W TSE) of the lumbar spine.

Materials and Methods

Our study was approved by the Swedish Ethical Review Authority (DNR 2019-06321), and all participants gave written informed consent to participate. We conducted a single-center study with a within-subjects design.

Study Population

Participants were selected through consecutive sampling of patients clinically referred to the study center for lumbar MRI. Study exclusion criteria were contraindication for MRI (eg non-MR-compatible implants), pregnancy, emergency referrals, and participants with spatial and temporal disorientation or in need of sedatives. After eligible participant selection and prior to their exam, each invited participant was tested with a Diagnostic Audiometer AD229 (Interacoustics A/S, Assens, Denmark) for pure tone air conduction sound hearing sensibility corresponding to American Speech-Language-Hearing Association’s occupational hearing loss monitoring scheme.30 To enable data collection of participants’ noise level ratings, we chose to exclude anyone with a hearing level that exceeded 80 dB in the better ear, i.e. had bilateral profound hearing loss. Hearing level was defined as the better ear hearing threshold in decibels averaged over frequencies 0.5 kHz, 1, 2 kHz, and 4 kHz.31,32

Image Acquisition

Participants were scanned on a 1.5 T MAGNETOM Avanto Fit MR scanner (Siemens Healthcare, Erlangen, Germany). All exams were carried out between March and April 2020. Each participant was scanned feet-first in a supine position using the patient table integrated 32-channel spine coil combined with a 30-channel body matrix coil placed on the abdomen. In order to minimize potential hearing injuries, all participants were required to wear the MR system’s standard headphones inside the scanner.

Sagittal T2W TSE was considered an appropriate sequence for comparison, as it is commonly used for spinal imaging55 and has both QS and WM as available ANR options. Thus, three sagittal T2W TSE sequences were performed during the exam in a randomized order: T2W TSE alone (conventional), T2W TSE with QS, and T2W TSE with WM. The participant was blinded to the specific sequence order. Prior to the T2W TSE sequences, a T2W GRE
we increased the minimum allowed TR to enable the scan to proceed.

In those instances where bore temperature increased or more image slices were
needed to ensure anatomical coverage, the MR system restricted fur-
ther energy deposition (specific absorption rate, SAR). In such cases,
we increased the minimum allowed TR to enable the scan to proceed.

Except for gradient mode and echo spacing (ESP), we attempted
to retain the same image parameters for all three sequences. The
parameters were as follows: field of view (FOV), 350 mm × 350 mm;
acquisition matrix, 336 × 448; slice thickness/slice gap, 3/0.3 mm;
bandwidth, 180 Hz/pixel; TR/TE, 4210/88 msec; echo train length
(ETL), 14; number of signals averaged (NSA), 2; acceleration factor
(generalized autocalibrating partial parallel acquisition, GRAPPA), 2;
acquisition time, 3 minutes 11 seconds. Both conventional TSE and
QS used fast gradient mode. The ESP is typically given the shortest
possible value by default and was automatically increased when the gra-
dient mode was changed from “fast” to “whisper.” To enable further
SPL reduction, we intentionally opted for a 20% increased ESP on the
QS sequence compared to the conventional default setting. Therefore,
ESP was set to 9.9 msec, 11.9 msec, and 10.8 msec for conventional,
QS, and WM, respectively.

All imaging was performed in “normal operating mode” to
ensure the same maximum allowed terms for gradient output. In
instances where bore temperature increased or more image slices were
needed to ensure anatomical coverage, the MR system restricted fur-
ther energy deposition (specific absorption rate, SAR). In such cases,
we increased the minimum allowed TR to enable the scan to proceed.

Acoustic Noise Measurements

Peak SPLs (A-weighted decibels, dBA) were assessed through an
MRI-compatible sound level meter (OptiSLM 100; Optoacoustics
Ltd., Mazor, Israel), using the high level range (65–130 dBA) and
max hold response rate (decay <1 dB/3 minutes), with the micro-
phone (OPTIMIC™ 1155) placed on the right ear of the partici-
ant’s headphones.

Differences in mean SPLs, ΔL, between conventional T2W
TSE (A) and QS or WM T2W TSE (B) were calculated as

\[ \Delta L = A - B. \]

Decibel is a logarithmic scale. Therefore, to linearly compare sound
pressure differences, ΔSP, we also chose to convert dB to Pascal
(Pa), using

\[ \Delta SP = 10^{\Delta L/20}. \]

Immediately after each sequence, participants were asked via the built-
in speaker system to verbally rate how they experienced the noise level
on a Borg CR10 scale—a categorical ratio scale from 0 to 10 appro-
priate for assessment of perceptions and feelings.24 The scale takes into
account the participant’s earlier experiences as an anchor for reference
of the perception, where, in this context, 10 represents the loudest
sound experience they have ever experienced. If they perceived the
sound level to exceed 10, they could use >11 as a new absolute maxi-
mum.34 The scale was shown and explained at the start of the exam
and also visible on the gantry ceiling, so that the participant could
look up and visualize the scale when asked to. Participants were
allowed to use decimals between the outlined values.

Image Quality

For quantitative analysis, signal-to-noise ratio (SNR) and contrast-
to-noise ratio (CNR) were calculated. Using syngo.via version
VB30A (Siemens Healthcare, Erlangen, Germany), five circular
0.20 cm² regions of interest (ROIs) were manually placed on a
selected midplane slice, visualizing the spinal canal, for each patient
at the same position for all three sequences (Fig. 1). If patient move-
ment had occurred between the three sequences, ROI placement
was manually adjusted; ensuring it covered the same anatomical
region in order to enable reproducibility.2,26

Relative SNR and CNR were calculated as

\[
\text{SNRTissue}A = \frac{\text{Signal}_{\text{TissueA}}}{\text{SD}_{\text{Background}}},
\]

\[
\text{CNRTissueA} = \frac{\text{Signal}_{\text{TissueA}} - \text{Signal}_{\text{TissueB}}}{\text{SD}_{\text{Background}}},
\]

where \text{signal} is the mean signal in the ROI of the given tissue (disc, cerebrospinal fluid [CSF], vertebra, or conus medullaris) denoted
\( A \) or \( B \), and SD is the standard deviation of the noise in the image
background air at L3-level (see Fig. 1, ROI no. 5).3,13,25

For qualitative assessment, three radiologists (reader 1, 2, and
3, with 21, 8, and 9 years of clinical MRI experience, respectively)
blindly evaluated the images on separate workstations. To minimize
bias, the three T2W TSE sequences were coded and renamed, and
the image order was randomized for each subject. The radiologists
were asked independently to grade the presence and extent of

FIGURE 1: Region of interests (ROIs) positions. Five ROIs were
selected for signal and noise measurements: (1) conus medullaris
at Th12 to L1-level; (2) L3 vertebral body; (3) cerebrospinal fluid
(CSF) at L3-level; (4) L3–L4 intervertebral disc; (5) image
background at L3-level.
artifacts, the overall image quality, and the ability to depict anatomical structures in the spinal canal, soft tissues, and skeleton from adjacent tissues, on an ordinal scale of 1–4 (Table 1). They also assigned which sequence or sequences provided the best overall image quality.

**Switched Gradient Magnetic Field Exposure**

The switched gradient magnetic field was measured separately during scanning of a phantom, using a Narda ELT B-Field probe (Narda Safety Test Solutions, Pfullingen, Germany) with three orthogonal induction coils combined with a field measuring mode (320 μT, High, 1 Hz). As a proxy of the time derivative of the magnetic field, the 2010 International Commission on Non-Ionizing Radiation Protection’s (ICNIRP) evaluation mode was used (% general public, High, 1 Hz, std). The three T2W TSE sequences were applied on a water phantom, with the probe placed in a fixed position at the bore entrance, corresponding to where the patient’s head is commonly positioned during a lumbar MRI: 587 mm from isocenter in z-position; 40 mm above table height in y-position; and probe edges at 285 mm to the right and 315 mm to the left from the gantry wall in x-position. The current feeding the gradient coils was also measured (PicoScope 5444B, Pico Technology, Cambridgeshire, UK).

**Image assessment | Scoring system**
---|---
1. Image artifacts | 1, unreadable; 2, major artifacts interfering image interpretation; 3, minor artifacts slightly interfering image interpretation; 4, no artifacts interfering image interpretation
2. Overall image quality | 1, poor; 2, moderate; 3, adequate; 4, excellent
3. Ability to depict structures in:
   - (a) spinal canal | 1, inadequate; 2, moderate; 3, good; 4, excellent
   - (b) soft tissues | 1, inadequate; 2, moderate; 3, good; 4, excellent
   - (c) skeleton from adjacent tissues | 1, inadequate; 2, moderate; 3, good; 4, excellent
4. Best overall image quality | Mark which sequence/-s have the best overall quality (multiple choices possible)

**Statistical Analysis**

All data were analyzed using SPSS version 26 (IBM Corp., Armonk, NY). Data for SPLs, SNR and CNR values derived from individual ROIs, and Borg CR10®-scores were analyzed using repeated measures analysis of variance (ANOVA). These data were controlled with Mauchly’s test of sphericity. If the sphericity criterion was not met, a non-parametric Friedman’s ANOVA was used. First, all statistical tests compared the three sequences together. If statistically significant, a post hoc Bonferroni correction for pairwise comparison between any paired combination of the three sequences was interpreted. Qualitative assessments were analyzed with Friedman’s ANOVA; comparing the three T2W TSE sequences’ scores by each radiologist separately. Interobserver agreement for each sequence’s rating score in each assessment category between radiologists was calculated using descriptive agreement percentages. In all tests, a P-value of ≤0.05 was considered as statistically significant. For non-parametric paired comparisons, we used Wilcoxon’s Signed-Rank Test with a Bonferroni-adjusted alpha level of 0.017 (0.05/3).

**Results**

Forty-four patients were asked to participate, of which four declined: three due to disease risk (COVID-19) and one due to claustrophobia. No participants were excluded due to hearing impairment. A total of 40 adults were included in the study (27 female and 13 male, age range: 21–83; mean ± SD: 51.5 ± 18.2 years).

**Sound Pressure Level**

The distribution of A-weighted peak SPLs is presented in Fig. 2. There was a significant difference between the three sequences: conventional, 89.9 ± 1.4 dBA; QS, 74.3 ± 2.4 dBA; WM, 78.8 ± 1.6 dBA, Wilks’ Lambda = 0.021, F (2, 38) = 868.181, P < 0.05. There was a mean difference of 15.6 dBA (P < 0.05) between the conventional and QS sequence. This corresponded to an 84% reduction in sound pressure with QS. Between conventional and WM, there was a mean difference of 11.1 dBA (P < 0.05), corresponding to a 72% reduction in sound pressure with WM. The mean difference between WM and QS was...
4.5 dBA ($P < 0.05$), where QS reduced the sound pressure by 40% compared to WM.

Due to SAR restrictions, the TR was increased for one or several sequences in eight participants. In seven of which, the TR increased between 40 msec and 200 msec; resulting in an additional scan time between 3 seconds and 9 seconds. In the eighth case it was necessary to add six slices (28 total). This resulted in an increased TR between 90 msec and 600 msec, corresponding to 4–42 seconds increased scan time. SPL was tested without these eight cases ($N = 32$). These data did not fulfill the criteria for Mauchly’s test of sphericity ($P < 0.05$). Friedmann’s ANOVA showed statistically significant differences among conventional (89.9 ± 1.4 dBA), QS (73.6 ± 1.1 dBA), and WM (78.8 ± 1.6 dBA), $F(2) = 64$, $P < 0.05$. For pairwise comparisons, significant differences were observed among all three pairs ($P < 0.017$, corrected).

### Perceived Noise Levels

The Borg CR10*-scores for participants’ perceived noise levels of the conventional, QS, and WM sequences were 5.7 ± 0.2, 3.9 ± 0.2, and 4.6 ± 0.2, respectively. The scores differed significantly between the three sequences: Wilks’ Lambda = 0.312, $F(2, 38) = 41.988$, $P < 0.05$. Paired tests demonstrated significant differences in the Borg CR10*-scores between conventional and QS (mean difference: −1.8, $P < 0.05$), between conventional and WM (mean difference: −1.1, $P < 0.05$), and between WM and QS (mean difference: −0.7, $P < 0.05$).

### TABLE 2. Qualitative Image Assessment Scores ($N = 40$)

| Reader | Conventional | QS | WM | $P$-value |
|--------|--------------|----|----|-----------|
| Reader 1 | (1) Artifacts 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (2) Image quality 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (3a) Spinal canal 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (3b) Soft tissues 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (3c) Skeleton 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (4) Best overall ($N$) 40 | 40 | 39 | 0.37 |
| Reader 2 | (1) Artifacts 3.93 ± 0.27 | 3.95 ± 0.22 | 3.95 ± 0.22 | 0.61 |
|         | (2) Image quality 3.90 ± 0.30 | 3.93 ± 0.27 | 3.92 ± 0.27 | 0.61 |
|         | (3a) Spinal canal 3.97 ± 0.16 | 3.97 ± 0.16 | 4.00 ± 0.00 | 0.37 |
|         | (3b) Soft tissues 3.98 ± 0.16 | 3.98 ± 0.16 | 3.98 ± 0.16 | 1 |
|         | (3c) Skeleton 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (4) Best overall ($N$) 38 | 38 | 39 | 0.61 |
| Reader 3 | (1) Artifacts 4.00 ± 0.00 | 4.00 ± 0.00 | 4.00 ± 0.00 | 1 |
|         | (2) Image quality 3.58 ± 0.50 | 3.65 ± 0.48 | 3.62 ± 0.49 | 0.10 |
|         | (3a) Spinal canal 3.47 ± 0.51 | 3.50 ± 0.51 | 3.47 ± 0.51 | 0.72 |
|         | (3b) Soft tissues 3.25 ± 0.44 | 3.33 ± 0.47 | 3.28 ± 0.45 | 0.25 |
|         | (3c) Skeleton 3.50 ± 0.51 | 3.50 ± 0.51 | 3.53 ± 0.51 | 0.61 |
|         | (4) Best overall ($N$) 32 | 35 | 34 | 0.58 |

Questions (1)–(3c) describe the mean values ± SD of qualitative scoring on ordinal scale 1–4. Question (4) describes number of times ($N$) each sequence was rated as best overall image quality (multiple choices possible). QS = Quiet Suite; WM = Whisper Mode.
Image Quality Assessment

Qualitative image scoring by the three radiologists is seen in Table 2. All image assessments were rated either as 3: “adequate/good” or “minor artifacts,” or 4: “excellent” or “no artifacts.” There were no significant differences for any of the assessed image quality categories between conventional, QS nor WM (all $P > 0.05$, see Table 2). An example of image quality, comparing the three sequences in the same patient, is shown in Fig. 3.

Percentage agreement data are shown in Table 3. Ratings of artifacts, image quality, and best overall sequence or sequences had all ≥75% agreement. Assessments of ability to depict structures in the spinal canal, soft tissues, and skeleton agreed between 50% and 68%.

**TABLE 3. Interobserver Percent Agreement**

| Image assessment | Conventional | Quiet Suite | Whisper Mode |
|------------------|--------------|-------------|--------------|
| (1) Artifacts    | 95%          | 97%         | 97%          |
|                  | (37/40; 40/40; 37/40) | (38/40; 40/40; 38/40) | (38/40; 40/40; 38/40) |
| (2) Image quality| 75%          | 75%         | 75%          |
|                  | (37/40; 26/40; 27/40) | (37/40; 26/40; 27/40) | (37/40; 25/40; 28/40) |
| (3a) Spinal canal| 65%          | 67%         | 65%          |
|                  | (39/40; 19/40; 20/40) | (39/40; 20/40; 21/40) | (40/40; 19/40; 19/40) |
| (3b) Soft tissues| 50%          | 55%         | 52%          |
|                  | (39/40; 10/40; 11/40) | (39/40; 13/40; 14/40) | (39/40; 11/40; 12/40) |
| (3c) Skeleton    | 67%          | 67%         | 68%          |
|                  | (40/40; 20/40; 20/40) | (40/40; 20/40; 20/40) | (40/40; 21/40; 21/40) |
| (4) Best overall | 83%          | 90%         | 87%          |
|                  | (38/40; 32/40; 30/40) | (39/40; 35/40; 34/40) | (38/40; 33/40; 33/40) |

Data reported as percent agreement among reader 1 (R1), reader 2 (R2), and reader 3’s (R3) scoring of assessed image quality aspects (total amount of agreements out of maximum $N = 40$ between R1/R2; R1/R3; R2/R3).
The data for quantitative evaluation of SNR and CNR are presented in Table 4. All anatomical regions (conus medullaris, CSF, vertebral body, and intervertebral disc) showed significant differences in SNR and CNR between the three sequences (all $P < 0.05$). With pairwise comparisons, QS and conventional TSE were significantly different in all regions (all $P < 0.05$); where QS consistently showed an increased SNR and CNR compared to the conventional sequence. Although WM had higher mean SNR and CNR values compared to the conventional sequence, the differences were not significant (all $P > 0.05$). When comparing QS with WM, we found that all CNR values between CSF and adjacent tissues were significantly increased with QS ($P < 0.05$) and that SNR values were significantly improved at the level of conus medullaris ($P < 0.05$) and in CSF ($P < 0.05$). In one participant, large hemangiomas in both the L3 and L2 body made it not suitable to measure signal there, so the ROI was placed in the L1 vertebra instead.

### Switched Gradient Magnetic Field Exposure

The measured gradient currents are shown in Fig. 4 for the conventional, WM, and QS sequences. The maximum coil current was decreased using ANR sequences, where QS had the lowest peaks coinciding with its triangular shaped gradient curves. The measured gradient magnetic field and the weighted peak approach (in line with ICNIRP, 2010) are shown in Table 5.

QS and WM reduced the averaged standard switched gradient field exposure by 66% and 48%, respectively, compared to conventional scanning. In addition, peak gradient magnetic field strength was 39% lower using QS and 25% lower using WM compared to conventional scanning.

### Discussion

Compared with the conventional T2W TSE sequence, both software-based ANR options, QS and WM, reduced the peak SPL and the switched gradient field exposure considerably and were perceived as less noisy by the participants without degrading image quality.

When switching gradient mode to WM, it directly limits the gradient slew rate and amplitude, but does not alter the gradient shape. A previous study evaluated WM’s effect on SPLs and showed a maximum reduction in SPL of 7.3 dBA and 4.3 dBA in cranial T1W and T2W TSE, respectively; whereas our study had a mean reduction of 11.2 dBA for T2W TSE. However, that study used longer TRs with WM compared to corresponding conventional sequences, which showed a trend in increasing the SPL. Furthermore, FOV, slice thickness, TE, ESP, and ETL all affect SPL. A comparison between lumbar and cranial image sequences will inherently have variations in these scan parameters, and could be explanations for the differences in SPL outcome. WM showed a significant mean sound pressure decrease between the conventional and ANR sequences.
reduction in our study, and thus seems to have merit for ANR purposes. Still, as WM does not alter the shape of the gradient waveform, it leaves room for possible inter-pulse improvement to further decrease vibrational forces of the gradient coils.\textsuperscript{16,23,27} QS does modify the gradient forms within each pulse, and was shown to further reduce the acoustic noise in our study. However, the degree of sound reduction with QS varies somewhat in the literature. For instance, when applying the QS algorithm on a fluid attenuated inversion recovery (FLAIR) TSE sequence, a mean sound pressure reduction of 19.7\% was shown.\textsuperscript{13} In another study evaluating QS, Heismann et al\textsuperscript{4} reduced the sound pressure by 52\% and 74\% on cranial T2W TSE and T1W three-dimensional GRE, respectively. It should be noted, though, that manual optimization adjustments are further needed for greater SPL reductions. By extending ESP in combination with increased readout bandwidth, Heismann et al\textsuperscript{4} achieved a total of 81\% sound pressure reduction in their T2W TSE sequence. Similarly, in a 7 T study,\textsuperscript{28} the SPL in a FLAIR TSE sequence

| TABLE 5. Measured Gradient Magnetic Field and Weighted Peak Approach |
|---------------------|---------------------|---------------------|
|                     | Conventional | Quiet Suite | Whisper Mode |
| % General public    | 2000–2500     | 750–780     | 1100–1250    |
| Magnetic field (mT) |             |             |             |
| rms                 | 0.7          | 0.5         | 0.6          |
| peak                | 2.8          | 1.7         | 2.1          |

% of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2010) reference value for general public (min–max); rms = root mean square.
was reduced by 80% using QS and a manually increased ESP and bandwidth. These findings are very similar to our outcome of 84% sound pressure reduction. In our study, we deliberately increased the ESP by 2 msec on the QS sequence in order to provide more time for gradient ramping and thus decrease the slew rate further. The use of parallel imaging is another suggested optimization method for SPL reduction.22 This enables shorter ETLs in order to net longer ESP while maintaining the same acquisition time, although resulting in decreased SNR. In our sequence protocols, we already used GRAPPA with an acceleration factor, R, of 2 and, therefore, chose not to modify ETL/ESP/R any further.

Our observed differences in dBA agreed well with our participants’ subjective assessment of noise levels. Accordingly, QS was perceived as the quietest image sequence, with a mean Borg CR10-score describing it as slightly loader than “moderate.” WM was labeled closer to “strong” or “loud,” whereas the conventional sequence was rated as somewhere between “strong” and “very strong.” Similar subjective ratings have been shown in other studies, where ANR-imaging is perceived as quieter and more comfortable than conventional scanning.22,25,27,36

ANR may be particularly valuable for certain patient groups. For example, among children, claustrophobic and non-cooperative patients, but also among patients with tinnitus, hyperacusis, or other sensitive hearing, loud noise can trigger fear and discomfort.27,36,37 For children between 3 and 36 months of age where sedatives are needed to facilitate brain MRI, ANR sequences had higher success rates, fewer cases of complimentary sedation doses, and less motion artifacts when compared to the conventional sequence.36 Our results also support the use of software-based ANR imaging to promote patient-centered care.

Using software-based ANR does come with some drawbacks. Due to SAR regulations, the maximum number of allowed slices for a given TR was decreased in our study for both QS and WM compared to the conventional sequence using fast gradient mode. If time optimization is of utmost importance, using fast gradient mode with no ANR software will enable a slightly shorter TR for a given amount of slices, thus shortening the scan time. If the potential loss in T2 contrast (given the shortened TR) is not an issue, the conventional sequence in our study could, in such instance, have had a 23 seconds shorter scan time. From an acoustic noise perspective, reducing TR for a given amount of slices might on its own increase SPLs—although prolonging the ESP has a much bigger impact overall, regardless of slices per TR ratio.25 Still, in the four cases in our study where more slices were needed and where minimum TR increased due to SAR limitations (effectively increasing the relationship of number of slices times ETL/TR from 0.073 msec to 0.076 msec), the peak SPL with QS reached above 80 dBA. A wide range in SPL was also seen in the study by Fuelkell et al.13 The reason for that variance was unclear, although they speculated that patient factors could have importance, but they excluded patient size as an explanatory variable. However, this variance does limit QS’s noise reduction predictability. Given a more heterogeneous population, it is likely that more slices or increased TR is warranted, and that would result in an average SPL reduction not as large as that given in our study.

Furthermore, restricting gradient efficiency or changing sequence parameters has historically raised concerns about potentially degrading the image quality.3,39 Clinical ANR evaluations have shown that image quality is affected for better or worse depending on sequence and software type. For example, Holdsworth et al37 showed less well-defined vessel anatomy using silent arterial spin labeled angiographic imaging than with a conventional time-of-flight technique. In abdominal imaging, T1W GRE with QS degraded the ability to identify anatomic structures27 and silent T2W periodically rotated overlapping parallel lines with enhanced reconstruction added more streaking artifacts than its non-silent version.26 Other studies have reported a minor decrease in SNR and/or CNR using ANR software than its conventional equivalents, although not affecting the diagnostic value in qualitative assessments by radiologists.4,28,36 Alternatively, Ohlmann-Knafo et al24 reported superior image quality using ANR T1W and T2W sequences; however, protocol parameters differed somewhat between the conventional and ANR versions, which could possibly have influenced the results.

In our study, although qualitatively assessed image quality did not differ, QS increased SNR and CNR compared to conventional and WM scanning. We chose the American College of Radiology single image method to calculate SNR values, as it has been used in previous studies.4,13,25,28 However, with our sequence parameters, this method is uncertain as it assumes that the noise has a Rician distribution. Such distribution is not necessarily the case since we used parallel imaging.40 Therefore, our SNR and CNR calculations might be misrepresentative. On the other hand, as we combined an acceleration factor of 2 with an NSA of 2, we effectively get a noise amplification-relationship of 1. No other image parameters that affect the geometry factor differed. A Rician noise probability distribution will be most asymmetric if the signal amplitude is small compared to the noise amplitude, which was not the case in our study. We therefore assumed there would be a similar noise distribution among the three compared sequences. Our results corroborate those from Fuelkell et al,13 who also reported increased SNR in brain tissue when using QS, stating algorithmic programming as a possible explanation. Still, TSE is not the most gradient demanding sequence and, therefore, possibly allows for gradient manipulation to some extent without affecting image quality.

We have also shown that using ANR sequences can reduce the magnetic flux density and its derivatives, which can be useful both as a measure to reduce the risk of PNS
but also potentially to reduce the risk of interference with medical implants.\textsuperscript{12} The measured % of ICNIRP values are weighted to the reference levels for the general public and are not comparable with the IEC safety standard of patients.\textsuperscript{21} Nonetheless, it brings insight to how much the switched gradient field can be reduced using ANR sequences. However, as these are theoretical assumptions, a prospective evaluation of PNS prevalence using conventional and ANR imaging would be of interest. From an occupational perspective, WM has also been shown to decrease the occupational gradient field exposure by a factor 1.5.\textsuperscript{18}

**Limitations**

We did not measure mean SPL over time; instead, we chose peak SPL as output. The same method was used by Fuelkell et al.\textsuperscript{15} arguing that peak noises are potentially more harmful with regard to noise-induced temporary or permanent hearing loss, and, therefore, more appropriate to measure. This will, however, make it difficult to compare our results with other similar studies using time-averaged SPL.

Another limitation is that we have not adjusted for chance input when comparing reader assessments. The lack of variance in assessment scores made interobserver reliability testing with Cohen’s kappa or Krippendorff’s alpha not feasible. Consequently, we chose to report agreement percentages instead. For full disclosure, we have revealed mean scores of the assessments and \(P\)-values of related statistical tests.

Furthermore, standardized ratings for image quality assessment of lumbar MRI are not available; so we developed our own categories after consulting a radiologist and testing the categories in a pilot study. Thus, specific discrimination of certain image criteria could be missed by being generalized into one of the categories. It might also be a cause for the lack of variance among the radiologists’ image assessments. Perhaps, with more alternatives or broader scales, larger differences could have appeared. Also, we did not calculate power prior to data sampling, but decided to include 40 participants based on comparison of studies with similar designs.\textsuperscript{5,13,24}

Another limitation is that QS and WM are only applicable on a Siemens MR system. Even between two different Siemens systems or within different field strengths, eg 1.5 T and 3 T, it is possible that other results would occur. However, gradient waveform smoothing, prolonging the ESP and/or restricting the gradient amplitude and slew rate, regardless of the MR system, will affect both acoustic noise\textsuperscript{4,16} and magnetic flux density.\textsuperscript{18}

Finally, all audiograms took place in an office that was not fully sound-proof adjacent to the MR control room. For optimal screening, an experienced audiologist with professional audiogram instruments and settings would have been preferred. However, as each participant was their own control, where any potential hearing impairment was the same irrespective of sequence for that participant, we do not believe this would affect the trends in Borg CR10\textsuperscript{®}-scores differently.

**Conclusion**

Using a 1.5 T Siemens MR system, QS is a promising tool for acoustic noise and switched gradient field reduction in lumbar imaging with T2W TSE without degrading image quality. In sequences where QS is not applicable, WM is a viable alternative. Additionally, both QS and WM were perceived as quieter than conventional T2W TSE, and, thus, might be useful techniques in providing both patients and staff a safer and more comfortable MR environment.

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