Making MRI Scanning Quieter: Optimized TSE Sequences with Parallel Imaging

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Introduction

Turbo Spin-Echo sequences at 1.5T can generate noise at over 100dB$_A$ inside the bore [1–3]. This noise is equivalent to standing 5 meters away from a jackhammer [3], and would be even louder on higher field systems. Despite the use of ear-protective equipment, reducing the Sound Pressure Level (SPL) generated by these standard clinical sequences could noticeably improve patient comfort [4]. MRI pulse sequences mostly generate acoustic noise because of rapidly varying gradient waveforms: The resulting Lorentz forces applied on the gradient coils make the entire scanner structure vibrate [5]. To circumvent this issue, several hardware solutions have been proposed. For example, the whole gradient coil can be enclosed in a vacuum chamber [6–8], or gradient field rotation can be performed mechanically [9]. While these solutions achieve significant noise reduction for all types of sequences, they can noticeably increase manufacturing cost, and can even decrease gradient efficiency. Mechanical and acoustic balanced designs of gradient coil systems including windings performing active acoustic control have also been considered and investigated [10, 11].

Modifying and/or optimizing pulse sequences can also reduce acoustic noise effectively. One such solution is to time the ramping up and ramping down of the gradient waveforms so that the induced scanner vibrations cancel each other out [12]. Another approach is to use lower gradient amplitude and slew rates of the gradient waveforms [13]. By low-pass filtering the gradient, vibration frequencies for which the acoustic response of the gradient coil is high can be avoided.

Elaborate redesigns of gradient waveforms coupled with parallel imaging have demonstrated further reduction

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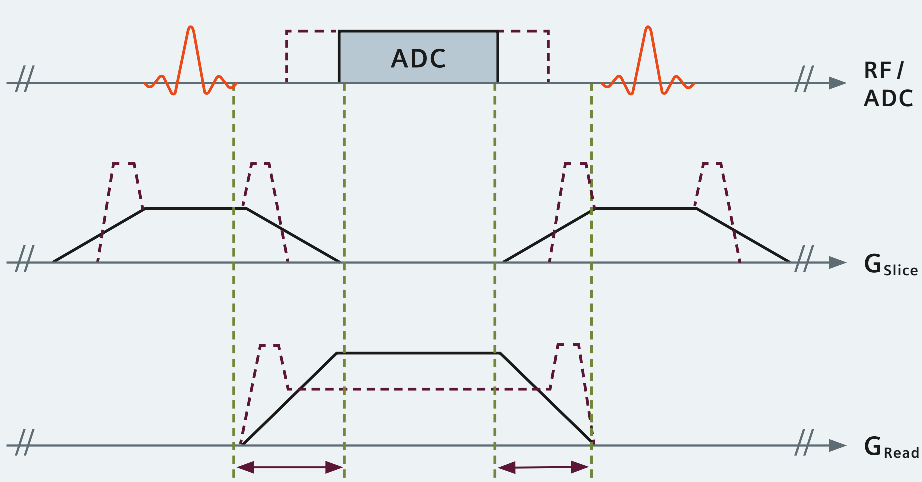
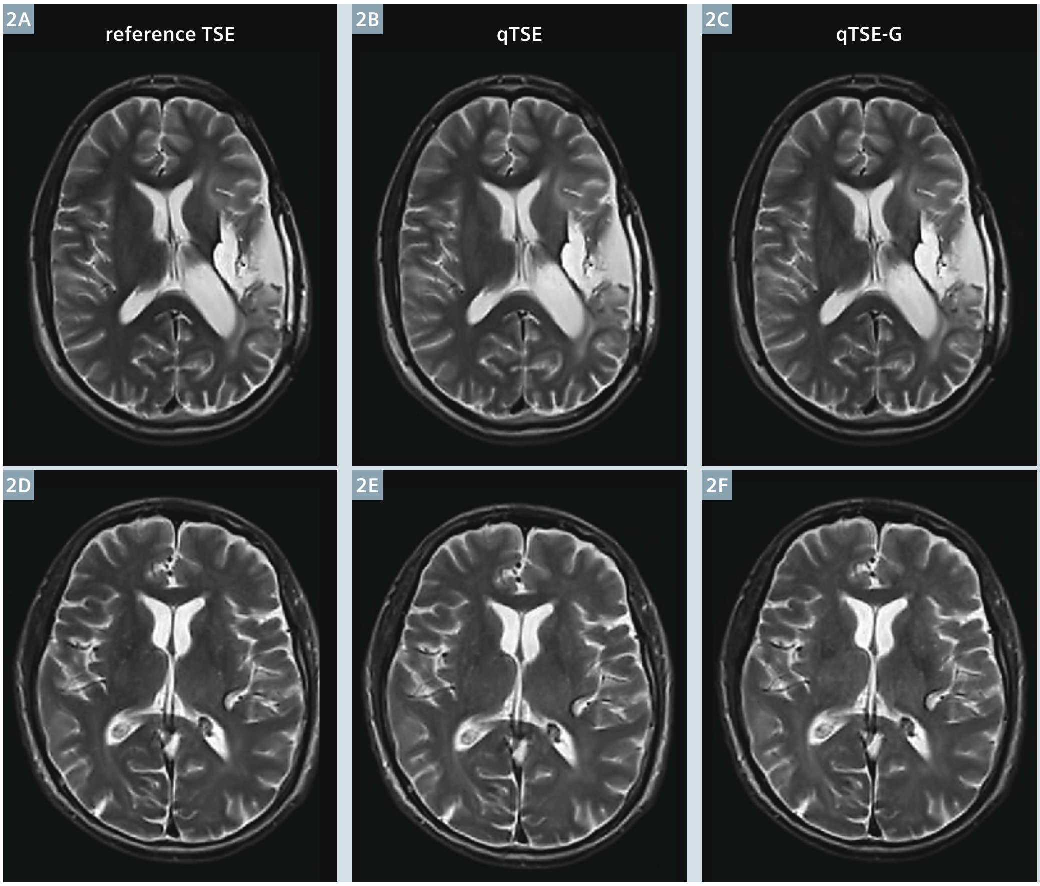


1 Comparison of conventional sequence (dashed lines) with quiet sequence (solid lines). The reduction of ADC represents a BW increase.



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Representative slices from 2 patients acquired with the reference TSE sequence (left column), the qTSE sequence (center column) and the qTSE-G sequence (right column).

of acoustic noise in Echo Planar Imaging (EPI) [14, 15]. The reduction was achieved by counterbalancing lengthened gradient waveforms with increased acquisition speed, thereby reducing acoustic noise without increasing acquisition time while maintaining inter-echo spacing, only at cost of signal-to-noise ratio (SNR). By extending such principles to other generally-used standard clinical MR sequences, this article demonstrates that with minor SNR reductions (≤ 10%), effective reduction in acoustic noise can be further achieved without noticeable degrade of diagnostic information or imaging time, as well as without sacrificing gradient efficiency.

Two types of modifications in a T2-weighted Turbo Spin-Echo (TSE) sequence were investigated for acoustic noise reduction: First by solely modifying the gradient waveforms and second by additionally using GRAPPA at a reduction factor of two (R=2)*. Comparative SPL measurements at the bore were performed between standard TSE, quiet TSE (qTSE)* and quiet TSE with GRAPPA (qTSE-G)*. A statistical analysis of comparative scores from a reader's study was conducted.

Methods

The gradient waveforms of the TSE sequence were optimized with an automatic gradient optimization algorithm that extends any slope duration to its maximum and reduces the number of slopes to their minimum. For instance, with minor changes in protocols, spoiling and crusher gradient lobes are replaced by long rising or descending slopes, while maintaining the crusher moment unchanged. To keep the same total acquisition time, the reduction of the gradient slew rate is constrained by the fixed inter-echo spacing. The decreased slew rate of readout gradient will slightly reduce readout sampling time (Fig. 1). In consequence, the readout bandwidth (BW) increases slightly, with a tradeoff between reduction of SPL and SNR loss.

* WIP, the product is currently under development and is not for sale in the US and other countries. Its future availability cannot be ensured.

In addition, parallel acquisition could be further employed to reduce the echo-train length, i.e. number of echoes per train, by a factor of R. Keeping the acquisition time constant, the inter-echo spacing can be extended by R, allowing further stretching of the gradient moments. This effectively represents a benefit of parallel imaging acceleration in acoustic noise reduction rather than imaging time reduction.

The acquisition protocols changes are as follows: The readout BW was increased by about 10%, from 107 Hz/pixel in the standard protocol to 125 Hz/pixel. The effective TR/TE were increased from 5000/93 ms to 5180/85 ms, which resulted in only a 3 second increase in acquisition time, from 1:37 min to 1:40 min. The qTSE-G parameters were identical to the qTSE protocol, but with use of GRAPPA with R=2. For both qTSE and qTSE-G protocols, and the gradient slopes were maximally stretched as illustrated in figure 1.

Table 1: Comparison of dB_A values

Sequence type	Standard TSE	qTSE	qTSE-G	Background
LAEQ (30 sec average)	92.5	81.3	72.7	53.0
Max Peak	102.8	95.8	92.0	77.7

Comparison of dB_A values for standard TSE, qTSE, qTSE-G sequences, and measured background noise. Measurements were performed inside the bore at patient head position using a 2238 Mediator sound level meter (Brueel & Kjaer GmbH, Bremen, Germany).

Table 2: Ratings by readers

Sequence type	All techniques compared to themselves	qTSE : TSE	qTSE-G : TSE
Reader #1	0.35 ± 0.40 (0.06, 0.64) p = 0.02	-0.20 ± 0.26 (-0.38, -0.02) p = 0.04	0.20 ± 0.59 (-0.22, 0.62) p = 0.31
Reader #2	-0.03 ± 0.11 (-0.11, 0.04) p = 0.34	1.30 ± 1.96 (-0.10, 2.70) p = 0.07	3.95 ± 0.86 (3.33, 4.57) p < 0.0001
Reader #3	0 ± 0 –	0.73 ± 1.59 (-0.41, 1.86) p = 0.18	3.08 ± 1.25 (2.18, 3.97) p < 0.0001
Average	0.11 ± 0.14 (0.01, 0.21) p = 0.04	0.61 ± 1.17 (-0.23, 1.45) p = 0.13	2.41 ± 0.80 (1.83, 2.98) p < 0.0001

Mean and standard deviation, 95% confidence interval, and p-value of the scores given by each radiologist to the different types of image volume pairs after self-bias correction. Positive score show preference of the right volume over the left volume, on a -10 to +10 scale.

In-vivo studies were performed on a 3T MAGNETOM Verio MRI scanner (Siemens Healthcare, Erlangen, Germany) with a 12-channel head coil with patients admitted for head examination. Informed consent was obtained from the volunteer before the start of the study in accordance with IRB protocol. A total of 10 different patient scannings were performed, each comparing standard TSE images with qTSE and qTSE-G images. The image resolution (192 × 256 matrix), number of slices (26), slice thickness (5 mm) and slice orientation were kept identical throughout the 3 different acquisitions.

To measure acoustic noise level LAEQ (Equivalent Continuous Sound Level in A-weighting) with 30 seconds average and peak values, a professional device, 2238 Mediator sound level meter (Brueel & Kjaer GmbH, Bremen, Germany), was used, which was placed inside the bore at patient head position. The background noise is mainly generated by the cold-head pump and the ventilation among other sources.

To evaluate the image quality, a total of 7 image-volume-pairs were assembled from each of the 10 patient datasets. The first 2 pairs compared qTSE with TSE volumes, alternatively with qTSE on the left and TSE on the right. Similarly, another 2 pairs compared qTSE-G with TSE volumes in both left-right orders randomly. Finally, 3 pairs were assembled with the same volume on the left and right, which consist of TSE vs. TSE, qTSE vs. TSE, and qTSE-G vs. qTSE-G volumes, respectively.

All 70 volume pairs were presented in the same random order to 3 trained radiologists blinded to the acquisition technique, who were asked the following question: "On a scale from -10 to +10, how much better is the image quality of the volume on the right compared to the volume on the left, with a positive score indicating superiority of the right volume, and 0 representing no difference in quality between left and right?". The graphical user interface used for the reading allowed user-navigation through the paired-volume slices, and simultaneous image windowing of the 2 displayed images.

To avoid possible left-right bias, the average of the qTSE vs. TSE score and the TSE vs. qTSE score multiplied by -1 was then calculated for each reader's reading on each patient. The average of the corrected scores across readers was then computed for each patient. Corrected scores were calculated in the same way for the qTSE-G vs. TSE comparison. One-sample t-tests were used to test whether the mean average reader scores differed from zero, and 95% confidence intervals (CI) for the mean scores were also calculated. One-sample t-tests and CI were also carried out using each reader's scores

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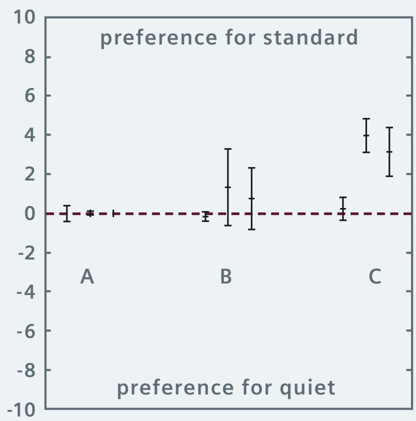

A. self image comparison (all methods)
(p < 0.05)

B. qTSE vs. standard TSE
Non significant difference for all 3 readers
(p = 0.20, p = 0.06, p = 0.18)

C. qTSE+GRAPPA vs. standard TSE
(p < 0.0001)

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(A) 95% confidence intervals for averages scores by readers for volumes compared to themselves; (B) qTSE vs. standard TSE; and (C) qTSE-G vs. standard TSE. Positive scores show preference for standard TSE in the last two cases.

separately. A reader's average rating of these three self-comparisons using images from each patient were averaged, and then the three reader averages were averaged for each patient. A t-test was used to test whether the average of the reader ratings across patients differed from zero. One-sample t-tests and CI were also carried out for each reader separately.

Results

The respective average and peak SPL in [dB_A] measurements for standard TSE, qTSE and qTSE-G protocols are listed in table 1. The achieved reduction of average SPL for qTSE and qTSE-G were 10 dB_A and near 20 dB_A (30 seconds average), respectively.

Discussion

Optimizing the gradient waveforms alone with a 10% increase in bandwidth achieves an 11 dB_A SPL reduction (Table 1), with little cost to image quality (Fig. 3). These results are in accordance with [16] though here the measurements were made directly at the bore. This cost might be more noticeable with lower SNR systems, however in this configuration, no statistically significant difference in image quality was observed (Table 2), making gradient redesign a viable solution to make TSE sequences quieter.

With additional use of Parallel Imaging, the modified quiet TSE sequence allows on average a 20 dB_A reduction in SPL (Table 1). The modified sequence had an effect on in image quality (Fig. 3): The average preference score across readers for standard TSE images over qTSE-G images was +2.41 (p<0.0001, Table 2), and the 95% confidence interval places its true value between +1.8 and +3. However it should be noted that this change in image quality is to be expected as Parallel Imaging was used. In compensation, the reduction of acoustic noise was highly effective: the SPL at the bore of the standard TSE sequence was 39.5 dB_A higher than the background noise, compared to 19.7 dB_A for the modified sequence.

Conclusion

In comparison with standard MR sequences, gradient wave modifications in TSE sequence coupled with Parallel Imaging can achieve over a factor 10 of acoustic noise reduction, yielding an improved patient comfort with nearly identical diagnostic information and imaging time. Without any hardware modifications or upgrade, both proposals described in this article, qTSE and qTSE-G, can be easily implemented on a conventional MRI system for routine clinical applications. In addition, scanning on a high field system with multiple channel coils, such as the 32-channel head coil, provides more flexibility to make MRI scanning quieter.

* Work in progress: The product is still under development and not commercially available yet. Its future availability cannot be ensured.

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