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FULL PAPER

Comparison of image quality characteristics on Silent MR versus conventional MR imaging of brain lesions at 3 Tesla

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Objective: To compare signal- and contrast-to-noise-ratio (SNR, CNR), conspicuity values and subjective image quality characteristics of Silent MRI and conventional MRI in brain disorders at 3T.

Methods: 26 patients were prospectively examined with a 3T MRI. Silent Scan was added to standardized MR protocol. Silenz T_1 weighted (T1w) and Silent T_2 weighted (T2w) sequences were compared to standard T1w and T2w. Analysis was performed quantitatively (SNR, CNR, conspicuity values) and by visual assessment on a 4-point scale with regard to lesion visibility, lesion delineation, grey-white differentiation and diagnostic usefulness. Data were analyzed using Wilcoxon signed-rank and Sign test. $p \leq 0.05$ was considered significant.

Results: Silenz T1w vs T1w provided decreased SNR, but increased CNR (SNR_{parenchyma}, SNR_{lesion}: $p = 0.000$,

CNR_{lesion}: $p = 0.003$). Silent T2w vs T2w showed better SNR and CNR values (SNR_{parenchyma}: $p = 0.014$; SNR_{lesion}, $p = 0.005$; CNR_{lesion}, $p = 0.005$). Conspicuity values were not significantly different on Silenz T1w vs T1w and Silent T2w vs T2w. The visual assessment revealed Silenz T1w to be significantly superior to T1w in terms of grey-white differentiation ($p = 0.000$), lesion visibility ($p = 0.003$) and overall diagnostic usefulness ($p = 0.001$). In terms of Silent T2w vs T2w, there was a significant difference in grey-white differentiation in favour of Silent T2w ($p = 0.016$).

Conclusion: Silent Scan is suitable for 3T with image quality characteristics comparable to conventional MRI.

Advances in knowledge: Silent Scan has a diagnostic value comparable to conventional MRI, with the advantage of a quiet MR exam improving patient MR experience.

INTRODUCTION

It is a fact that high-field MRI, like 3.0 T, provides a better signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) than lower field strengths.¹ An increase in signal intensity and image contrast at higher field strengths leads to an improvement of image quality. At best, it facilitates the depiction of small anatomical structures and pathologies and improves radiologic diagnostics.^{2–5}

Moreover, adapted fast sequence protocols at high-field MRI provide shorter scan times for patients and optimize patient throughput during clinical routine.^{6,7}

But, to date, one drawback remains at all MR field strengths: the acoustic noise generated by the MR system during MRI scan. Acoustic noise levels even increase in higher field systems and with the application of fast-pulsed sequences.^{8,9}

Not only that, MR acoustic noise hampers verbal communication and disturbs healthcare personnel and patients. It can

also intensify patient anxiety, inner unrest and body movement causing image motion artefacts or aborted MR scans.^{10,11}

On the basis of the above, much research has been performed to diminish MR acoustic noise.

Mainly, passive methods for noise reduction such as vacuum-enclosed gradients—the main source of auditory noise—in addition to insulators were implemented.^{12–14} Other studies evaluated the so-called active noise control. By the superposition of a sound (antinoise) that is exactly the inverse of the original sound (antiphase acoustic waves), the original noise can be cancelled.^{15–18} However, most approaches were complex, required a considerable redesign of the MR system structures or caused other limitations.

An alternative solution to reduce the acoustic noise level is to optimize imaging parameters and to run MR sequences with reduced gradient parameters.^{19–21} This approach includes the area of newly available Silent Scan technology.²¹ In contrast to

conventional MR, the gradients of Silent Scan are used continuously and are changed in only very small gradient steps. As a consequence, the MR acoustic noise is decreased near ambient level and the MR examination is more comfortable. Especially, patients who are sensitive to acoustic noise can benefit from MR noise reduction.

But, research on this new method is still in its early stages and needs to be extended to implement Silent Scan confidently and safely in a routine clinical setting.

The rationale for the present prospective study was to examine the utility of new Silent Scan technology in clinical practice. Silent Scan is compared with conventional noisy MR sequences at 3.0 T in order to investigate whether Silent Scan imaging is similar to or different from standard imaging. For this purpose, we determined the image quality characteristics of both MR techniques based on SNR, CNR and conspicuity values as well as on qualitative analysis of MRI of vascular and neoplastic brain disorders.

METHODS AND MATERIALS

26 consecutive patients with neurological disease (13 females and 13 males; median age $\pm$ standard deviation: 65.2 $\pm$ 14.76 years) underwent brain MRI between September 2014 and January 2015 on a 3.0-T wide bore system (Discovery™ MR 750w; General Electric Healthcare, Milwaukee, WI). Reasons for MRI referral of patients were different, *e.g.* known or suspected brain metastases or primary brain tumour, suspicion of cerebral ischaemia, strong headache *etc.* Local ethics committee approved the study and all patients gave their written informed consent before the MR examination.

MRI protocol

Standard protocol comprised the following sequences: coronal T_2 weighted (T_2 w) fluid-attenuated inversion recovery (FLAIR), axial diffusion-weighted imaging with $b = 0$ and 1000, apparent diffusion coefficient, axial T_2 w* gradient echo (GRE), axial T_1 weighted (T_1 w) FLAIR echo time (TE), axial T_2 w Propeller TE and three-dimensional (3D) time-of-flight MR angiography. In 15 patients, 3D fast spoiled gradient-echo post-contrast images

were acquired as well. In addition, two sequences from the Silent Scan software product were acquired: sagittal “Silenz T_1 w” sequence—a 3D volume technique—and axial “Silent T_2 w” Propeller. Silenz T_1 w is acquired in sagittal orientation first and needs to be reconstructed offline in different planes.

Non-contrast sagittal Silenz T_1 w data were originally acquired at 1-mm slice thickness, reconstructed at 5-mm thickness in axial orientation and compared with axial T_1 w FLAIR in 5 mm ($n = 6$ patients). Post-contrast sagittal Silenz T_1 w was acquired at 1 mm, reconstructed in axial orientation at 1 mm and compared with post-contrast axial 3D fast spoiled gradient echo in 1 mm ($n = 15$). Non-contrast axial Silent T_2 w Propeller was acquired in 5 mm and compared with axial T_2 w Propeller in 5 mm ($n = 25$). The sequence parameters are given in Table 1.

MRI evaluation

A total of 26 patients with brain lesions were examined. Number of patients varied depending on the chosen image assessment criterion: the calculation of SNR of brain lesion was performed in $n = 24$ of 26 patients because 2 patients revealed no brain lesions but were included in the calculation of SNR or CNR of normal brain parenchyma. In one patient, conventional T_2 w imaging revealed too many motion artefacts and comparison with Silent T_2 imaging was not possible.

For a reliable measurement in each patient, the most homogeneous, largest tissue lesion in an artefact-free localization was chosen (hypointense (T_1 w), hyperintense (T_2 w), contrast-enhancing lesion in case of post-contrast images). In the sum, 24 representative brain lesions were analyzed.

Objective image quality assessment

Freehand region of interest (ROI) measurements were performed on the GE Advantage Workstation 4.6/Volume Share 5. ROI was drawn as large as possible in the representative vascular or neoplastic lesion without extending over its edges to avoid measurement errors (S_{lesion}). Next, ROI of identical size and at the same level of the lesion was placed in the white matter of the

Table 1. Compared MR sequences out of the MR scan protocol of the brain at 3.0 T

MR sequence parameters	T_1 w FLAIR	3D FSPGR post-contrast	Silenz T_1 w non-contrast ^a / post-contrast	T_2 w Propeller	Silent T_2 w Propeller
TR (ms)	2939	7	989	6709	7490
TE (ms)	28	2.5	0	105	113
FOV (cm)	22	22	22	22	24
Slice thickness/ gap (mm)	5/0.5	1/0.5	1/0.5	5/0.5	5/0.5
TI (ms)	860	—	450	—	—
Matrix (pixels)	448 $\times$ 224	288 $\times$ 288	384 $\times$ 384	480 $\times$ 480	320 $\times$ 320
NEX	2	1	1.3	1.2	1.5
Scan time (min, s)	1.20	3.12	4.07	1.38	2.02

3D, three-dimensional; FLAIR, fluid-attenuated inversion recovery; FOV, field of view; FSPGR, fast spoiled gradient echo; NEX, number of excitations; T_1 w, T_1 weighted; T_2 w, T_2 weighted; TE, echo time; TI, inversion time; TR, repetition time.

^aSilenz T_1 w non-contrast in 1 mm was reconstructed to 5 mm in axial orientation to compare it with standard T_1 w FLAIR.

Figure 1. Brain MRI of a 64-year-old female patient with brain metastases (arrow) of breast cancer: subjective image analysis was performed on standard T1w (a) and corresponding Silenz T1w (b) imaging. Lesion visibility, grey-white differentiation and overall diagnostic usefulness were judged to be superior on Silenz T1w.

contralateral hemisphere in order to obtain enough area for equal ROI measurement ($S_{\text{parenchyma}}$). Then, ROI measurement of background noise (S_{noise}) was performed by drawing the ROI in the surrounding airspace outside the cranium avoiding ghosting, aliasing and eye movement artefact regions.

Mean values of S_{lesion} and $S_{\text{parenchyma}}$ were divided by background noise values in order to obtain $\text{SNR}_{\text{lesion}}$ ($S_{\text{lesion}}/S_{\text{noise}}$) and $\text{SNR}_{\text{parenchyma}}$ ($S_{\text{parenchyma}}/S_{\text{noise}}$). In addition, the CNR of the lesion was defined as the difference in signal intensity between the brain lesion and normal white matter divided by the background noise ($\text{CNR}_{\text{lesion}} = (S_{\text{lesion}} - S_{\text{parenchyma}})/S_{\text{noise}}$). Furthermore, lesion conspicuity was defined in every subject as an absolute value of $(S_{\text{lesion}} - S_{\text{parenchyma}})/S_{\text{parenchyma}}$. The term lesion conspicuity represents the visibility of a lesion including its structure and the parenchyma surrounding it.

SNR, CNR and lesion conspicuity values were compared on Silent (Silenz T1w, Silent T2w Propeller) and conventional (T1w, T2w Propeller) MRI.

Subjective image quality assessment

Subjective image quality criteria have been analyzed by three board-certified radiologists with a minimum of 4 years' MR experience and with special focus on neurological and oncological imaging. All three readers were trained and familiarized with the subjective image analysis prior to the study by evaluation of four example objects with brain lesions. Readers were instructed to use a 4-point ordinal scale (1 = not diagnostic, 2 = poor, 3 = good, 4 = fully diagnostic) for image quality characterization on silent and conventional MRI including four categories: lesion visibility, lesion delineation, grey-white matter differentiation and diagnostic usefulness. Diagnostic usefulness of a sequence was determined as a general measure for its diagnostic quality in general and also for its usefulness to confirm or exclude underlying disease compared to the other sequence (silent vs standard) and to all information from the complete standard MR protocol. Every reader independently scored the four categories for each sequence Silenz T1w vs T1w and Silent T2w vs T2w (Figures 1 and 2).

Figure 2. A 27-year-old male with clinical diagnosis of multiple sclerosis: arrows indicating associated brain lesions in the white matter on standard T2w (a) and Silent T2w (b). Lesion visibility and lesion delineation are comparable on both T2w techniques (a, b).

Statistical analysis

The aim of the analysis was to obtain statistically firm decisions whether, and in which cases, the silent method may be preferred to conventional MRI.

Analysis of objective data (differences of SNR, CNR and conspicuity values between silent and non-silent imaging) was performed by using Wilcoxon signed-rank test for the mean values.

Analysis of subjective assessment of image quality for each category was performed using the Sign test with the one-sided alternative hypothesis that the silent method is preferred over conventional MRI, and also *vice versa*.

This analysis was performed for each reader assessments individually and, in addition, for a combination of them obtained by majority decision. To achieve a majority decision, we proceeded as follows: instead of rating values themselves, we used the results of the comparison of the respective values for silent *vs* non-silent imaging. Comparison for each patient yields the value -1, 0 or 1, respectively, if the reader rated the first method worse, equally good or better than the second one. These values were then consolidated by a majority function: if the majority of readers rate one imaging method better (or equal or worse) than the other method, then this method is considered to be better (or equal or worse, respectively). If there is no majority, the common value is set to 0 ("equal"), because in this case a decision in favour of one of the imaging methods is not supported by the data.

For the resulting value, the Sign test was applied.

Significance was set at $p \leq 0.05$. IBM SPSS® Statistics v. 22 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL) was used as the statistical analysis tool. For further information, we refer to Indrayan Abhaya Medical Biostatistics.³³

RESULTS

Analysis of objective data

Results of the objective image quality criteria of silent *vs* conventional MRI are shown as mean value, standard deviation and median in Table 2.

ROI measurements on Silenz T1w imaging revealed decreased SNR, but increased CNR values compared with conventional T1w imaging with significant differences ($\text{SNR}_{\text{lesion}}$, $\text{SNR}_{\text{parenchyma}}$, $p = 0.000$; $\text{CNR}_{\text{lesion}}$, $p = 0.003$) (Figure 3).

On Silent T2w, SNR and CNR values were superior to measured values on conventional T2w imaging with significant results ($\text{SNR}_{\text{lesion}}$, $\text{CNR}_{\text{lesion}}$, $p = 0.005$; $\text{SNR}_{\text{parenchyma}}$, $p = 0.014$) (Figure 4).

Conspicuity values on Silenz T1w and Silent T2w were not significantly different from conventional T1w and T2w imaging (Silenz T1w *vs* T1w, $p = 0.16$; Silent T2w *vs* T2w, $p = 0.08$).

Analysis of subjective assessment of image quality by individual readers

The results of this analysis are shown in Table 3.

Each of the three readers separately judged Silenz T1w imaging to be significantly superior in terms of grey-white differentiation and lesion visibility compared with conventional T1w imaging. The overall diagnostic usefulness on Silenz T1w was rated significantly better than on conventional T1w by two readers. The category lesion delineation was scored significantly higher on Silenz T1w *vs* conventional T1w by one reader only.

On Silent T2w, two readers independently judged the grey-white differentiation significantly better than on conventional T2w imaging (Figure 5). In the other categories, lesion visibility, lesion delineation and overall diagnostic usefulness, all three readers found no significant preference on Silent T2w over conventional T2w. The opposite alternative hypothesis (conventional MRI preferred over silent MRI) could not be accepted with significance in any of the sequences and categories.

Analysis of subjective assessment of image quality combined by majority decision

The results of this analysis are shown in Table 4.

Table 2. Quantitative assessment of silent *vs* non-silent sequences of brain MRI at 3.0 T

Quantitative assessment parameters	T1w	Silenz T1w	T2w	Silent T2w
$\text{SNR}_{\text{lesion}}$	$n = 24$		$n = 23$	
	17.39 ± 9.64 (14.32)	4.24 ± 1.77 (4.17)	53.73 ± 41.15 (41.62)	88.38 ± 72.65 (60.07)
$\text{SNR}_{\text{parenchyma}}$	$n = 26$		$n = 25$	
	22.21 ± 12.00 (18.75)	5.69 ± 1.19 (5.92)	28.98 ± 17.33 (25.31)	45.91 ± 33.20 (42.86)
$\text{CNR}_{\text{lesion}}$	$n = 24$		$n = 23$	
	-4.62 ± 7.09 (-2.49)	-1.32 ± 1.91 (-1.30)	24.87 ± 31.16 (14.56)	42.14 ± 47.63 (23.68)
Lesion conspicuity	$n = 24$		$n = 23$	
	-0.15 ± 0.29 (-0.13)	-0.22 ± 0.33 (-0.27)	0.90 ± 0.82 (0.66)	1.00 ± 0.85 (0.74)

CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio; T1w, T_1 weighted; T2w, T_2 weighted.

Mean values $\pm$ standard deviation and median (in brackets) of variables calculated from region of interest measurements at 3.0 T.

Figure 3. Region of interest (ROI) measurements on both systems: signal intensity (SI) values were obtained from brain parenchyma and from outside the brain. According to signal- and contrast-to noise ratios (SNR, CNR), analysis revealed decreased SNR values but increased CNR values on Silenz T1w (b) vs T1w (a). sd, standard deviation.

Again, the test asked whether there is a significant difference in quality between the silent and the corresponding conventional MRI method in favour of the silent method. This was true for the categories grey–white differentiation, lesion visibility and overall diagnostic usefulness when comparing Silenz T1w vs T1w, and the difference goes in favour of Silenz T1w. In terms of Silent T2w vs T2w, there was a significant difference in grey–white differentiation in favour of Silenz T2w. No significance was detected in the other categories. The opposite alternative hypothesis (conventional MRI preferred to silent MRI) was not significantly accepted in any of the sequences and categories.

DISCUSSION

In the present study, objective and subjective image quality characteristics between silent (“Silenz T1w” and “Silenz T2w”) and non-silent conventional MR sequences were compared on the basis of 3.0-T MRI of vascular and neoplastic brain lesions.

Comparisons of objective as well as subjective image analysis on both systems indicate promising results for Silent Scan technology.

In the quantitative analysis, Silenz T1w was advantageous owing to an increased CNR, but restricted by a decreased SNR compared with standard T1w.

In the analysis of image quality ratings by all readers in common, Silenz T1w was significantly better rated than the corresponding standard T1w in three of the categories, while no difference was revealed in one category.

Silent T2w revealed significantly better quantitative image quality characteristics in terms of SNR and CNR than standard T2w and its quality was significantly better rated by the majority of readers in one of the four categories, while no difference was revealed in the other categories.

Figure 4. Region of interest (ROI) measurements revealed increased SNR and CNR values on Silent T2w (b) vs T2w (a). sd, standard deviation; SI, signal intensity.

Table 3. Qualitative assessment by each reader with one-sided alternative hypothesis (favouring silent method)

Categories for qualitative assessment		T1w	Silenz T1w		T2w	Silent T2w	
Lesion visibility		n = 24			n = 23		
	Score	n	n	p-value	n	n	p-value
Reader 1	2	10	3	0.008	1	1	0.060
	3	10	16		9	5	
	4	4	5		13	17	
Reader 2	1	1	–	0.002	–	–	0.250
	2	11	3		1	–	
	3	8	13		10	10	
	4	4	8		12	13	
Reader 3	1	1	–	0.003	–	–	0.500
	2	10	3		1	–	
	3	9	14		8	9	
	4	4	7		14	14	
Lesion delineation		n = 24			n = 23		
	Score	n	n	p-value	n	n	p-value
Reader 1	2	13	9	0.500	3	2	0.500
	3	6	12		13	15	
	4	5	3		7	6	
Reader 2	2	12	6	0.212	2	–	0.363
	3	8	14		13	15	
	4	4	4		8	8	
Reader 3	1	1	–	0.017	–	–	0.377
	2	11	5		2	1	
	3	10	15		13	13	
	4	2	4		8	9	
Grey–white differentiation		n = 26			n = 25		
	Score	n	n	p-value	n	n	p-value
Reader 1	1	1	–	0.000	–	–	0.363
	2	16	–		6	5	
	3	9	11		15	15	
	4	–	15		4	5	
Reader 2	1	1	–	0.000	–	–	0.008
	2	17	–		9	5	
	3	8	7		13	14	
	4	–	19		3	6	
Reader 3	1	4	–	0.000	2	–	0.016
	2	14	–		9	8	
	3	8	8		11	13	
	4	–	18		3	4	
Overall diagnostic usefulness		n = 26			n = 25		

(Continued)

Table 3. (Continued)

Categories for qualitative assessment		T1w	Silenz T1w		T2w	Silent T2w	
	Score	<i>n</i>	<i>n</i>	<i>p</i> -value	<i>n</i>	<i>n</i>	<i>p</i> -value
Reader 1	2	1	–	0.344	1	1	0.500
	3	19	19		6	6	
	4	6	7		18	18	
Reader 2	2	3	–	0.002	1	–	0.500
	3	18	11		6	7	
	4	5	15		18	18	
Reader 3	2	1	–	0.000	1	–	0.500
	3	24	9		4	5	
	4	1	17		20	20	

n, number of patients, T1w, T_1 weighted; T2w, T_2 weighted.

Score: 1 (not diagnostic), 2 (poor), 3 (good), 4 (optimal).

Statistical examination was made with exact Sign test; $p \leq 0.05$ was considered statistically significant. All the computed probabilities are ≤ 0.5 , which excludes acceptance of the opposite alternative hypothesis (favouring conventional method) in all cases.

The lesion conspicuity was not significantly different on silent vs non-silent imaging.

It must be pointed out that image quality is a wide term which is difficult to assess quantitatively.²² The aforementioned objective and subjective image quality criteria are only a part of a wide variety of factors that define and influence the quality of an image.^{23,24} Moreover, image quality should be always seen in the context of its usefulness in accomplishing a radiological task.²⁴

As a general principle, when the physical image quality improves, important radiological details will be recognizable and diagnostic task-based performance might improve.²⁵ But, their relationship between each other is complex.^{24,26}

In general, the higher the SNR and CNR values, the better the image quality and the detectability of a lesion. But, SNR and

CNR values never represent the full noise information or the real complexities of structures within a diagnostic image, which means they cannot directly be related to any specific radiological task.^{27,28}

The same applies to lesion conspicuity: high lesion conspicuity correlates with high lesion visibility and detectability. But, the conspicuity formula used in the present study does not include other factors which might influence the conspicuity and the diagnostic potential of an image too such as lesion size, the sharpness of lesion edges or the difference in average grey levels between the lesion and the surrounding parenchyma *etc.*²⁸

In terms of subjective image quality assessment, images with high quality ratings might improve task-related performance. But, it is not self-evident that the fulfilment of all image quality criteria is necessary or sufficient for a correct diagnosis.^{26,29,30}

Figure 5. Brain MRI of a male patient: Silent T2w (b) was judged to be superior to T2w (a) in terms of grey-white differentiation.

Table 4. Absolute frequencies of the majority decision of the three readers with one-side *p*-values (alternative: favouring silent method)

Categories for qualitative assessment	Silent T2w vs T2w				Silent T1w vs T1w			
	Lesion visibility	Lesion delineation	Grey-white differentiation ^a	Overall diagnostic usefulness	Lesion visibility ^a	Lesion delineation	Grey-white differentiation ^a	Overall diagnostic usefulness ^a
	<i>p</i> -value = 0.250	<i>p</i> -value = 0.500	<i>p</i> -value = 0.016	<i>p</i> -value = 0.250	<i>p</i> -value = 0.003	<i>p</i> -value = 0.194	<i>p</i> -value = 0.000	<i>p</i> -value = 0.001
-1	0	4	0	0	1	4	0	1
0	21	14	19	23	12	12	0	12
1	2	5	6	2	11	8	26	13
<i>n</i>	23	23	25	25	24	24	26	26

T1w, T₁ weighted; T2w, T₂ weighted.*n* = sample size; 0 and 1 denote that Silent T2w resp. Silent T1w is rated worse, equally good or better than T2w resp. T1w.^aSignificance (*p* ≤ 0.05).

For example, a missed lesion could be the result of the radiologist's wrong decision rather than restricted detectability; lesion visibility could be masked by the surrounding inhomogeneous anatomical background which might deteriorate human performance despite an excellent image quality. Furthermore, in terms of technical/diagnostic duality, an image of moderate or low quality might be accepted by the radiologist as adequate for the clinical task, whereas an image of good quality might need technical modifications.²⁴

Nevertheless, image quality should be adequate for clinical purpose and provide sufficient information to the radiologist to allow medical decisions with a high degree of certainty.

It is important to mention that acquisition parameters between silent and non-silent sequences were slightly different. The relationship between the choice of scan parameters and MR image quality might have influenced the study results (Table 1).

In this sense, results in favour of Silent T1w might be an enhanced contrast, *e.g.* between grey and white matter following different sequence parameters such as a shorter repetition time and a shorter TE on Silent T1w, compared with standard T1w.

Silent T2w imaging parameters are quite similar to conventional T2w (Table 1). But, Silent T2w scan parameters might have a stronger positive effect on higher SNR and CNR values and a better rated grey-white differentiation, *e.g.* by a little higher repetition time, increased FOV, decreased matrix size *etc.* compared with T2w.

One reason for slightly different scan parameters of silent vs non-silent sequences is based upon the different scan technology. In case of Silent T1w, the actual TE has to be 0 (TE = 0 vs TE = 28 ms on standard T1w) because the readout gradient is set before the excitation and gradient encoding starts immediately upon signal excitation. Comparable with standard T1w FLAIR, Silent T1w is generated by an inversion pre-preparation pulse (inversion time = 450 ms) to obtain T1w properties. On the other hand, comparing 3D imaging (Silent T1w) with 2D imaging (native T1w FLAIR) might have produced quality restrictions solely based on the imaging technique *per se*, *e.g.* problems of partial volume effects or slice misregistration in 2D technique which can be avoided in 3D technique—a fact that was not separately examined.

In contrast to standard MR scan, Silent Scan technology uses only small gradient steps and therefore, Silent T1w can be acquired completely silent except for the ambient noise. Silent T2w with imaging parameters similar to standard T2w is slightly louder than Silent T1w, but still more silent than standard T2w.

Furthermore, to maintain the original silent sequence type, new silent sequence parameters were hardly changed after Silent Scan technology was implemented in the 3.0T MR system at the institution. On the other hand, the pulse parameters of conventional T1w and T2w sequences were not altered as well because they have been proven to be of excellent diagnostic quality over years.

However, to which degree slightly different scan parameters might have influenced study results was not part of this study and will be a topic of further investigational medical physics experiments. The purpose will be to determine the optimal choice of pulse parameters for a high image quality depending on MR hardware, examined object, desired spatial resolution, acceptable degree of artefacts or scan time.

Silent Scan technology is comparable with conventional MRI in this investigational study. And in contrast to conventional MRI, Silent Scan compensates a main drawback of conventional MRI—the acoustic noise generated from the MR system. As a consequence, Silent Scan might allow for more patient comfort by improving the MR experience, especially in case of patients who are sensitive to acoustic noise, e.g. those with tinnitus, migraine or children.^{21,31,32}

But, it must be taken into account that Silent Scan takes more time than conventional imaging. Especially, Silenz T1w takes much longer (approximately 4 min) than standard T1w (1.2 min). On one hand, this fact could be acceptable for patients as long as there is particularly a quiet and relaxed MR atmosphere. On the other hand, a slightly longer scan time might be an issue for patients who are uncooperative or suffer from claustrophobia. These patients may not be able to stay still long enough for an MRI and therefore, a shorter MR examination time is preferred.

On a final note, Silenz T1w has restrictions concerning image geometry. Silenz T1w is a 3D volume technique. Firstly, Silenz

T1w image acquisition is performed in sagittal orientation first owing to isotropic resolution and the need for covering the whole brain which has its longest diameter in sagittal direction. Afterwards, Silenz T1w 3D data set can be viewed in any orientation and thickness offline saving examination time in this way.

The present study has some limitations: it must be noted that the number of patients enrolled in this study is limited. However, this is a pilot study on the comparative image quality characteristics of silent vs non-silent MR scans. Furthermore, at the time of performing this study, Silent Scan technology had been restricted to the brain and only several sequences out of a conventional brain MR protocol had been developed. Only recently, software products in market are allowing a full silent brain MR scan. Further reasonable and substantial research including larger samples and additional sequences will be necessary to support our study results. Next, the subjective image quality assessment cannot be controlled. Results based on the individual reader opinion are always a source of bias, uncertainty and interreader or intrareader variability, e.g. if one reader tends to judge one method better or poorer than the other reader or if one reader is more self-confident or experienced in image quality assessment.

In conclusion, Silent Scan technology provides comparable image quality characteristics than standard MRI at 3.0 T with the advantage of a quiet MR examination. It might have the potential of being applied as an integral part of the routine MRI in the near future.

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