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Original contribution

Evaluation of magnetic resonance imaging acoustic noise reduction technology by magnetic gradient waveform control

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ABSTRACT

Background: ComforTone is a noise reduction technology used in magnetic resonance imaging (MRI) systems; it suppresses acoustic noise by modifying pulse sequences, which appropriately changes the magnetic field gradient waveforms. Although ComforTone can be used to solve the acoustic noise problems that affect patients who are exposed to acoustic noise from MRI, to the best of our knowledge, the associated technical details have not been published and its effects on acoustic noise reduction remain unclear.
Purpose: To evaluate the efficacy of acoustic noise reduction and the impact of acoustic noise reduction technology involving magnetic field gradient waveform control on image quality.
Population: The study included 18 healthy volunteers (11 males and 7 females; median age, 34 years; age range, 24–51 years).
Field strength: 1.5 T Philips Ingenia using a SENSE head–spine coil.
Assessment: The sound pressure level (SPL) and 1/3 octave spectra of MRI acoustic noise with the human head positioned in the iso-center of the MRI system were measured for five different pulse sequences used in clinical MRI. This subjective evaluation of noise included 18 healthy volunteers. The degree of discomfort experienced by the subjects was measured using a visual analog scale. The image quality was assessed objectively and subjectively. For objective assessment, signal-to-noise ratio (SNR) and contrast-to -noise ratio (CNR) of diffusion-weighted images were measured; for subjective assessment, visual evaluation was performed by two radiologists.
Statistical tests: Data were analyzed using Welch's *t*-test, and a p value < 0.05 defined significance.
Results: ComforTone could recognize a decrease in sound pressure, and the sound pressure of the acute high-frequency portion of the auditory characteristics was reduced. As reported by the subjects, discomfort caused by the sound pressure was significantly alleviated with ComforTone ($p < 0.01$). The sound pressure reduction in the high-frequency region with high audibility characteristics was recognized by ComforTone. The visual evaluation of the image quality of the diffusion-weighted images revealed that although there was no difference between SNR and CNR, the image quality was reduced by distortion artifacts.
Data conclusion: ComforTone reduced the SPL in the frequency range where auditory characteristics were sensitive, suggesting that ComforTone was useful for auditory protection and alleviation of discomfort in patients undergoing MRI. However, because magnetic field gradient waveform control is involved, such noise-reducing techniques should be used by considering their possible influence on the image quality.

1. Introduction

Acoustic noise in magnetic resonance (MR) imaging (MRI) is caused by electromagnetic force (Lorentz force) generated when a current passes through a gradient coil [1]. The magnitude of the acoustic noise depends on the performance and structure of the MRI system [2]. For example, Lorentz force is proportional to the static magnetic field strength and current magnitude, with higher magnetic field strength being positively correlated with higher acoustic noise. Furthermore, because spatial resolution and imaging time depend on the strength of the magnetic field gradient and switching speed, acoustic noise is particularly high in ultrafast imaging, such as echo planar imaging (EPI). Studies have reported acoustic noise levels exceeding 130 dBA in EPI performed by MRI systems with high magnetic field strengths

Abbreviations: MRI, Magnetic resonance imaging

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[3–5]. Inner ear cells damaged by such excessive acoustic noise can cause temporary or permanent deafness [2,6]. Therefore, sufficient hearing protection is required while performing MRI to limit the peak sound pressure level (SPL) to 140 dB (120 dB in children) and ensure that the equivalent noise level is < 99 dBA [7]. Additionally, acoustic noise associated with scanning using MRI is not only hazardous for hearing but also associated with discomfort and fear. Particularly, in children and patients with claustrophobia, tinnitus, or sensitive hearing, loud sound can trigger fear and is considered an obstacle to performing MRI. The usage of hearing protection reduces the exposure to acoustic noise; however, it does not reduce discomfort in all the patients. In addition, because of the size of the hearing-protection devices, ensuring appropriate protection in children may be challenging. Techniques for reducing acoustic noise in MRI systems that are currently in clinical use can be roughly divided into methods that use hardware and those that control pulse sequences. The methods that use hardware reduce acoustic noise either by reducing the vibration of the gradient coil to suppress sound propagation or by generating a simulated sound with the same amplitude and the opposite phase compared with those of the noise, resulting in active noise control [8–10]. Conversely, methods that control pulse sequences reduce acoustic noise by optimizing the magnetic field gradient waveforms. These methods share similarities with the conventional pulse sequence but use magnetic field gradient waveforms with more gradual rise and fall times. Another method applies a low-pass filter to form a plateau-less sine wave [11–14]. Additionally, the acoustic noise generated by the magnetic field gradient is represented using the product of the frequency response function (FRF) unique to the device and the frequency distribution of the magnetic field gradient waveforms [15]; therefore, the acoustic noise can be reduced using a gradient current that reduces the amplitude of the FRF [16]. ComforTone MRI scan (ComforTone, Philips Healthcare, Best, The Netherlands) is an imaging method based on pulse sequence control that attempts to achieve acoustic noise reduction aiming to resolve acoustic noise problems that affect patients. However, to the best of our knowledge, the technical details of this method have not been published and its effects on acoustic noise reduction and MRI acquisition remain unclear.

The purpose of this study was to validate the effectiveness of ComforTone for reducing the acoustic noise in patients undergoing MRI. Further, the effectiveness of this acoustic noise reduction technology was evaluated using the experimental data and subjective assessments.

2. Materials and methods

2.1. Equipment

All experiments were performed using a 1.5-T MRI system (Ingenia 1.5 T, release 5.3.1, Philips Healthcare) with a 40-mT/m maximum gradient strength, 200-T/m/s slew rate, and a phased-array receiver head–spine coil. For measuring MRI acoustic noise, a cylindrical phantom (160 mm in diameter) encapsulating a 0.014-mol/l copper sulfate solution with a volume similar to that of the human head was placed at the center of the magnetic field and an optical microphone (Optimic 1140, Optoacoustics, Or Yehuda, Israel) [17] was installed. The optical microphone was connected to a precision sound level meter (Type 6238, ACO, Tokyo, Japan) via a light/electricity conversion unit (electric optical unit; Kobateru, Kanagawa, Japan), and the acoustic noise was measured. A 1/3-octave real-time analysis software (NA-0038, ACO Co., Ltd., Tokyo, Japan) attached to the sound level meter was used for frequency analysis.

2.2. Parameters for measuring acoustic noise during MRI

In the current study, we evaluated spin-echo T_1-weighted (T_1WI), turbo spin-echo T_2-weighted (T_2WI), turbo spin-echo T_2-weighted fluid-attenuated inversion recovery (FLAIR), echo planar diffusion-weighted imaging (DWI), and gradient-echo time-of-flight angiography (MRA) sequences, which are commonly used in brain imaging [18,19]. All the sliced cross-sections were set to the axial position, and the following parameters were used for all the pulse sequences excluding MRA: thickness, 5 mm; number of slices, 23; and field of view (FOV), 220 mm. The T_1WI parameters were as follows: TR/TE, 584 ms/12 ms; matrix size, 256 × 192; BW, 272 Hz; and scan time, 3 min 11 s. The T_2WI parameters were as follows: TR/TE, 5000 ms/100 ms; matrix size, 320 × 320; echo train length (ETL), 15; BW, 150; and scan time, 2 min 35 s. The FLAIR parameters were as follows: TR/TE, 10000 ms/110 ms; matrix size, 256 × 204; ETL, 30; echo space (ES), 7.1 ms; BW, 237; and scan time, 2 min 30 s. The DWI parameters were as follows: TR/TE, 6000 ms/70 ms; matrix size, 128 × 128; BW, 21.4; and scan time, 1 min 12 s. The MRA parameters were as follows: TR/TE, 24 ms/6.9 ms; slice thickness, 1 mm; number of slabs, 150; FOV, 200 mm; matrix size, 368 × 184; BW, 144; and scan time, 5 min 12 s.

The following parameters were changed from conventional scan settings when conducting a scan using ComforTone. T_1WI sequences: TR, 627 ms; scan time, 3 min 24 s; T_2WI sequences: BW, 165; FLAIR sequences: ETL, 24; ES, 8.8; BW, 293; scan time, 3 min; DWI sequences: TE, 82 ms; BW, 11.6. The parameters used in the present study are summarized in Table 1.

2.3. Measurement of MRI acoustic noise and frequency analysis

The phantom was installed in the head–spine coil. Ambient noise was defined as the room sound pressure when MRI imaging was not performed, and acoustic noise was defined as the room sound pressure during conventional and ComforTone scan sessions in the scanning room. The measurement methods for noise complied with the National Electrical Manufacturers Association MS 4 (2010), which is an MRI

Table 1
Magnetic resonance imaging and acoustic noise parameters.

Scan Parameter	Scan Mode									
	Conventional Scan					ComforTone Scan				
	T_1WI	T_2WI	FLAIR	DWI	MRA	T_1WI	T_2WI	FLAIR	DWI	MRA
TR (ms)	584	5000	10000	6000	24	627	5000	10000	6000	24
TE (ms)	12	100	110	70	6.9	12	100	110	82	6.9
FOV (mm)	220	220	220	220	200	220	220	220	220	200
ETL		15	30				15	24		
Echo space (ms)		12.5	7.1				12.5	8.8		
Band width (Hz)	272	150	237	21.4	144	272	165	293	11.6	144
Acquisition (min)	3:11	2:35	2:30	1:12	5:12	3:24	2:35	3:00	1:12	5:12

(T_1WI), T_1-weighted sequence; (T_2WI), turbo spin-echo T_2-weighted sequence; (FLAIR), turbo spin-echo T_2-weighted fluid-attenuated inversion recovery sequence; (DWI), echo planar diffusion-weighted imaging sequence; (MRA), gradient-echo time-of-flight angiography; (ETL), echo train length.

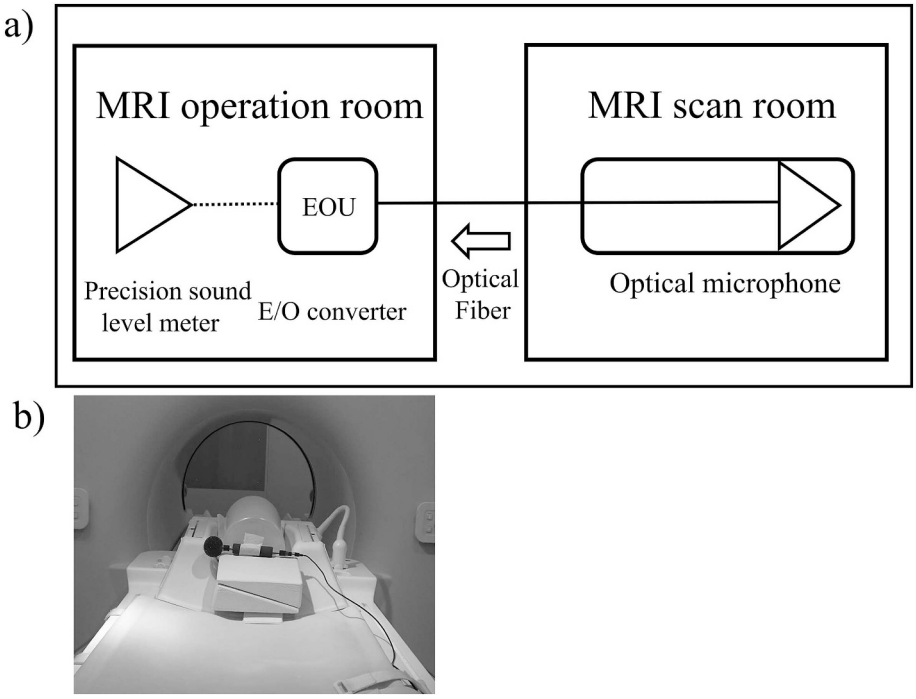

Fig. 1. Equipment used to measure acoustic noise of magnetic resonance imaging as shown in the schematic diagram. (a) Installation of equipment to measure noise of the MRI device as shown in this schematic diagram. (b) Experimental set-up for acoustic noise measurement.

Table 2
Scoring system used to evaluate the image quality parameters.

Image characteristic	Scoring system
Overall image quality	1, unacceptable; 2, poor; 3, acceptable; 4, good; 5, excellent
Image contrast	1, unacceptable; 2, poor; 3, acceptable; 4, good; 5, excellent
Image artifacts	1, unreadable; 2, extreme artifact; 3, moderate artifact; 4, mild artifact; 5, no artifact

Table 3
Comparison of LAeq and LCpeak values between conventional and ComforTone scans.

Scan Mode	SPL	SPL_b	T_1WI	T_2WI	FLAIR	DWI	MRA	Total
Conventional	LAeq (dBA)		96.2	96.6	96.4	100.5	100.8	98.6
	LCpeak (dB)		106.8	112.7	115	116.6	111.2	116.2
ComforTone	LAeq (dBA)		92	86.9	80	91.8	87.5	88.2
	LCpeak (dB)		102.9	105.5	101	108.6	100.2	106.8
	LAeq (dBA)	53.1						
	LCpeak (dB)	78						

(SPL), sound pressure level; (SPLb), room sound pressure level when MRI imaging was not performed; (T1WI), T1-weighted sequence; (T2WI), turbo spin-echo T2-weighted sequence; (FLAIR), turbo spin-echo T2-weighted fluid-attenuated inversion recovery sequence; (DWI), echo planar diffusion-weighted imaging sequence; (MRA), gradient-echo time-of-flight angiography; (Total), acoustic noise measured during the entire pulse sequence acquisition.

acoustic noise measurement standard [20]. The sensor part of the optical microphone was affixed to the phantom such that it was horizontal to the table surface and perpendicular to the body axis; the phantom was then installed in the head–spine coil. The optical fiber cable was connected to the electric optical unit in the scanning room through a waveguide and the sound level meter and was installed in the scanning room (Fig. 1).

For noise parameters, equivalent noise level (LAeq; equivalent continuous A − weighted SPL) and peak SPL (LCpeak; C − weighted peak SPL), which are standardized in International Electrotechnical Commission (IEC) [21] were measured. For SPL assessment, measurements were performed using the sound level meter functions for calculating LAeq and LCpeak. LAeq expresses the fluctuating noise as an energy average, whereas LCpeak is a numerical value that is obtained by leveling the maximum absolute value of the instantaneous sound pressure within the noise measurement time. The dynamic characteristics of the noise level meter at the time of measurement of the acoustic noise were set to fast mode (time constant, 125 ms). The acoustic noise of each pulse sequence was measured for 30 s. In addition, LAeq and LCpeak were also calculated during continuous acquisitions of all the pulse sequences.

For assessment of frequency characteristics, measurements were performed using the 1/3-octave band calculation function of the sound level meter. Frequency analyzers for acoustic vibration are divided by purpose into octave analyzers and fast Fourier transform analyzers. An octave analyzer obtains the SPL for each band through a band-pass filter of a constant-ratio type defined in the 1/1 octave or 1/3 octave standard for the noise to be measured. The frequency resolution of human auditory characteristics is equivalent to 1/3 octave bandwidth; therefore, an octave analyzer is used for frequency analysis primarily to

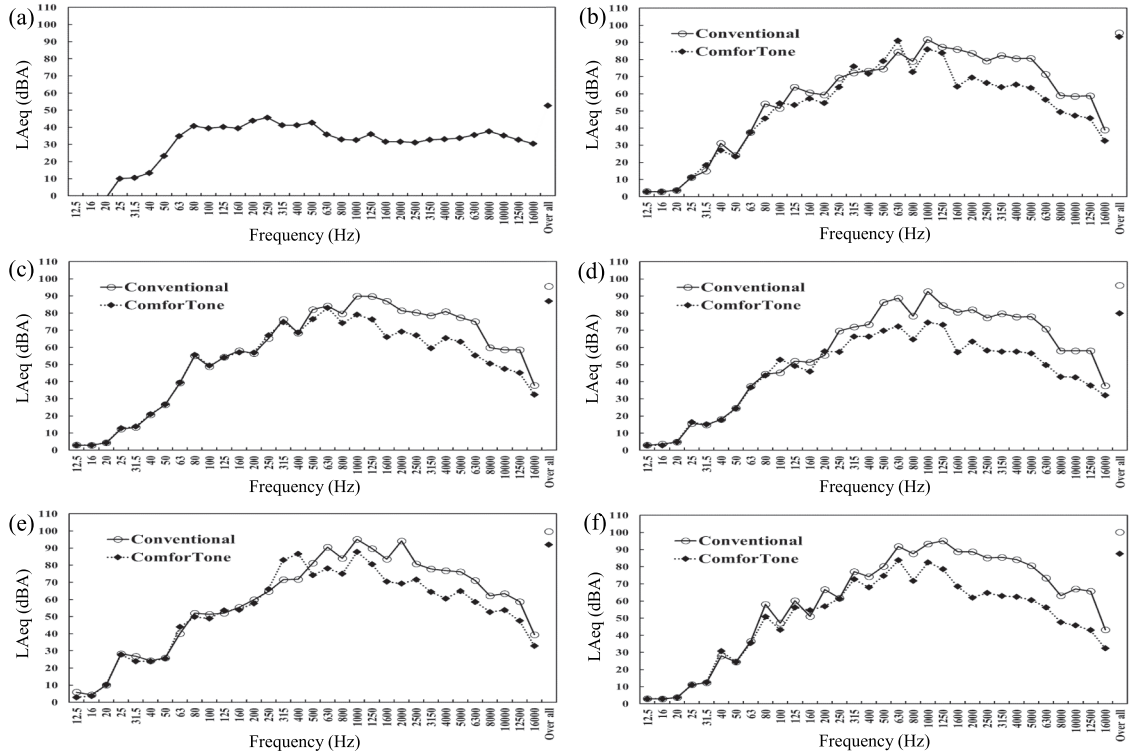

Fig. 2. Acoustic noise spectra. The ComforTone scan not only lowers the sound pressure in the frequency band sensitive to auditory characteristics but also causes a shift in the maximum sound pressure peak to the low-frequency side. In all pulse sequences, sound pressure reduction of approximately 10–20 dBA was observed from the center frequency of 2 kHz to 4 kHz.
Conventional, spectra of the conventional scan; ComforTone, spectra of the ComforTone scan; overall, sum of the noise levels for each band level.
(a), ambient noise; (b), T_1-weighted sequence; (c), turbo spin-echo T_2-weighted sequence; (d), turbo spin-echo T_2-weighted fluid-attenuated inversion recovery sequence; (e), echo planar diffusion-weighted imaging sequence; (f), gradient-echo time-of-flight angiography.

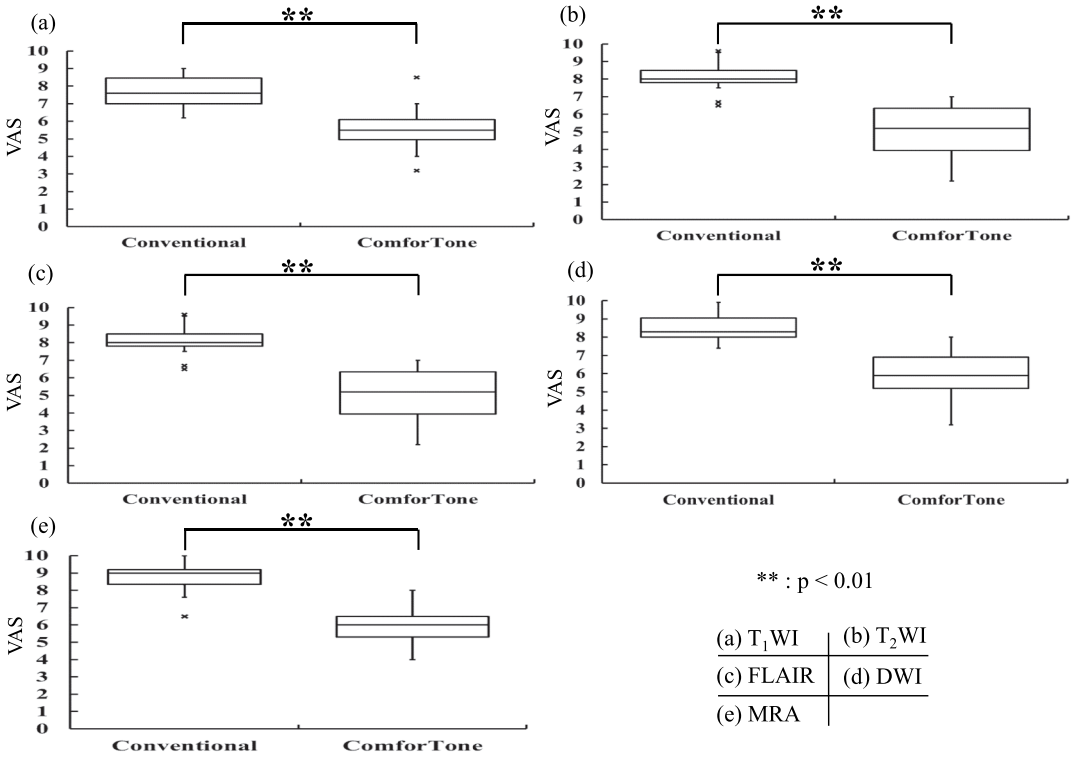

Fig. 3. Box-and-whisker plot showing the results of evaluation of acoustic noise discomfort with MRI using the visual analog scale. (a), T_1-weighted sequence; (b), turbo spin-echo T_2-weighted sequence; (c), turbo spin-echo T_2-weighted fluid-attenuated inversion recovery sequence; (d), echo planar diffusion-weighted imaging sequence; (e), gradient-echo time-of-flight angiography.

Table 4
Comparison of the SNR and CNR values between conventional and ComforTone scans.

	Scan mode		*p* value
	Conventional	ComforTone	
SNR (WM)	14.0 ± 3.1	13.1 ± 3.3	0.26
SNR (GM)	26.3 ± 5.4	25.4 ± 5.4	0.63
CNR (WM-GM)	12.2 ± 5.9	12.3 ± 4.5	0.96

(WM), white matter; (GM), gray matter.

evaluate sensory quantity and other factors associated with noise [22,23]. In the current study, we measured SPL in a frequency band from 12.5 Hz to 20 kHz using a 1/3-octave band filter and examined changes in frequency characteristics due to the use of ComforTone during scanning compared with those of the conventional scan. The dynamic characteristics setting and measurement time of the sound level meter were similar to the measurement of SPL.

2.4. Subjective evaluation of acoustic noise

The subjective assessment of the acoustic noise was conducted in the presence of the quiet sound effect of ComforTone during imaging using different pulse sequences in healthy volunteers. The subjects were 18 medical staff members who underwent MRI (11 males, 7 females; median age, 34 years; age range, 24–51 years). This prospective study was approved by the Institutional Review Board of the study institution. The subjects were provided the explanation of the study purpose and safety of the assessments, and all participants provided written informed consent prior to participation in the study. All subjects underwent audiometric tests for all subjects, and no abnormalities were identified. The hearing protection equipment provided with the MRI system, designed to protect the hearing of patients undergoing MRI for clinical purposes, was used to reproduce the same conditions in the study subjects. The imaging conditions were the same as those used for SPL measurement and frequency analysis. The order of the pulse sequences was randomized, and verification was performed to cancel the order effect.

The VAS used in the current study was a score scale for a more objective evaluation of subjective symptoms that were difficult to measure, such as pain sensation and hearing discomfort [24–26]. The most unpleasant outcome was set as the maximum score in the VAS (100-mm scale, 1-mm pitch). Each subject was asked to indicate the degree of discomfort for the noise of each pulse sequence on the VAS. This evaluation was performed three consecutive times, and the mean values that were recorded were statistically analyzed using Welch's *t*-test, and a p value of < 0.05 was considered statistically significant. BellCurve for Excel (Social Survey Research Information, Tokyo, Japan) was used for statistical analysis of the VAS data.

2.5. Image evaluation

Because DWI parameters were modified, particularly the readout BW and TE, it was important to assess whether images acquired with the ComforTone scan maintained image quality compared with those acquired with the conventional scan. The image quality was evaluated by measuring the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of the DWI scans and evaluating the image quality by two radiologists.

Mean signal intensity (SI) and standard deviation (SD) values were determined using the ImageJ software 1.47v (Wayne Rasband, National Institute of Health, USA) [27]. The mean SI and SD of white matter (WM) and gray matter (GM) were measured to compare the SNR and CNR of the DWI scans. The size of the regions of interest for measuring mean SI and SD was defined as small as possible; the average size of the regions of interest to determine the mean SI and SD for WM and GM was 15 mm^2. The SNRs of WM and GM were calculated using the mean SI and SD as follows:

$$\mathbf{SNR\,(WM, GM) = SI/SD} \quad (1)$$

The CNRs of WM and GM were calculated using the SNRs as follows:

$$\mathbf{CNR = |SNR\,(WM) - SNR\,(GM)|} \quad (2)$$

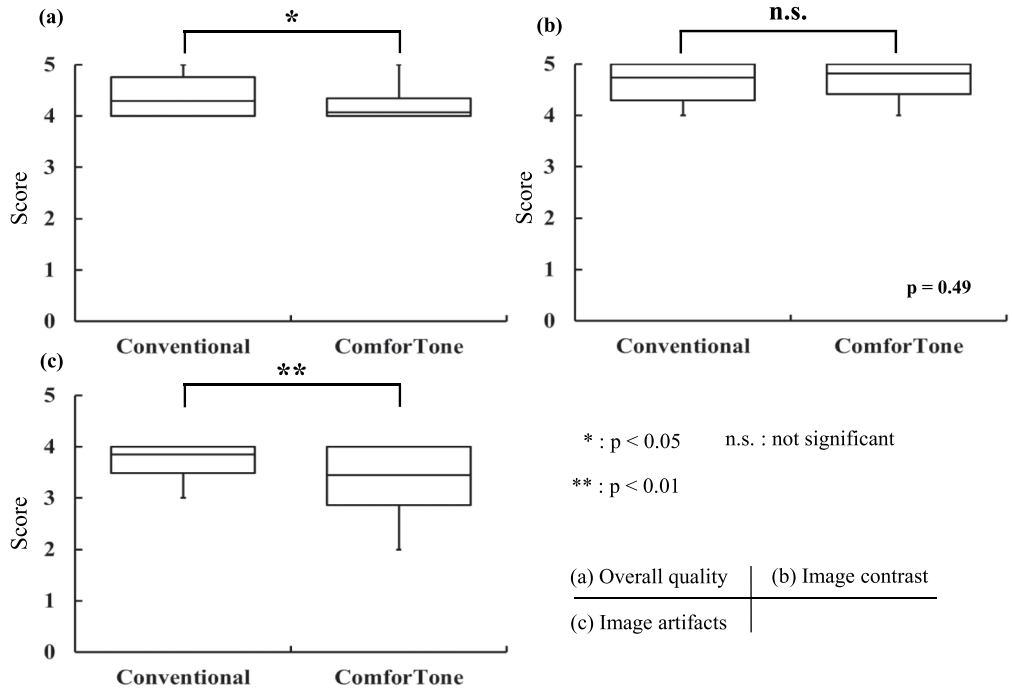

Fig. 4. A Box-and-whisker plot showing the average of image analysis scores of the two readers who evaluated the conventional and ComforTone DWI scans for (a) overall quality, (b) image contrast, and (c) image artifacts.

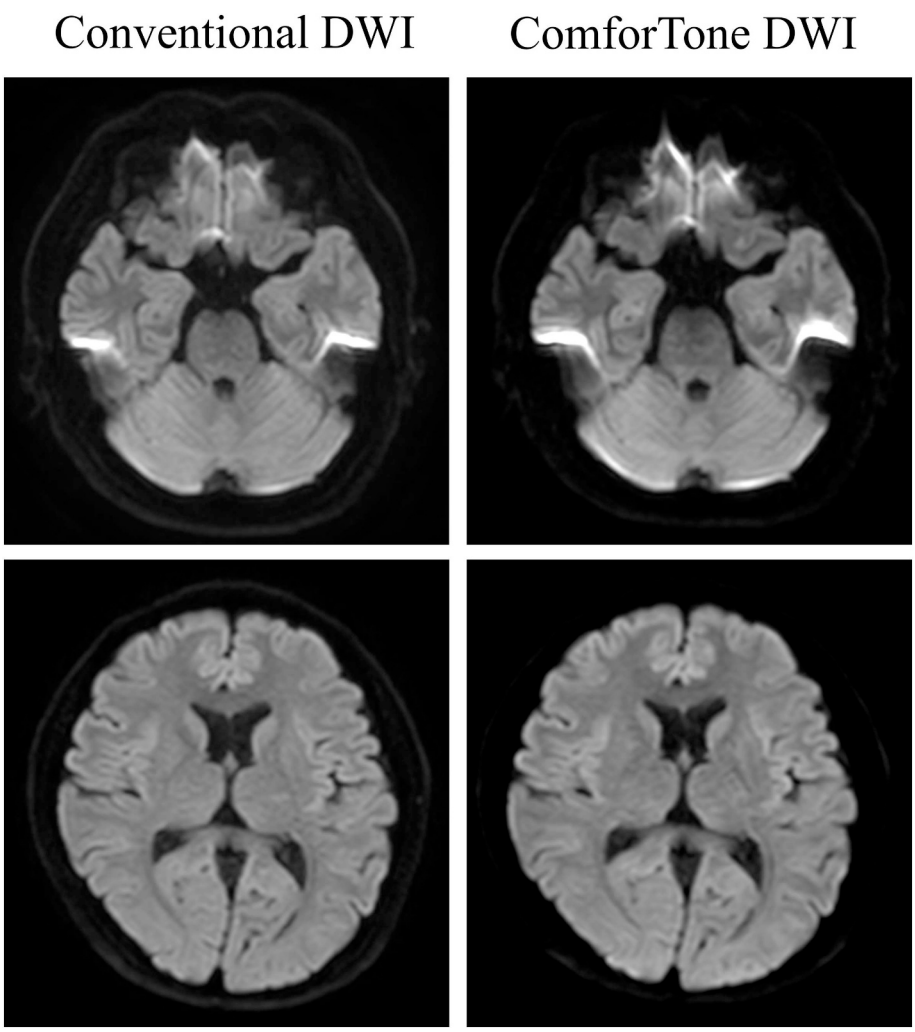

Fig. 5. Representative slices of the conventional DWI sequence (left column) and the ComforTone sequence (right column) of a healthy volunteer reveals that the susceptibility artifact is increased in the ComforTone DWI.

The resulting SNRs and CNRs were analyzed using Welch's *t*-test, and a p value of < 0.05 was considered statistically significant.

Image analysis was performed based on the head MRI images of 18 healthy volunteers who participated in the subjective evaluation. The image quality of the conventional and ComforTone DWI sequences was independently compared and rated by one radiologist with 28 years of experience in MR imaging and one resident in radiology with 2 years of experience in MR imaging. Imaging analysis was performed using a PACS workstation (Synapse Enterprise-PACS, Fujifilm Medical, Japan) that allowed the simultaneous display of both the sequences. The two observers graded image quality on a five-point scale blinded to the status of ComforTone use. For the DWI image of 18 healthy volunteers, three image quality parameters were rated on a scale from 1 to 5, with 5 indicating the most desirable quality: overall image quality, image contrast, and image artifacts, such as susceptibility. Details of the scoring system are summarized in Table 2. Data assessed by observers were analyzed using Welch's *t*-test, and a p value < 0.05 was considered statistically significant.

3. Results

3.1. SPL measurement

Table 3 shows the results of ambient noise measurements in the magnetic field center of the MRI system and the changes in noise when ComforTone was added to each pulse sequence. For each pulse sequence, the equivalent noise level measured during MRA acquisition was 100.8 dBA, which was higher than the allowable limit of 99 dBA and never below this value. However, the 140-dB tolerance limit of the peak SPL was not exceeded by any of the pulse sequences. With ComforTone, the mean equivalent noise level of each pulse sequence was 10.4 dBA, and the peak SPL was reduced by 9.4 dB. These results confirmed the sound pressure-reducing effect of ComforTone.

3.2. Frequency analysis

Fig. 2 shows the results of ambient noise measurements in the magnetic field center of the MRI system and the acoustic noise spectra after ComforTone was added to each pulse sequence. The frequency characteristics of the pulse sequence showed different peaks, and the maximum noise peak was observed around the center frequency of 1 kHz. Furthermore, high noise levels of > 80 dBA were distributed between 400 Hz and 4 kHz in all pulse sequences. Conversely, the frequency characteristics of sequences obtained using ComforTone showed a reduction in noise levels between 400 Hz and 4 kHz. Moreover, the maximum noise peak shifted from the high-frequency to the low-frequency side with T_2WI and DWI sequences.

3.3. Subjective evaluation

The results of the subjective evaluation using the VAS are presented in Fig. 3. Briefly, the VAS score with the ComforTone scan in each pulse sequence was significantly lower than that without ComforTone ($p < 0.01$). These findings confirmed that the addition of ComforTone reduced the discomfort resulting from noise.

3.4. Image evaluation

Table 4 shows the comparison of the SNRs and CNRs between conventional and ComforTone DWI. Briefly, no significant differences were noted in the SNRs or CNRs in any of the scanning methods. The box plot of scores averaged between the readers is presented in Fig. 4. Analysis of the averages with Welch's *t*-test revealed significant differences in overall quality and artifact parameters between conventional DWI and ComforTone DWI (Welch's *p*, 0.031 and 0.001, respectively). However, no significant difference was noted in the results for image contrast between the two readers.

A representative comparison between the images acquired with conventional DWI and ComforTone DWI is presented in Fig. 5. ComforTone DWI showed distortion in areas with great changes in magnetic susceptibility, such as the inner ear canal and paranasal sinuses, and magnetic susceptibility artifacts were more frequent in ComforTone DWI than in conventional DWI.

4. Discussion

Humans are rarely exposed to loud noises in narrow spaces in daily living. Therefore, acoustic noise generated during MRI acquisition may cause discomfort in patients undergoing MRI. Although various techniques have been developed to mitigate acoustic noise [8–16], increasing levels of acoustic noise with the development of high-field MRI systems and ultrafast MRI scanning highlight the urgent need to improve acoustic noise reduction in MRI.

The Japan Society for Occupational Health recommendations regarding hearing protection as part of occupational health [28] presents permissible noise standards, which are converted with the octave band level allowed for each frequency and the A characteristic equivalent noise level. In the current study, we measured acoustic noise for each frequency through the octave band filter and found that the acoustic noise did not exceed the allowable limit (Table 3). Additionally, comparison of the noise measurement value acquired over a 15-min measurement time while capturing the entire pulse sequence with the allowable limit of the A characteristic equivalent noise level (100 dBA for 15-min exposure) revealed that the measured noise value did not exceed the recommended value (Table 2). However, we acknowledge that the difference was negligible, and there remains the possibility that the allowable limit is breached following changes in imaging protocols or scan parameters.

We found that the ComforTone scan reduces not only acoustic noise but also discomfort with acoustic noise unlike that with the conventional scan (Fig. 3). Human auditory sensation depends on the magnitude of sound as well as on its frequency and duration. Humans feel sounds louder as the sound pressure increases even if the frequency remains constant. However, because the sensitivity of human hearing varies depending on the frequency, even with the same sound pressure, differences in sound frequency will result in a difference in the magnitude of the perceived sound. The curve for normal hearing ability is thus defined as a perceptual curve (equal-loudness-level contours for pure tones) based on checking a constant sound volume at the center frequency of 1 kHz and a value perceived by the same sound volume for each frequency [29]. This curve reflects that the auditory sensation of humans differs in the magnitude of sounds experienced according to frequency, even at identical physical sound pressures. At low frequencies, the sensitivity of the ear decreases, and it is the highest near 3–4 kHz. The ComforTone scan not only lowers the sound pressure in the frequency band sensitive to auditory characteristics but also causes a shift of the maximum sound pressure peak to the low-frequency side. Consecutively, the acoustic noise generated during scanning for all pulse sequences included in the current study decreased by 10 dBA at both the equivalent noise levels and peak SPL (Table 3). In all the pulse sequences, a sound pressure reduction of approximately 10–20 dBA was observed from the center frequency of 2–4 kHz (Fig. 2). The frequency analysis with the 1/3-octave filter and subjective evaluation of discomfort degree using VAS revealed the mechanism underlying the relatively reduced discomfort facilitated by the ComforTone scan compared with the conventional scan.

As a countermeasure against acoustic noise, hearing protection equipment, such as earmuffs and earplugs, should be appropriately used [2,6,7]. The SPL is estimated to fall within the allowable limit, even during usual pulse sequences, because SPL is reduced by 25–30 dB at the center frequency of 2 kHz with the hearing protection equipment. However, the shape and size of hearing protection devices might not be suitable for all patients. In newborns and premature babies, finding the appropriate hearing protection equipment is challenging and therefore requires close monitoring. These results indicate that a relatively greater hearing protection effect can be expected with the use of hearing protection equipment and ComforTone in combination. In pediatric patients, including neonates and premature babies, neither of whom can use hearing protection equipment appropriately, implementation of noise-reducing technologies, such as ComforTone, is necessary.

When performing ComforTone during pulse sequences, it is important to note the effect of optimization of pulse sequence parameters on image quality. At the time of image acquisition with the ComforTone scan, parameters were automatically optimized on the equipment side (Table 1). Among the parameters, BW, TR, TE, and ETL are considered as factors that affect image quality. Changes in BW were recognized in T_2WI, FLAIR, and DWI sequences. Specifically, the narrowing of BW and extension of TE were noted in DWI. The narrowing of the bandwidth in DWI was considered to increase the magnetic susceptibility artifact, and the extension of TE was considered to cause a decrease in the SNRs and CNRs. As shown in the representative comparison between the images acquired with conventional and ComforTone DWI (b factor = 1000 s/mm^2) in Fig. 5, the susceptibility artifact was increased in the ComforTone scan. As a result of image analysis for DWI (b factor = 1000 s/mm^2), the SNRs and CNRs were not significantly different between the scans. However, based on the image evaluation conducted by radiologists, significant differences were noted in the overall image quality and image artifacts when the two scan methods were compared (Table 4). One potential explanation for this observation is the increase in the susceptibility artifact with the narrowing of BW with concomitant increase in the SNR of the image. Narrowing the bandwidth reduces the amount of noise introduced into the signal and increases the signal-to-noise ratio (SNR) within the MR image. However, because the narrow bandwidth frequency spans each pixel, the inhomogeneities and distortion artifacts of the magnetic field from the ferromagnet are also emphasized. Among the pulse sequences, the phase shift in the DWI sequence is accumulated when the signal is filled in the k-space. Therefore, in the DWI sequence, the change in any parameter influences the image quality [30].

To the best of our knowledge, the technical details of ComforTone have not been published previously. However, for this verification study, the vendor provided information on changes in the gradient maximum strength (Gmax) and slew rate (SR). The report provided by the vendor stated that there was no change in Gmax and that the SR was reduced to 1/3 in DWI sequences with ComforTone. Also, no information on variations in Gmax and SR for other pulse sequences was provided by the vendor. Therefore, based on the changes in parameters, it is likely that the rise time was controlled by ComforTone in DWI as well. Parameter optimization using ComforTone depends on imaging

conditions, magnetic field gradient performance, and other factors related to the equipment used. The change in pulse sequence parameters by ComforTone can be confirmed on the operation console. Before performing MRI, it is important to check changes in pulse sequence parameters and understand the impact on image quality using ComforTone.

5. Conclusion

The current study evaluated the acoustic noise-reducing effect of ComforTone, which utilizes pulse sequence control and found that ComforTone reduced the sound pressure in the frequency range where auditory characteristics are sensitive, supporting its efficacy in hearing protection and discomfort alleviation. However, an increase in the susceptibility artifacts of the DWI sequence with changing parameters resulted in a decrease in the image quality. Such acoustic noise reduction techniques that control the magnetic field gradient waveforms should be used by considering their possible influence on the image quality.

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References

[1] Mansfield P, Chapman BL, Bowtell R, Glover P, Coxon R, Harvey PR. Active acoustic screening: reduction of noise in gradient coils by Lorentz force balancing. Magn Reson Med 1995;33:276–81.
[2] Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. Radiology 2004;232:635–52.
[3] More SR, Lim TC, Li M, Holland CK, Boyce SE, Lee JH. Acoustic noise characteristics of a 4 Telsa MRI scanner. J Magn Reson Imaging 2006;23:388–97.
[4] Ott M, Blaimer M, Grodzki DM, Breuer FA, Roesch J, Dörfler A, Heismann B, Jakob PM. Acoustic-noise-optimized diffusion-weighted imaging. MAGMA 2015;28(6):511–21. Dec.
[5] Foster JR, Hall DA, Summerfield AQ, Palmer AR, Bowtell RW. Sound level measurements and calculations of safe noise dosage during EPI at 3 T. J Magn Reson Imaging 2000;12(1):157–63.
[6] Brummett RE, Talbot JM, Charuhas P. Potential hearing loss resulting from MR imaging. Radiology 1988;169:539–40.
[7] International Electrotechnical Commission. Safety standard for MR systems. 3rd ed. 2010. IEC 60601–2–33.
[8] Edelstein WA, Hedeen RA, Mallozzi RP, El-Hamamsy SA, Ackermann RA, Havens TJ. Making MRI quieter. Magn Reson Imaging 2002;20:155–63.
[9] Katsunuma A, Takamori H, Sakakura Y, Hamamura Y, Ogo Y, Katayama R. Quiet MRI with novel acoustic noise reduction. MAGMA 2002;13:139–44.
[10] McJury M, Stewart RW, Crawford D, Toma E. The use of active noise control (ANC) to reduce acoustic noise generated during MRI scanning: some initial results. Magn Reson Imaging 1997;15:319–22.
[11] Hennel F. Fast spin echo and fast gradient echo MRI with low acoustic noise. J Magn Reson Imaging 2001;13:960–6.
[12] Hennel F, Girard F, Loenneker T. “Silent” MRI with soft gradient pulses. Magn Reson Med 1999;42:6–10.
[13] Pierre EY, Grodzki D, Aandal G, Heismann B, Badve C, Gulani V, et al. Parallel imaging-based reduction of acoustic noise for clinical magnetic resonance imaging. Invest Radiol 2014;49:620–6.
[14] Heismann B, Ott M, Grodzki D. Sequence-based acoustic noise reduction of clinical MRI scans. Magn Reson Med 2015;73:1104–9.
[15] Hedeen RA, Edelstein WA. Characterization and prediction of gradient acoustic noise in MR imagers. Magn Reson Med 1997;37:7–10.
[16] Holdsworth SJ, Macpherson SJ, Yeom KW, Wintermark M, Zaharchuk G. Clinical evaluation of silent T1-weighted MRI and silent MR angiography of the brain. AJR Am J Roentgenol 2018;210:404–11.
[17] Nakajima J, Kato K, Takahashi T, et al. Development of new system using bi-directional voice communication in the MRI noise environment. JART 2016;63:1521–8.
[18] Lu H, Nagae-Poetscher LM, Golay X, Lin D, Pomper M, et al. Routine clinical brain MRI sequences for use at 3.0 Tesla. J Magn Reson Imaging 2005;22(1):13–22.
[19] Mehan Jr. WA, González RG, Buchbinder BR, Chen JW, Copen WA, et al. Optimal brain MRI protocol for new neurological complaint. PLoS One 2014;9(10):e110803.
[20] National Electrical Manufacturers Association. Acoustic noise measurement procedure for diagnostic magnetic resonance imaging devices. NEMA Standards Publication MS–4. 2010.
[21] INTERNATIONAL ELECTROTECHNICAL COMMISSION. Electroacoustics-Sound level meters-Part 1: Specifications (IEC 61672-1). 2013. Geneva, Switzerland.
[22] Moelker A, Maas RA, Vogel MW, Ouhlous M, Pattynama PM. Importance of bone-conducted sound transmission on patient hearing in the MR scanner. J Magn Reson Imaging 2005;22:163–9.
[23] Miyati T, Banno T, Fujita H, Mase M, Narita H, Imazawa M, et al. Acoustic noise analysis in echo planar imaging: multicenter trial and comparison with other pulse sequences. IEEE Trans Med Imaging 1999;18:733–6.
[24] Bijur PE, Silver W, Gallagher EJ. Reliability of the visual analog scale for measurement of acute pain. Acad Emerg Med 2001;8:1153–7.
[25] Guimarães AC, Carvalho GM, Voltolini MM, Zappelini CE, Mezzalira R, Stoler G, et al. Study of the relationship between the degree of tinnitus annoyance and the presence of hyperacusis. Braz J Otorhinolaryngol 2014;80:24–8.
[26] Watanabe S, Takaue R, Yao F, Matsumoto Y, Tsukamoto H, Shirahama N, et al. Correlation between the subjective evaluation by using visual analog scale and heart rate variability analysis for the effects of the unpleasant sound. Biomed Soft Comput Human Sci 2012;14:19–26.
[27] Rasband WS. ImageJ. Bethesda, Maryland, USA: U. S. National Institutes of Health; 1997–2012http://rsb.info.nih.gov/ij/.
[28] The Japan Society for Occupational Health: recommendation of occupational exposure limits. J Occup Health 2018;60:441–2.
[29] Suzuki Y, Takeshima H. Equal-loudness-level contours for pure tones. J Acoust Soc Am 2004;116:918–33.
[30] Le Bihan D, Poupon C, Amadon A, Lethimonnier F. Artifacts and pitfalls in diffusion MRI. J Magn Reson Imaging 2006;24:478–88.