Analysis of Chemical Shift Artifacts Using the TSE Pulse Sequence and Bandwidth at MR Imaging

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Abstract - In order to experimentally analyze the artifacts of the chemical shift of water and oil, we made a phantom by mixing water and oil to change the turbo spin-echo (TSE) pulse sequence and various bandwidth (BW) and parameters. A phantom made of water and canola oil was prepared, and an eight-channel head coil of MRI 1.5 T and 3.0 T was used. The scan parameters were TR (5069 ms), TE (100 ms), water fat shift (0.999 and 1.891 pix) at 1.5 T and TR (3000 ms), TE (100 ms), and water fat shift (3.836 pix) at 3.0 T. In all sequences, a matrix (256×256), field of view (FOV) (240 mm), and slice thickness were scanned at 3 mm; the frequency direction was RL (right-left), and the BW was calculated using the Philips ACR Bandwidth Calculator. The images were analyzed by obtaining the plot profile and the Fourier transform image. The signal-to-noise ratio (SNR), peak signal-to-noise ratio (PSNR), mean square error (MSE), root mean square error (RMSE), and maximum absolute error (MAE) were calculated to evaluate the images according to the 1.5 T and 3.0 T BWs of MR. In order to compare the image of chemical shift artifact, the layer of the chemical shift artifact was larger than that of 1.5 T of BW 114.9 Hz compared to 217.5 Hz, and at 3.0 T, 113.2 Hz compared to 218.1 Hz, and chemical shift artifact. The spatial frequency changes due to the Fourier transform were 1.5 T and 3.0 T. The reference image (BW 55.7 kHz) and the test image (BW 29.4 kHz) had the SNR of 7.753 dB, PSNR of 22.869 dB, RMSE of 26.808, and MAE of 7.758 in the 1.5 T MRI. The reference image (BW 55.9 kHz) and the test image (BW 29 kHz) had the SNR of 17.79 dB, PSNR of 34.062 dB, RMSE of 33.401, and MAE of 5.971 in the 3.0 T MRI. The SNR and PSNR were measured at 1.5 T and 3.0 T when the BW parameter was changed. At the 1.5 T and 3.0 T MRI, there was a statistically significant difference (p-value < .05). The chemical shift artifacts occurred in the phantom of water and oil, and the artifact was less at 1.5 T than at 3.0 T, and the artifact decreased as the BW increased. In order to reduce the chemical shift artifact in MRI, it is considered appropriate to decrease the intensity of the field and to broaden the BW.

Key words : Chemical shift, MRI, Parameter, Pulse sequence, Turbo spin-echo

INTRODUCTION

Magnetic resonance imaging (MRI) is a method of generating images through mathematical processing on a computer by measuring the degree of difference in the signal generated in a tissue by resonating hydrogen nuclei in the tissue region. It is widely used as a diagnostic imaging device that facilitates the diagnosis of disease and the discovery of disease by utilizing it as information of physiology, anatomy, and pathology (Zhu *et al*. 2016). The protons of the hydrogen nuclei in the human body are almost coincident with the direction of the magnetic field when a magnetic field is applied from the outside. In such external magnetic field, when the hydrogen nuclei in the magnetized state emit a radio-frequency (RF) signal of a certain frequency, hydrogen

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nuclei of some low ground state absorb the high-frequency energy and enter a high-energy state (excited state). The phenomenon where a proton of hydrogen causing the excitation resonance returns to its original ground state with a low energy level is called relaxation, and a magnetic resonance signal is generated in the tissue of the human body at this time (Ann *et al*. 2017).

MRI is an important measurement instrument in clinical practice because it is not harmful to the human body and images the characteristics of the internal constituent material compared with other imaging diagnostic devices. The MRI apparatus can obtain tissue parameters such as spin density, T1, T2, chemical shift, spectroscopy, and blood flow, which are inherent in the information of a living body, and various biological information images can be obtained through these parameters. However, it is somewhat difficult to obtain accurate images in MRI because of the presence of fat and water components in living tissue. Fat and water induce T1 and T2 relaxation time differences in MRI, and depending on the sensitivity of the MR signals, artifacts occur in conventional MRI technique due to inadequate contrast and chemical shift. In particular, the detailed anatomical shape of a marginal part of the structures surrounded by fat is lost owing to the chemical migration phenomenon due to fat and water components, and the fat tissue of high signal intensity generates phase artifacts due to respiration.

Chemical shift artifacts are generally classified as artifacts caused by special waveforms externally applied in special environments owing to the inherent characteristics of MRI, improper image acquisition methods, malfunctions of the machine itself, and special or adjacent tissue characteristics. Therefore, in order to remove various artifacts, we should try to obtain accurate images by using the MRI parameter of turbo spin-echo (TSE).

In this study, a phantom was fabricated by mixing water and oil to analyze the artifacts of the chemical migration of water and fat. Using the parameterization of TSE pulse sequence and various bandwidth (BW) and frequency encoding, the chemical shift artifacts were studied experimentally.

THEORY

1. Chemical Shift

A water molecule forms an electron cloud around hydrogen atoms, oxygen atoms and oxygen atoms with strong electron affinity, and the fats combine with hydrogen atoms and carbon atoms and form electron clouds around hydrogen. Among these various artifacts, the chemical shift artifacts due to the different chemical environments of water molecules and fats were studied. The spectral frequency u of the chemical shift is expressed in units of Hz (1/sec). However, this unit has the inconvenience that it can change the frequency depending on the strength of the magnetic field, which is applied from outside, even for the same material. Therefore, the units expressed in terms of frequency are expressed in terms of ppm (parts per million), and the unit of a chemical shift is measured in terms of a relative value, in units of R, which does not depend on the strength of the magnetic field. This represents the degree of a chemical shift (δ) from the reference material and can be expressed using the following equation.

$$\text{Chemical shift}\,(\delta) = \frac{\nu_{\text{sample}} - \nu_{\text{ref}}}{\nu_{\text{ref}}} \times 10^6 \quad (1)$$

ν_{sample} is the absolute resonance frequency of the sample, and ν_{ref} is the absolute resonance frequency of a standard reference compound, measured in the same applied magnetic field B_0. Since the numerator is usually expressed in hertz, and the denominator in megahertz, δ is expressed in ppm.

The water molecule δ is 4.7 ppm and the fat δ is 1.2 ppm. Therefore, water molecules and fats have a chemical shift of 3.5 ppm in an external magnetic field of 1.5 T (resonance frequency of 60 MHz, f = 64 MHz) (3.5 ppm) [$(64 \times 10^6$ HZ) (3.5×10^{-6})]. That is, a high effective magnetic field larger than ^{1}H of water molecules. A chemical shift is a phenomenon that occurs owing to the difference in the shielding effect of the device field, which is generated by the type and number of electrons and adjacent nuclei around the nucleus, even though it is the same kind of nucleus. Therefore, if there is a tissue containing water around it, a black line appears on one side and a bright white line appears on the opposite side. These lines appear in the direction of frequency encoding. The higher the field strength of the magnet, the greater the chemical shift artifacts and the number of pixels shifted by the chemical shift is 1.5 Tesla.

$$224\ \text{Hz}/(\text{BW}/\text{Nx}) \quad (2)$$

BW is the bandwidth and Nx is the pixel size in the frequency encoding direction.

According to this equation, the larger the BW and the smaller the Nx values, the less the artifact due to the chemi-

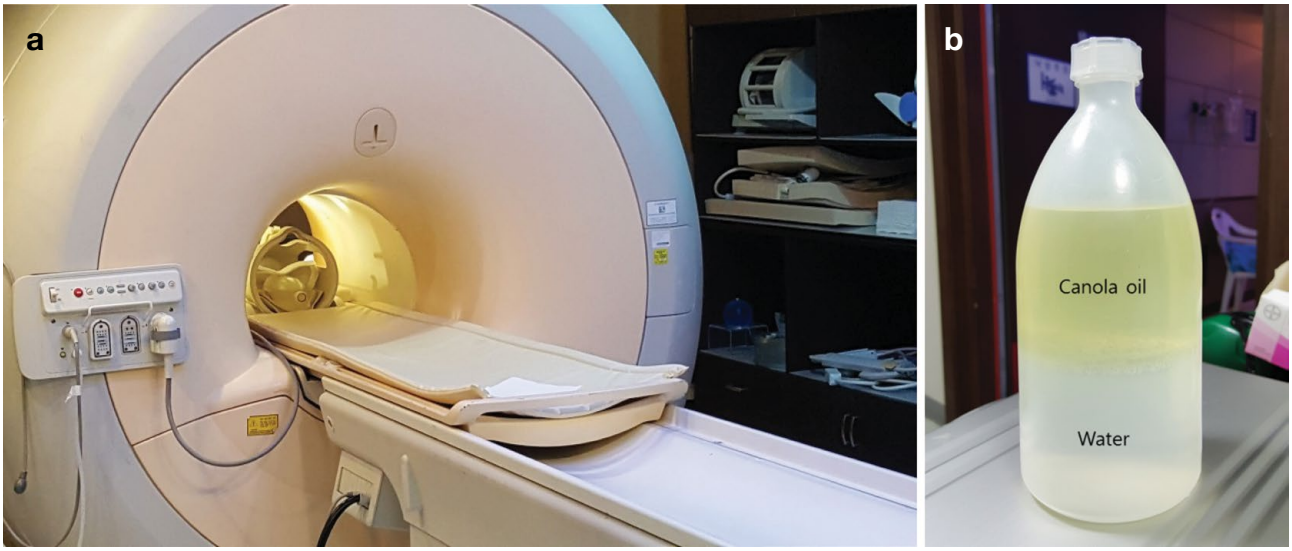

Fig. 1. MRI apparatus and water-canola oil phantom.

cal shift misregistration.

2. Evaluation of Imaging

The signal-to-noise ratio (SNR) and peak signal-to-noise ratio (PSNR) were calculated by dividing the signal intensity value in the tissue by the standard deviation of the signal intensity value of the background. The most commonly used objective data measures are the maximum absolute error (MAE), mean square error (MSE), root mean square error (RMSE), SNR, and PSNR. The SNR, PSNR, RSME, and MAE applied in this study are as follows (Ghrare *et al*. 2008; Gonzalez *et al*. 2008).

$$\mathrm{SNR} = \frac{\text{Signal intensity of region, surrounding tissues}}{\text{Standard deviation of noise in background}} \quad (3)$$

$$\mathrm{SNR} = 10\log\left\{\frac{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}(f*(i,j))^2}{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[f(i,j)-(f*(i,j))^2]}\right\}\mathrm{dB} \quad (4)$$

$$\mathrm{PSNR} = 10\cdot\log_{10}\left\{\frac{\max(r(x,y))^2}{\frac{1}{n_x n_y}\cdot\sum_{0}^{n_x-1}\sum_{0}^{n_y-1}[r(x,y)-t(x,y)]^2}\right\} \quad (5)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n_x n_y}\cdot\sum_{0}^{n_x-1}\sum_{0}^{n_y-1}[r(x,y)-t(x,y)]^2} \quad (6)$$

$$\mathrm{MAE} = \frac{1}{n_x n_y}\cdot\sum_{0}^{n_x-1}\sum_{0}^{n_y-1}|r(x,y)-t(x,y)| \quad (7)$$

MATERIALS AND METHODS

1. MRI Scanning

The phantom was prepared by mixing water and canola oil (Cheiljedang Co. Ltd., Seoul, Korea) to investigate the artifacts of the chemical shifts according to the parameter changes using the TSE pulse sequence of MRI. The phantom was scanned experimentally after a clean sterilized bottle was filled with 300 mL of both water and oil, and the water and oil separated in the bottle on keeping them at rest for about 5 min, as shown in Fig. 1. An image was examined using an eight-channel head coil using MRI 1.5 T and 3.0 T (Achieva, Philips Medical Systems, The Netherlands), and the frequency direction experimented with was right-left (RL). The sequence used for the test was a TSE pulse sequence. The scan parameters used in the TSE pulse sequence were TR (5069 ms), TE (100 ms) and water fat shift (WFS) 0.999 and 1.891 pix at 1.5 T (Table 1) (100 ms), and the WFS scanned at 3.0 T was 1.991 and 3.836 pix (Table 2). In all sequences, a matrix (256 × 256), field of view (FOV) (240 mm), and slice thickness were scanned at 3 mm. The BW applied to the TSE pulse sequence was calculated using the Philips ACR Bandwidth Calculator. The BW used for the phantom scan is shown in the following equation.

$$\text{ACR BW (kHz)} = \text{Philips BW (Hz)} \times \text{ACQ Measurement Matrix}/1000\,\text{Hz} \quad (8)$$

Table 1. MR imaging scanning parameters used in the TSE pulse sequence of 1.5 T MR

Pulse sequence	Water fat shift (pix)	Frequency* (Hz)	BW (kHz)	TR (ms)	TE (ms)	ACQ matrix	Slice thickness (mm)	FOV (mm)
TSE	0.999 1.891	217.5 114.9	55.7 29.4	5069 5069	100 100	256×256 256×256	3	240

*Frequency: Frequency difference between fat and water

Table 2. MR imaging scanning parameters used in the TSE pulse sequence of 3.0 T MR

Pulse sequence	Water fat shift (pix)	Frequency* (Hz)	BW (kHz)	TR (ms)	TE (ms)	ACQ matrix	Slice thickness (mm)	FOV (mm)
TSE	1.991 3.836	218.1 113.2	55.9 29	3000 3000	100 100	256×256 256×256	3	240

*Frequency: Frequency difference between fat and water

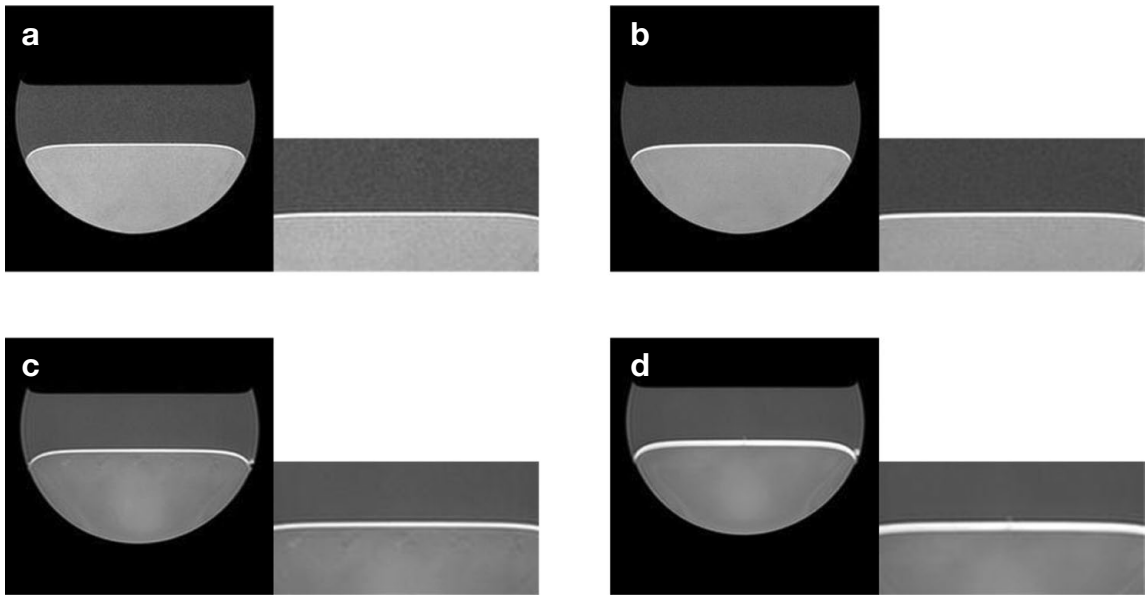

Fig. 2. TSE pulse sequence image and the magnified images at 1.5 T with the BW of 207.5 Hz (a) and 114.9 Hz (b), and at 3.0 T with the BW of 218.1 Hz (c) and 113.2 Hz (d) of the canola oil phantom.

2. Imaging Analysis

In order to analyze the chemical shift artifacts quantitatively, the image profile was analyzed using the ImageJ program (NIH, Bethesda, MD, USA) to obtain the plot profile and the Fourier transform image. The PSNR, RMSE, RMSE, and MAE were calculated to evaluate the images according to the 1.5 T and 3.0 T BWs of MR.

3. Statistical Analysis

Statistical significance was set at $p < .05$ using SPSS (Version 21, IBM Corp., NY, USA) for statistical processing of data according to the TSE pulse sequences.

RESULTS

In order to compare the image of the chemical shift artifact, the layer of the chemical shift artifact was larger than that of 1.5 T of BW 114.9 Hz compared to 217.5 Hz, and at 3.0 T, 113.2 Hz compared to 218.1 Hz, and chemical shift artifact (Fig. 2). The spatial frequency changes due to the Fourier transform were 1.5 T and 3.0 T (Fig. 3).

In the ImageJ program, there was a difference in gray value between the chemical shifts at 1.5 T and 3.0 T (Fig. 4). The SNR, PSNR, RMSE, and MAE values were obtained using the ImageJ program in order to evaluate the scanned MR images by a quantitative evaluation method. The ref-

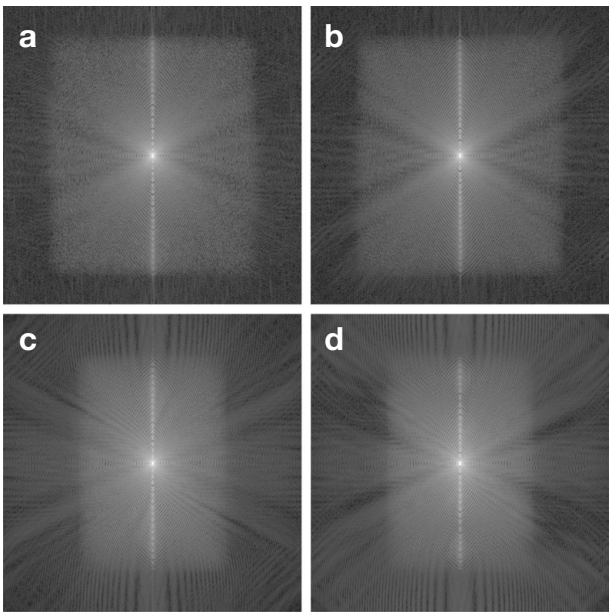

Fig. 3. Fourier transform of the TSE imaging. All spatial frequency information necessary to create this MR image is stored in the Fourier space of 1.5 T with the BW of 207.5 Hz (a) and 114.9 Hz (b), and 3.0 T with the BW of 218.1 Hz (c) and 113.2 Hz (d) in the canola oil phantom.

erence image (BW 55.7 kHz) and the test image (BW 29.4 kHz) had the SNR of 7.753 dB, PSNR of 22.869 dB, RMSE of 26.808, and MAE of 7.758 in the TSE pulse sequence scan image at with the magnetic field strength of 1.5 T (Table 3). The reference image (BW 55.9 kHz) and the test image (BW 29 kHz) had the SNR of 17.79 dB, PSNR of 34.062 dB, RMSE of 33.401, and MAE of 5.971 in the TSE pulse sequence with a magnetic field strength of 3.0 T (Table 4). The SNR and PSNR were measured at 1.5 T and 3.0 T when the BW parameter was changed (Fig. 5). At 1.5 T and 3.0 T, there was a statistically significant difference (p-value $< .05$) between the SNR and PSNR with parameter changes.

DISCUSSION

In this study, we experimented to observe the chemical shift artifact. When MRI was performed by mixing water and oil, it was confirmed that the artifact occurred at the interface. In addition, we can confirm that the artifact is reduced when the main field strength is lowered and the BW is widened. Although there were various frequency encoding directions, in this experiment, only the part that performed in the RL direction was used as an unsatisfactory point, and it was also unsatisfactory that the quantitative evaluation was different but the qualitative evaluation was not significantly different. Chemical shift artifacts are artifacts caused by a frequency difference. If an equipment with a low main magnetic field is used, the frequency difference between fat and water is higher and the image is improved in terms of artifacts than when using an equipment with a stronger magnetic field.

MRI has difficulties in capturing accurate images because of the presence of fat and water components in living tissue, and it causes artifacts. Fat and water induce time differences in MRI and generate artifacts of inadequate contrast and chemical mobility, depending on the sensitivity of the MRI signal. This phenomenon of chemical migration causes the loss of the anatomical shape of the structure surrounded by fat, and the fat tissue of high signal intensity generates phase artifacts due to respiration, making it difficult to draw images for an accurate diagnosis (Zhu *et al*. 2016).

The TSE (also called fast spin-echo), which is commonly used in MRI, is a pulse sequence technique preferred by many radiologists for abdominal examination (Keogan *et al*. 2001; Ward *et al*. 2006). Breath-hold TSE and breath-hold HASTE images are used as an option to reduce the respiratory tract. Artifacts and short acquisition times or other approaches, such as respiratory triggering, enhance the TSE technology with a high spatial resolution, can improve the detection of lesions, and have been applied to the abdomen and respiration (Kanematsu *et al*. 1999; Pauleit *et al*. 2001).

In this study, by using MRI to experimentally study the artifacts of chemical migration, it was confirmed that the artifacts occur at the interface, where water and canola oil are mixed. In the same way as the theoretical part, it was confirmed that the artifacts were reduced when the main field strength was lowered and the width of the BW was widened. There were various frequency coding directions, and there was a difference in quantitative evaluation, but there was no significant difference in qualitative evaluation.

The artifacts of chemical migration are artifacts that occur more often under higher magnetic fields. Magnetic resonance spectroscopy of the human body by using the chemical transfer effect provides a lot of diagnostic information, but the quality of the image is deteriorated in the anatomical diagnosis. It is an artifact that occurs in the phase or frequency direction and is generated only in the gradient echo pulse sequence. The chemical transfer artifacts were more severe at 3.0 T than at 1.5 T (Goo *et al*. 2016). As a method

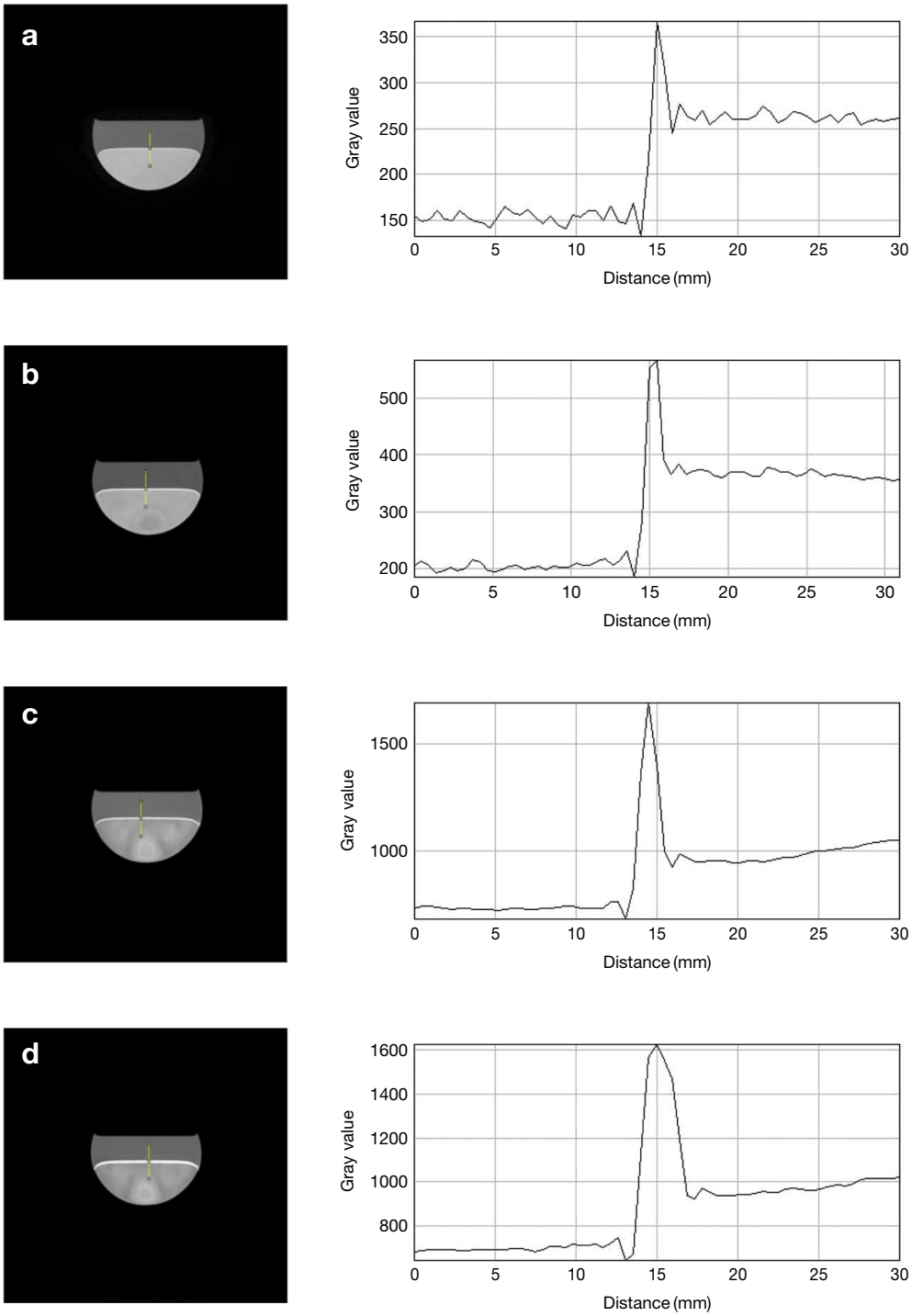

Fig. 4. Plot profile of the TSE imaging at 1.5 T with the BW of 207.5 Hz (a) and 114.9 Hz (b), and at 3.0 T with the BW of 218.1 Hz (c) and 113.2 Hz (d) in the canola oil phantom.

Table 3. SNR, PSNR, RMSE and MAE in the TSE pulse sequence of 1.5 T MRI

Reference image	Test image	SNR (dB)	PSNR (dB)	RMSE	MAE
BW (55.7 kHz)	BW (29.4 kHz)	7.753	22.869	26.808	7.758

$p < .05$

Table 4. SNR, PSNR, RMSE and MAE in the TSE pulse sequence of 3.0 T MRI

Reference image	Test image	SNR (dB)	PSNR (dB)	RMSE	MAE
BW (55.9 kHz)	BW (29 kHz)	17.79	34.062	33.401	5.971

$p < .05$

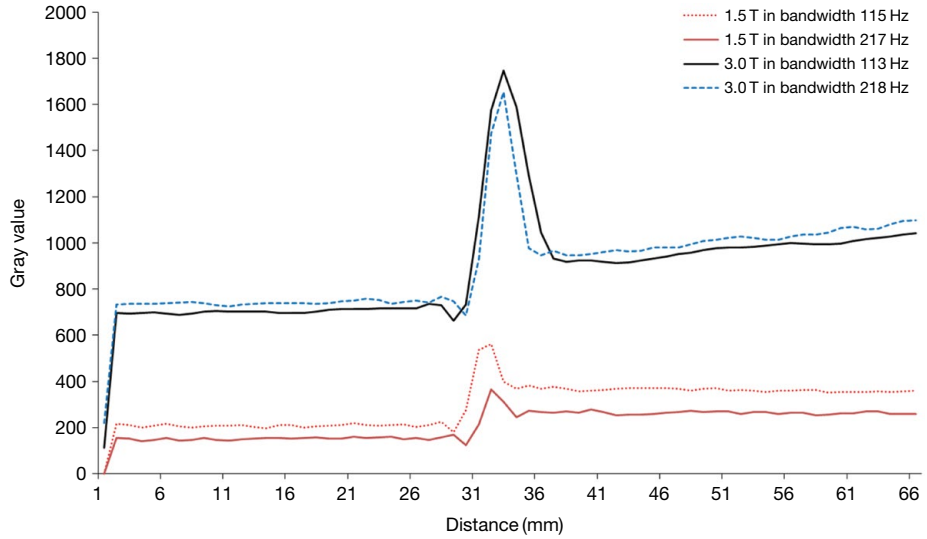

Fig. 5. Plot profile of the TSE pulse sequence of gray value and distance in the 1.5 T and 3.0 T difference in BW using the canola mixed water phantom.

of preventing the artifacts of chemical migration, fat and water are generated owing to different car wash frequency, so a fat suppression technique or a low magnetic field should be used.

The amount of chemical shift is often expressed in arbitrary units known as parts per million (ppm) of the main field strength. This value is always independent of the main field strength and is about 3.5 ppm for fat and water, but the car wash frequency is proportional to the run length B_0 (e.g., the car wash frequency difference at 1.5 T is 224 Hz). That is, the fat wash is 224 Hz lower than water. At 1.0 T, this difference is 147 Hz at a lower field strength (less than 0.5 T) and is generally not important. Chemical shift similar to changes in susceptibility, the chemical shifts measured in ppm are linearly proportional to the chemical shifts measured in hertz, independent of the field strength.

$$\text{Chemical shift [measured in Hz]} \propto B_0 \quad (9)$$

Water resonates at a Larmor frequency of about 3.3~3.5 ppm higher than lipid. This corresponds to about 140~150 Hz per tesla. A range of frequencies occurs because the geological resonance is relatively large with its multiple components being short T2. Therefore, water at 3.0 T is about 420~440 Hz higher than fat at Larmor frequency (Goo 2016). Since MRI has both fat and water components in living tissues, the chemical shift selective saturation (CHESS) technique is used in clinical applications to obtain accurate images. Prior to applying the MR pulse, an RF-frequency pulse is applied to selectively excite only water or fat to acquire only one component (Antoine *et al*. 2000; Cabanes *et al*. 2001). The chemical shift refers to the change in the resonance frequency depending on the bonding type of electrons. In the image, the signal of fat tissue shifts toward the tissue containing water in the frequency encoding direction, one side shows a black signal and the other side shows the signal of fat and water. The resonance frequency of the fat CH_2 group is 3.5 ppm less than the resonance frequency of the -OH group of water, so the chemical shift of fat and water is approximately 223 Hz in case of a magnetic field of 1.5 T. When the frequency band of a pixel is set to approximately 120 Hz, the boundary between fat and water can be seen to move in the frequency direction by about two pixels. The degree of movement gets more remarkable as the frequency band is narrowed or the run length is increased. Chemical shifts have been applied clinically by using in-phase and out-of-phase (Henrick *et al*. 1997; Ragab *et al*. 2009). Currently, it is applied to diagnosis of tumor and embolism in clinical practice. Therefore, it is necessary to apply and study the artifacts of chemical movement, so that artificial oil and water are mixed and experimentally applied various parameters of MRI experimentally as a phantom (Douis *et al*. 2016; Priolaa *et al*. 2016). Therefore, in order to reduce the chemical artifacts in the 1.5 T and 3.0 T MRI scan of the chemical shift runners weak field strength, it is thought to be appropriate to widen the width of the BW (Kweon 2016).

PSNR is a measure of image quality. It shows that there is a difference between images under 1.5 T (22.869 dB) and 3.0 T (34.062 dB). Most MR images are limited by the SNR in the reconstructed MR image. Particularly, when the SNR increases by 20 dB or more, it is not clinically important for the analysis of MR imaging (Hayes *et al*. 1990; Roemer *et al*. 1990). The gain rate of the image increases and therefore is used to reduce the image cost and motion. If the SNR is more than 20 dB, there is no difference in image quality (Masuda *et al*. 2001). The MSE is expressed as the square of the pixel difference, and the larger the distortion, the larger the value is. The square root of this MSE is expressed as the pixel error magnitude with the RMSE and is useful for comparing the scales of objective image quality. The RMSE increased to 1.5 T (26.808) and 3.0 T (33.041) as the magnetic field strength was increased.

The artifacts of chemical migration are artifacts caused by frequency difference. If an equipment with a low intensity of the main magnetic field is used, the frequency difference between fat and water is better than when using an equipment with stronger intensity.

The limitations of the study on the artifacts of chemical migration of water and oil are as follows. First, it is necessary to measure the image quality by using various pulse sequences. Second, the artifacts of chemical migration using the BW and various parameters should be studied.

CONCLUSION

The occurrence of chemical shift artifacts was observed in images scanned with the TSE pulse sequence using a phantom consisting of mixed water and oil. We can confirm that the artifact is relatively smaller at 1.5 T than at 3.0 T. In addition, we can confirm that the artifact decreases as the width of bandwidth increases in each parameter. Therefore, in order to reduce the chemical shift artifact in MRI, it is considered that the intensity of the magnetic field is weakened and the bandwidth is broadened.

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