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Accuracy Confirmation of the Compress-Sensing Technique in the TOF MRA Test using Flow Phantom

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This study evaluated the effects of applying the compress-sensing technique and the increase of the CS factor on the quality of the image in the test using the time-of-flight sequence. A 3D TOF MRA test was performed while maintaining a constant flow rate (2.0 ml/sec) by connecting an auto-injector to a self-fabricated flow phantom. Images were obtained by applying the 3D TOF sequence without CS and with CS to evaluate the difference in image quality with or without application of the CS technique. Moreover, in order to analyze the quality of images according to the CS factor, images were obtained while increasing the CS factor from 1.2 to 1.8 by 0.2. The examination time was 44 seconds when the CS technique was not used. When the CS technique was applied, the examination time decreased to 30, 27, 25, and 23 with the CS factor of 1.2, 1.4, 1.6, and 1.8, respectively. On the other hand, the application of the CS technique did not change the SNR or the CNR of the image significantly ($p > 0.05$). Moreover, the SNR and the CNR of the image were not significantly affected by the changes in the CS factor ($p > 0.05$). However, as the CS factor increased, the similarity and precision decreased more than in the images where the CS technique was not used. The application of the CS technique to the TOF MRA test can reduce the examination time drastically without changing SNR and CNR. However, we found that, as the CS factor increased, the similarity and precision decreased more than in the test without the CS technique. Therefore, it is necessary to continuously verify the effectiveness of the CS technique and study it more.

Keywords : magnetic resonance imaging, compressed sensing, parallel imaging, Time of Flight MRA

1. Introduction

Cerebrovascular disease (*e.g.*, arteriosclerosis and vascular occlusion) has been increasing rapidly because of the increased cholesterol in the blood vessel owing to a fatty diet and smoking, which results in angiostenosis [1]. Angiography and computed tomography (CT) have been used to evaluate cerebrovascular disease. However, their applications are limited by the invasive nature of the radiation exposure. On the other hand, cerebrovascular imaging using magnetic resonance imaging (MRI) is non-invasive and free from radiation exposure. Furthermore, it can provide rich information on diseases because it offers high-resolution images. Particularly, the time of flight (TOF) MRA test method has an advantage in presenting blood-flow information without using a contrast medium, because it uses the flow related signal enhancement. time-of-flight (TOF) MRA is the dominant non-contrast enhanement bright-blood method for imaging the vascular system [2]. Therefore, it is useful for patients who suffer from side effects of the contrast medium or have decreased renal function. However, the TOF MRA test takes longer than other methods, because it reconstructs images through repetitive resonance and position encoding for each direction. The long examination time of MRI not only is inconvenient for patients but also maximizes the effects of motion. Therefore, these factors greatly affect the quality of the image and may decrease its sensitivity and specificity [3]. In order to solve these shortfalls, various methods, such as Fast spin echo, parallel imaging,

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and the synthetic technique, have been devised and used in clinical practice [4-9]. Nonetheless, the long examination time of MRI still causes issues. Particularly, the TOF technique, providing information on the flow of blood in vessels, is more sensitive to the motions by patients than are other sequences. Consequently, it is urgently needed to shorten the examination time. However, because the TOF MRA is based on a gradient sequence, it is not easy to incorporate other test techniques (*e.g.*, Fast spin echo and synthetic) except for parallel imaging. Therefore, there are only limited ways to reduce the examination time. Recently, however, compress sensing(CS) has been incorporated into the TOF MRA test in order to reduce the examination time. It is a way to sample data randomly based on parallel imaging (PI) and to remove noise by using a denoising algorithm. It can reduce the examination time much more than the conventional methods can [10-12]. However, the quality of images has not been verified enough, because the problems that may occur while obtaining missing data and removing noise are not standardized. Also, it is an important topic regarding how accurately the CS technique can express the non CS technique. Therefore, the objective of this study was to evaluate the effects of applying the CS technique and increasing the CS factor by making a phantom that can show the blood flow in vessels.

2. Materials and Method

2.1. Basic principles of the CS technique

One must sample more than twice the maximum input signal frequency in order to restore the original analog signal from the quantized digital data. However, under certain conditions, such as frequency or wavelet domain, a complete signal can be reconstructed without sampling more than twice data, as suggested by Nyquist theory [13, 14]. The frequency signal is sparse, so only the coefficient of a portion of the signal has a non-zero value, and the rest of the signal has a zero value. Therefore, when the signals obtained from the time domain are transformed into the frequency domain through the Fourier transform, most of the signals have zero values, and only a few show sparse signals, not zero. Therefore, it is possible to compress the sparse signals that present coefficient values and thus reduce the examination time. The sparse signal has the inherent characteristic that it can be restored completely. The CS technique is to restore the minimum frequency-domain data obtained from magnetic resonance imaging to the fully sampled data, which can be expressed as follows [15-18]:

$$y = \phi x \tag{1}$$

where y represents the missing data of the frequency domain obtained from magnetic resonance imaging and x indicates the restored data to acquire k-space fully based on y. Equation 1 can be solved as follows.

$$\text{Minimize } \|\psi_x\|_0, \text{ subject to } \|\partial - \phi_x\|_2 \le \varepsilon \tag{2}$$

where ψ, ∂, and ϕ represent the sparsifying transform, the measured vector value, and the CS measurement matrix, respectively; ε is related to signal and noise levels [19].

2.2. Configuration of Phantom

A circular acrylic cylinder was perforated in order to express the flow, and a sheath was placed through the hole. The space not occupied by the sheath was filled with physiological saline. One end of the sheath was connected to the extension line to be connected to the auto-injector device (Fig. 1).

2.3. Image Acquisition Method

The saline was injected into the flow phantom using the

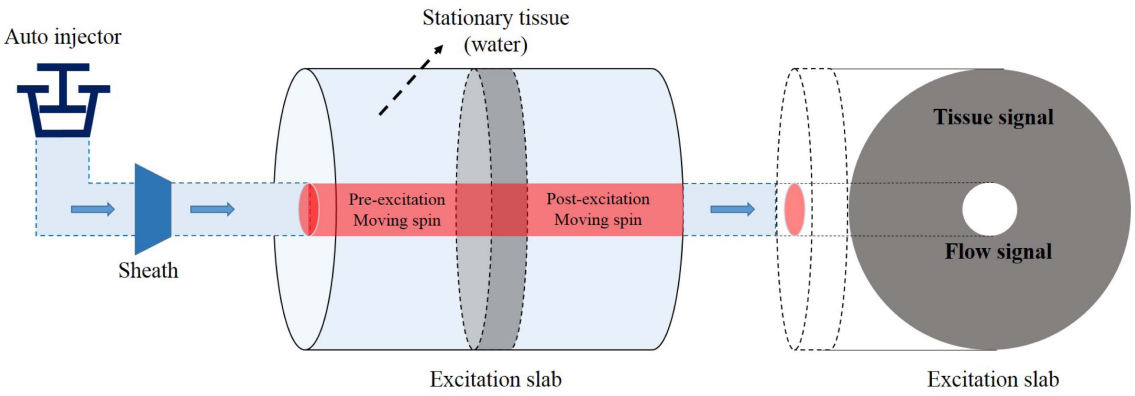

Fig. 1. (Color online) Flow phantom diagram; The pre-excitation moving spin is before RF pulse and the post-excitation moving spin is after RF pulse.

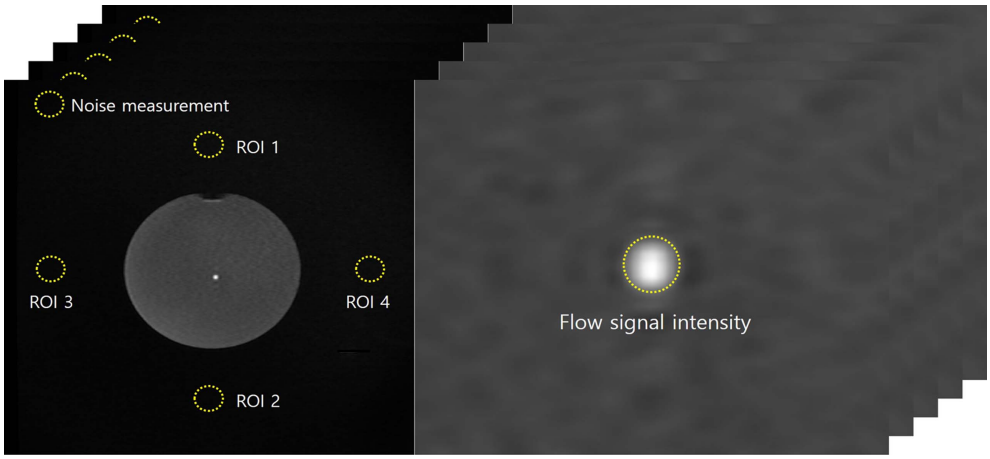

Fig. 2. (Color online) Flow Signal intensity and ROI 1 to 4 is noise standard deviation measurement; Multiple acquisition method.

auto-injector device, and the cross section of the phantom was inspected using the TOF MRA technique (Fig. 2). The flow rate was set at 2.0 ml/sec (120 ml/min), which is similar to the mean blood-flow rate of the middle cerebral artery (MCA) [20]. Moreover, the temperature of the laboratory was maintained at 20-22 °C in order to minimize the difference in the net magnetization vector shown by the Boltzmann equation.

$$N_+/N_- = \exp\left(-\frac{\Delta E}{kT}\right) \tag{3}$$

ΔE : energy difference between up and down spin states
k : Boltzmann's constant (1.38×10^{-34} J/K)
T : temperature in Kelvin (K)
N_+ (N_-): number of protons with up (down) spin

3.4. MR Equipment and Parameter

The 3.0T MR system (Discovery 750, GE Medical System, Milwaukee, WI, USA) with a 32-channel head coil was used for obtaining the MRI. The MR contrast-delivery system (SONIC SHOT 7, Nemoto Kyorindo Co., Tokyo, Japan) was used for the auto-injector device. The 3D TOF with and without CS was used to evaluate the difference in image quality according to whether the CS technique is used or not. For the TOF with CS, images were obtained while increasing the CS factor from 1.2 to 1.8 by 0.2 steps to analyze the difference in image quality that depends on the CS factor, while all other variables were fixed (Table 1).

2.5. Statistical Analysis

Signal to noise ratio (SNR), Contrast to noise ratio (CNR), Structural similarity (SSIM), and Root mean square error (RMSE) were used to evaluate the quality of the acquired images quantitatively. The SNR and CNR of the obtained images were tested by the use of the CS technique and the increase of the CS factor. An independent sample t-test was conducted to analyze the difference in SNR and CNR when using the CS technique. ANOVA was conducted to examine the difference in SNR and CNR that resulted from the increase of the CS factor in TOF with CS. The SPSS program (ver.24, SPSS, Inc., Chicago, USA) was used for the analyses, and a $p < 0.05$ was considered statistically significant.

2.5.1. SNR and CNR analysis

SNR was measured by drawing Region of interest (ROI) in Digital imaging and communications medicine (DICOM) file, which was obtained with a flow phantom, using a GE workstation (version 2016b, MathWorks, Natick, MA, USA). SNR was the ratio of the signal intensity, measured on the cross section of the blood flow, to the background noise Standard deviation (SD), measured at the four points of the image cross-section (*i.e.*, up, down, left, and right) (Fig. 2).

We were performed multiple acqusitin method for SNR measurement. The multiple acquisition method is given by

$$\text{SNR} = \frac{S_t}{\sigma_t} \tag{4}$$

Where S_t is the average signal, σ_t is the standard deviation of the signal measured from multiple images acquired over time.

CNR was calculated by dividing the difference between the signal intensity of the blood flow and that of the around fixed tissue by background noise SD.

$$[\text{CNR} = SI_{flow} - SI_{static\ tissue}/\sigma_{background}] \tag{5}$$

Where SI_{flow} is the moving flow signal intensity and the $SI_{static\ tissue}$ is the static tissue signal intensity, $\sigma_{background}$ is

the background noise standard deviation.

2.5.2. Similarity and Precision Evaluation

The similarity and the precision were evaluated by measuring the structural similarity index metric (SSIM) and root-mean-square error (RMSE) of the TOF with CF while increasing the CS factor based on the TOF without CS by using the ICY program ver.1.9.5.1 (http://icy.bioimageanalysis.org). It is possible to estimate the luminance, contrast, and structure of the image by using the mean, standard deviation, and covariance (Eq. 6-8) [21].

$$\alpha(x, y) = \frac{2\mu_x\mu_y + C_1}{\mu_x^2 + \mu_y^2 + C_1} \quad (6)$$

$$\beta(x, y) = \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2 + \sigma_y^2 + C_2} \quad (7)$$

$$\gamma(x, y) = \frac{\sigma_{xy} + C_3}{\sigma_x\sigma_y + C_3} \quad (8)$$

SSIM is a way to measure the similarity against the reference image to the generated distortion. It can be calculated as shown in Eqs. (9-10):

$$\mathrm{SSIM}(x, y) = [\alpha(x, y)\}^{\alpha} \cdot [\beta(x, y)\}^{\beta} \cdot [\gamma(x, y)\}^{\gamma} \quad (9)$$

$$\mathrm{SSIM}(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \quad (10)$$

RMSE is the standard deviation of the residual. It shows the precision of the image by comparing each pixel value of a target image with that of the reference image (Eq. 11) [22].

$$\mathrm{RMSE} = \sqrt{\frac{1}{m \cdot n}\Sigma_{i=0}^{m-1}\Sigma_{j=0}^{n-1}[I(i, j) - U(i, j)]^2} \quad (11)$$

Table 1. MR imaging parameter.

	3D TOF sequence	
	Without CS	With CS
TR/ TE (ms)	24 × 2.7	24 × 2.7
FOV (mm)	240 × 180	240 × 180
Slincethickness/gap (mm)	1.2 / 0.0	1.2 / 0.0
Acquisition matrix	384 × 224	384 × 224
ETL	8	8
BW (Hz/pixel)	31.25	31.25
CS factor	-	1.2, 1.4, 1.6, 1.8
Scan time (sec)	44	30, 27, 25, 23

Note) CS; Compressed sensing, ETL; Echo train length, BW; Bandwidth.

3. Result

3.1. Examination Time, SNR, and CNR

The examination time of the TOF without CS was 44 seconds, whereas the TOF with CS decreased to 30, 27, 25, and 23 seconds when the CS factor was 1.2, 1.4, 1.6, and 1.8, respectively (Table 1). The SNR and the CNR of the image for TOF without CS were 77.07 ± 11.16 and 59.04 ± 21.19, respectively. Those of the image for TOF with CS were 80.35 ± 8.22 and 54.93 ± 13.94, respectively (Table 2).

3.2. Statistical Analysis

The results of the independent sample *t*-test showed that using the CS technique did not change the SNR or CNR of images significantly ($p > 0.05$) (Table 2). The SNR of the obtained images under the TOF with CS was 78.35 ± 10.00, 80.75 ± 6.85, 81.36 ± 7.34, and 80.94 ± 8.77 when the CS factor was 1.2, 1.4, 1.6, and 1.8, respectively. The CNR of obtained images under the TOF with CS was 55.10 ± 15.04, 54.49 ± 13.11, 55.69 ± 13.94, and 54.46 ± 14.94 when the CS factor was 1.2, 1.4, 1.6, and 1.8,

Table 2. SNR, CNR values for 3D TOF images of the phantom without and with CS.

3D TOF squence	SNR	CNR	*F*	p	F^*	p^*
Without CS	77.07±11.16	59.04±21.19	3.609	0.189	6.88	0.471
With CS	80.35±8.22	54.93±13.94				

Note) *F*. p, *F*, p^* is without CS and with CS SNR and CNR independent t-test.

Table 3. SNR and CNR values of the phantom according to the CS factor increase.

With compress sensing	SNR	CNR	*F*	p	F^*	p^*
CS factor 1.2	78.35±10.00	55.10±15.04	0.424	0.737	0.026	0.994
CS factor 1.4	80.75±6.85	54.49±13.11				
CS factor 1.6	81.36±7.34	55.69±13.94				
CS factor 1.8	80.94±8.77	54.46±14.94				

Note) *F*. p, F^*.p is the SNR and CNR average comparison between CS factor 1.2 ~ 1.8 for the ANOVA test.

Table 4. SSIM and RMSE values for 3D TOF with CS images of the flow phantom.

TOF sequence		SSIM	RMSE
Without CS	With CS (CS factor 1.2 ~ 1.8)		
Reference	CS _1.2	0.895	5.786
	CS _1.4	0.891	6.827
	CS _1.6	0.887	7.920
	CS _1.8	0.882	9.222

respectively. The results showed that there were no significant ($p > 0.05$) differences among the SNR and CNR values of the phantom according to the CS factor increase (Table 3).

3.3. Similarity and Distortion

The similarity and precision of the images for TOF with CS were analyzed by increasing the CS factor based on the TOF without CS. SSIM was 0.895, 0.891, 0.887, and 0.882 when the CS factor was 1.2, 1.4, 1.6, and 1.8, respectively. RMSE was 5.786, 6.827, 7.920, and 9.222 when the CS factor was 1.2, 1.4, 1.6, and 1.8, respectively (Table 4).

4. Discussion

MRI is being used more and more in clinical practice because it can express various contrasts based on diverse unique factors of the tissue and can provide high-resolution imaging better than other examination equipment can. However, the movement of a patient generates an artifact, which deteriorates the quality of the image. In other words, the examination time needed for MRI is an important factor that can potentially affect the quality of the image. The methods actively used in clinical practice to reduce the examination time include techniques for regulating image parameters (*e.g.*, TR, phase encoding number, and NEX), which are directly related to the examination time, and the PI technique, which reduces the examination time by filling a portion of the k-space and reconstructing the image [23-25]. In addition, the CS technique has been applied to clinical practice recently. It obtains information by using a random-sampling method that transforms data into noise and then removes the noise by repeating a denoising algorithm [26-28]. Particularly, the CS technique can reduce the examination time drastically compared to the conventional method because it is used together with the PI technique. However, it may increase the distortion of the signal, by missing more data because of the reduced examination time. Especially, it may cause another issue, because the parameter of the phase displacement caused by the blood flow is added in the MRA test. This study aimed to evaluate the effects of the CS technique and the effects associated with the increase in the CS factor in the 3D TOF technique by using the self-fabricated flow phantom. The results showed that using the CS technique reduced the examination time up to 23 sec out of 44 sec (approximately 48 %), but neither the SNR nor the CNR was significantly changed ($p > 0.05$). Moreover, even when the CS factor was increased from 1.2 to 1.8 by 0.2 steps, the SNR and the CNR were not changed ($p > 0.05$). The results indicated that using the CS technique could shorten the examination time without deteriorating the diagnostic value, and the increase of the CS factor had no effects on the TOF MRA test. The similarity between the TOF with CS and the TOF without CS was evaluated by varying the CS factor. When SOMETHING of the TOF without CS was set as 100 %, the SSIM of the TOF with CS decreased by approximately 12 % when the CS factor was changed from 1.2 to 1.8. The results indicated that the similarity between the two tests decreased with a larger CS factor. The precision between the TOF with CS and the TOF without CS was examined by varying the CS factor. The RMSE of the two methods increased to 9.222 from 5.786 when the CS factor was increased from 1.2 to 1.8, showing that the increased CS factor decreased the precision. This result indicated that the changes in the CS factor decreased the precision. In other words, as the CS factor increases, the similarity can be degraded slightly, and the precision can be decreased greatly, which can lower the quality of the image. Many studies have been carried out to apply the CS technique to the TOF sequence in order to reduce the examination time. Miles *et al.* (2010) reported that they conducted an MRA test using 7Tesla MRI equipment with applying the CS technique and could achieve acceptable image quality with very low sampling [29]. Yamamoto et al. (2018) compared the test using only the PI technique to a test using the PI technique and the CS technique for the MRA test using the 3D TOF. They argued that the CS technique could reduce the examination time without deteriorating the spatial resolution for diagnosing Moyamoya vascular disease [30]. However, most of the previous studies could not consider the image distortion, because of the susceptibility of the human body and the pulsation phase shift of the blood flow, caused by the continuous heart rate, because they were mostly conducted using the human body. However, this study could minimize the influence of the pulsation phase shift by using the self-fabricated flow-phantom to eliminate the effects of magnetization susceptibility and

using an auto-injector to maintain constant flow velocity. Additionally, the accuracy of the CS technique was improved by applying the CS factor. The limitation of this study is that it cannot be validated for blood flow that is faster or slower than 2.0 ml/sec, because it evaluated only a blood-flow velocity of 2.0 ml/sec, which is the mean blood-flow velocity of the MCA.

5. Conclusion

Applying the CS technique to the TOF MRA test can reduce the examination time drastically without changing SNR and CNR. Moreover, when the CS technique was applied, there was no difference in SNR or CNR even when the CS factor was increased. However, we found that, as the CS factor increased, the similarity and precision decreased more than in the test without the CS technique. Therefore, we need to continue to verify the effectiveness of the CS technique and to study that technique more.

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