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DWI based thermometry: the effects of b-values, resolutions, signal-to-noise ratio, and magnet strength*

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Abstract— **Among MR methods, the most clinically applicable temperature measurement method at deep brain might be the diffusion-weighted image (DWI) thermometry. Although only applicable to cerebrospinal fluid (CSF), it is thought to be potentially useful in assessing the thermal pathophysiology of the brain in both patients and healthy subjects. The purpose of this study was to investigate the effects of b-value, pixel resolution, magnet strength and signal to noise ratio (SNR) for the DWI-thermometry with healthy volunteer. Formerly, an ADC from b=0 and b=1000 has been thought to be useful for diffusion thermometry, this study revealed b=200 to 800 was more appropriate for DWI thermometry. The SNR was strongly affected the results of DWI thermometry.**

I. Introduction

Noninvasive MRI based thermometry techniques have been proposed [1, 2, 3, 4, 5]. Among these MR methods, the most clinically feasible one might be the diffusion-weighted image (DWI) thermometry [4, 5]. Although only applicable to cerebrospinal fluid (CSF), the DWI thermometry is thought to be potentially useful in assessing the thermal pathophysiology of the brain in both patients [6, 7] and healthy subjects [5]. In spite of the DWI thermometry has shown its potential to be the clinical application, there are still remaining unclear parameters for to be a stable thermometry, such as the effects of subjects, magnetic resonance image (MRI) acquisition, and data processing.

The purpose of this study was to investigate the appropriate b-value, pixel resolutions, the affection of signal to noise ratio (SNR), and magnet strength among the MR acquisition parameters for the stable DWI-thermometry with healthy volunteer by conventional MRI machines.

II. Methods

A. Subjects

The DWI data of three healthy subjects (aged 34-46 years, mean 41.0 years ± 6.2 SD) were acquired for thermometry. The study was approved by the Ethics Committee of Kyoto University.

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B. Data acquisition

MR examinations were performed on both a 1.5 Tesla and a 3 Tesla whole body imagers (Siemens Medical Solutions, Erlangen, Germany). The DWI was done with an image acquisition time of approximately 3 minutes for one b-value. A single-shot echo-planar imaging technique was used for DWI (TR/TE = 6000/88 ms, PAT mode was GRAPA, acceleration factor was 3) with a b-value of 0, 200, 400, 600, 800, 1000, and 1200 s/mm^2 and image averaging of 2 times. Motion sensitizing gradients were applied to 12 directions. A total of 40 sections were obtained with a thickness of 3 mm without intersection gaps (AC-PC aligned). The FOV was 200 x 200 mm^2 and the resolutions were 1.8 x 1.8 mm^2 and 1.25 x 1.25 mm^2.

C. Temperature calculation

The temperature was calculated by the following equation[4];

$$T_i = \frac{2256.74}{\ln\left(\frac{4.39221}{D_i}\right)} - 273.15 \qquad (1),$$

where D [mm^2/s] is the diffusion coefficient which is obtained from DWI measurement [5]. The mean ventricular temperature was calculated by two histogram curve-fitting method [9]. The lateral ventricle (LV) area was manually segmented on b=0 images (by KS) and confirmed by a radiologist (RS). As a reference, we used the sublingual temperature (electric thermometer, OMRON DALIAN CO LTD. MC-9018, Kyoto, Japan), which is known to be approximately 1ºC lower than the brain temperature [10].

D. Signal to noise ratio calculation

The signal to noise ratio (SNR) was calculated by difference method [11]. The SNR was defined by the following equation (2);

$$SNR = \frac{S}{\sigma} = \frac{mean\,(S_1 + S_2)/2}{SD\,(S_1 - S_2)/\sqrt{2}} \qquad (2),$$

where S means signal, which is half average signal from the ROI in the sum image (S_1+S_2), σ means noise which obtained by the SD in the ROI of difference image (S_1-S_2) divided by $\sqrt{2}$.

E. Statistics

Group comparison was performed using a non-parametric Wilcoxon rank sum test (Matlab; The Mathworks, Natick, MA, USA). The correlation was evaluated as significant for P values <0.05.

III. RESULTS AND DISCUSSION

A. *Effects of b-values*

Table I and II summarizes the results of DWI thermometry (temperature was calculated with b=n, which means both signal at b=0 and at b=n were used) with magnet strength 1.5 Tesla and 3 Tesla, respectively.

TABLE I. THE RESULTS OF DWI THERMOMETRY WITH 1.5 TESLA MRI

Subject	Sex	Age	Sublingual temp. [℃]	resolution [mm]	DWI thermometry [℃] b value [mm²/sec] 200	400	500	600	800	1000	1200	200-800
1	M	46	36.7	1.8x1.8	39.0	38.8	38.3	37.9	36.2	32.7	27.9	37.8
				1.25x1.25	40.9	38.0	37.1	36.2	32.5	27.3	21.5	34.4
2	M	43	36.1	1.8x1.8	38.5	37.7	36.3	36.3	34.0	30.6	25.6	34.7
				1.25x1.25	37.7	36.8	36.1	34.7	30.4	24.9	19.1	35.1
3	M	34	36.8	1.8x1.8	39.1	39.0	38.2	38.2	36.8	33.3	28.1	37.6
				1.25x1.25	38.0	37.3	37.0	35.9	32.4	26.8	20.8	36.3

TABLE II. THE RESULTS OF DWI THERMOMETRY WITH 3 TESLA MRI

Subject	Sex	Age	Sublingual temp. [℃]	resolution [mm]	DWI thermometry [℃] b value [mm²/sec] 200	400	600	800	1000	1200	200-800
1	M	46	36.7	1.8x1.8	37.9	37.8	37.6	38.2	37.4	35.5	38.3
				1.25x1.25	39.3	39.3	39.1	38.3	36.4	32.7	37.9
2	M	43	36.1	1.8x1.8	39.1	38.6	38.3	38.0	37.1	34.6	37.7
				1.25x1.25	38.9	38.9	38.0	36.8	34.4	30.1	36.1
3	M	34	36.8	1.8x1.8	38.4	38.5	38.4	38.5	38.4	36.6	38.5
				1.25x1.25	38.0	38.0	38.0	37.9	36.4	33.1	37.8

Figure 1 shows the differences between DWI thermometry and the sublingual temperature (℃) at different b-value, in different pixel resolutions, and on different magnet strengths.

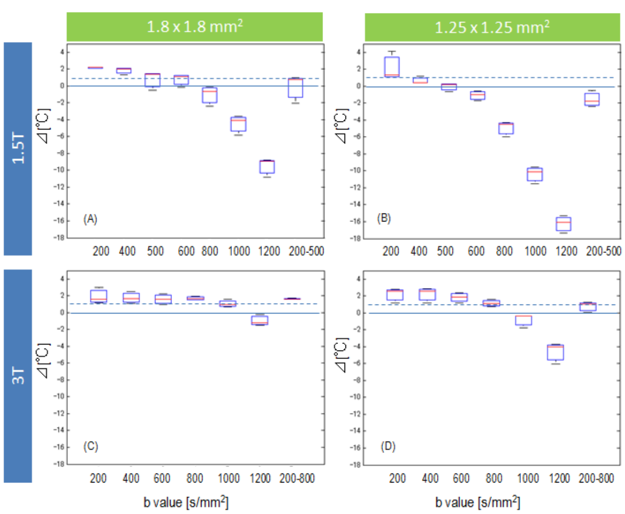

Figure1. The differences between DWI thermometry and the sublingual temperature.*(The vertical axis means the difference and the horizontal axis means b values. A: 1.5Tesla and 1.8mm, B: 1.5Tesla and 1.25mm, C: 3Tesla and 1.8mm, D: 3Tesla and 1.25mm)*

Figure 2 shows the signal decay plots of Figure 1 at the LV. In Figure 1A and 1B, the estimated temperature with b=1200 images were lower than the sublingual temperatures. In the case of b=1000, the estimated temperature with the pixel size of 1.25 x 1.25 mm^2 was also lower than the reference.

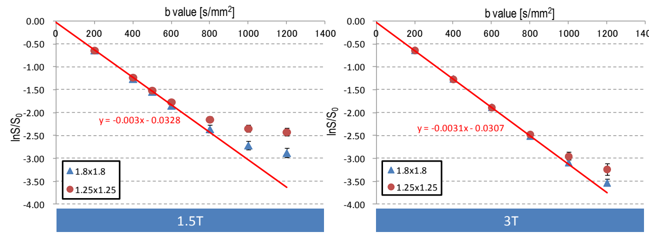

Figure2. The signal decay plots at the lateral ventricle (LV). *(left: 1.5Tesla, right: 3Tesla, triangle: 1.8mm, circle: 1.25mm)*

The reason of these under estimations were explained by the discrepancy between linear regression line (ln S/S_0 refer to b=200-800 at the pixel size of 1.25 x 1.25 mm^2, R^2=1.00) and the ln S/S_0 values at b=1000 and 1200 in Figure 2.

The discrepancy might be caused by low signal to noise ratio at the b-values. In the case of the pixel size of 1.8 x 1.8mm^2, the ln S/S_0 value at b=1000 remained on the regression line. Therefore, the estimated temperature showed reasonable value (Figure 1A).

The linear regression line, in Figure 2, showed that the y-intercept was under the origin. This means that there might exist the effect of perfusion-factor-like flow [3] which can be detected by DWI in the LV. From the above, there were two affection factors, in the aspect of b-value, for DWI thermometry; 1) CSF pulsation and/or CSF flow under b=200; 2) the affection of noise floor over b=800. In Figure 1, the estimated temperature from b=200-800 showed suitable result which fit to the expected value (1℃ higher than reference [10]) at the pixel size of 1.25 x 1.25 mm^2 and was 0.5℃ higher than the expected temperature at 1.8 x 1.8 mm^2 pixel resolution. Therefore, the stable diffusion coefficient which was regressed at b=200-800 will be useful for calculation of appropriate temperature by DWI thermometry.

B. *Effects of SNR*

Figure 3 shows the results of SNR calculation at different b-value, in different pixel resolutions, and on different magnet strengths.

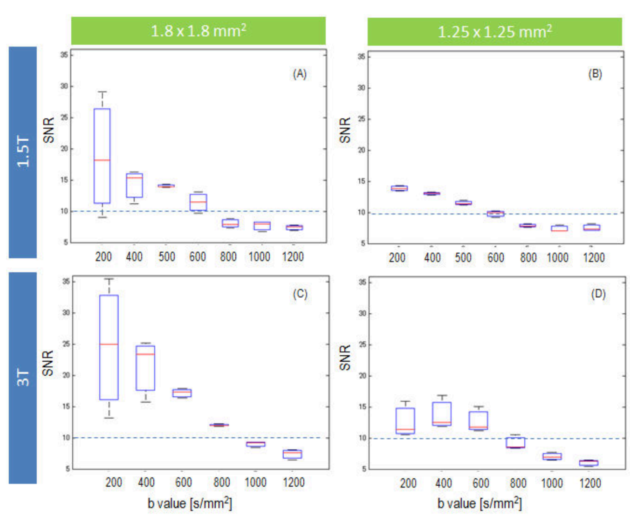

Figure3. The results of SNR calculation *(A: 1.5Tesla and 1.8mm, B: 1.5Tesla and 1.25mm, C: 3Tesla and 1.8mm, D: 3Tesla and 1.25mm)*

As shown in Figure 1 and 2, DWI thermometry might be strongly affected by the noises in the image. From Figure 3, when the SNR was higher than 10, the DWI thermometry showed approximately same as sublingual temperature in Figure1. On the other hand, when the SNR was smaller than 10, DWI thermometry showed lower values than the sublingual temperature.

C. Effects of pixel resolution

Figure 4 shows the results of Wilcoxon's rank sum test to the effects of pixel resolutions for DWI thermometry.

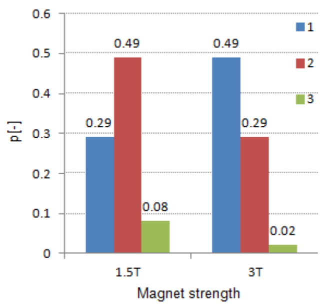

Figure4. The results of Wilcoxon rank sum test between 1.8mm and 1.25mm resolution on 1.5Tesla and 3 Tesla magnet strengths*(the numbers indicate p-values, the digits 1-3 indicate subjects)*

From Figure 4, the subject 3 only showed the significant difference ($p<0.05$) at 3Tesla. The effects of pixel resolution to the SNR was estimated by Wilcoxon's rank sum test on the values of Figure 3. The results were $p=0.46$ (1.5Tesla), $p=0.31$ (3Tesla). When the pixel resolution was smaller than 1.8mm, the effects might be small to the DWI thermometry.

D. Effects of magnet strength

Figure 5 shows the results of Wilcoxon's rank sum test to the effects of magnet strength for DWI thermometry.

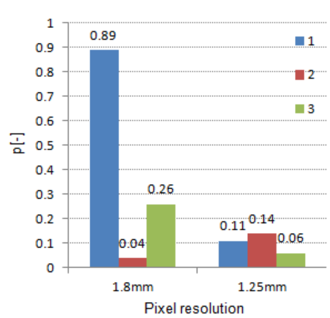

Figure5. The results of Wilcoxon rank sum test between 1.5Tesla and 3Tesla magnet strength with 1.8mm and 1.25mm resolutions *(the numbers indicate p-values, the digits 1-3 indicate subjects)*

From Figure 5, the subject 2 only showed the significant difference ($p<0.05$) at 1.8mm pixel resolution. On the other hand, the effects of magnet strength to the SNR showed $p=0.39$ (1.8mm), $p=0.82$ (1.25mm). Therefore, When the pixel resolution was smaller than 1.8mm, the magnet strength might not effect to the DWI thermometry.

IV. CONCLUSUION

The LV temperature in healthy subjects was measured by DWI thermometry with multiple b-values, two pixel resolutions, and two magnet strength to assess those effect. There were two affections at the outside of b=200-800; CSF flow and noise. The diffusion coefficient obtained from b=200-800 might provide stable value for DWI thermometry. The pixel resolution, when that was smaller than 1.8mm, has no significant effect. There was no clear difference between 1.5 Tesla and 3 Tesla magnet strength for DWI thermometry. The phantom studies, such as, controlled temperature, artificial CSF with pulsation, and variable DWI acquisition settings will be needed to estimate the true efficacy of the DWI based MR thermometry.

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