TECHNICAL NOTE

Isotropic Diffusion-weighted MR Imaging with Tetrahedral Gradients in the Upper Abdomen

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A tetrahedral gradient diffusion sequence for body imaging for a 1.5T scanner was implemented, and we compared the quality of images acquired with the new technique and with the conventional orthogonal technique. Image quality was better using the tetrahedral technique in terms of signal homogeneity in the right liver lobe and signal loss artifact in the left lobe, and the technique was considered useful for magnetic resonance imaging in the upper abdomen.

Keywords: *magnetic resonance, abdomen, liver, diffusion*

Introduction

Diffusion-weighted magnetic resonance (MR) imaging is possible by analyzing the spin dephasing and signal loss caused by random motion along magnetic field gradients.¹ Clinical application of the technique has expanded in the last decade. It is currently used routinely in many hospitals, especially for acute stroke, and has been applied recently as well to body imaging for detecting² and characterizing^{3,4} tumors. However, one problem with diffusion-weighted MR imaging is its relatively lower image quality, especially when using higher b values. Although the clinical introduction of parallel imaging techniques has yielded much better images than before, further improvement in quality has been desired. One method would be to use shorter echo time (TE) for the sequence.

In the conventional diffusion-weighted MR imaging technique, i.e., the orthogonal technique, images are obtained by separately applied x-, y-, or z-motion probing gradient (MPG) pulses (Fig. 1a). Using MPG pulses while simultaneously applying all 3 directions rather than a single orthogonal direction enables shortening of echo time (TE) without reducing b values. This method can gener-

Fig. 1. Pulse sequence diagram

Diagrams show magnetic resonance (MR) pulse sequences for (a) conventional orthogonal diffusion-weighted MR imaging and (b) tetrahedral imaging. The duration of motion-probing gradient pulses for a certain b value is shorter with the tetrahedral technique than with the orthogonal technique when the strengths of the orthogonal components of motion-probing gradient pulses are the same.

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Fig. 2. Tetrahedral gradient vectors

The x, y, and z directions are toward the left, anterior, and head of patient. In the technique using motion-probing gradient pulses with simultaneous application of all 3 orthogonal directions, 4 different gradient vectors that uniformly span 3-dimensional space can be generated. The gradients have a strength that is a square root of 3 times that of its orthogonal components.

ate 4 different gradient vectors that uniformly span 3-dimensional space (Fig. 2); thus, it is called the tetrahedral technique.⁵ The strength of the tetrahedral gradients is a square root of 3 times that of the individual orthogonal components. Consequently, if diffusion-weighted images with a certain b value are required, the duration of MPG pulses could be shorter with the tetrahedral technique than with the orthogonal technique when the strengths of the orthogonal components of the MPG pulses are the same (Fig. 1b). This makes it possible to shorten TE without reducing b value and probably improves the quality of diffusion-weighted images.

The purposes of this study were to implement an isotropic diffusion-weighted single-shot spin-echo (SE) echo planar MR sequence for body imaging using the tetrahedral technique and to determine the efficacy of the sequence in the upper abdomen by comparing the tetrahedral technique with the conventional technique using 3 sequential orthogonal gradients.

Materials and Methods

We implemented the isotropic diffusion-weighted single-shot SE echo planar MR sequence using the tetrahedral technique for a 1.5T clinical imaging MR scanner (Signa Excite-HD 1.5T, GE Health-

care, Milwaukee, WI). The scanner provided a maximum gradient strength of 33 mT/m with a peak slew rate of 120 mT/m/ms. Use of the newly developed tetrahedral sequence enabled acquisition of diffusion-weighted images (b value, 800 s/mm²) of the upper abdomen with a TE of 53 ms, compared to 62 ms when using commercially available conventional diffusion-weighted sequence with orthogonal gradients. Isotropic diffusion-weighted images were generated from the 4 series of images obtained by the tetrahedral MPG pulses for the tetrahedral technique, and those were generated from the 3 series of images obtained by separately and sequentially applied x-, y-, and z-MPG pulses for the orthogonal technique.

In November 2005, 34 consecutive patients (15 men, 19 women; age range, 49 to 85 years, mean 67 years) with suspected liver tumors underwent MR imaging that included diffusion-weighted images obtained by both orthogonal and tetrahedral techniques. Those patients were enrolled in this retrospective study. This study was approved by our institutional review board. Single-shot SE echo planar isotropic diffusion-weighted transverse images of the upper abdomen were obtained during a single breathhold using both (a) conventional sequence using orthogonal gradients (TE 62 ms) and (b) new sequence using tetrahedral gradients (TE 53 ms) and a b value of 800 s/mm². Other imaging parameters were the same, as follows: repetition time (TR) 4000 ms, matrixes 128 × 128, 8-mm thickness, 2-mm gap, number of excitations (NEX) 1, receiver bandwidth ± 250-kHz, and field of view (FOV) 36 × 36 cm. Because images without MPG pulses are required to obtain apparent diffusion coefficient (ADC) map images, 4 series of imaging were performed by orthogonal technique and five by tetrahedral technique. As a result, image acquisition times were 16 s for orthogonal technique and 20 s for tetrahedral technique. Spectrally selected water excitation pulses were applied for both techniques. An 8-channel body phased-array coil was used for signal reception, and a parallel imaging technique (ASSET, GE Healthcare) was employed (acceleration factor, 2).

Using a 4-point scale (1 = poor, 2 = fair, 3 = good, 4 = excellent), 2 experienced abdominal radiologists subjectively graded diffusion-weighted images on soft copy obtained with both techniques in terms of (a) signal homogeneity in the right lobe of the liver, (b) image distortion, (c) signal loss in the left lobe of the liver, and (d) overall image quality. Type of sequence was not displayed on images during the evaluation, and the order of the cases was randomized. The radiologists were al-

Fig. 3. Diffusion-weighted images for a 72-year-old woman without chronic liver disease (b value, 800 s/mm²)

(a) The orthogonal technique showed inferior signal homogeneity in the right lobe of the liver (score, 3: both readers) to (b) the tetrahedral technique (score, 4: both readers).

Fig. 4. Diffusion-weighted images for a 71-year-old man with liver cirrhosis (b value, 800 s/mm²)

(a) The orthogonal technique showed greater signal loss artifact (arrow) in the left lobe of the liver (score, 3: both readers) than (b) the tetrahedral technique (score, 4: both readers).

lowed to adjust window settings of the images. Wilcoxon signed-rank sum test was used for statistical analysis. ADC values were also calculated for the right lobe of the liver, the lower pole of the spleen, and the left kidney. Areas with severe artifact were avoided in calculating the value. For each organ, mean values obtained with the 2 techniques were compared using the Student t test for paired data. Then, the ADC values were also analyzed by Spearman's rank correlation analysis. We used this nonparametric method instead of Person's correlation analysis because the data did

not fit a normal distribution. For all tests, a *P* value less than 0.05 was considered statistically significant.

Results

Quality of images acquired using the tetrahedral technique was significantly superior to those obtained using the orthogonal technique in terms of signal homogeneity in the right lobe of the liver (*P* < 0.0005 for Reader 1 and *P* < 0.01 for Reader 2, Fig. 3) and overall image quality (*P* < 0.0001 and

Fig. 5. Apparent diffusion coefficient value calculated by the 2 techniques

Graph shows significant and excellent correlation between apparent diffusion coefficient values calculated by the 2 techniques (Spearman's rank correlation analysis: $r=0.849$, $P=1 \times 10^{-6}$). The equation " $y=0.951x+0.113$ " was obtained by least-squares method.

$P<0.02$). With regard to signal loss in the left lobe of the liver, only the scores assigned by Reader 1 were significantly superior with the tetrahedral technique to the orthogonal technique ($P<0.002$ and $P=0.052$, Fig. 4). There was no significant difference in the degree of image distortion ($P=0.65$ and $P=0.36$) between the techniques (Table). Mean ADC values ($10^{-3} \text{ mm}^2/\text{s}$) were 1.14 ± 0.13 (liver), 0.86 ± 0.14 (spleen), and 2.12 ± 0.17 (kidney) calculated with the orthogonal technique and 1.20 ± 0.13 (liver), 0.89 ± 0.14 (spleen), and 2.17 ± 0.20 (kidney) with the tetrahedral technique. For each organ, the differences were not statistically significant between the techniques ($P>0.07$, >0.3 , >0.2). The ADC value calculated by the tetrahedral technique was significantly correlated with the value by the orthogonal technique ($r=0.849$, $P=1 \times 10^{-6}$; Fig. 5).

Discussion

A tetrahedral gradient diffusion sequence for

Table. Distribution of image scores for two types of diffusion-weighted magnetic resonance (MR) sequences

		1	2	3	4	Median		
Reader 1								
Signal homogeneity in the right lobe of the liver	Orthogonal	1	23	8	2	2	]	$P<0.0005$
	Tetrahedral	0	11	18	5	3		
Image distortion	Orthogonal	0	0	31	3	3	]	NS ($P=0.65$)
	Tetrahedral	0	0	32	2	3		
Signal loss in the left lobe of the liver	Orthogonal	13	15	6	0	2	]	$P<0.002$
	Tetrahedral	9	12	10	3	2		
Overall image quality	Orthogonal	1	24	9	0	2	]	$P<0.0001$
	Tetrahedral	0	10	20	4	3		
Reader 2								
Signal homogeneity in the right lobe of the liver	Orthogonal	0	16	13	5	3	]	$P<0.01$
	Tetrahedral	0	10	14	10	3		
Image distortion	Orthogonal	0	1	13	20	4	]	NS ($P=0.36$)
	Tetrahedral	0	1	9	24	4		
Signal loss in the left lobe of the liver	Orthogonal	5	21	7	1	2	]	NS ($P=0.052$)
	Tetrahedral	3	19	10	2	2		
Overall image quality	Orthogonal	0	18	13	3	2	]	$P<0.02$
	Tetrahedral	0	12	16	6	3		

The values were scored by a radiologist using a 4-point scale (1: poor, 2: fair, 3: good, and 4: excellent quality). Wilcoxon signed-rank sum test was used for statistical analysis.

body imaging was successfully implemented for a 1.5T clinical MR imaging machine. The tetrahedral technique showed significantly better image quality than the conventional orthogonal technique, probably as a result of the higher signal strength achieved by the technique. Therefore, use of the tetrahedral technique would improve the value of diffusion-weighted body imaging in clinical use. Moreover, the tetrahedral technique has a capability for making higher b value diffusion-weighted imaging fit for practical use.

If TR is much longer than the longitudinal relaxation time (T_1), the diffusion-weighted MR signal intensity I can be written as follows:

$$I \propto \exp\left(-\frac{TE}{T_2}\right) \cdot \exp(-bD),$$

where TE is the echo time, T_2 is the transverse relaxation time, b is the gradient b value, and D is the observed diffusion coefficient.⁶ In our present study, TE was 53 ms with the tetrahedral technique, whereas it was 62 ms with the orthogonal technique. Because T_2 relaxation time of the liver is around 45 ms,⁷ the hepatic signal intensity of the tetrahedral technique is predicted by the above equation to be 1.2 times that of the orthogonal technique. We think that this phenomenon contributed to the improved image quality of the tetrahedral sequence in this study. Moreover, the equation reveals that shorter TE is favorable for suppressing T_2 contrast of diffusion-weighted images, though we did not investigate the role in image contrast in our current study.

Using the tetrahedral technique, isotropic diffusion-weighted image was generated from 4 images obtained by the MPG pulses, and from three images using the orthogonal technique. Theoretically, images with NEX of 4 would have better signal-to-noise ratio (SNR) than images with NEX of 3 by a factor of 1.16, though SNR cannot be evaluated in our study because we used parallel imaging technique in our imaging sequences. This better SNR could also contribute to the better image quality obtained using the tetrahedral technique. We think that the above-mentioned 2 effects together played significant roles in improving image quality.

Artifacts caused by physiologic movement are serious problems in diffusion-weighted body imaging. To reduce the effect of respiratory movement, breathing was held during scanning. With the tetrahedral technique, the scanning time was 20 s, 4 s longer than that used for the orthogonal technique. This is potentially disadvantageous in terms of respiratory motion artifact, although it

will not be a severe problem for most patients. Another problem is the effect of cardiac motion. In particular, subcardiac signal loss appears frequently and significantly decreases diagnostic efficacy in the left lobe of the liver.⁸ Cardiac motion in the systolic phase shakes the adjacent liver within the duration of MPG pulses, which attenuates the signal from the left lobe of the liver. We also observed subcardiac signal loss on images acquired using both techniques. We think that a cardiac trigger technique may be necessary to resolve this problem. However, the tetrahedral technique showed slight, but significantly better signal loss artifact in the left liver lobe compared to the orthogonal technique in the evaluation by the Reader 1. Shorter TE with the tetrahedral technique may contribute to this decreased signal loss artifact in the left lobe of the liver because the ratio of TE to cardiac cycle would be smaller with the technique, and the probability of severe cardiac movement during the time between RF excitation and signal acquisition would decrease.

In conclusion, we have implemented a tetrahedral gradient diffusion sequence for body imaging that we consider superior to conventional sequence in producing images of better quality than the conventional sequence, and we consider this technique useful for MR imaging in the upper abdomen.

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