TECHNICAL NOTE

Preoperative Identification of Subthalamic Nucleus for Deep Brain Stimulation Using Three-dimensional Phase Sensitive Inversion Recovery Technique

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Purpose: We assessed the feasibility of utilizing three-dimensional (3D) phase sensitive inversion recovery (IR) images for preoperatively determining deep brain stimulator position.

Methods: We measured geometric distortion with a grid phantom and evaluated images of 3 volunteers to determine optimum imaging parameters for 3D phase sensitive IR.

Results: Geometric distortion measured less than 1.0%. Respective inversion and recovery times, which provided high T₁ contrast between the subthalamic nucleus and adjacent tissue, were 200 and 4000 ms. In studies of 3 volunteers and 2 patients, the subthalamic nucleus was clearly depicted in 3D phase sensitive IR images. The measured coordinates of the subthalamic nucleus agreed well with those calculated by conventional estimation from midpoint of the anterior and posterior commissure.

Conclusion: Three-dimensional phase sensitive inversion recovery was useful in visualizing the subthalamic nucleus for effective deep brain stimulation.

Keywords: *deep brain stimulation, MRI, Parkinson's disease, subthalamic nucleus, three-dimensional phase sensitive IR*

Introduction

Deep brain stimulation (DBS) has been widely recognized as an effective treatment of Parkinson's disease in recent years.¹⁻³ Determination of electrode position using magnetic resonance (MR) imaging with T₂-weighted image and T₁-weighted spoiled gradient recalled (SPGR) method has been reported.⁴⁻⁷ However, limited visibility of the subthalamic nucleus and electrode implantation with these methods require estimation of the target position calculated from anterior (AC) and posterior commissure (PC).

We have reported that three-dimensional (3D) phase sensitive inversion recovery (IR), which pro-

vides high signal-to-noise ratio even with thin slice images, is useful for preoperatively assessing the position of the subthalamic nucleus.⁸ The purpose of this study is to optimize its inversion time (TI) and repetition time (TR) imaging parameters and demonstrate the usefulness of 3D phase sensitive IR in visualizing the subthalamic nucleus.

Materials and Methods

All studies were performed on a 1.5T MR imaging system (VISART/EX Ver.5.30 Toshiba Medical Systems, Japan) equipped with a head quadrature coil. Imaging parameters for the 3D fast spin echo sequence were: TR = 4,000 ms; effective echo time (TE_{eff}) = 10 ms; echo train length (ETL) = 12; echo spacing = 10 ms; field of view (FOV) = 23 cm; matrix = 230 × 230; slice thickness = 2 mm; 9 axial

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slices; and single excitation per one slice encoding. Total scan time was 16 min 56 s. Three healthy volunteers and 2 patients with Parkinson's disease underwent MR imaging. In 4 cases, axial images provided sufficient information to determine the subthalamic nucleus. However, in one case, the coronal slab was added.

1. Measurement of distortion

The degree of geometric distortion of the MR image was measured using a cylindrical phantom filled with copper sulfate solution with a grid structure of 1-cm spacing in an acrylic disk (Fig. 1a). We measured the phantom radii in 8 directions at the center of the magnet and 10 cm off-center in the z-direction. To clarify how a stereotactic frame for DBS affects distortion, we acquired images of a bottle phantom with and without the frame in place. The frame used for the evaluation was Leksell stereotactic system Model G. The bottle phantom was

13.5 cm in diameter (Fig. 1b) and contained distilled water and sodium chloride copper sulfate.

2. Volunteer study with various TRs, TIs

Three healthy volunteers (2 men, one woman, aged 27 to 38 years) participated in the study of optimization for acquisition parameters. Written informed consent was obtained from each subject before the study. First, to find the optimum TI for the subthalamic nucleus, we acquired images with TIs ranging from 100 to 900 ms, while maintaining TR of 2,000 ms. Second, to determine optimum TR, we obtained images with TRs of 2,000, 3,000, 4,000, and 5,000 ms. The signal intensities of the subthalamic nucleus and adjacent tissue were calculated as a measure of image quality. In addition, contrast between gray and white matter was calculated for comparison.

The contrast between the 2 tissues was defined as:

$$\% \text{ Contrast (stn-h1)} = \frac{(\text{signal intensity of subthalamic nucleus}) - (\text{signal intensity of adjacent tissue})}{(\text{maximum signal intensity}) - (\text{minimum signal intensity})} \times 100$$

$$\% \text{ Contrast (gm-wm)} = \frac{(\text{signal intensity of gray matter}) - (\text{signal intensity of white matter})}{(\text{maximum signal intensity}) - (\text{minimum signal intensity})} \times 100$$

Two radiologists and one neurosurgeon, who were blinded to imaging parameters, evaluated all the images for subthalamic nucleus visibility. The reviewers scored image quality on a 3-point scale (3: good; 2: fair; and 1: poor), and the scores from each reviewer were averaged.

Fig. 1. Grid phantom images for distortion measurement. Geometric distortion was estimated using grid phantom (a). The cylinder phantom had a grid of 1-cm spacing in the disk of acrylics and was filled by cupric sulfate solution. In the experiments with the frame using the bottle phantom 13.5-cm in diameter, the image with the frame was subtracted from that without to evaluate distortion caused by the frame (b).

Results

The grid phantom for distortion measurement was 200 mm in diameter. Table 1 shows the measured radii in 8 directions on MR imaging. Geometric distortion was calculated as less than 1.0%. In the bottle phantom experiment to investigate the effect of the frame, subtraction of the image with the frame from the image without showed no difference. Based on these results, the degree of distortion was not considered a major obstacle to accurately assessing electrode placement. Images acquired from healthy volunteers using TIs from 100 to 900 ms are shown in Fig. 2. Table 2 shows the

Table 1. Grid phantom measured the diameter

Direction	Length (mm)
Upper	100.5
Upper right	100.4
Right	100.5
Lower right	100.8
Lower	101.0
Lower left	100.9
Left	101.0
Upper left	100.8

Fig. 2. Volunteer images (inversion time [TI] = 100 to 900 ms). Healthy volunteer (38-year-old man) images (repetition time [TR] = 2000 ms). TIs were changed from 100 to 900 ms, and signal intensity was measured. The visual evaluation at the subthalamic nucleus (arrow) and adjacent tissue showed that TI of 100 and 200 ms provided high T₁ contrast.

Table 2. Comparison of different TI in the visualization of subthalamic nucleus

TI	Good	Fair	Poor	Average
100	3	0	0	3
200	3	0	0	3
300	0	3	0	2
400	0	1	2	1.3
500	0	0	3	1
600	0	0	3	1
700	0	0	3	1
800	0	0	3	1
900	0	0	3	1

visual evaluation scores of the 3 reviewers for these images and indicates the optimum TI for providing high contrast between the subthalamic nucleus and adjacent tissue was 100 or 200 ms. Further investigation by contrast measurement, shown in Fig. 3, indicated that TI of 200 ms produced highest contrast.

Volunteer images with different TRs are shown in Fig. 4 and the scores of visual evaluation for these images in Table 3. TR of 4,000 ms resulted in good contrast image, which agreed with contrast measurement shown in Fig. 5.

Figure 6 shows images of a 64-year-old woman with Parkinson's disease who underwent DBS surgery. In the phase sensitive IR image, the X, Y, and Z coordinates of the left subthalamic nucleus with

Fig. 3. Contrast between subthalamic nucleus and adjacent tissue as a function of inversion time (TI). The contrast between the subthalamic nucleus and adjacent tissue was measured. Whereas gray and white matter contrast was the highest at TI = 500 ms, at the subthalamic nucleus level, TI = 200 ms gave the best result.

Fig. 4. Volunteer images (repetition time [TR] = 2000–4000 ms). Healthy volunteer images (38-year-old man). Signal intensity was measured using inversion time (TI) = 200 ms, TR = 2000, 3000, 4000, and 5000 ms. The results of visual evaluation showed the best score at TR = 4,000 ms.

Table 3. Comparison of different TR in the visualization of subthalamic nucleus

TR	Good	Fair	Poor	Average
2000	1	1	1	2
3000	2	0	1	2.3
4000	2	1	0	2.6
5000	0	3	0	2

Fig. 5. Contrast between subthalamic nucleus and adjacent tissue as a function of repetition time (TR). The contrast between the subthalamic nucleus (arrow) and adjacent tissue was measured. Whereas gray and white matter contrast was highest at TR = 5,000 ms and above, at the subthalamic nucleus level, TR = 4,000 ms gave the best result.

Fig. 6. Three-dimensional (3D) phase sensitive inversion recovery (IR) image of a 64-year-old woman with Parkinson's disease. A cross shows the position of the subthalamic nucleus by 3D phase sensitive IR image. After operation, Hoehn-Yahr staging classification improved from 3 to 2.

their origin at the center of the stereotactic frame were directly measured as 114, 91, and 106 mm, respectively. The coordinates calculated from the midpoint of AC and PC using conventional estimation method were $x = 111\text{--}112$ mm, $y = 90\text{--}91$ mm, and $z = 104\text{--}106$ mm. The measured coordinates of the 2 methods showed consistent results. Three weeks after surgery, Hoehn-Yahr staging classification improved from 3 to 2. The patient showed a palliation of tremor and improvement in walking

speed.

Discussion

DBS therapy involves surgical implantation of a medical device that sends electrical impulses to specific parts of the brain and is used in patients with severe essential tremor and with tremor, rigidity and bradykinesia (slow movement) associated with Parkinson's disease as well as with primary dystonia and other conditions. Brain pacemakers were approved by the Food and Drug Administration (FDA) in 1997 as a treatment for epilepsy. In Japan, DBS has been covered by health insurance since 2000.

Some distortion is inevitable in images used for DBS electrode implantation, and we examined whether 3D phase sensitive IR images had sufficiently low distortion. In addition, because metal disturbs the uniformity of a magnetic field and may produce distortion on MR images, we measured image distortion with the metal frame in place as 1.0% or less and considered it to have no effect on positioning accuracy. With regard to optimum inversion time, $TI = 100\text{--}200$ ms produced the highest visual evaluation score. The measurement of contrast between subthalamic nucleus and adjacent tissue showed the highest contrast at $TI = 200$ ms. It should be noted that the highest contrast between gray and white matter was obtained at $TI = 500$ ms, which did not necessarily agree with the optimum TI for identifying the subthalamic nucleus.

Starr and colleagues obtained the same result, with $TI = 200$ ms being good in the IR method. The results of both visual evaluation and contrast measurement showed that the appropriate TR was 4,000 ms, which was thought to be reasonable from the viewpoint of acquisition time.

If MR images are visualized by 230×230 matrices in the case of $FOV = 230$ mm, one-pixel size is 1.0×1.0 . Maciunas's group⁹ reported accuracy of the stereotactic neurosurgery by 1-mm slice thickness CT images as 1.5 mm with 95% reliability. Although we wanted to scan using 1-mm slice thickness, we used slices 2-mm thick to obtain good signal-to-noise ratio. However, examination of both axial and coronal images can mitigate slice thickness error. An operation target point is actually determined synthetically, contrasting axial and coronal images. In this particular case with small cerebral atrophy, the result was inherently expected to agree with that of conventional method. However, in cases with anatomical distortion of brain structure from heavy cerebral atrophy or in other cases, this method is thought to be clinically use-

ful.

Conventionally, electrode implantation position of DBS is determined by calculating and identifying the AC and PC based on the anatomical measurement value from the division.^{10,11} However, a certain amount of individual difference in the grade of cerebral atrophy and cerebral configuration may preclude correct positioning of the implanted electrode. In that respect, 3D phase sensitive IR is advantageous because it describes the subthalamic nucleus directly to determine implantation position. Three-dimensional phase sensitive IR provides sufficient T₁ contrast images with thin slice, which is considered a useful pulse sequence in the preoperative depiction of the subthalamic nucleus for the DBS.

Conclusion

Three-dimensional phase sensitive IR is confirmed to provide distortion-free images, which enables determination of electrode positioning in DBS surgery. This pulse sequence gives high contrast-to-noise ratio in the area of the basal ganglia with thin slice images, which provides less partial volume effect and is useful in visualizing the subthalamic nucleus for effective DBS.

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