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Clinical Application of 7.0 T Magnetic Resonance Images in Gamma Knife Radiosurgery for a Patient with Brain Metastases

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In the study we assessed the distortion of 7.0 T magnetic resonance (MR) images in reference to 1.5 T MR images in the radiosurgery of metastatic brain tumors. Radiosurgery with Gamma Knife Perfexion® was performed for the treatment of a 54-yr-old female patient with multiple brain metastases by the co-registered images of the 7.0 T and 1.5 T magnetic resonance images (MRI). There was no significant discrepancy in the positions of anterior and posterior commissures as well as the locations of four metastatic brain tumors in the co-registered images between 7.0 T and 1.5 T MRI with better visualization of the anatomical details in 7.0 T MR images. This study demonstrates for the first time that 7.0 T MR images can be safely utilized in Perfexion® Gamma Knife radiosurgery for the treatment of metastatic brain tumors. Furthermore 7.0 T MR images provide better visualization of brain tumors without image distortion in comparison to 1.5 T MR images.

Key Words: 1.5 T MRI; 7.0 T MRI; Co-registered Images; Radiosurgery

INTRODUCTION

Metastatic brain tumor is the most common malignant brain tumors. Because of their rapid progression, early detection of metastatic brain tumors is essential for the treatment. For the early detection of the metastatic brain tumors, high-field magnetic resonance (MR) images such as 7.0 T MR images may be helpful since smaller tumors can be detected by virtue of higher spatial resolution and better visualization of anatomical details (1, 2).

There have been several anecdotal reports of 7.0 T MR images in a small group of normal subjects or patients with stroke, cavernous malformations, or multiple sclerosis (1, 3-10). However, the report about the use of 7.0 T MR images for brain tumors is limited only to animal model due to technical and safety issues (11, 12).

Hereby we report a case of multiple metastatic brain tumors in a patient who was treated by Gamma Knife Perfexion® (Elekta AB, Stockholm, Sweden) with the co-registered images of the 7.0 T and 1.5 T MR images. Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE) gadolinium-enhanced T1-weighted MR images of 7.0 T and 1.5 T were fused by using ImageMerge™ (Elekta AB, Stockholm, Sweden), a fusion software program integrated in a treatment planning software, Leksell Gamma Plan® v8.3 (Elekta AB, Stockholm, Sweden).

CASE DESCRIPTION

A right upper lung mass was detected in the routine examination of simple chest radiography of a 56-yr-old woman. Her chest computed tomography (CT) scan revealed a 4-cm sized mass lesion in the right upper lung field with obstruction of right upper lung apical segmental bronchus. Her abdominal CT scan revealed a mass at the distal rectum with serosal invasion. A percutaneous needle aspiration biopsy of the right upper lung mass was performed. A colonoscopic biopsy of a rectal mass was done. Both revealed adenocarcinomas. Her 1.5 T brain MR images demonstrated three small mass lesions in her left parieto-temporal lobe. She refused to undergo surgical resection and received six cycles of anticancer chemotherapy over six months. After completion of chemotherapy, mass lesions in the lung and the rectum remained stable. She received Gamma Knife Radiosurgery (GK RS) for brain metastases on September 1st, 2009.

She had taken 7.0 T MR images (Magnetom 7.0 T, Siemens®) one day before GK RS. We received the permission from the Korean Food and Drug Administration and the Institutional Review Board of Seoul National University Hospital and the Neuroscience Research Institute of Gacheon Medical Center (IRB Num-

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ber: 0802-046-234). A written consent was obtained from the patient. The 7.0 T MR images (Magnetom 7.0 T, Siemens®) at Neuroscience Research Institute of Gacheon University of Medicine and Science were used for imaging of the patient. The 7.0 T magnet, with a clear bore of 90 cm, is equipped with a water cooled gradient and RF coils. The gradient system operates at 2,000 V/650 Amp with gradient amplitude of 40 mT/m, a maximum slew rate of 200 mT/m/ms, and a minimum gradient rise time of 200 microseconds. A birdcage TX/RX single channel coil was used. T1-weighted magnetic resonance images (MRI) was scanned

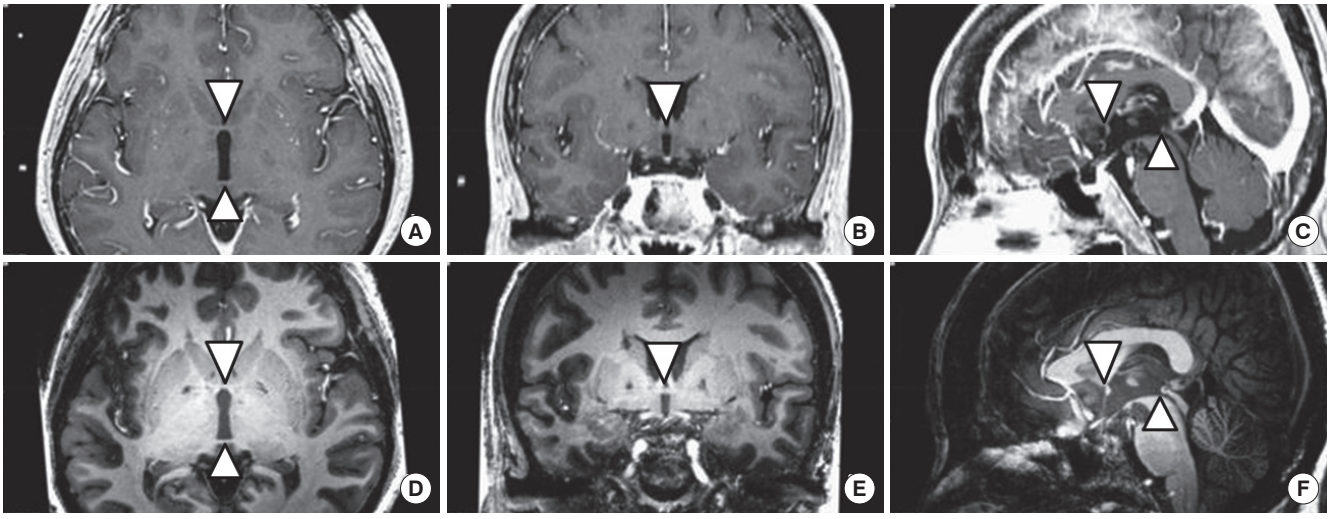

Fig. 1. Axial, coronal, and sagittal images of the anterior commissure (▽) and the posterior commissure (Δ) in 1.5T and 7.0 T magnetic resonance images (MRI). In the co-registered images of the 7.0T MRI and 1.5T MRI, there is no significant difference in the location of the AC and PC between 1.5T (**A**-**C**) and 7.0T MRI (**D**-**F**) whereas enhanced anatomical details of the metastatic brain tumors are provided by 7.0T MRI.

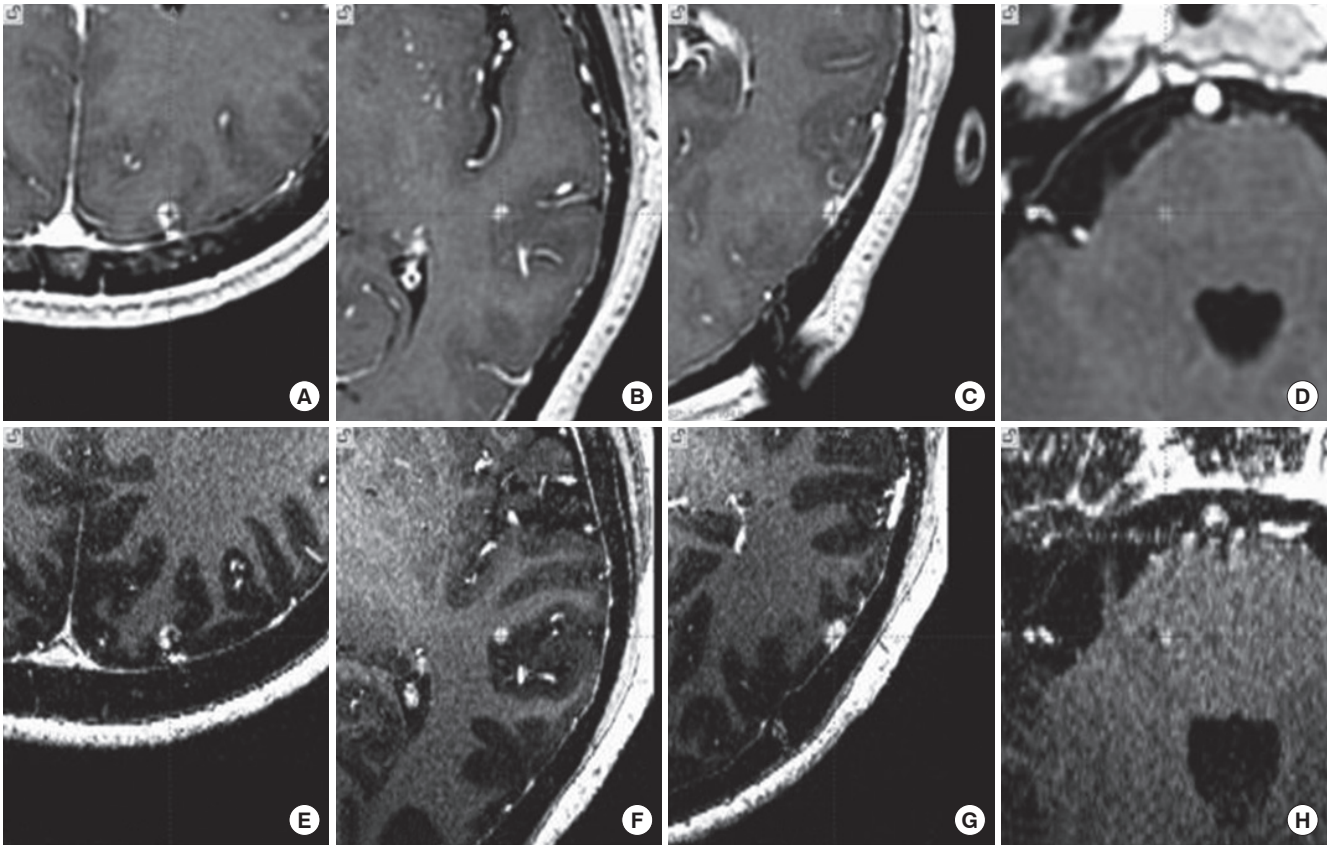

Fig. 2. Axial images of four metastatic brain tumors in the co-registered images of 1.5 T and 7.0 T magnetic resonance images (MRI). Upper panel shows 1.5 T MRI (**A**-**D**) and lower panel shows 7.0 T MRI (**E**-**H**). Total four metastastic brain tumors are found; three lesions in the left parietal (**A**, **E**) and temporal lobe (**B**, **C**, **F**, **G**) and one in the right side of the pons (**D**, **H**).

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before and after injection of a contrast agent. The Magnevist (Bayer Healthcare Pharmaceuticals Inc., Liverkusen, Germany) was used as the contrast agent by 0.2 mL/kg (0.01 mM/kg). Pulse sequence used was 3D Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE) and the followings are the scanning parameters: TR = 4,000 ms, TE = 3.92 ms, TI = 1,000 ms, Thickness = 0.7 mm, flip angle = 10°, number of slice = 256, voxel size = 0.35 × 0.35 × 0.7 mm, and matrix size = 448 × 448.

GK RS was performed at Seoul National University Hospital. A Leksell stereotactic frame G (Elekta AB, Stockholm, Sweden) was applied to the patient head under local anesthesia. T1-weighted 3D MPRAGE images were obtained before and after double dose gadolinium enhancement using Signa Excite 1.5 T MR (General Electric Medical System, Milwaukee, WI, USA). Scanning parameters were: TR = 11.7 ms, TE = 5.2 ms, thickness = 1.5 mm, voxel size = 0.94 × 0.94 × 1.5 mm and matrix size = 256 × 256.

Total four metastastic brain tumors were found; two lesions in the left parietal lobe and one in temporal lobe, and one in the right side of the pons. The measured tumor volume were 0.096 mL, 0.079 mL, 0.0314 mL, and 0.0062 mL which were treated with 22 Gy, 22 Gy, 22 Gy, and 20 Gy at the 50% isodose line, respectively.

7.0 T axial images were co-registered to 1.5 T axial images using a commercial software, ImageMerge™ (Elekta AB, Stockholm, Sweden), which was integrated into a treatment planning software, Leksell Gamma Plan® v8.3 (Elekta AB, Stockholm, Sweden). Co-registration was automatically performed by an algorithm based on the mutual information method. Locations of AC and PC, and tumor volumes were measured five times with Leksell Gamma Plan® v8.3 (Elekta AB, Stockholm, Sweden) in both image sets and compared.

We found that in the co-registered images of the 7.0 T MR images and 1.5 T MR images, there was no significant discrepancy of the location of the AC and PC as well as the locations of four metastatic brain tumors. Images of the 7.0 T and 1.5 T MPRAGE gadolinium-enhanced T1-weighted MRI are co-registered by using ImageMerge™ (Elekta AB, Stockholm, Sweden), a fusion software program integrated in a treatment planning software, Leksell Gamma Plan® v8.3 (Elekta AB, Stockholm, Sweden) (Fig. 1). All images were realigned to midsagittal AC-PC line. In the co-registered images of the 7.0 T MRI and 1.5 T MRI, there was no significant difference in the location of the AC and PC between 1.5 T (Fig. 1A-C) and 7.0 T MRI (Fig. 1D-F). Difference between locations of AC measured in 1.5 T and 7.0 T image sets was 1.1 +/- 0.1 mm and PC was 1.1 +/- 0.2 mm. Maximum deviation was 1.3 mm. In the co-registered images of the 7.0 T MRI and 1.5 T MRI, total four metastastic brain tumors were found; three lesions in the left parietal and temporal lobe, and one in the right side of the pons (Fig. 2). In the co-registered images of 1.5 T (Fig. 2A-D) and 7.0 T MRI (Fig. 2E-H), there was no discrep-

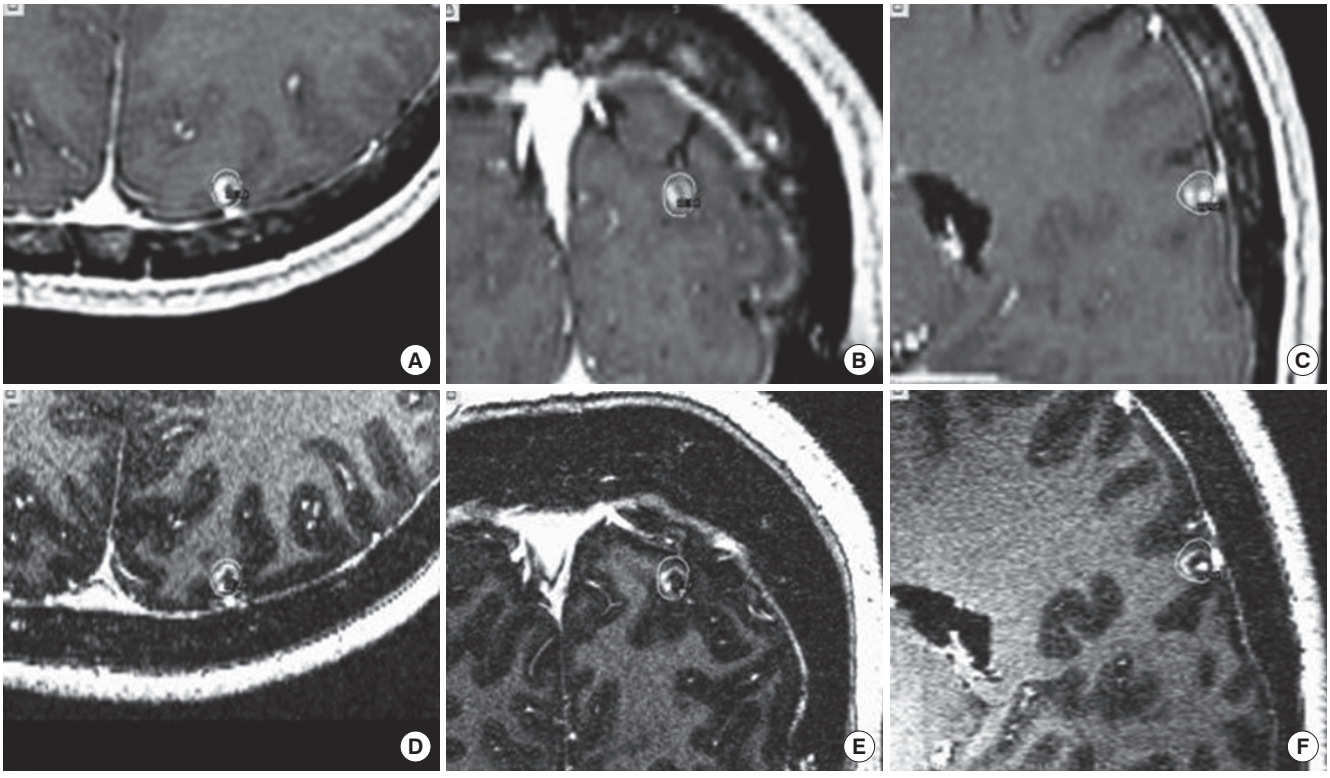

Fig. 3. Axial, coronal, and sagittal images of a metastatic lesion in the left parietal lobe in the co-registered images of 1.5 T and 7.0 T magnetic resonance images (MRI). The tumor is demarcated in blue line and its 50%-isodose volume of 22 Gy is marked with yellow line in the left parietal lobe in the axial, coronal, and sagittal view of the co-registered images of 1.5 T (**A**-**C**) and 7.0 T MRI (**D**-**F**).

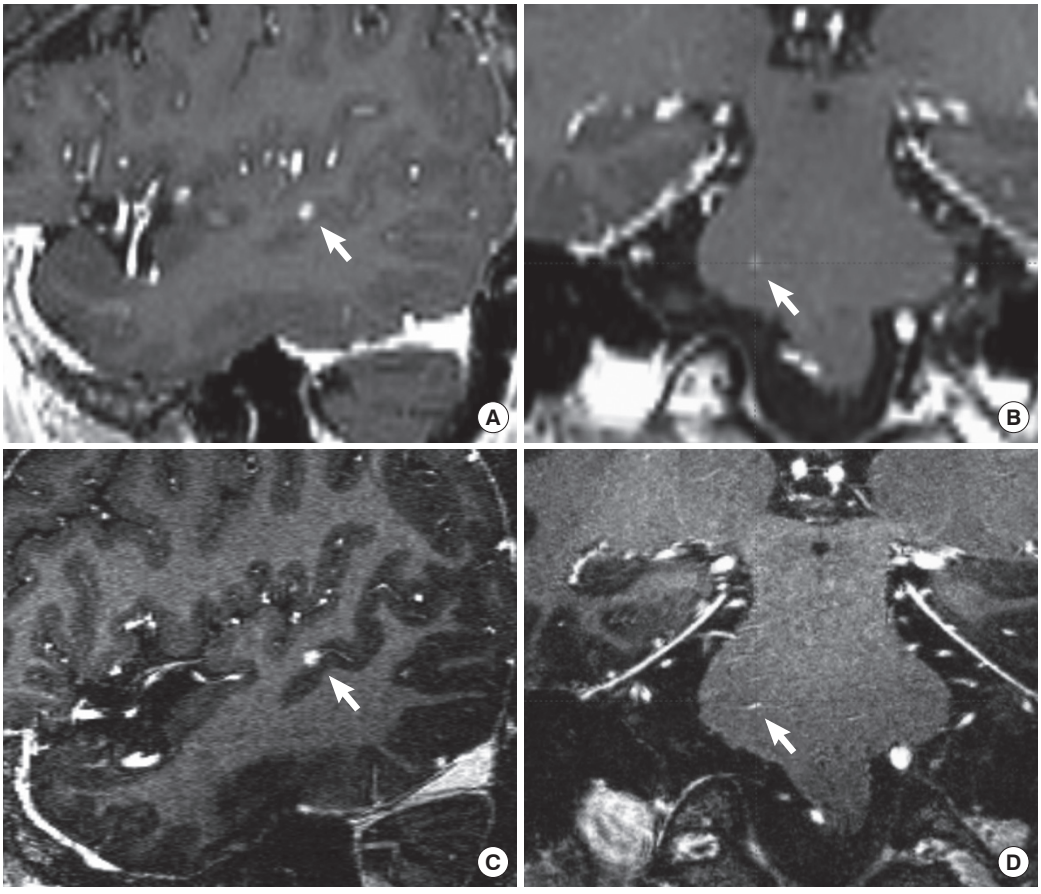

Fig. 4. Sagittal and coronal images of metastatic lesions (arrow) in the left temporal lobe and the right side of the pons in the co-registered images of 1.5 T and 7.0 T magnetic resonance images (MRI). While only high signal intensity regions in 1.5 T MRI (**A**, **B**), blood vessels connected to the tumors are clearly identified in high resolution images of 7.0 T MRI (**C**, **D**).

ancy of the position of four metastatic lesions between the 1.5T and 7.0T MRI whereas enhanced anatomical details of the metastatic brain tumors were provided by 7.0 T MRI. There was no significant discrepancy of the tumor volume (blue line) and its 50%-isodose volume of 22 Gy (yellow line) in the left parietal lobe (a lesion of Fig. 2A) between 1.5 T (upper panel) and 7.0 T MRI (lower panel), which were plotted in the axial, coronal, and sagittal view of the co-registered images (Fig. 3). The volume of the tumor measured in 1.5 T and 7.0 T MRI were 0.096 cm^3 and 0.088 cm^3, respectively. Among the four metastatic lesions, two lesions which were of volume 0.096 cm^3 and 0.079 cm^3, respectively, were included in volume comparison because the other two were too small (< 0.03 cm^3). Volume of the bigger tumor measured in 1.5 T images were 0.096 cm^3 and 0.088 cm^3 in 7.0 T images, respectively. The difference was larger than standard deviation of volume measurement in each set (0.003 cm^3). The smaller one was measured as 0.079 cm^3 in 1.5 T and 0.078 cm^3 in 7.0 T, and difference was smaller than standard deviation of measurement (0.004 cm^3).

Co-registered sagittal images of the third tumor (a lesion shown in Fig. 2C) (Fig. 4A, C) and coronal images of the fourth tumor (a lesion shown in Fig. 2D) (Fig. 4B, D) are demonstrated in Fig. 4. While only high signal intensity regions in 1.5 T MRI (Fig. 4A, B), blood vessels connected to the tumors are clearly identified in high resolution images of 7.0 T MRI (Fig. 4C, D). Enhanced anatomical details of the metastatic brain tumors were provided by 7.0 T MR images. In 7.0 T MR images, we could clearly see blood vessels connected to the lesion whereas only high signal intensity regions are identified in 1.5 T MR images.

DISCUSSION

We have demonstrated in this case that gadolinium-enhancing 7.0 T MR images were safely taken in a patient with mestastatic brain tumors to provide high resolution imaging. In the past, there were anecdoctal reports of high field MR images of 7.0 T or higher performed in a small group of normal subjects or patients (1, 3-10). Thomas et al. (9) described the in vivo 7.0 T MR images of higher signal-to-noise and novel contrast to provide enhanced scrutiny of hippocampal anatomy with their microvenous structures in six normal subjects Kollia et al. (5) compared the 7.0 T MR images with conventional 1.5 T MR images in twelve consecutive patients with clinically definite multiple sclerosis. They have reported that ultra-high-field imaging of patients with multiple sclerosis at 7.0 T MR images was well tolerated and provided better visualization of multiple sclerosis lesions in the gray matter. However, there is no report about the use of 7.0 T MR images for brain tumors yet and only animal brain tumor model

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is reported because of the technical and safety issues (2, 11, 12). Cha et al. (11) evaluated the growth and vascularity of implanted GL261 mouse gliomas by using 7.0 T MR images with conventional T1- and T2-weighted imaging and dynamic, contrast-enhanced T2-weighted imaging in 34 C57BL6 mice at different stages of tumor development.

To our knowledge, this is the first report in that the gadolinium-enhanced 7.0 T MR images were safely taken in the patients with metastatic brain tumors and detailed distortion effect was documented in comparison with low field MR images. After automatic co-registration procedures, the discrepancy of the location of AC and PC between two image sets was within 1.5 mm. The discrepancies were combined effects of image distortion and image co-registration. Errors along the cranio-caudal direction were larger than the other two perpendicular directions. The fact that slice thickness of 1.5 T axial images was more than twice thicker than that of 7.0 T images may explain the larger errors in this direction. Geometric distortion due to static field and local susceptibility effects has been a major concern in high-field MR images (4). Despite these technical issues, we found that the co-registered 7.0 T MR images have only a little discrepancy in the positions of the physiological landmarks such as AC and PC as well as the locations of four metastatic brain tumors from 1.5 T MR images. We think this is an important finding for the future users of ultra-high field MR images for radiosurgery of brain tumors.

Recent studies reported that the 3D MPRAGE shows the superior performance, such as contrast and sensitivity, in the brain tumor imaging compared to others (13, 14). Our study demonstrated that the contrast enhanced T1-weighted imaging at high field 7.0 T MR images, using 3D MP RAGE sequence can be safely used for GK radiosurgery of metastatic brain tumors. It is expected that the superior signal to noise ratio (SNR) of the 7.0 T MR images than the lower field MRI can provide the higher sensitivity and resolution in the brain tumor imaging. We also demonstrated in this case that 7.0 T MR images taken a day before Gamma Knife radiosurgery can be safely utilized in targeting and the dosiplanning for the treatment of metastatic brain tumors with the fusion of 1.5 T MR images taken in the patient with the Leksell frame on the day of Gamma Knife radiosurgery by using the image fusion program, ImageMerge™ (Elekta AB, Stockholm, Sweden) integrated in the GammaPlan® v8.3 of Perfexion® (Elekta AB, Stockholm, Sweden).

In conclusion, our study demonstrates that ultra-high-field imaging of the metastatic brain tumors at 7.0 T using 3D MP RAGE sequence is well tolerated with reasonable scanning time and little image distortion, which provides better visualization of anatomical details than 1.5 T. We believe that combination of higher signal-to-noise ratio of 7.0 T MR images and more accurate geometrical characteristics of 1.5 T MRI can provide better results for GK RS of brain metastases.

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