

Positional effect of preoperative neuronavigational magnetic resonance image on accuracy of posterior fossa lesion localization

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OBJECTIVE The aim of this study was to analyze the positional effect of MRI on the accuracy of neuronavigational localization for posterior fossa (PF) lesions when the operation is performed with the patient in the prone position.

METHODS Ten patients with PF tumors requiring surgery in the prone position were prospectively enrolled in the study. All patients underwent preoperative navigational MRI in both the supine and prone positions in a single session. Using simultaneous intraoperative registration of the supine and prone navigational MR images, the authors investigated the images' accuracy, spatial deformity, and source of errors for PF lesions. Accuracy was determined in terms of differences in the ability of the supine and prone MR images to localize 64 test points in the PF by using a neuronavigation system. Spatial deformities were analyzed and visualized by in-house–developed software with a 3D reconstruction function and spatial calculation of the MRI data. To identify the source of differences, the authors investigated the accuracy of fiducial point localization in the supine and prone MR images after taking the surface anatomy and age factors into consideration.

RESULTS Neuronavigational localization performed using prone MRI was more accurate for PF lesions than routine supine MRI prior to prone position surgery. Prone MRI more accurately localized 93.8% of the tested PF areas than supine MRI. The spatial deformities in the neuronavigation system calculated using the supine MRI tended to move in the posterior-superior direction from the actual anatomical landmarks. The average distance of the spatial differences between the prone and supine MR images was 6.3 mm. The spatial difference had a tendency to increase close to the midline. An older age (> 60 years) and fiducial markers adjacent to the cervical muscles were considered to contribute significantly to the source of differences in the positional effect of neuronavigation ($p < 0.001$ and $p = 0.01$, respectively).

CONCLUSIONS This study demonstrated the superior accuracy of neuronavigational localization with prone-position MRI during prone-position surgery for PF lesions. The authors recommend that the scan position of the neuronavigational MRI be matched with the surgical position for more precise localization.

<https://thejns.org/doi/abs/10.3171/2019.4.JNS1989>

KEYWORDS navigation MRI; posterior fossa; prone position; prone MRI; localization; accuracy; surgical technique

SINCE the introduction of intraoperative navigation devices in 1986, use of a neuronavigation system with MRI has become common for brain tumor surgery.²⁵ Since the introduction of the MRI-based neuronavigation system (MRI-NVS) for brain surgery, accurate localization of brain lesions during surgery has been intuitively possible through imaging, leading to innovation in neuro-

surgery.^{14,15,18} In general, careful positioning of the patient and registration will result in fine accuracy when using the MRI-NVS. However, because the MRI used for the MRI-NVS usually is performed before surgery and thus not in real time, inaccuracies may occur during registration of the fiducial marker (FM). Additionally, various factors, such as CSF leakage, the surgical position, or bleeding,

ABBREVIATIONS FM = fiducial marker; MRI-NVS = MRI-based neuronavigation system; PF = posterior fossa.

SUBMITTED January 14, 2019. **ACCEPTED** April 19, 2019.

INCLUDE WHEN CITING Published online July 19, 2019; DOI: 10.3171/2019.4.JNS1989.

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TABLE 1. Clinical characteristics of 10 patients with PF lesions

Case No.	Sex	Age (yrs)	Operation	Pathology	Test Point			Test Point		Test Point (total)	No. of FMs
					CBL	Dura Mater	Scalp	Midline	Lat		
1	M	33	MLSOC	Diffuse midline glioma	2	3	2	2	5	7	8
2	M	25	Nav-guided Bx	Diffuse astrocytoma	1	1	3	2	3	5	8
3	M	18	MLSOC	Pilocytic astrocytoma	2	3	3	3	5	8	8
4	M	60	MLSOC	Anaplastic astrocytoma	3	3	3	2	7	9	8
5	M	31	MLSOC	Ependymoma	1	2	3	1	5	6	8
6	F	70	Nav-guided Bx	Diffuse large B-cell lymphoma	1	1	2	2	2	4	8
7	M	56	MLSOC	Glioblastoma	2	3	2	4	3	7	8
8	M	19	Nav-guided Bx	Anaplastic astrocytoma	1	1	4	1	5	6	8
9	F	58	Nav-guided Bx	Demyelinating disease	1	1	4	2	4	6	8
10	M	60	Nav-guided Bx	Diffuse large B-cell lymphoma	1	1	4	3	3	6	8

CBL = cerebellum; MLSOC = midline suboccipital craniotomy and tumor removal; Nav-guided Bx = navigation-guided biopsy.

can cause inconsistencies between the registered MR image and the brain in the actual surgical field. These discrepancies are daily issues for neurosurgeons, and studies have attempted to find ways to overcome them.^{7,11,20,21,24,30}

Cerebellum and brainstem tumors of the posterior fossa (PF) comprise approximately 5% of the total brain tumor incidence in adults and approximately 50% in children, with most requiring resection or biopsy for diagnosis and treatment.^{2,3,17} When performing PF tumor surgery, MRI-NVS is applied mostly with patients in the prone surgical position. However, in contrast to its use for cerebral lesions, the MRI-NVS is frequently inaccurate in these cases and does not assist with surgical localization.^{22,34} In particular, higher accuracy is required for biopsy of a small PF lesion—less than 1 cm—using MRI-NVS. Failure to meet this condition may lead to a serious neurological deficit if the lesion is close to the brainstem.^{10,26,29} The purpose of this study was to verify that the inaccuracy of MRI-NVS during PF surgery is caused by differences between the surgical position and the position of the patient when performing the MRI that is applied to the MRI-NVS.

Previous studies have investigated brain movements in response to the position adopted for the brain MRI, and have reported that 1.7- to 11.46-mm brain movements can occur depending on the position.^{24,27,29,30} However, no studies have determined the impact of such brain movement on the MRI-NVS according to the position adopted during MR scanning. Typically, the MRI-NVS applies MR images from the supine position regardless of the surgical position. Thus, when the prone position, which is different from the MR scanning position, is chosen for PF surgery, the FMs attached to the scalp adjacent to the muscles of the head and neck may cause errors due to posture changes for the surgical position during registration—changes due to movement of the FMs compared to the original location of the skull.^{22,32} Additionally, the PF contains a relatively large amount of CSF compared to that in the cerebral area. Previous literature has suggested that a larger subarachnoid space causes more brain movement during posture changes due to gravity.^{20,31} In addition, studies have sug-

gested that movements of the pons and cerebellum occur when the head and neck are bent in the prone position and that the degree of movement is proportional to the angle of bending of the head and neck.^{12,13} Overall, the PF has a high probability of movement among the intracranial structures due to its position, which must be considered when obtaining MRI information for a therapeutic purpose, such as the MRI-NVS, instead of for diagnostic purposes.

Therefore, we aimed to find a solution for better lesion localization by analyzing differences in the MRI-NVS according to the preoperative MRI position, degree of distortion, and cause aggravating the distortion.

Methods

Patients and MR Scanning

This investigation was planned as a prospective study and was approved by the ethics committee of Seoul National University Hospital. A total of 10 patients were included in the study with their voluntary consent between June 2017 and April 2018. The clinical characteristics of the patients are summarized in Table 1. All patients had a lesion in the cerebellum presumed to be a brain tumor that required surgery for tumor resection or a biopsy for diagnosis, and all patients required access from the prone position. Of the 10 patients, 8 were men and 2 were women. The youngest patient was 18 years old and the oldest was 70 years old. Five patients underwent midline suboccipital craniotomy and tumor removal, and 5 patients underwent burr-hole trephination and MRI-NVS-guided biopsy. Ultimately, 9 patients were diagnosed with brain tumors, and 1 patient was diagnosed with demyelinating disease.

All patients underwent MR scanning with 8 FMs attached to the scalp corresponding to the overall parietal and occipital areas. The MRI-NVS camera can recognize the FM when the prone position is adopted in the same pattern in all patients by the same neurosurgeon. All patients included in this study underwent 2 types of MRI for MRI-NVS according to the posture adopted for scanning

(i.e., both the prone and supine positions). This process was carried out consecutively in a single session. Approximately 1 hour was required to acquire the 2 MR images. The contrast agent was administered only once, and no difference was noted in the degree of contrast enhancement between the 2 MR images. Other conditions (attachment location of the FMs, MR scanner, and protocols) were the same except for changing the patient's position for MR scanning. None of the patients experienced any inconvenience during MR scanning in the prone position, and no problems occurred during the procedure. The MRI obtained in the prone position was defined as the prone MRI and that obtained in the supine position was defined as the supine MRI (Fig. 1).

Application of the Neuronavigation System During the Surgery

For the surgery, all patients underwent skull fixation with the Mayfield fixator by bending their heads far enough to place 2 fingers between the chin and neck without rotating the head. The Medtronic StealthStation S7 Surgical Navigation System was used for the MRI-NVS. After uploading both the prone and supine MRI images to the MRI-NVS, each MR image was registered independently and simultaneously by using the same FMs. In all cases, the errors between the patient and each MR image were less than 1 mm (median 0.6 mm, range 0.2–0.9 mm) when registering the 2 MR images based on the FMs. Therefore, we could localize specific locations (scalp, dura mater, and cerebellum) in the patients during actual surgery by using the supine and prone MR images, and we could store each location; in this environment, we could analyze differences between the 2 MR images and the actual locations as a gold standard and we could visually verify which MR image showed the highest accuracy.

A total of 64 test points was specified in the 10 patients. Each of the corresponding test points was identified in the supine and prone MR images, and the MRI-NVS screen was captured with a photograph specifying the test points during surgery. The accuracy of the MR images for the test points was independently verified by 3 neurosurgeons. The 64 test points were used for the analysis by dividing them into the scalp, dura, and cerebellum (including the tumor) based on the depth, midline area (defined from the center to the borderline of the brainstem in the axial plane), and lateral area (defined as outside the brainstem and borderline in the axial plane) according to the left and right positions. Because CSF drainage could change the position of cerebellar structures, care was taken to minimize CSF leakage by preventing damage to the arachnoid membrane when incising the dura.

Image Analysis Program and Phase and Distortion Analyses

To calculate the differences between the 2 MR images in the MRI-NVS more systematically and quantitatively, we analyzed the patterns and degrees of distortion by using a self-developed image reconstruction and analysis program (BrainVAAS [Visualization & Analysis-Aided Software], http://gdisk.gachon.ac.kr:8081/api.link/3d_baLoPHr3eR-YJ-g~.zip). The details of the algorithm principles of the program and the image analy-

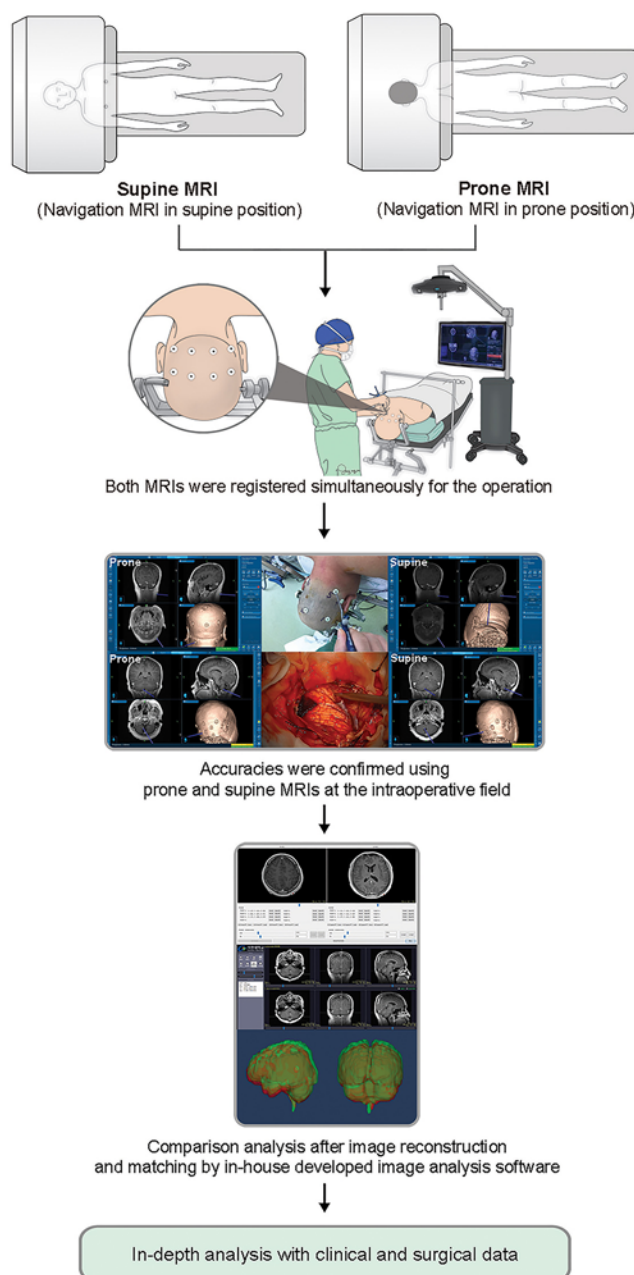


FIG. 1. Schematic presentation of the flow of this study. Copyright Mi-Jin Jung, Biomedical Illustration & Design Company. Published with permission. Figure is available in color online only.

sis method are provided in the Supplementary Materials. Briefly, we used the 2 methods to observe differences in distortion according to the brain location with BrainVAAS. First, we analyzed the degree of distortion based on the area by combining images taken from the prone and supine positions. The degree of distortion was defined as “the area of the distorted part of the section/the total area of the section of the prone MR image” of overlapping images. The other method was calculation of the degree of distortion by referring to 16 stable anatomical landmarks that could be consistently identified in T1-weighted con-

trast-enhanced images of the brain region from the prone and supine MR images coordinated based on the FMs. After specifying the same location in each MR image, the distance between two points was measured. The 16 locations were divided into 3 groups based on the tentorium. We confirmed any differences in the degrees of distortion in the upper part of the tentorium (cerebral area), tentorium, and lower part of the tentorium (cerebellar area) and we verified the statistically significant differences.

Prediction of the Causes of Distortion

To identify factors that could affect the degree of distortion, the patients were divided into 2 groups based on an age of ≤ 60 or > 60 years, and distance data for the 16 locations defined above for the 2 groups were compared and analyzed. In addition, the locations of the FMs were divided into 2 groups (FMs attached to the scalp adjacent to the craniocervical muscle and those attached to the scalp far away from the muscle). Three neurosurgeons verified the locational changes of the FMs in the 2 groups based on the stored MRI-NVS images.

Statistical Analysis

The ANOVA test was used to verify difference in distances among the 3 groups divided by the tentorium. Two sample t-tests were used to determine differences in distances between the 2 groups based on the patient age of ≤ 60 or > 60 years. The R 3.4.0 program was used as the statistical program (R Core Team [2014]. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>). Differences with a p value < 0.05 were considered statistically significant.

Results

The Difference in Accuracy Between the Prone and Supine MR Images Depending on Intuitive Verification

The difference in accuracy for all 64 test points between the prone and supine MR images was verified in the 10 patients during surgery. Fifteen test points on the scalp, 19 on the dura, and 30 on the cerebellum were specified in the actual surgical field according to their depths. Among them, 22 were located in the midline area and 42 were located in the lateral area. When specifying the test points in all patients, locational differences were found in the prone and supine MR images. Indeed, 60 of the 64 test points (93.8%) had higher accuracy on the prone MRI, whereas only 4 (6.2%) were more accurate on the supine MRI when the 3 neurosurgeons verified their locations independently (Fig. 2). Regardless of the depth, the prone MRI showed higher accuracy in all scalp, dura, and cerebellum locations. Moreover, the prone MRI was more accurate in both the midline and lateral areas. In general, there was a tendency for the supine MRI to localize at a point deeper than the actual location.

Quantitative Analysis of Distortion Between the Prone and Supine MR Images

The prone and supine MR images were synthesized

based on the FMs by using BrainVAAS and reconstructed into 3D images. Although some differences existed in the degree, the brain region of the supine MRI in all 10 patients was distorted in the posterior-superior direction compared to that of the prone MRI (Fig. 3A and B). To quantitatively evaluate the degree of distortion on the axial, coronal, and sagittal planes, we specified 64 test points in the 2 MR images. First, we checked the coordinates of 2 of the 64 test points, and then the vector value of the coordinate of the supine MRI was analyzed, with the coordinate of the prone MRI taken as the reference point ([0,0,0]) (Fig. 3C). In the 3D space, the X vector values were all 0, which indicated that the brains in the prone and supine MRI were not distorted to the left or right. Compared to the coordinates specified in the prone MRI in the 3D space, all coordinates specified in the supine MRI were located in the posterior-superior area; as a result, both the Y and Z vector values were all positive. The Y and Z vector values at each of the 64 points are shown in Fig. 3D. On average, the supine MRI was distorted in the posterior-superior direction by 6.3 mm (including the standard error between the patient and each MR image [median 0.6 mm, range 0.2–0.9 mm]) compared to that of the prone MRI (Fig. 3C).

Analysis of Differences in Distortion According to the Brain Region

Using the BrainVAAS, the brain regions of the prone and supine MR images were combined based on the FMs and sectioned according to the axial, coronal, and sagittal planes in units with a 1-mm thickness. Then, the degree of distortion of each section (the area ratio of the distorted area to the total area of the prone MRI) was calculated. For each of the 10 patients, the area ratio of the distorted area to the total area of the prone MRI was verified for each plane. In the axial sections, the ratio of the distorted area of the caudal side was greater than that of the cranial side. In the coronal sections, the ratio of the distorted area of the posterior side was greater than that of the anterior side. In the sagittal sections, the ratio of the distorted area of the midline region was greater than that of the lateral region. All 10 patients showed the same tendency. Considering the overall distortion rate of the 3 sections, we could verify that the PF showed relatively greater distortion than the other regions. Figure 4 shows the segmentation of each cross-section in the combined prone and supine MR images, and the graph describes the mean values of the distortion ratio in each series of 10 patients.

Sixteen points were specified based on anatomical landmarks in the T1-weighted contrast-enhanced prone and supine MR images, which were aligned based on the FMs. After localizing the points on the 2 MR images, the distance between 2 points was measured. A total of 160 distances were measured in the 10 patients, and the distance values were analyzed for each group depending on the region by dividing them into 3 groups corresponding to the upper part of the tentorium (cerebrum), lower part of the tentorium (cerebellum), and areas of the tentorium. The upper part of the tentorium showed a significantly larger distance than the lower part of the tentorium ($p < 0.001$) (Fig. 5).

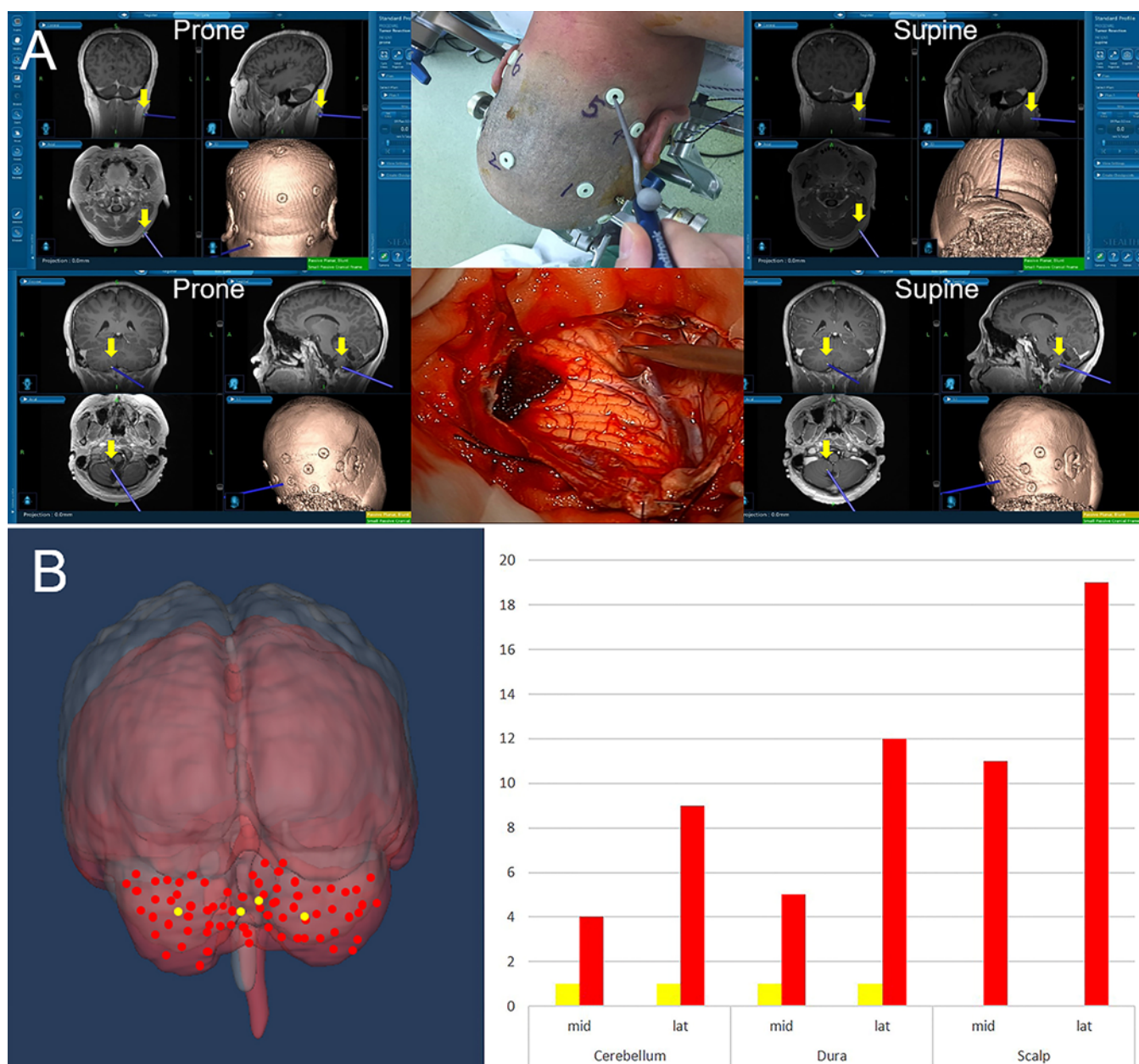


FIG. 2. A: The posterior fossa localization process during the surgery. After localization of the same test points, we confirmed the accuracies of the prone and supine MR images. The prone MRI showed better accuracy (yellow arrows). **B:** Posterior fossa localization was performed at the 64 test points, and the accuracies of the points were compared between the 2 MR images. Red dots—accurate in the prone MR image (n = 60, 93.8%); yellow dots—accurate in the supine MR image (n = 4, 6.2%). lat = lateral area; mid = midline area. Figure is available in color online only.

Analysis of Factors Affecting the Degree of Distortion

We assumed that elderly patients' brains would have a greater range of postural movement due to increased intracranial space caused by brain atrophy. The differences in distances of the 2 MR images at 160 points based on anatomical landmarks that were consistently observed in the prone and supine MR images were analyzed based on an age of ≤ 60 or > 60 years. A significantly greater distance was found in patients > 60 years than in patients ≤ 60 years ($p < 0.001$) (Fig. 6A).

We analyzed the accuracy by localizing the 17 FMs attached to the skin adjacent to the craniocervical muscles near the PF and the 36 FMs attached to the parietal and occipital areas (areas not affected by the muscles). All 17 points (100%) on the skin adjacent to the craniocervical muscles were more accurate in the prone MRI. Additionally, 26 (72.2%) of the 36 parietal and occipital points showed higher accuracy in the prone MRI, and 10 points (27.8%) showed higher accuracy in the supine MRI; these differences were statistically significant ($p = 0.01$) (Fig. 6B).

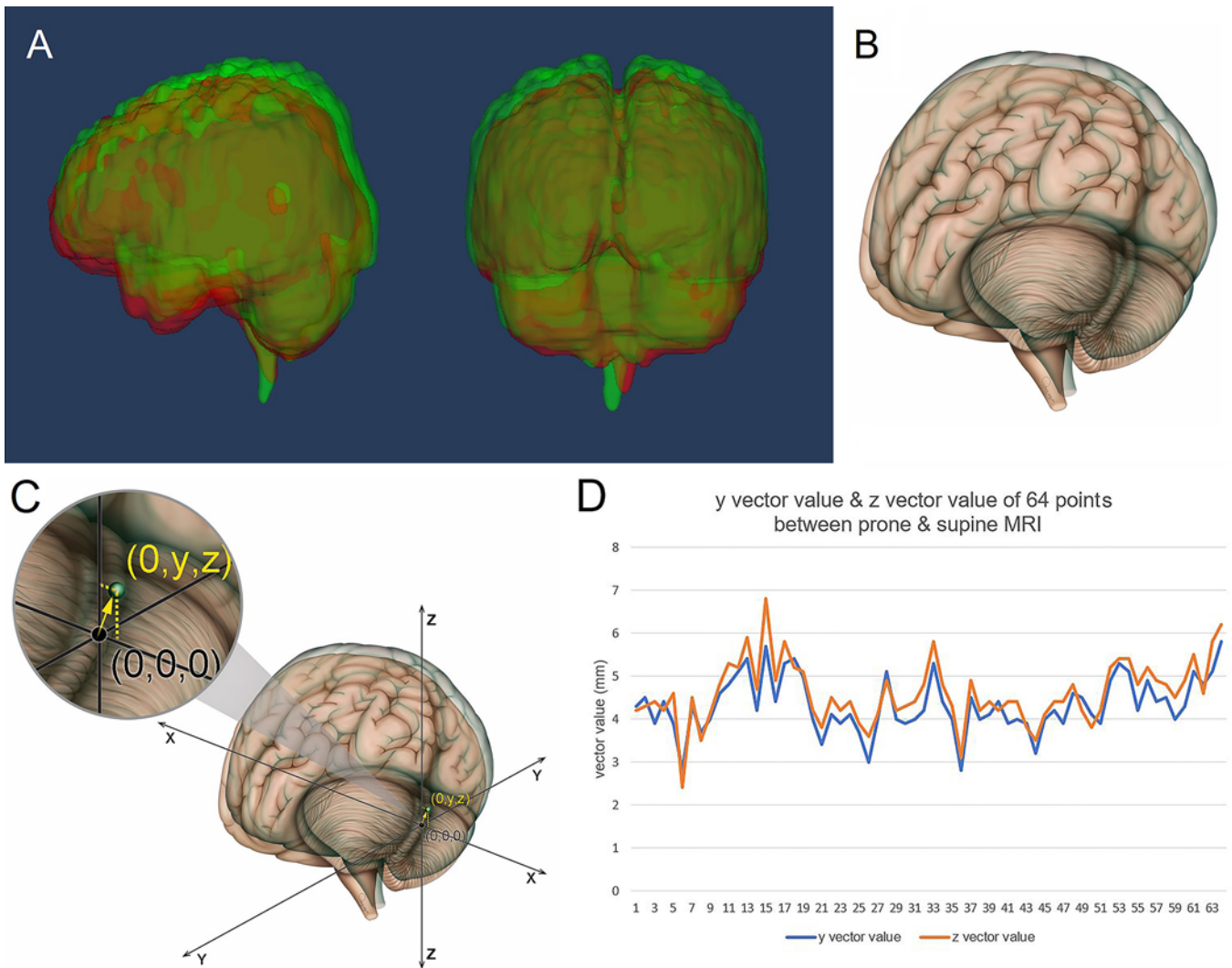


FIG. 3. A: The brains from the prone and supine MR images were reconstructed and synthesized 3-dimensionally by using BrainVAAS. Red: the brain from the prone MRI; light green: the brain from the supine MRI. **B:** The figure shows the actual distortion between the 2 brains based on panel A. The brain from the supine MRI is located in the posterior and superior direction compared to the brain from the prone MRI. **C:** Positional differences of the 2 specified coordinates in the brain on the prone and supine MR images, which shows the magnitude and direction of the vector between the 2 coordinates. For the coordinates specified in the prone MRI in the 3D space, all coordinates specified in the supine MRI are located in the posterior and the superior direction. The average distance of distortion between the prone and supine MR images was 6.3 mm. **D:** The X vector values between 2 coordinates in the 3D space were all 0, whereas both the Y and the Z vector values were positive. Copyright Mi-Jin Jung, Biomedical Illustration & Design Company (panels B and C). Published with permission. Figure is available in color online only.

Discussion

In this study, we verified that the navigational MRI obtained in the prone position was more accurate than the MRI obtained in the general supine position when the PF lesion was surgically treated in the prone position. The factors reported in previous studies that could cause distortion using the MRI-NVS included the effect of gravity, increased intracranial pressure, registration error of FMs, CSF leakage, and medication.^{1,5,8,9,16,19,21,33} Among them, the technically correctable factors when preparing the surgery were errors arising from the direction of gravity and the registration; to improve these factors, we performed the navigation MRI in the prone position instead of in the

supine position and found that the MRI-NVS accuracy increased. This study is the first to identify differences in the accuracy of MRI-NVS by MR scanning simultaneously in both the prone and supine positions. A similar study reported that imaging should be performed in the same position as the procedure when performing stereotactic brain surgery due to errors of up to 2.8 mm between the prone and supine positions.²⁷ The errors can also be corrected during surgery. Recently, the use of intraoperative MRI has been expanding. With intraoperative MRI, complete resection or biopsy at the correct target of a small tumor in the PF can be confirmed before completing the surgery. Therefore, intraoperative MRI may be a means to over-

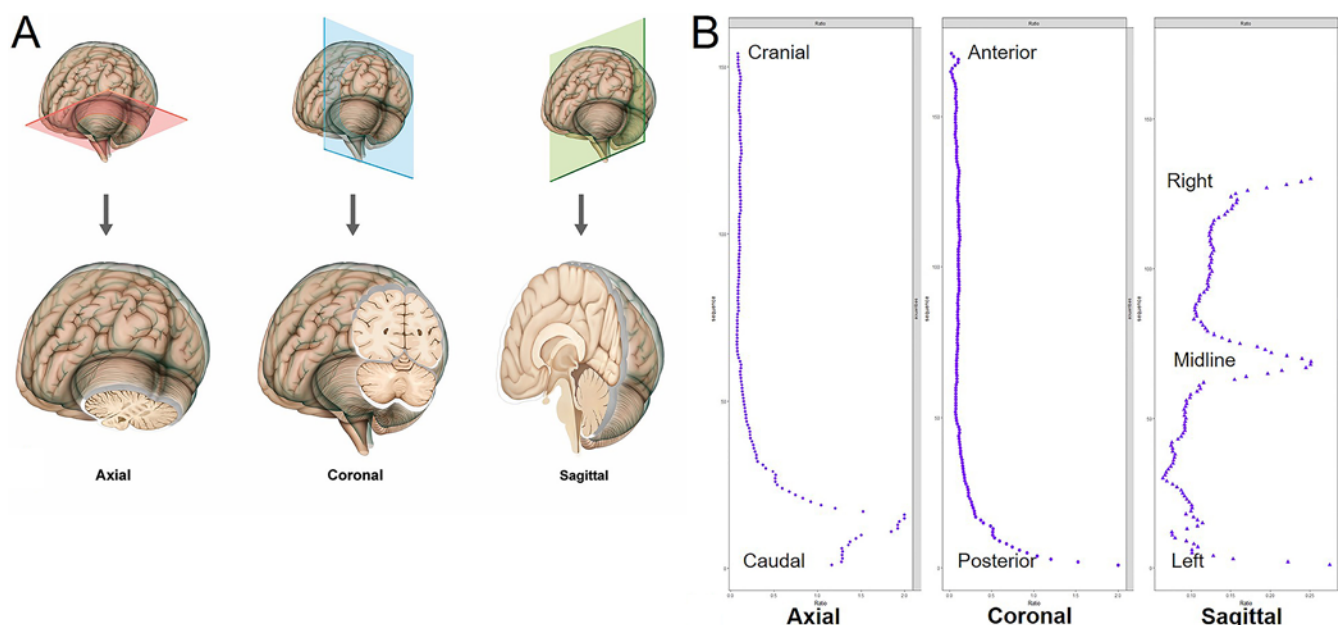


FIG. 4. A: The brain from the prone and supine MR images was synthesized based on the FMs and sectioned by the axial, coronal, and sagittal planes in units with a 1-mm thickness. *Gray area:* distorted area of the brain on supine MRI compared to that of the brain on prone MRI; *white area:* distorted area of the brain on prone MRI compared to that of the brain on supine MRI. **B:** The degree of distortion of each cross-section (the ratio of the distorted area of the cross-section [the gray and white areas in panel A] the total area of the prone MRI of the cross-section) was calculated and plotted in association with the brain region. Axial plane: the ratio of distortion is large on the caudal side. Coronal plane: the ratio of distortion is large on the posterior side. Sagittal plane: the ratio of distortion is large on the midline area. Copyright Mi-Jin Jung, Biomedical Illustration & Design Company (panel A). Published with permission. Figure is available in color online only.

come the discrepancy between the actual surgical position and the navigational MR scanning position.

This study included 5 patients who underwent biopsy using the MRI-NVS. In these 5 patients, the same locations were targeted in the prone and supine MR images and the biopsy was approached using the pathway confirmed by the prone MRI. Applying the approaching pathway confirmed by the prone MRI to the supine MRI in this process, we could verify that the error between the target and pathway was greater than 4 mm (median 4.4 mm, range 4.3–4.8 mm) in all cases. In all patients, the biopsy was successful under the prone MRI and we verified that the biopsy was performed correctly on the set target by the postoperative MRI. In particular, use of prone MRI will improve the accuracy of biopsy of a small PF lesion because the biopsy may fail with even minimal error.^{1,22,26}

Shifting of the brain due to the effect of gravity is well known. However, most studies investigating the direction and pattern of brain movement have used 2D analyses, and few studies have performed 3D analyses; therefore, these studies have only analyzed the effect of gravity due to posture changes.^{20,27,30} In this study, we performed MR scanning after attaching FMs to patients who would undergo surgery, and we developed a software that could combine 2 MR images based on the FMs. The MRI data were analyzed 3-dimensionally, and ultimately we selected the orientation simulating the actual operation, which might have caused errors in the FM registration process. However, because the actual operation was performed with the skull fixated, the situation might not be entirely the same. Based

on the 3D reconstruction of the brain and the vector values of the axial, coronal, and sagittal planes after coordination, we verified that the brain in the supine MRI was located superiorly and posteriorly relative to the brain in the prone MRI. This result implied that the MRI-NVS using the supine MRI localized the lesion to a deeper point than its actual position. In other words, use of a general MRI-NVS with a supine MRI for PF lesion surgery in the prone position may cause misidentification of the surgery location as deeper than the actual location. As a result, if the lesion is not clearly distinguishable from the cerebellum or if a biopsy using the MRI-NVS is conducted subsequent to burr-hole trephination, the tumor may not be removed sufficiently or the biopsy may fail because the actual lesion is located deeper in the tissue.

According to the degree of distortion of the axial, coronal, and sagittal planes verified in this study, the cerebellar region has a relatively greater degree of distortion than the other regions. However, when comparing the absolute magnitude of the distortion based on the distance between 2 points, we confirmed that the cerebellum was less distorted than the cerebrum. Based on these findings, we can conclude that the degree of relative distortion is large in the cerebellum even though the absolute degree of distortion is less than that of the cerebrum because the cerebellum itself has a relatively low volume (accounting for approximately one-eighth of the brain) compared to that of the cerebrum. Moreover, an average distortion of 3.4–4 mm in the cerebrum has been reported to have no significant effect on the MRI-NVS accuracy.^{10,26} However,

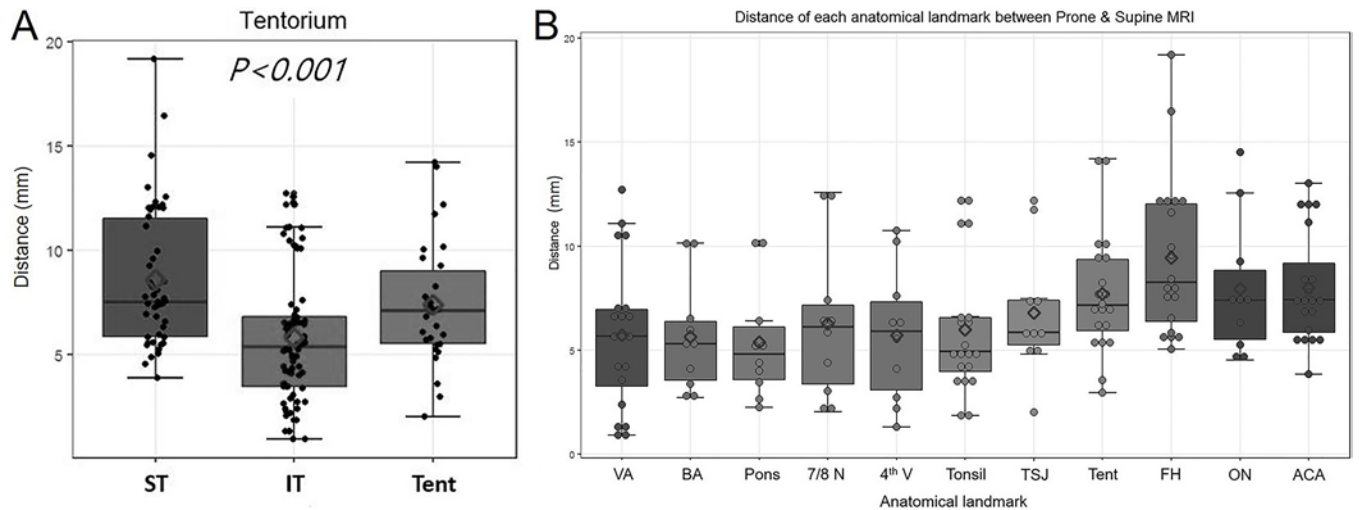


FIG. 5. Box-and-whisker plots. **A:** Sixteen points were specified based on the anatomical landmarks of the prone and supine MR images, which were synthesized based on the FMs. After localizing the points on the 2 MR images, the distance between 2 points was measured. The locations in the supratentorial area had significantly greater distances than the locations in the infratentorial area ($p < 0.001$). **B:** The figure shows the distances between the prone and supine MR images for each of the 11 anatomical landmarks. The structures located in the supratentorial area have a larger distance value than the structures located in the infratentorial area. ACA = anterior cerebral artery; BA = basilar artery; FH = frontal horn; IT = infratentorial; ON = optic nerve; ST = supratentorial; Tent = tentorium; Tonsil = cerebellar tonsil; TSJ = transverse-sigmoid sinus junction; VA = vertebral artery; 4th V = fourth ventricle; 7/8 N = seventh/eighth cranial nerve complex.

in the case of the cerebellum, the overall size is significantly smaller than that of the cerebrum, and the lesion can be deep and be greatly affected by CSF leakage. In addition, if the size of the cerebellar lesion is tiny, the surgery should be performed under higher magnification than that used for a cerebral lesion under a microscope. Thus, we can infer that even though the degree of absolute distortion

is less than that of the cerebrum, the distortion feels relatively large.^{1,4,10}

In this study, a greater difference in distance was found in patients > 60 years than in patients ≤ 60 years ($p < 0.001$). Studies of brain movement and the range of movement within the intracranial space have been reported.^{12,13,20,24,30} When brain atrophy occurs, the intracranial space

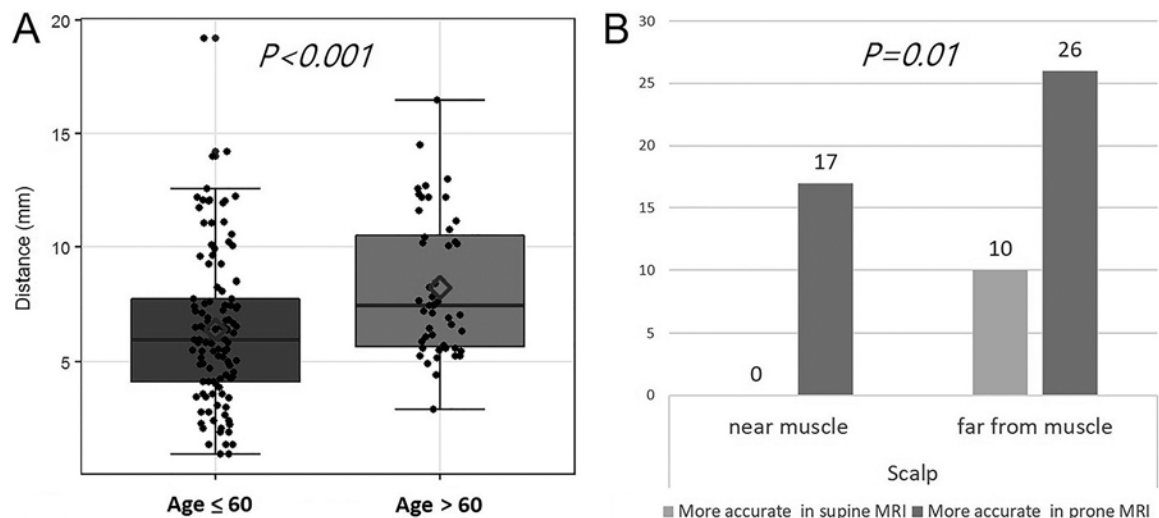


FIG. 6. **A:** Sixteen points were specified based on the anatomical landmarks of the prone and supine MR images, which were synthesized based on the FMs. After localizing the points on the 2 MR images, the distance between 2 points was measured. Patients > 60 years have significantly greater distances than those of patients ≤ 60 years ($p < 0.001$). **B:** All 17 points (100%) on the scalp adjacent to the craniocervical muscles were more accurate in the prone MRI, 26 (72.2%) of the 36 parietal and occipital areas showed higher accuracy in the prone MRI, and 10 points (27.8%) showed higher accuracy in the supine MRI; these differences were statistically significant ($p = 0.01$).

outside the brain increases. In previous studies, the brain volume was measured by serial brain MR images with aging, and the degree of brain atrophy was measured using the brain volume in the serial MR images; these studies reported that patients > 60 years of age showed more pronounced brain atrophy than those ≤ 60 years.^{6,23,28} Therefore, we can infer that the extent of brain movement in the intracranial space is relatively large in patients > 60 years, which might have a greater impact on the degree of distortion in the MRI-NVS. The registration error caused by pushing the FM-attached skin is one of the most common causes of inaccuracy when using the MRI-NVS, and various methods have been attempted to overcome this limitation.^{8,9,22,32,33} In particular, FMs attached to the scalp adjacent to the head and neck muscles near the PF lesion have a tendency to change their locations due to movement of the scalp compared to those attached to the scalp far from the muscles, even if the FMs are attached in an effort to avoid the muscles as much as possible. This issue is an important reason why errors can occur if supine MRI is applied to the MRI-NVS for use during a PF lesion operation in the prone position. This type of movement from the FMs can be minimized by applying prone MRI to the MRI-NVS. To minimize movement of the FMs, if an operation must be performed in a nonsupine position, future studies should consider applying the MR images obtained using the MRI-NVS in the same position as the surgical position instead of applying the supine MRI as a default.

Conclusions

Although prone MRI reflects the brain in the actual prone surgical position, this environment is not perfect. Brain movement due to brain atrophy requires additional verification due to the small number of cases in this study, and additional study of other positions is needed to generalize the findings of this study. We were able to prove that using the prone MRI for MRI-NVS is more accurate than using the supine MRI for PF lesion surgery performed in the prone position. Additionally, the direction and extent of the distortion were identified, and the causes of the error were verified. In cases involving surgery or biopsy for a small cerebellar lesion, especially in elderly patients, the MRI for the MRI-NVS should be obtained in the same position as the surgical position to ensure better MRI-NVS accuracy.

Acknowledgments

This research was supported by the Bio & Medical Technology Development Program of the NRF funded by the Korean government, MSIP (NRF-2015M3A9A7029740).

We thank Hee Sook Kam, RN, and Min-Jung Park, RN, (Department of Neurosurgery, Seoul National University Hospital) for their efforts in clinical data acquisition and management. We also thank Ms. Mi-Jin Jung of the Biomedical Illustration & Design Company for her artwork used in this manuscript.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Park, Dho, KG Kim. Acquisition of data: Dho, Choi. Analysis and interpretation of data: Dho, YJ Kim, Hwang, KH Kim, KG Kim. Drafting the article: Dho, YJ Kim. Critically revising the article: Park, Dho, KG Kim. Reviewed submitted version of manuscript: Park, Dho, YJ Kim, JW Kim, YH Kim, Choi, KG Kim. Statistical analysis: Dho. Administrative/technical/material support: Park. Study supervision: Park.

Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

Supplementary Materials. <https://thejns.org/doi/suppl/10.3171/2019.4.JNS1989>.

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