Contemporary stereotactic functional neurosurgery for movement disorders, mapping of the basal ganglia is based on localizing the AC and PC, determining the functional targets using the Schaltenbrand and Wahren Atlases, and identifying the neural structure using the electrophysiological method. For a visualization of the AC–PC line, ventriculography is considered the gold standard and is still used in some medical centers. Recently, the use of intraoperative ventriculography has decreased and is being replaced by MR imaging for preoperative target localization. Magnetic resonance imaging is superior to CT scanning in the resolution of reconstructed images and in the identification of landmark structures. Moreover, image-guided neurosurgical planning software with the aid of MR images can correct the slight tilting and rotation of the head within the stereotactic headframe, which cannot be corrected in ventriculography. Functional targets have been indirectly localized by calculations based on the coordinates of AC and PC with CT or MR images, or directly visualized with MR imaging.

Object. The goal of this study was to focus on the tendency of brain shift during stereotactic neurosurgery and the shift’s impact on the unilateral and bilateral implantation of electrodes for deep brain stimulation (DBS).

Methods. Eight unilateral and 10 bilateral DBS electrodes at 10 nuclei ventrales intermedii and 18 subthalamic nuclei were implanted in patients at Kaizuka Hospital with the aid of magnetic resonance (MR) imaging–guided and microelectrode-guided methods. Brain shift was assessed as changes in the 3D coordinates of the anterior and posterior commissures (AC and PC) with MR images before and immediately after the implantation surgery. The positions of the implanted electrodes, based on the midcommissural point and AC–PC line, were measured both on x-ray films (virtual position) during surgery and the postoperative MR images (actual position) obtained on the 7th day postoperatively.

Results. Contralateral and posterior shift of the AC and PC were the characteristics of unilateral and bilateral procedures, respectively. The authors suggest the following. 1) The first unilateral procedure elicits a unilateral air invasion, resulting in a contralateral brain shift. 2) During the second procedure in the bilateral surgery, the contralateral shift is reset to the midline and, at the same time, the anteroposterior support by the contralateral hemisphere against gravity is lost due to a bilateral air invasion, resulting in a significant posterior (caudal) shift.

Conclusions. To note the tendency of the brain to shift is very important for accurate implantation of a DBS electrode or high frequency thermocoagulation, as well as for the prediction of therapeutic and adverse effects of stereotactic surgery. (DOI: 10.3171/JNS-07/11/0989)

Key Words • brain shift • brain sinking • deep brain stimulation • stereotactic surgery

In contemporary stereotactic functional neurosurgery for movement disorders, mapping of the basal ganglia is based on localizing the AC and PC, determining the functional targets using the Schaltenbrand and Wahren Atlas, and identifying the neural structure using the electrophysiological method. For a visualization of the AC–PC line, ventriculography is considered the gold standard and is still used in some medical centers. Recently, the use of intraoperative ventriculography has decreased and is being replaced by MR imaging for preoperative target localization. Magnetic resonance imaging is superior to CT scanning in the resolution of reconstructed images and in the identification of landmark structures. Moreover, image-guided neurosurgical planning software with the aid of MR images can correct the slight tilting and rotation of the head within the stereotactic headframe, which cannot be corrected in ventriculography. Functional targets have been indirectly localized by calculations based on the coordinates of AC and PC with CT or MR images, or directly visualized with MR imaging. However, it should be noted that the information on MR imaging concerning the patient’s condition is obtained before surgery, whereas ventriculography provides the information after the bur hole opening. Therefore, even if the brain is shifted for any reason during surgery, ventriculography can update the real-time position of the AC and PC.

The efficacy in stereotactic surgery for movement disorders depends on accurate lesioning or electrode positioning, as well as localizing the neural structure anatomically and physiologically ideal for each symptom. In 1975 Gerdes et al. first described the error resulting from subdural air invasion and “brain sinking” in the stereotactic procedure. It is empirically known that an intracranial air invasion and CSF outflow are associated with brain sinking during surgery; however, authors of few studies have shown the ef-
fect of a brain shift on stereotactic functional neurosurgery. Given that intraoperative brain shift or “brain sinking” has been an unavoidable problem even in burr hole surgery, it could be a significant pitfall for stereotactic neurosurgery. The goal of this retrospective study was to investigate the tendency, direction, and extent of brain shifts in unilateral and bilateral surgeries.

Clinical Material and Methods

Patient Population

We retrospectively analyzed the data obtained in 18 consecutive patients who underwent DBS lead implantation in Kaizuka Hospital between December 2000 and July 2001. Of these patients 16 had PD and two had essential tremor. Eight patients (six with PD and two with essential tremor) underwent a unilateral implantation to one STN and seven VIMs; 10 patients (all with PD) underwent bilateral implantation to eight STNs bilaterally, one VIM bilaterally, and one combination (right STN and left VIM). Clinical profiles of the patients are summarized in Table 1. There was no significant difference in the patients’ clinical profiles between unilateral and bilateral surgery groups except for operation time.

Target Determination and Surgical Procedure

The patient was placed in a sitting position, and a stereotactic headframe (Leksell model G, Elekta Instruments) was affixed to the patient’s head after administration of a local anesthetic with 1% carbocaine. The headframe was secured perpendicular to the facial plane (including forehead and bilateral zygomatic processes). The patient underwent preoperative MR imaging and CT scanning for the localization of the AC and PC and MCP. Two protocols for preoperative sequences of 3D MR angiography were followed using a 1.5-tesla MR imaging unit (VISART, Toshiba). To obtain 30-mm-thick fine-resolution images around the AC–PC area, the following parameters were used: TR 22 msec, TE 9 msec, field of view 340 mm, matrix size 512 × 512 pixels, slice thickness 1.0 mm, and resolution 0.66 mm. For 1400-mm-thick normal-resolution images through the whole brain area the following parameters were used: TR 22 msec, TE 9 msec, field of view 300 mm, matrix size 256 × 256 pixels, slice thickness 1.2 mm, and resolution 1.2 mm. The latter protocol (lower resolution and wider area) was used for correcting the slight head tilt and rotation and for determining the entry point of the functional path. All axial images were transferred to the workstation computer in the operating room in a DICOM format. The data were imported into computer software (SurgiPlan 2.02, Elekta). After the 3D images reconstructed from MR imaging and CT scanning were completely matched as confirmed by the image fusion tool, the AC and PC were calculated by the software. The target coordinates for a lead implantation were tentatively determined based on the AC–PC line (STN: 12 mm lateral, 2 mm posterior, 4 mm ventral to the MCP; VIM: 11 mm lateral to ventricular wall, 5.5 mm anterior to the PC on the AC–PC plane). This procedure was done separately by manual calculation on the x-ray film and by the “functional target” tool of SurgiPlan software to obtain a consensus of the coordinates.

The patient’s head in the headframe was secured to the operative table, and the patient was placed in a supine semisitting position (Table 1) to minimize the outflow of the CSF through the twist-drilled cranial window during the surgery.

The detail of the surgical procedure is described elsewhere. A 2-cm linear skin incision was made at the coronal suture, 2.5 cm lateral to the midline. The skull was perforated with a twist drill in a 4-mm diameter. The dura mater was cauterized using a monopolar coagulator and perforated. The dorsoventral range of the STN or VIM was physiologically investigated by single-track MER, which should have been repeated sequentially until the centers of the target structures were detected. In all cases in this study, the first single-track MER detected an acceptable range of the neural activity of STN or VIM and the track was replaced by a DBS lead; therefore, no patient actually underwent the second MER. Although an x-ray study obtained just after MER did not detect intracranial air, the x-ray study obtained after procedures such as lead implantation, refinement of position, and fixation to the skull detected the gradual increase in intracranial air. After the physiological target localization with both MER and macrostimulation methods, the DBS electrode (model 3387, Medtronic, Inc.) was implanted and tentatively fixed with a titanium miniplate on the skull, as described by Favre et al.: The parameters used for intraoperative macrostimulation by DBS electrode were as follows: pulse width 60 μsec, frequency 180 Hz, and amplitude up to 4.0 V for the STN; and pulse width 100 μsec, frequency 150 Hz, and amplitude up to 2.0 V for the VIM. Generation of dystonic muscle contraction or paresthesia in contralateral extremities or the perioral region below the intended amplitude suggested the proximity to the adjacent internal capsule or sensory thalamus, respectively; therefore in such cases, fine repositioning of the electrode was needed to get an optimum therapeutic effect. After attaining the optimum therapeutic effect, the final position of the electrode was consistently ascertained with intraoperative x-ray films. After the electrode was secured with a titanium miniplate, the subcutaneous layer and skin were closed with 4-0 vicryl and 5-0 nylon sutures, respectively. Finally, an x-ray film was obtained in the supine position to obtain the final coordinates of the most distal contact of electrodes. The patients were transferred to the MR imaging unit while being kept in a supine position. After the postoperative MR image was obtained, the headframe was removed from the patient’s head. The postoperative AC and PC coordinates in a high-resolution MR imaging protocol were determined again using SurgiPlan 2.02.

Evaluation of the Brain Shift and the Location of the DBS Lead

The 3D AC and PC coordinates that were calculated before and immediately after the implantation surgery were compared. The direction of the contralateral shift away from the DBS lead (the first operative side in the case of a bilateral surgery) was defined as positive of the x axis, and the posterior (caudal) shifts and the downward (ventral) shifts were defined as positive of y and z axes, respectively. One week postoperatively when the intracranial air disappeared on x-ray studies, the patient underwent the third MR imaging session. In this examination, the sagittal slices parallel to the AC–PC plane, including the contacts of the
Brain shift during DBS lead implantation

**TABLE 1**

Clinical profiles of 18 patients undergoing DBS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unilat</th>
<th>Bilat</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of patients</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>PD</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Essential tremor</td>
<td>63.0 ± 11.6 (38–75)</td>
<td>65.5 ± 8.4 (58–78)</td>
</tr>
<tr>
<td>age in yrs (range)*</td>
<td>5.3</td>
<td>7.3</td>
</tr>
<tr>
<td>3rd ventricle width in mm (range)*</td>
<td>6.3 ± 2.3 (3.0–9.2)</td>
<td>7.1 ± 2.6 (4.6–11.2)</td>
</tr>
<tr>
<td>AC–PC distance in mm (range)*</td>
<td>23.0 ± 1.3 (21.5–25.0)</td>
<td>23.5 ± 1.7 (21.5–26.9)</td>
</tr>
<tr>
<td>functional target (no. of patients)</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>STN</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>STN/VIM</td>
<td>40.6 ± 5.6 (35–52)</td>
<td>36.2 ± 4.3 (28–43)</td>
</tr>
<tr>
<td>semisitting angle in ° (range)*</td>
<td>145.6 ± 32.9 (90–210)†</td>
<td>221.8 ± 43.2 (100–280)†</td>
</tr>
</tbody>
</table>

* Values are shown as mean ± SD.
† p < 0.01.

DBS lead, and the coronal slices, including the DBS lead and perpendicular to the midsagittal plane, were obtained. Sagittal T1-weighted images including the metallic artifacts of electrode contacts were fused together with the midsagittal plane, including the third ventricle (Fig. 1C), and the coordinates of the metallic artifact of the first contact was calculated assuming the MCP as an origin and the AC–PC line as the y axis (MCP-based coordinates).

**Measurements of Brain Atrophy**

Brain atrophy was assessed as an enlargement of the ventricle or the subdural space. The former included the size of the third ventricle (the width of the third ventricle and the AC–PC distance) and the CVI measured at the level of maximal width of the bilateral anterior horn (bifrontal CVI) and at the level of caudate head (bicaudate CVI). The latter was the ratio (percentage of the subdural space) of the subdural area to that of intracranial area in the axial section at the AC–PC level on the T2-weighted MR images. The areas were calculated with the aid of computer software (Adobe Photoshop version 7.0).

**Statistical Analysis**

All values were expressed as the mean ± SD. Using the Mann–Whitney U-test, the patients’ profiles (age, width of the third ventricle, AC–PC distance, operation time, and semisitting angle) were compared with respect to the unilateral and bilateral surgery groups. To detect the changes in each set of AC and PC coordinates before and after the surgery, the values before and after the surgery were compared using a paired t-test. The statistical differences in the shift in each direction between unilateral and bilateral surgeries were compared using the Mann–Whitney U-test. The correlation between brain atrophy and the extent of brain shift were analyzed using the Spearman rank correlation. Probability values less than 0.05 were considered to be significant.

**Results**

**Patient Profile and Operative Condition**

The patients’ ages were similar between the two groups (unilateral surgery group, 63.0 ± 11.6 years; bilateral surgery group, 65.5 ± 8.4 years; p = 0.73). As an indicator of brain atrophy, the width of the third ventricle and the AC–PC distance were compared in the two groups. The width of the third ventricle was not different between the unilateral and bilateral surgery groups (6.3 ± 2.3 mm in the unilateral surgery group compared with 7.1 ± 2.6 mm in the bilateral group, p = 0.64), and the AC–PC distance was not different between two groups (23.0 ± 1.3 mm in the unilateral surgery group compared with 23.5 ± 1.7 mm in the bilateral group, p = 0.40). The angle of the semisitting position was also similar between the two groups (40.6 ± 5.6° in the unilateral group and 36.2 ± 4.3° in the bilateral group, p = 0.14).

However, the operation time was significantly longer in the bilateral surgery (145.6 ± 32.9 minutes in unilateral surgery and 221.8 ± 43.2 minutes in bilateral surgery, p < 0.01).

**Intraoperative Shift of the AC and PC**

The 3D coordinates of AC and PC before and immediately after the implantation surgery were compared. As shown in Fig. 2A, the direction of the contralateral shift away from the electrode (or medial shift) was defined as a positive value along the x axis, and the posterior (caudal) shift and the downward (ventral) shift were defined as positive values along the y and z axes, respectively. In both unilateral and bilateral surgeries, the AC shifted in the direction contralateral to the electrode, and the extent of contralateral shift of AC was significantly greater in unilateral surgery than in bilateral surgery (unilateral, 0.69 ± 0.45 mm; bilateral, 0.27 ± 0.22 mm; p < 0.05; Fig. 2B). Similarly, the PC shifted in the same direction as AC with a smaller extent; therefore, there was no statistical difference in the extent of the contralateral shift of PC between unilateral and bilateral surgeries (unilateral, 0.35 ± 0.26 mm; bilateral, 0.13 ± 0.18 mm; p = 0.06). The posterior shifts (y axis) of AC in bilateral surgery were significantly larger than that of unilateral surgery (unilateral, 1.15 ± 0.91 mm; bilateral, 2.23 ± 0.93 mm; p < 0.05). Similarly, the PC shifted in the same direction as the AC; however, there was no statistical difference in the extent of the posterior shift of PC between unilateral and bilateral surgeries (unilateral, 0.72 ± 0.56 mm; bilateral, 1.03 ± 0.90 mm). In both unilateral and bilateral surgeries, the AC shifted downward (z axis) to the same extent (unilateral, 0.58 ± 0.77 mm; bilateral, 0.39 ± 0.68 mm). Similarly, the PC shifted in the same direction as the AC; however, there was no statistical difference in the extent of the downward shift of PC, either between unilateral and bilateral surgeries (unilateral, 0.37 ± 0.47 mm; bilateral, 0.37 ± 0.30 mm). As a result, AC–PC distances were not changed before and after unilateral surgery (23.60 ± 1.72 mm before and 23.14 ± 1.57 mm after, p > 0.05); however, the AC–PC distance was significantly shortened after bilateral surgery (23.96 ± 1.50 mm before and 22.77 ± 2.09 mm after, p = 0.004). The MCP, which is generally used as a standard origin for a functional target in the brain atlas, shifted laterally more than 0.5 mm in five unilateral cases (62.5%) and in no bilateral cases (0%), posteriorly more than 0.5 mm in six uni-
Effect of Brain Atrophy on Brain Shift During Stereotactic DBS Lead Implantation

We investigated the possible effect of brain atrophy on the extent of brain shift. Brain atrophy was assessed based on the size of the third ventricle, namely the width of the third ventricle (ventricle width) on an axial image and the AC–PC distance on a midsagittal MR image. In addition, the following three parameters of brain atrophy were calculated on the MR images: bicaudate CVI; bifrontal CVI; and the craniosubdural index, which is the percentage of the subdural area in the intracranial area of the axial AC–PC plane. The analysis with the Spearman rank correlation indicated that there were no significant correlations between the ventricular size and the extent of AC shift. The analysis with the PC shifts was not investigated because they were always smaller than those of the AC.

Discrepancy of Estimated Electrode Location Between Postoperative MR Imaging and Intraoperative X-Ray Studies

The coordinates of the distal contact of electrode can be calculated when the MCP is assumed as an origin of the three axes and the AC–PC line as the y axis (MCP-based coordinates). In this method, however, the coordinates of AC–PC lines cannot be updated during surgery, despite a possible brain shift. As a result, MCP-based coordinates obtained from the MR imaging–guided AC–PC line and the intraoperative x-ray films might not indicate the actual position in the target structure (STN or VIM) after a brain shift. The MR images, which were obtained 1 week after implantation when the intracranial air disappeared and the brain shift was completely restored, were used for calculating the actual MCP-based coordinates (Fig. 1). Figure 3 shows the gaps between the MCP-based coordinates calculated on intraoperative x-ray films and those on MR images from the 7th postoperative day. In unilateral surgery, the distal contact of electrode was located more laterally (0.79 ± 0.66

Fig. 1. A–C: The MCP-based coordinates as shown on MR images. Midsagittal T1-weighted image (A) and parallel image including the metal artifacts of electrode (B) were fused into one image (C). The AC–PC line was designated as the y axis and perpendicular line from MCP was designated as the z axis. The coordinates of most distal contacts were measured. D: Coronal MR image showing the DBS lead. The plane is perpendicular to the midsagittal plane.
Brain shift during DBS lead implantation

mm, p < 0.01) and more anteriorly (0.69 ± 1.15 mm, p < 0.01) on the postoperative MR images than on the intraoperative x-ray films; however, the gap in the upward direction was not significant (0.01 ± 0.85 mm, p = 0.40). In bilateral surgery, the distal contact of the second electrode was located more anteriorly (0.77 ± 1.02 mm, p < 0.01) on the postoperative MR images than on the intraoperative x-ray films; however, the gaps in the lateral direction (0.07 ± 0.64 mm, p = 0.92) and upward direction (0.05 ± 0.76 mm, p = 0.39) were not significant. The gaps in the lateral direction between the MCP-based coordinates calculated on intraoperative x-ray films and postoperative MR images were significantly larger in unilateral surgery than in bilateral surgery (p < 0.01); however, those in the anterior and upward directions were not different between unilateral and bilateral surgeries. The maximal posterior shift of AC in bilateral surgery was 4.00 mm; however, the maximal gap of electrode position between virtual and actual position was 2.30 mm.

Discussion

Brain Shift in Stereotactic Functional Neurosurgery

So far, a limited number of studies have shown the effect of a brain shift on stereotactic functional neurosurgery. In recent years, DBS has been increasingly performed for...
medically intractable movement disorders because of several advantages, such as nondestructive and functional ablation and adjustability of stimulatory parameters, to minimize complications and to maximize therapeutic effects. As one of the unexpected benefits, DBS also provides us the chance to observe the surgical track during a stereotactic procedure. Although a microelectrode or an insertion cannula advances straight toward the target (the center of a ste-

![Diagram](image-url)
Brain shift during DBS lead implantation

The contour of an inserted DBS lead after the removal of rigid stylet occasionally presents the slight curve in the track of the electrode on intraoperative x-ray films. In most cases, the slight curve in the electrode contour indicates the shift of the brain itself during electrode insertion, but not a migration of the electrode. Two factors may affect the brain shift during the stereotactic surgery. The first factor is related to the resistance or friction between a lead (or cannula) and brain tissue. A rigid lead or an insertion cannula proceeds straight through several brain components with heterogeneous resistance such as subarachnoid membrane on the deep sulci, white matter, ventricle, basal ganglia nuclei, and/or possible physiological calcification. In particular, the blunt tip of an insertion cannula prefers to proceed in the direction of a soft tissue with less resistance rather than a rigid tissue with greater resistance. This phenomenon can be recognized on an x-ray film as a curvilinear contour of the DBS lead localized in the lateral ventricle after the removal of insertion cannula in the case of a transventricular implantation of a DBS lead. The second factor is related to gravity, which is the focus of the present study. There is a dilemma in the current procedures: lowering the head position may result in the facilitation of CSF outflow from the cranial window, whereas raising the head position may result in the facilitation of air invasion due to the augmented negative intracranial pressure by hydrostatic pressure discrepancy.

Tendency of Brain Shift During Stereotactic Functional Neurosurgery

In the present study we have demonstrated that the contralateral shift and posterior shift of the AC–PC line were the characteristics of unilateral and bilateral procedures, respectively. These findings suggested the mechanisms of brain shift depending on negative intracranial pressure, atmospheric pressure, and the site of intra- and extracranial air communication. Namely, the first unilateral procedure for electrode implantation elicits ipsilateral intracranial air invasion through the cranial window, and the resultant pressure discrepancy between the hemicrania facilitates the brain shift in the direction contralateral to the cranial window (Fig. 4A). At the second procedure in the contemporaneously bilateral surgery, the pressure discrepancy between bilateral hemicrania is lost and the contralateral shift is reset to the midline. At the same time, the anteroposterior support by the contralateral hemisphere against the gravity is lost because of bilateral air invasion, which facilitates a significant posterior shift due to gravity (Fig. 4B). The intracranial air accumulation with the CSF level formation, which was observed on x-ray films during the surgery, increased in a time-dependent manner. Therefore, the significant posterior shift in the bilateral surgery group was considered to be due to both the longer operation time and bilateral intracranial air invasion.

Bilateral Intracranial Air Invasion During Unilateral Surgery

In the anteroposterior view of the x-ray film, the intracranial air invasion in most patients was limited to the surgical side of the unilateral procedure; however, three of 18 patients (two unilateral cases and one bilateral case) showed the intracranial air invasion bilaterally at the time when a unilateral procedure was completed (Fig. 4c). In such cases, the contralateral AC shift was very small (0.5 and 0.2 mm in two cases) and the posterior shifts of AC were prominent (1.9 and 2.9 mm in two cases), compared with the other cases of unilateral surgery (Fig. 4D). In addition, one patient in the bilateral surgery group who had a bilateral intracranial air invasion, even after the first unilateral procedure, also presented with a prominent posterior shift (4.0 mm) after the bilateral procedure. According to these results, the sign of contralateral air invasion underneath the falx cerebri may indicate an unexpectedly great posterior shift due to brain sinking, irrespective of unilateral or bilateral procedure. The pulsation of the brain may occasionally allow the contralateral air invasion underneath the falx cerebri, which is associated with CSF redistribution in the subdural space.

Impact of Brain Shift on Stereotactic Surgery

It is essential to place the high-frequency lesion or to locate the active contact of a DBS electrode in the physiologically ideal position where the maximal benefit with minimal adverse effects can be expected. So far, little attention has been given to an intraoperative brain shift in stereotactic functional neurosurgery; however, several technical problems should be considered in clinical practice. The study on the discrepancy in the AC and PC coordinates between MR imaging— and ventriculography-guided localization should be always interpreted with consideration of the possibility of brain shift before ventriculography. Although the physiological investigation by MER is crucial to ensure the structure of basal ganglia along the track, it should be noted that the longer the time that is spent for MER, the greater the brain shift that could occur. If an intracranial air accumulation seen on intraoperative x-ray films differs markedly between the before- and after-landing of MER, the results of the physiological target coordinates by the earlier track recording cannot be warranted until the completion of electrode implantation. On the other hand, the gaps between the virtual position during surgery and actual positions of DBS electrode were not so large as expected from the AC shift (see Figs. 1 and 2). That is because brain shifts evaluated in this study included the significant shifts during the procedures from the intracerebral lead insertion to skin closure, which did not affect the track of lead itself.

How Can We Prevent Brain Shift?

Because loss of CSF leads to an intracranial air invasion and brain shift, suctioning subdural CSF through the burr hole even for the clear visualization of the cortical surface should be avoided. A saline injection into the subdural space does not work to prevent the brain shift because brain sinking is always associated with the CSF redistribution from the inside (ventricle) to the outside (subdural space). Filling the ventricle with air may help, to some extent, to minimize brain sinking and deformation; however, the exact volume of air needed for restoration of brain shape is unknown. Furthermore, air-ventriculography itself enlarges the width of the third ventricle and dislocates the commissures anteriorly. Therefore, it is important to minimize CSF loss and intracranial air invasion before brain shift, but not to restore them after the occurrence of brain shift. In-
Tracranial air invasion occurs even though there is no CSF outflow from a cranial window. Therefore, it seems to be crucial to cut off the communication between subdural space and external air. To our knowledge, there are two ways that might be effective to prevent the intracranial air invasion: one is the use of fibrin glue or melted bone wax covering the operative field in the bur hole, and another is the completely flat supine position. In our experience, opening the bur hole at the uppermost of the frontal bone (far rostral to the coronal suture) facilitates the communication between intra- and extracranial air, instead of preventing the CSF outflow. However, the efficacy of these methods needs to be elucidated by further study.

Most of the brain shift as presented in this study may not be a significant problem or within a range that can be cancelled by optimizing the DBS parameters. The unexpected effect of DBS might be, in part, a result of intraoperative brain shift; therefore, it is of great help to know the tendencies of intraoperative brain shift in unilateral and bilateral surgeries.

Conclusions

A brain shift during stereotactic DBS electrode implantation was found to occur with some tendencies. The contralateral (or medial) shift of the AC–PC line away from the electrode was typical in the unilateral surgery, whereas the posterior shift of the AC–PC line and restoration of contralateral shift were typical in the contemporaneously bi-

![Fig. 4. A and B: Schematic drawings of the intraoperative brain shift. Unilateral intracranial air invasion results in a significant contralateral shift of the midline structure (horizontal arrow); however, the concomitant posterior shift is minimal (vertical arrow) because of the antigravity support by the contralateral hemisphere (A). During the second implantation of contemporaneously bilateral surgery, a bilateral intracranial air invasion results in a significant posterior shift because the antigravity support by contralateral hemisphere is lost; however, the lateral shift is restored (B). C: An x-ray film showing the representative sign of bilateral air invasion at the unilateral procedure in two cases suggests the brain shift mimicking a bilateral surgery. D: Scatterplot showing the relationship between the extent of x and y shifts in the AC in unilateral (open circle) and bilateral (closed circle) surgeries. Arrows indicate three cases in which x-ray films revealed a bilateral air invasion sign at the time of completion of unilateral electrode implantation (or first unilateral procedure of bilateral implantation) during the surgery.](image)
lateral surgeries. The tendency of brain shift was well explained by the intracranial air invasion.

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