A New Brain-Shift Model for Neurosurgery with Fronto-Temporal Craniotomy

Kengo Suzuki1, Yukinori Akiyama1, Toshiya Sugino1, Takeshi Mikami1, Masahiko Wanibuchi1, Toru Inagaki2, Shinsuke Irie2, Koji Saito2 and Nobuhiro Mikuni1*

1Department of Neurosurgery, Sapporo Medical University, Japan
2Department of Neurosurgery, Kushiro Kojinkai Memorial Hospital, Japan

Abstract

Neuronavigation systems have become standard neurosurgical tools; however, there is a major concern to be solved. Brain shift occurs during surgery, which compromises the system’s accurate anatomical representation. We developed and evaluated a convenient new method for a rapid intraoperative correction of brain shift during neuronavigation. We assessed four patients (4 females; mean age 61.0 years) that underwent a fronto-temporal craniotomy. Each voxel movements of CT images in the brain parenchyma are analyzed as displacement vector using neuronavigation system, and a new free-form deformation method was established among these patients and verified in another one. The shape concordance rate between the actual intraoperative CT image and CT image, which was corrected by our model, was 75.1%. On the basis of nonlinear geometric algorithms that involve intraoperative measurements of anatomical landmark positions, our model might be useful especially in pterional craniotomy, which is one of the most common approaches employed in neurosurgery. Future improvements and further accumulation of patients’ data will enable our model to be applied to a variety of surgeries.

ABBREVIATIONS

CT: Computed Tomography; MRI: Magnetic Resonance Image

INTRODUCTION

Neuronavigation systems have become increasingly popular and are now standard neurosurgical tools. However, a key challenge is that brain shift occurs during surgery, which compromises the system’s accurate anatomical representation. Since Kelly et al. [1] first reported the brain shift phenomenon, many researchers have investigated the causes of intraoperative brain shift, and gravity has been identified as a major factor [2]. Intraoperative displacements of the brain surface are identified with the aid of image-guidance systems by comparing the position of surface markers during surgery with the position shown in images acquired before surgery or after dural opening [3,4], as well as by measuring changes in three coordinates on brain surface using focal points of microscope by laser beams [2], and measuring the two-dimensional changes in brain surface by using video images [2]. These approaches all focus on the motion of the brain surface. However, the functional significance of association fibers underscores the importance of determining and correcting the displacements of deep brain structures.

Documented correction methods generally use either intraoperative scans or nonlinear geometric models. Several groups have attempted to develop an ultrasound-based intraoperative compensation for the displacement of deep brain structures [5-9]. Such approaches have drawbacks such as poor resolution and only provide information about regions close to the exposed craniothy field. Compensation methods also employ intraoperative Computed Tomography (CT) [10-13] and Magnetic Resonance Imaging (MRI) [14-21]. None of these methods have wide acceptance due to problems associated with radiation exposure, inaccuracy, costs, and time [22]. In contrast, nonlinear biomechanical approaches to brain shift compensation rely on brain geometry [23-27]. These approaches also have shortcomings. For example, the results could often be inaccurate because the brain is not a true sphere, but rather a complicated three-dimensional architecture with complex internal structures such as the cerebral falx and tentorium.

Here, we report a convenient new method rapidly correcting registration errors and is based on intraoperative measurement of the surface brain shift. Our approach may improve neurosurgical outcomes by enabling surgeons to evaluate local brain functions and neural networks more precisely.
MATERIALS AND METHODS

Subjects
A total of 41 patients (20 males, 21 females; mean age 50.2 years [range, 3-80]) who underwent navigation-assisted open neurosurgery between October 2011 and September 2012, were assessed. Surgery was performed for brain tumor removal (n = 28), aneurysm dipping (n = 8), callosotomy (n = 2), superficial temporal artery-middle cerebral artery anastomosis (n = 2), or epileptic focus resection (n = 1) (Table 1). All patients were eligible for surgery on the basis of clinical and radiologic evaluations and complied with the protocol after providing informed consent. Four of these patients underwent a fronto-temporal craniotomy with the head rotated 8.6-27.0 degrees to the contralateral side, which is one of the most frequently used neurosurgical approaches, and intraoperative CT scans was performed. Data from these last four patients were used to develop the brain shift compensation model.

Image acquisition
All 41 patients underwent preoperative MR and CT scans. T1-weighted MRIs (T1WIs) were acquired using a 3.0T SIGNA HDx (GE Healthcare, Milwaukee, WI, USA) or Intera Achieva 3.0T Quasar Dual (Philips Medical Systems, Best, The Netherlands) scanner under the following conditions: 25-ms echo time, 2.2-ms repetition time, 200-mm field of view, and 256 × 256 matrix. The CT scans were acquired using a Light Speed VCT 64 (GE Healthcare) or Brilliance CT 64 Power (Philips Medical Systems) with a 1.0-mm slice thickness. The preoperative CT and MR images were merged on an image-processing workstation.

Intraoperative CT images were obtained using an Aquilion/LB 16 scanner (Toshiba Medical Systems, Otawara, Japan) or an Xper CT in a Hybrid operating room (Philips Medical systems) with a 1.0-mm slice thickness. The CT scans were acquired using a 1.0-mm slice thickness. Xper CT in a Hybrid operating room (Philips Medical systems) LB 16 scanner (Toshiba Medical Systems, Otawara, Japan) or an images were merged on an image-processing workstation.

The CT scans were acquired using a Light Speed VCT 64 (GE Healthcare) or Brilliance CT 64 Power (Philips Medical Systems) with a 1.0-mm slice thickness. The preoperative CT and MR images were merged on an image-processing workstation.

Table 1: Patients characteristics, all measured by neuro-navigation system.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>n</th>
<th>navi</th>
<th>pre CT</th>
<th>ICT</th>
<th>mean BS (mm)</th>
<th>max BS (mm)</th>
<th>time points to points (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranial surgery</td>
<td>n=41</td>
<td>20 men, 21 women; age, 50.2±22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meningioma</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>13.35±4.97</td>
<td>15.12±7.98</td>
<td>294.7±136.2</td>
</tr>
<tr>
<td>Glioma</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>0</td>
<td>10.71±6.11</td>
<td>13.78±8.87</td>
<td>224.1±77.2</td>
</tr>
<tr>
<td>Other tumors</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>11.46±3.47</td>
<td>14.13±3.18</td>
<td>166.2±58.1</td>
</tr>
<tr>
<td>Aneurysm</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>7.87±3.64</td>
<td>12.72±6.96</td>
<td>115.8±66.4</td>
</tr>
<tr>
<td>EC-IC anas.</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>12.98±9.38</td>
<td>14.24±8.89</td>
<td>121.5±16.3</td>
</tr>
<tr>
<td>Epilepsy</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>9.67±2.38</td>
<td>11.98±3.07</td>
<td>198.7±49.7</td>
</tr>
</tbody>
</table>

Abbreviations: navi: Neuronavigation; pre CT: Preoperative Computed Tomography; ICT: Intraoperative Computed Tomography; BS: Brain Shift

Surgical procedure and data acquisition
Following general anesthesia, the patients were placed in a posture suitable for surgery with the head rigidly fixed in position with a Mayfield head holder. CT-compatible head holders were used (DORO® Headrest System Radiolucent, Pro Med Instruments GmbH, Freiburg, Germany and MAYFIELD® Cranial Stabilization Radiolucent Systems, Schaeerer, Cincinnati, USA). The brain surfaces were scanned using an optical three-dimensional neuronavigation system (Kolibri, Brainlab, Munich, Germany) to determine the topography at a spatial resolution of 10⁻³ mm × 10⁻³ mm × 10⁻³ mm. Three-dimensional visualization and modeling software (Amira®, Visualization Sciences Group, Mérignac, France) was used to analyze the brain shift and to create and output intraoperative imaging data. The software identified and visualized deformations by applying displacement vectors to the original images.

Determination of the brain shift
To quantify the intraoperative displacement of the brain surface, four reference points (RP; i = 1, 2, 3, and 4) were determined arbitrarily in the open surgical field immediately after dural opening. The reference points were selected from the blood vessel furcations and were the same maximum distance from the center of the surgical field in order to represent the entire exposed area. The initial preoperative locations of the RP, after dural opening were registered using the positional coordinate system (xi, yi, zi) on the navigation system (Figure 1A). After completing microscope-assisted surgery, the neurosurgeon registered the final postoperative locations of the reference points using the positional coordinate system (xi', yi', zi') before dural closure (Figure 1B). The brain shift (S) was subsequently calculated using equation (1):

\[
S_{ij} = (x_i - x_i')^2 + (y_i - y_i')^2 + (z_i - z_i')^2
\]

Table 2: Patient underwent intraoperative CT.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age(yrs)/sex</th>
<th>Diagnosis</th>
<th>Craniotomy</th>
<th>Position</th>
<th>Rotation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58/F</td>
<td>Rt. MCA An</td>
<td>Rt. F-T</td>
<td>Supine</td>
<td>8.6 to L</td>
</tr>
<tr>
<td>2</td>
<td>44/F</td>
<td>Lt. IC-Anch An</td>
<td>Lt. F-T</td>
<td>Supine</td>
<td>18.1 to R</td>
</tr>
<tr>
<td>3</td>
<td>63/F</td>
<td>Rt. MCA</td>
<td>Rt. F-T</td>
<td>Supine</td>
<td>27.0 to L</td>
</tr>
<tr>
<td>4</td>
<td>79/F</td>
<td>Rt. IC-Anch, Acom An</td>
<td>Rt. F-T</td>
<td>Supine</td>
<td>14.9 to L</td>
</tr>
</tbody>
</table>

Abbreviations: CT: Computed tomography; yrs: Years; deg: Degree; An: Aneurysm; MCA: Middle Cerebral Artery; IC: Internal Cerebral Artery; anch: Anterior Choroidal Artery; Acom: Anterior Communicating Artery; Rt: Right; Lt: left; F-T: Fronto-Temporal
The brain shift was computed for each patient. In addition, the time from the opening to the closure of the dura (fenestration time) was measured on the basis of the recorded time of acquisition of the positional coordinates.

**Brain shift compensation**

Topographic changes of the cerebral surface and deep brain structures identified by comparison of the pre- and intraoperative CT measurements of four patients were used to develop a brain shift model for fronto-temporal craniotomy (Table 2). This model provided displacement vectors for each voxel of the preoperative CT image, thereby compensating for the fronto-temporal craniotomy-induced brain shift in real time based on the marker position data obtained using the navigation system.

Below are the details of the procedure used to create the brain shift model (Figure 2). During the four fronto-temporal craniotomies, CT scans and marker position data were acquired simultaneously by using the navigation system (Figures 3A and 3B). Preoperative T1WI and CT images were overlaid via affine registration, and brain parenchyma was extracted from pre- and

$$S = \frac{1}{4} \sum_{i=1}^{4} (x_i - x) + (y_i - y) + (z_i - z)$$  \hspace{1cm} (1)

**Figure 1** Measurements of the reference point positions using a navigation system. Positions of four anatomical landmarks were determined shortly after a dural opening (left) and shortly before a dural closing (right). Landmarks were chosen from blood vessel furcations on the cerebral surface.

**Figure 2** Algorithm of this brain shift model for fronto-temporal craniotomy. Preoperative work, intraoperative work, and evaluation of this study were documented separately.
intraoperative CT images (Figures 3C and 3D). The function of the affine transformation of the positional coordinates $x$ to $y$ could be described using the affine transformation matrix $A$ in equation (2):\[ y = f(x) = Ax + d \] where $d$ is a constant vector.

Using the Free-Form Deformation (FFD) method, displacements between the intraoperative CT images of the four patients who underwent fronto-temporal craniotomy acquired shortly after dural opening and shortly before dural closure were identified for each voxel (dimensions: 1 mm × 1 mm × 1 mm) (Figure 4A). The brain parenchyma and ventricle are analyzed separately and then combined. Specifically, FFD employed a deformation lattice superimposed over an object, and the control points of the lattice were selected and displaced to alter the surface of the enclosed object. The changes in the lattice cell points were expressed as displacement vectors. Dividing a parallelepiped deformation lattice encasing a three-dimensional brain image horizontally, vertically, and longitudinally into $l \times m \times n$ parts of equal size gave $(l+1) \times (m+1) \times (n+1)$ control points: $P_{ijk} (i = 0, 1, \ldots, l; j = 0, 1, \ldots, m; k = 0, 1, \ldots, n)$. When $P_{ijk}$ underwent a shift, the model vertex coordinate $X(s, t, u)$ moved to a position $X_{\text{ffd}}$, which could be expressed using basis functions $B(\bullet)$ as:

\[ X_{\text{ffd}} = \sum_{i=0}^{l} B_i(s) \sum_{j=0}^{m} B_j(t) \sum_{k=0}^{n} B_k(u) P_{ijk} \] (3)

To develop the model, we began with a global registration using a $16 \times 16 \times 16$ or similar grid and improved the simulation precision by increasing the number of lattice cells. The displacement vectors obtained from the four patients were standardized by dividing by the mean shifts of the four reference points measured earlier. The standardized vectors of the four patients were averaged and mapped to a spatially normalized average human brain MR image template. Because right and left pterional craniotomies were performed in three and one of the four patients, respectively, the vector data obtained from the left pterional craniotomy were converted to fit the right pterional approach for averaging purposes. Each vectors created from the four pterional craniotomy patients were summed separately the brain parenchyma and cerebral ventricles (Figure 4B).

To adjust for brain displacements during surgery, we updated the preoperative CT images by applying the present brain shift model and patient-specific mean reference point shifts (for a typical example, compare Figures 4C and 4D). In our FFD approach, B-splines were used to optimize grid point interpolation.

**Evaluation of correction accuracy**

The resulting images were refined with Gaussian smoothing.
filter for noise reduction. During the smoothing process, data points were averaged with their neighboring points. In contrast to a simple arithmetic mean of the surrounding pixel values, the Gaussian filter took advantage of the Gaussian (normal) distribution where closer points were assigned a greater weight. The refined images were compared to the CT scans obtained during surgery with respect to morphology by using the normalized cross correlation method. In this study, the pre-filter images were each divided into a $200 \times 200 \times 150$ grid containing $1.1 \text{ mm} \times 1.1 \text{ mm} \times 1.3 \text{ mm}$ cells. The areas encompassing three adjacent voxels along both directions of the $x$- and $y$-axes, i.e., square $7 \times 7$ regions centered on the voxel to be evaluated, were processed by gradient weights. The processed CT images were compared by a normalized cross correlation with the corresponding intraoperative CT image for voxel intensity by using a $200 \times 200 \times 150$ grid containing $1.1 \text{ mm} \times 1.1 \text{ mm} \times 1.3 \text{ mm}$ cells.

The present model from four cases was applied on another pterional approach case (64 year-old, female). The applied preoperative CT images compared by a normalized cross correlation with intraoperative CT.

Statistical analysis
Results were analyzed using a $t$-test at a two-tailed significance level ($p$) of 0.05.

RESULTS
Determination of brain shift
In terms of coordinate, the fronto-temporal craniotomies were characterized by a larger brain shift in the dorsal direction than any other direction. The mean ($\pm$ SD) brain shifts for cases involving extirpation of meningiomas and gliomas (space-occupying lesions) was $13.4 \ (\pm\ 5.0)$ and $10.7 \ (\pm\ 6.1)$ mm, respectively. By contrast, the mean ($\pm$ SD) brain shift for cases of cerebral aneurysm and epilepsy (non-space-occupying lesions) was $7.9 \ (\pm\ 3.7)$ mm and $9.7 \ (\pm\ 2.4)$ mm, respectively (Table 1). Thus, surgeries for space-occupying lesions yielded greater brain shifts than those for non-space-occupying lesions, although the differences were statistically insignificant ($p = 0.106$). For cases of extirpated space-occupying lesions, the mean brain shift for meningiomas and gliomas was not significantly different (mean $\pm$ SD; $13.4 \pm 50$ vs. $10.7 \pm 6.1$ mm, respectively, $p = 0.329$). However, a statistically significant correlation was observed between the mean brain shift and fenestration time ($r = 0.343, p = 0.028$).

Figure 4 Determination of displacement vectors and correction of preoperative images for a brain shift.
Displacement vectors were determined for four pterional craniotomy patients by applying the free-form deformation method to the intraoperative computed tomography images obtained shortly after opening and closing the dura. Four patients' vectors data was shown in figure 4A. Each vectors reveal voxel shift between pre-operation and post-operation for direction and magnitude. The magnitude of each brain shift is shown by color gradation qualitatively (4A). Displacement vectors detected for the four patients were averaged voxel-wise, and their mean values are displayed on a color scale (4B). Preoperative computed tomography image of Patient No. 4 (4C) was corrected using the displacement vectors to predict the craniotomy-induced morphological change (4D). Displacement vectors were computed considering the shifts of the four reference points.
Figure 5 Another case corrected by our brain shift model. Predicted CT image (5A) is similar to actual intraoperative CT image (5B).

Analysis of the pairs of intraoperative CT images acquired at the beginning and end of each craniotomy showed that a region spanning from the exposed cortical surface to the cerebral ventricle had the greatest shift in the direction of gravity. The magnitude of each brain shift is shown by color gradation qualitatively (Figure 4A).

Brain shift correction

We created sets of displacement vectors for the four patients who underwent perional craniotomy by separately applying semi-automatic FFD to the brain parenchyma and cerebral ventricles. These vectors were averaged for each voxel to develop the standardized brain shift model (Figure 4B). More specifically, brain displacements were determined by running the FFD method (see Materials and Methods) in the semi-automatic mode in the Amira software. The detected displacements were further tuned using the positional changes of the four reference points measured by intraoperative neuronavigation.

Evaluation of correction accuracy

The morphology of the corrected CT images explained in the preceding paragraph was compared in terms of voxel intensity to that of the intraoperative CT images acquired shortly before dural closure. The overall rates of agreement between the predicted and actual intraoperative CT images were 71.0%, 71.3%, 46.4%, and 87.2% for Patient Nos. 1, 2, 3, 4, respectively.

We also applied our model, which was developed from these four patients’ data, to another fronto-temporal craniotomy case (64 year-old, female) who had a frontal lobe glioma. Intraoperative CT image and corrected preoperative CT image were shown in Figure 5. The rate of agreement between two image series was 75.1%.

Obtaining the coordinate data only required 5 minutes, and afterwards, the correction algorithm required 15 minutes to compensate for the brain shift.

DISCUSSION

To date, most methods that have been proposed for correcting registration data have generally involved the use of intraoperative images and/or non-linear geometric models. As previously noted, intraoperative images are insufficient for this purpose since MRI is costly and time-consuming, CT has low diagnostic sensitivity and radiation risks, and ultrasound imaging has problems with precision and reproducibility. Moreover, nonlinear approaches do not provide accurate compensation because of the brain's complex three-dimensional structures.

Our results indicate that cranial operations that do not involve space-occupying lesions generally result in smaller brain shifts than does cerebral surgery performed to remove space-occupying lesions; however, the differences were statistically insignificant (Table 1). Further studies indicating volume of tumors and resected brain should be concerned.

To resolve brain shift problems, we exploited intraoperative CT data acquired from actual clinical cases and developed a predictive model to correct for craniotomy-induced morphological changes. The key feature of our model is that marker position data obtained intraoperatively by using a neuronavigation system are processed to update preoperative CT scans in real time. Consequently, our experimental model based on information from real craniotomy cases is an elaborate development of the geometric compensation method because it provides accurate compensation using navigation-based intraoperative data.

The time required for obtaining the reference points is 5 minutes at most, and the time for this algorithm is 10-15 minutes. It is faster than MRI required 20-40 minutes [28] and CT required 20 minutes [29]. Our results suggest that our method is rapid enough for practical applications. With our method, the operator need not to be interfered with for obtaining the four reference points coordinates in comparison to intraoperative MRI and CT.

Our study has several limitations. First, navigation system errors and imaging artifacts were present even through intraoperative CT scans were used to verify the accuracy of our model. Therefore, the concordance rates of the real-time intraoperative CT images and the reconstructed images from our model did not reach 100%. Second, since our correction model was developed using data from patients undergoing fronto-temporal craniotomy patients, without practical validation, our model cannot be generalized to other craniotomies. Thus, at present, our model may only be applicable for fronto-temporal...
craniotomies, but future studies of other craniotomies will refine the model algorithm. Third, the present model was constructed from four cases, and the brain deformation observed in one case, case 3, was different from that observed in the other cases. Our model was thus influenced by individual differences. The head rotation on CT images acquired during surgery also varied among all four cases [range, 8.6-27.0 degree; Table 2] Remodeling using three cases and excluding case 3 improved the concordance rate to 85.2%, 85.1%, and 84.7%. We speculate that the inclusion of more cases may reduce the influence of individual differences. Currently, it is impractical and even impossible to create a model that includes leakage of brain fluid, gravity, dural opening, and cerebrospinal fluid volume as well as other factors. Most models of brain shift incorporate only some of these factors in a simplified manner [23,25,26]. Although our model does not specifically consider individual factors that influence intraoperative brain shift, their cumulative effects are considered because the model is based on measurements of morphological change. The influence of gravity on the brain differs, depending on the angle of head rotation, and it is expected that the brain elasticity also differs depending on direction. In addition, it is clear that the reduction in brain volume differs depending on whether the surgery is performed to open cisterns, such as with vascular disorders, or to resect neoplastic lesions. It may be possible to apply our model to other surgical procedures such as an open biopsy via frontotemporal craniotomy and a deep brain stimulation surgery. In the future, it will be necessary to create other models for patients with rotations, close to the lateral or even prone position, for example, and for brain tumors.

Although our model is not approved for clinical use, and it needs to be further refined, it might be able to provide convenient and rapid real-time compensation for craniotomy-induced brain shift that are the main cause of inaccuracies during neuronavigation. We propose that, to improve our model for other applications, especially for space-occupying lesions such as brain tumors, more cases may reduce the influence of individual differences.

ACKNOWLEDGEMENT

The authors wish to thank Mr. Shigeru Yoneyama, CEO of Maxnet Co., Ltd., Tokyo, Japan, for his support in image manipulation and measurement.

REFERENCES