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Evaluation of Intraoperative Brain Shift Using an Ultrasound-Linked Navigation System for Brain Tumor Surgery

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Abstract

Image-guided neurosurgery using navigation systems is an essential tool to increase accuracy in brain tumor surgery. However, brain shift during surgery has remained problematic. The present study evaluated the utility of a new ultrasound (US)-linked navigation system for brain tumor surgery in 64 patients with intracranial tumors. The navigation system consisted of a StealthStation™ navigation system, a SonoNav™ system, and a standard US scanner. This system determines the orientation of the US images and reformats the images from preoperative computed tomography (CT) or magnetic resonance (MR) imaging to match the US images. The system was used intraoperatively to measure brain shift several times, using the results to guide tumor resection. US-linked navigation provided information regarding brain shift, and extent of tumor resection during surgery. Evaluation of brain shift was easily achieved in all patients, without using intraoperative CT or MR imaging. Accurate information regarding the true anatomical configuration of the patient could be obtained in all phases of the operation. Magnitude of brain shift increased progressively from pre- to post-resection and depended on the type of cranial structure. Integration of the US scanner with the navigation system allowed comparisons between the intraoperative US and preoperative images, thus improving interpretation of US images. The system also improved the rate of tumor resection by facilitating the detection of remnant tumor tissue. This US-linked navigation system provides information on brain shift, and improves the accuracy and utility of image-guided surgery.

Key words: navigation, ultrasound, brain shift, brain tumor, intraoperative imaging

Introduction

Frameless image-guided neurosurgery based on navigation systems is a widely used and valuable tool for intracranial surgery.[14,18,21,25] However, the accuracy of navigation systems based on preoperative imaging decreases with the progress of surgical manipulation due to a phenomenon called ''brain shift,'' which is caused by various factors, including the effect of gravity on the brain, escape of cerebrospinal fluid, brain swelling, and surgical maneuvers.[7,8]

Intraoperative imaging systems using computed tomography (CT)[5] or magnetic resonance (MR) imaging[15] have been introduced to counter the effects of brain shift. These intraoperative imaging systems allow update of the imaging data, but also require considerable time periods for operation.[7,9] Ultrasound (US) has been used as an intraoperative tool for detecting brain lesions in real time since the 1980s. Recent technological advances in US scanners have lead to reevaluation of the advantages of US for intraoperative use.[11,17] US scanners have been combined with a navigation system to display real-time US images with the corresponding preoperative images.[3,6,10,13,23] We previously introduced a US-linked navigation system into brain tumor surgery to evaluate intraoperative brain shift and allow real-time navigation based on intraoperative US images and preoperative CT or MR images.

The present study evaluates our experiences to examine the utility of the US-linked synchronized navigation system.

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Patients and Methods

I. Patient population

Sixty-four patients, 22 women and 42 men aged 6 months to 79 years (mean 49.1 years), with brain tumors were treated through 75 craniotomy procedures using a US-linked navigation system between 2003 and 2004. The histological diagnoses of the brain tumors were low-grade glioma (n = 3), anaplastic glioma (n = 9), glioblastoma (n = 22), meningioma (n = 11), schwannoma (n = 6), metastatic tumor (n = 4), craniopharyngioma (n = 4), germ cell tumor (n = 2), malignant lymphoma (n = 1), pituitary adenoma (n = 1), and central neurocytoma (n = 1). Intentional staged operations or tumor recurrence required two operations in nine patients, and three operations in one patient.

II. Imaging protocol for navigation

Preoperative imaging studies were performed using either CT (n = 7) or MR imaging (n = 68) after application of fiducial markers (4 to 9, mean 7.8). The slice thickness was 0.75 mm for CT, and 1.5 mm for MR imaging without intervening intervals or overlapping. The imaging data were transferred to the workstation of the navigation system with magneto-optical disks.

III. Neuronavigation technique

The navigation system (StealthStation™; Medtronic, Inc., Minneapolis, Minn., U.S.A.) used in this study consists of a table-mounted array incorporating two infrared cameras, a laptop computer with a high-resolution monitor, and handheld pointers with light-emitting diodes. The navigation system used two modes of registration: PointMerge™ registration, which identifies and registers equivalent points in image space and real space using fiducial markers; and SurfaceMerge™ registration, which defines surfaces using a greater number of non-matched points. PointMerge™ registration was based on correlation of positions of fiducial markers with the corresponding positions of image markers on the patient's markers after fixation of the head with the three-pin point Mayfield clamp. SurfaceMerge™ registration was then performed to allow adjustment of the correspondence between the images and patient anatomy by matching the surface of the three-dimensional (3D) model using 40 scalp surface points over the convexity. Preoperative imaging with the fiducial markers took 5 minutes, and the registration procedure in the operating room required an additional 10 minutes.

IV. Evaluation of brain shift during surgery

Evaluation of brain shift during surgery was performed using the US-linked synchronized navigation system, which combined the StealthStation™ navigation system with a US scanner (Prosound SSD-5500; ALOKA Co., Tokyo), a 7.5 MHz US probe (ALOKA Co.), and the SonoNav™ intraoperative imaging system (Medtronic, Inc.). The SonoNav™ system consists of four components: the SonoNav™ software, a calibration device, an image-guided attachment for a US probe, and a video cable. The StealthStation™ system tracks the position of the US probe, which is mounted to the attachment, and calculates the orientation of the probe in relation to the anatomy of the patient. The system reformats the preoperative CT or MR images to correspond to the

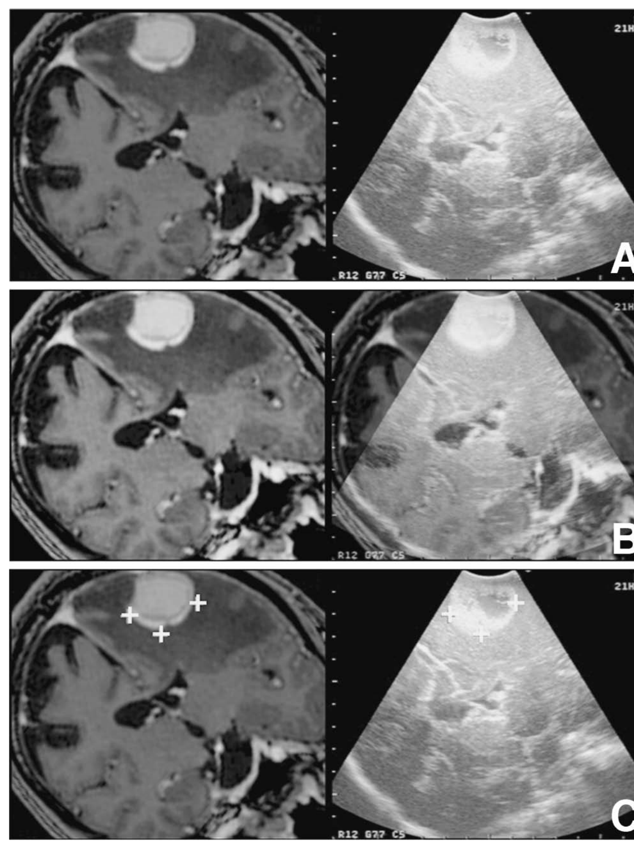

Fig. 1 Ultrasound (US)-linked navigation (synchronized navigation) findings in a patient with right parietal metastatic tumor. A: US image (*right*) and corresponding preoperative T_1-weighted magnetic resonance (MR) image with gadolinium (*left*). B: Visual orientation of the US image superimposed on the MR image (*right*). C: Evaluation of brain shift by placing of markers (*white crosses*) to mark the margins of the tumor on the US image (*right*) results in automatic placing of corresponding marks (*white crosses*) on the preoperative MR image (*left*).

orientation of the US images. The reformatted images and the US images are displayed side by side (Fig. 1A), allowing the surgeons to better understand the US images by superimposing the corresponding CT or MR images on the US images (Fig. 1B). To identify the perimeter of the tumor or certain specific structures, markers could be placed on either the US or the corresponding preoperative image, which resulted in automatic placing of the mark on the other image (Fig. 1C). The extent of any brain shift was evaluated by measuring the distance between the mark and the corresponding structure. The specific structures were the sulci, third and lateral ventricles, and meninges (falx and tentorium). More than three markers were placed at the margins of the tumor, sulci near the tumor, lateral walls of the third and lateral ventricles, falx, and tentorium. After measurement of each distance, the maximum shift was evaluated.

Shifts of various structures during procedures were measured using the SonoNav™ system after craniotomy, before tumor removal, and during or after tumor removal. Approximately the same plane of the US images was selected after craniotomy, before tumor removal, and during or after tumor removal. The markers for the measurement were also placed at the same points. Any difficulty in identifying the various structures on US images was resolved by comparing the US images with the corresponding preoperative CT/MR images.

The changes in the brain shift of various structures during surgery were evaluated. The differences in shift among the types of tumors were also examined. Various factors affecting the shift of tumor borders were evaluated in gliomas. Differences were examined using Mann-Whitney's U test.

V. Evaluation of intraoperative US imaging

Intraoperative US images at the first operations in 64 patients were evaluated by two neuroradiologists. The US images at the second or later operations were excluded. Visualization of tumor and other structures was graded according to the following criteria: good, good identification of both tumor and other normal structures; fair, good identification of either tumor or other normal structures, but poor identification of the other; and poor, difficulty in identifying both tumor and structures. Figure 2 shows representative US images evaluated as good, fair, and poor.

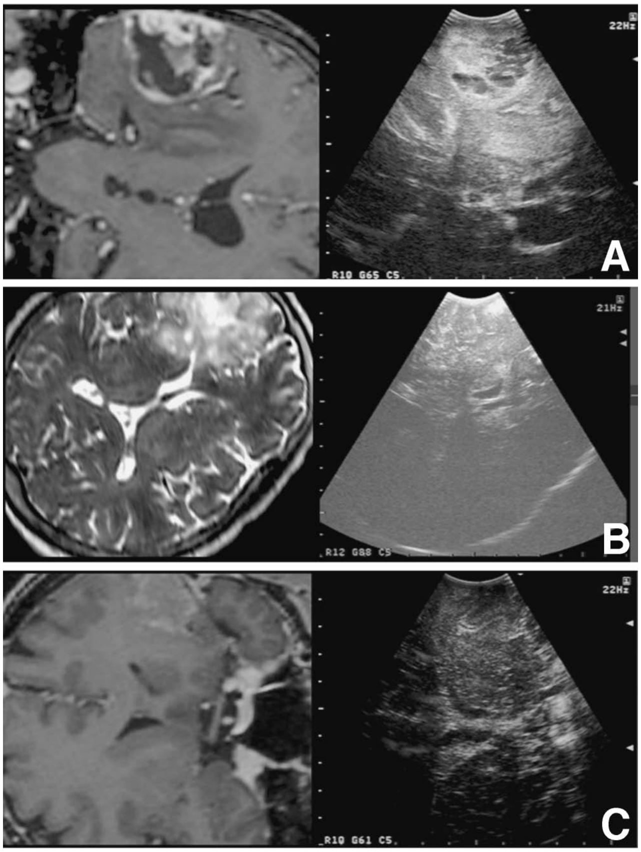

Fig. 2 Representative ultrasound images (*right*), with corresponding preoperative T_1-weighted with gadolinium (A, C) and T_2-weighted (B) magnetic resonance images (*left*), evaluated as good, fair, and poor quality. A: Good: a 79-year-old female with left temporal glioblastoma. B: Fair: a 69-year-old female with right frontal oligodendroglioma. C: Poor: a 64-year-old male with right frontal glioblastoma.

Results

I. Combination of the navigation system and US scanner

This US-linked navigation system could be arranged quite compactly to prevent interference with the operating theater staff. The navigation system was also easily transportable. However, adjustment of the surgical instruments was necessary to obtain visual contact between the infrared camera and the navigational apparatus. Furthermore, the US scanner had to be placed near the head of the patient, as the cable for the US probe was quite short.

II. Evaluation of intraoperative brain shift

Evaluation of intraoperative brain shift was easily achieved in all patients using the US-linked navigation system. Evaluation of brain shift could be per-

Table 1 Results of brain shift measurement during surgery

	Margin of tumor (n = 75)	Sulci (n = 54)	Ventricles		Meninges	
			Third (n = 40)	Lateral (n = 61)	Falx (n = 64)	Tentorium (n = 36)
Before dural incision	3.4 ± 1.9 (0.4–10.8)	3.9 ± 1.8 (1.1–9.1)	3.0 ± 1.2 (0.3–6.0)	3.3 ± 1.6 (1.3–9.5)	1.5 ± 1.1 (0.2–6.6)	1.6 ± 0.7 (0.5–4.0)
Before tumor removal	5.1 ± 2.7 (0.9–15.7)	5.8 ± 2.6 (1.1–9.1)	4.1 ± 2.0 (1.6–11.0)	4.9 ± 2.2 (1.3–14.1)	2.2 ± 1.3 (0.2–6.9)	2.1 ± 0.8 (0.5–4.1)
During or after tumor removal	8.5 ± 4.1 (11–19.0)	9.1 ± 3.6 (2.5–19.0)	6.4 ± 3.3 (2.2–16.3)	8.2 ± 3.9 (2.0–19.3)	2.9 ± 1.6 (0.2–8.1)	2.8 ± 1.2 (0.7–6.1)

Values represent mean ± standard deviation (minimum to maximum) in mm.

formed at any time during surgery, and accurate information regarding the true anatomical configuration of the brain was available in all phases of the operation.

Table 1 shows the findings of brain shift in the tumor margin and normal brain structures. In general, the magnitude of brain shift increased with progression of the surgery. The mean shift in all structures was 2.8 mm (range, 0.2–10.8 mm) before dural incision, increased to 4.2 mm (0.2–15.7 mm) before tumor removal, and reached 6.8 mm (0.2–19.3 mm) during or after tumor removal. The shift also depended on the type of cranial structures. The meninges such as the falx and tentorium showed low shifts, with mean shifts in the falx and tentorium cerebelli before dural incision of 1.5 mm (0.2–6.6 mm) and 1.6 mm (0.5–4.0 mm), respectively. The mean shift in the meninges was less than 3 mm after tumor removal. The sulci, tumor margin, and ventricles showed high shifts, which increased during surgery. The mean shift in these structures was not less than 3 mm before dural incision, and increased to over 6 mm during or after tumor removal.

Table 2 shows the shift in tumor margins for gliomas, meningiomas, and other tumors. The magnitude was greatest in patients with gliomas and smallest in patients with meningiomas. Significant differences between the shift in tumor margin in patients with gliomas and meningiomas were demonstrated before dural incision ($p < 0.01$), before removal ($p < 0.01$), and during or after removal ($p < 0.01$). Significant differences between the shift in tumor margin in patients with meningiomas and other tumors were also demonstrated before removal ($p < 0.05$), and during or after removal ($p < 0.01$). However, the shift was variable in individual patients. For example, the shift during or after tumor removal in patients with gliomas ranged from 5.0 to 19.0 mm.

Table 3 shows the shift in tumor margins in gliomas with regard to location, volume, and rate of tumor removal. The magnitude of shift of tumor margin in superficial tumors was significantly greater than that in patients with deep tumor before tumor removal ($p < 0.05$) and during or after tumor removal ($p < 0.01$). No significant differences were found between the shift in tumor margin with regard to volume or rate of tumor removal.

Table 2 Results of shift measurement of tumor margin

	Glioma (n = 40)	Meningioma (n = 11)	Others (n = 24)
Before dural incision	4.0 ± 2.1 (0.4–10.8)	2.0 ± 0.9 (0.9–3.1)	3.0 ± 1.5 (0.7–6.7)
Before tumor removal	5.9 ± 2.8 (2.6–15.7)	2.7 ± 1.2 (0.9–4.6)	4.9 ± 2.1 (1.9–8.0)
During or after tumor removal	9.5 ± 3.7 (5.0–19.0)	4.7 ± 2.9 (1.1–10.6)	8.5 ± 4.4 (3.0–18.0)

Values represent mean ± standard deviation (minimum to maximum) in mm.

III. Visualization of tumors and intracranial structures on US images

Visual quality of US images was good in 35 patients, with the tumors and intracranial structures easily identified based only on the US image. The quality of US images was fair in 26 patients and poor in 3 patients. The histological profiles in patients with fair or poor US images were as follows: low-grade glioma in 2, anaplastic glioma in 6, glioblastoma in 9, meningioma in 4, schwannoma in 5, craniopharyngioma in 2, and central neurocytoma in 1. The corresponding images of preoperative CT or MR imaging were useful for viewing and understanding conditions in areas where US images were not clear, and allowed better interpretation of the US images in 26 of the 29 cases with fair or poor image quality.

IV. Tumor removal using US-linked navigation system

The US-linked navigation system proved very use-

Table 3 Results of shift measurement of tumor margin in patients with gliomas

	Before dural incision	p Value	Before tumor removal	p Value	During or after tumor removal	p Value
Depth of tumor		NS		<0.05		<0.01
superficial (<3 cm, n = 21)	4.4 ± 2.3		6.9 ± 3.4		10.5 ± 3.3	
deep (≥ 3 cm, n = 19)	3.4 ± 1.7		4.8 ± 1.6		8.3 ± 3.7	
Volume of tumor		NS		NS		NS
small (<40 ml, n = 20)	3.7 ± 1.4		5.6 ± 2.5		9.1 ± 3.6	
large (≥ 40 ml, n = 20)	4.1 ± 2.6		6.2 ± 3.2		9.9 ± 3.7	
Rate of removal		NS		NS		NS
total or subtotal (n = 25)	3.8 ± 2.2		5.8 ± 3.0		9.5 ± 3.9	
partial or biopsy (n = 15)	4.2 ± 1.9		6.0 ± 2.6		9.5 ± 3.3	
Opening of ventricles during surgery		NS		NS		<0.05
open (n = 19)	4.1 ± 2.4		6.1 ± 3.3		11.0 ± 4.2	
not open (n = 21)	3.8 ± 1.8		5.7 ± 2.5		8.1 ± 2.4	

Values represent mean ± standard deviation in mm. NS: not significant.

ful for accurate image-guided surgery in patients with brain tumors. This system could be used not only as a conventional navigation system, but also as a tool for evaluation of shifts in tumor and other structures. More accurate information regarding the true anatomical situation of the patient was thus available in all phases of the operation than normal. The navigation system was also helpful for evaluating the extent of tumor removal and detecting residual tumor that was not apparent under the operating microscope.

Total resection was achieved in 19 of 75 operations, subtotal resection in 27, and partial resection in 29. Of the 40 glioma surgeries, total removal was performed in 10, subtotal removal in 15, and partial removal in 15.

V. Representative cases

Case 1: A 6-month-old boy with pineal anaplastic astrocytoma was admitted to our hospital with severe headache and upper gaze palsy. CT and MR imaging revealed an enhanced mass in the pineal region. Surgery was performed through an occipital transtentorial approach. US-linked navigation identified slight shift of the tumor margin in the pineal region (Fig. 3A–C). After partial removal of the tumor, brain shift was again evaluated using the navigation system. Although remnant tumor was present, brain shift caused conventional navigation to indicate complete removal of the tumor. However, the US-linked navigation system clearly demonstrated anterior shift of the tumor by 19 mm, and indicated that about one-third of the tumor volume remained (Fig. 3D–F). Tumor resection was therefore continued and the tumor was gross totally removed.

Case 2: A 56-year-old man with left frontal glioblastoma. MR imaging revealed a ring-enhanced mass in the left frontal lobe with marked peritumoral edema. After left frontal craniotomy, the US image clearly showed the tumor as a highly echoic lesion (Fig. 4A). After dural incision, four catheters were inserted at the tumor margin as "fence posts" using the conventional navigation system (Fig. 4D). The positions of the catheters were confirmed by the US-linked navigation system, which clearly demonstrated that the anterior catheter was inserted into the margin of the tumor (Fig. 4B). However, the posterior catheter was placed 6 mm posterior from the margin of the tumor (Fig. 4C). Considering the invasive nature of the tumor, the tumor could be totally resected using the catheters as indicators of the tumor margin. After tumor removal, the US-linked navigation system demonstrated the actual extent of tumor removal and absence of residual tumor (Fig. 5).

Discussion

I. Problems of conventional navigation systems and US scanning

Image-guided neurosurgical techniques using navigation systems have been performed in patients with brain tumor since the 1980s.[25] Reported benefits include improved surgical approach, reduced morbidity, shorter hospital stay, reduced hospital costs, and reduced requirements for postoperative analgesia.[1,20] The accuracy of navigation systems progressively decreases during surgical procedures, due to various factors described by the term "brain shift." Brain shift represents a crucial problem in neuronavigation systems.[2,8,19] Ex-

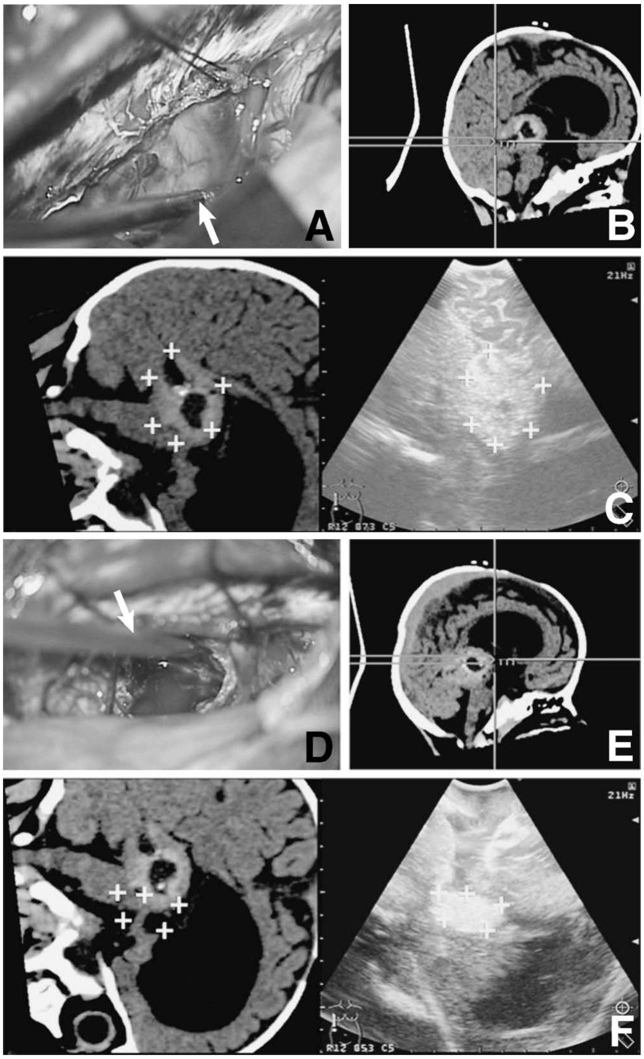

Fig. 3 Representative Case 1 with pineal anaplastic astrocytoma. Conventional (A, B) and ultrasound (US)-linked navigation (C) showed shift of the tumor margin was minor (0.9–3.0 mm) before tumor removal. After partial removal of the tumor, conventional navigation (D, E) suggested that tumor resection had apparently reached the anterior margin of the tumor, whereas the US-integrated navigation (F) clearly demonstrated anterior shift of the tumor by 19 mm with residual tumor mass. *Arrows* indicate the tips of the navigation probes (A, D). *White crosses* (C, F) mark the margins of the residual tumor on the US images (*right*) and the corresponding preoperative computed tomography images (*left*).

periences with conventional navigation systems have strongly raised the need for real-time imaging modalities.[6,9] Intraoperative CT and MR imaging are easily integrated into navigation systems and provide excellent images of anatomical deformation in the brain.[5,15,26] However, these imaging techniques are limited by factors such as manpower, cost, and restricted surgical access.[2,7,24]

US scanners have been used for intraoperative imaging for 20 years. However, US has not entered common use due to the limited image quality and user-dependent results. US imaging has seen a recent revival with improved image quality and new technical developments.[11,17] Therefore, US may provide a solution to brain shift based on obtaining real-time information. Various groups have connected US scanners with conventional navigation systems.[3,6,10,13,23]

II. Advantages of a US-linked navigation system (synchronized navigation)

The present US-linked navigation system was used during 75 surgical procedures in 64 patients with brain tumor. The system incorporated a navigation system that digitized the analog video signal from the US scanner, and displayed real-time US images on the navigation computer side-by-side with the corresponding preoperative CT or MR images. The system requires no special equipment other than reference devices for the US probes and the computer software. We call this US-linked navigation ''synchronized navigation'' as both the US image and the CT or MR image can be seen as synchronized.[19]

Our synchronized navigation system was very effective in the resection of brain tumors. One advantage was information for checking the accuracy of the conventional navigation system. In the present study, brain shift was effectively evaluated in all subjects by comparing the real-time US images with the corresponding preoperative images on the US-linked navigation system. US imaging was easily used at any time the surgeon wanted to obtain the exact orientations of images from preoperative CT or MR imaging. Use of US requires only a few minutes, whereas CT and MR imaging require transportation of patients in and out of a sterile-draped imaging gantry, usually requiring about 30–70 minutes.[26] In addition, US can be repeated on demand. Another advantage is information about the extent of tumor removal. Remnant tumor could be evaluated using the synchronized navigation system during tumor removal as illustrated in representative Case 1. If the US images identified remnant tumor, additional resection could be performed. The US-linked navigation system provided information regarding the degree of the intraoperative brain shift and the extent of tumor resection, so may improve the rate of tumor removal in brain tumor surgery. In this study, total or subtotal resection was achieved in 46 of 75 operations using the US-linked naviga-

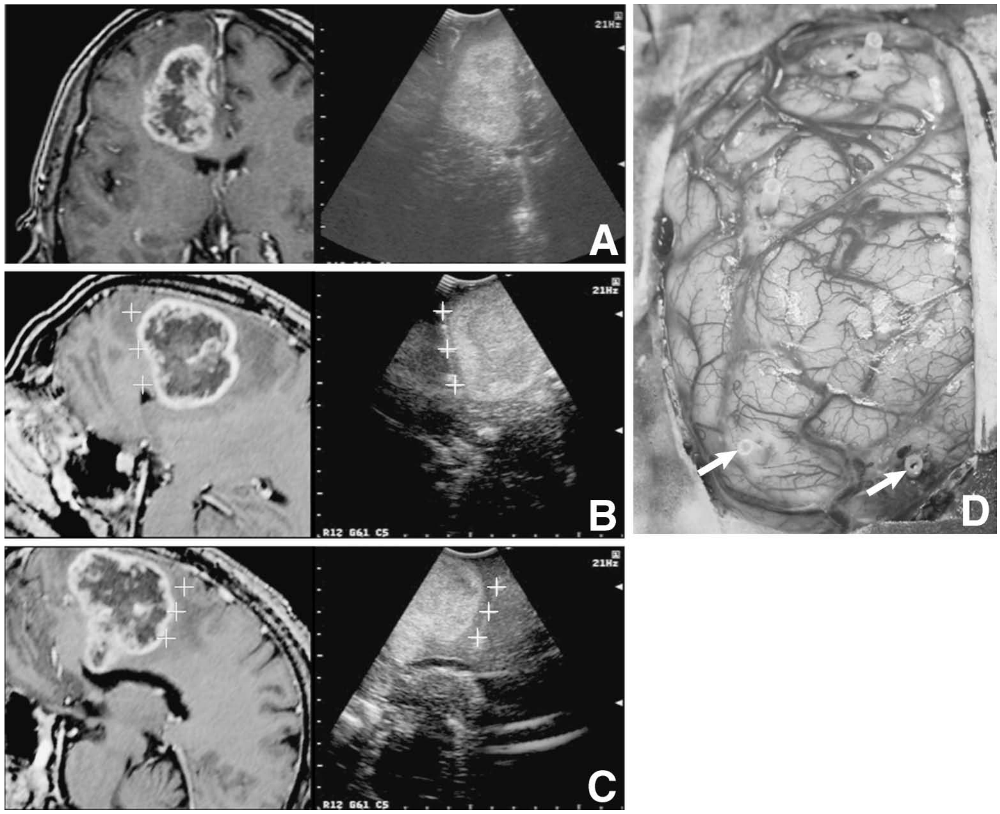

Fig. 4 Representative Case 2 with left frontal glioblastoma. Ultrasound (US) navigation clearly showed the tumor as a highly echoic lesion after left frontal craniotomy (A). After dural incision, four silicone catheters (*arrows*) were inserted at the tumor margin using the navigation system (D: intraoperative photograph). After insertion of the catheters, US-linked navigation clearly demonstrated the anterior catheter was inserted at the margin of the tumor (B), but the posterior catheter was placed 6 mm posterior from the margin of the tumor (C). *White crosses* mark the catheters on the US images (*right*) and the corresponding preoperative T_1-weighted magnetic resonance images with gadolinium (*left*).

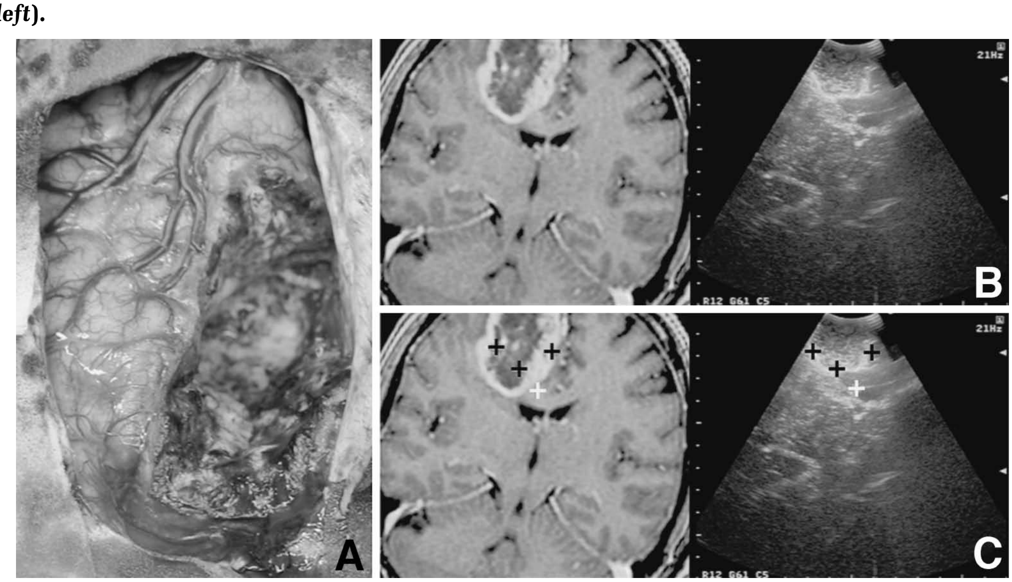

Fig. 5 Representative Case 2 with left frontal glioblastoma. Intraoperative photograph after tumor resection (A). The ultrasound (US) navigation demonstrated total removal (B) and a 6- to 10-mm brain shift towards the resection cavity (C). *Black and white crosses* mark the margin of the resection cavity and the ventricle wall on the US images (*right*) and the corresponding preoperative T_1-weighted magnetic resonance images with gadolinium (*left*).

tion system. Total removal was achieved in 10 of 40 glioma surgeries, subtotal removal in 15, and partial removal in 15. We have used a conventional navigation system in brain tumor surgeries since 1997. Using that system, total removal was achieved in 6 of 31 glioma surgeries, subtotal resection in 8, and partial removal in 17 between 1999 and 2001. The present US-linked navigation system increased the rate of tumor removal in contrast with the previous system.

The synchronized navigation system was also useful for facilitating the interpretation of US images, which have limited quality due to poor spatial and contrast resolution and artifacts, and the obliquely oriented images on the monitor can be difficult to relate to anatomical structures.[10] In our experience, good US image quality was obtained in only 54% of subjects. This disadvantage can be compensated by comparing the real-time US images with the corresponding images from preoperative CT or MR images using the navigation system.[4,10,13,16] Improved understanding of US images was obtained in about 90% of fair or poor US images. The borders of the tumors could be clearly identified in glioma patients with good US images, but not in glioma patients with fair or poor US images. Therefore, the remnant tumor was difficult to evaluate using the synchronized navigation system during surgery in patients with fair or poor US images. Recently, 3D US, which provides improved image quality, has been used in intracranial surgery,[9] and 3D US-linked navigation systems have been developed and applied in intracranial surgery.[9,24] Single rack navigation systems with an integrated US scanner have also been reported,[9,22] although our navigation system used an external US scanner connected to the navigation system.

III. Magnitude of brain distortion

Measurements of brain shift demonstrated that the magnitude of the shift increased progressively from pre- to post-resection, and depended on the type of cranial structure. However, the shift occurs in 3D, but the present methodology of assessing brain shift was two dimensional (2D). This study used approximately the same planes of US images for measurement of the shift. Although some underestimation of the shift may have resulted, this error was likely to be small.[12] Low shift structures included the meninges such as the falx and tentorium, and high shift structures included the tumor borders, sulci, and third or lateral ventricles. The shift of tumor margins was less in patients with meningiomas than in patients with other tumors. Similar shift measurements by US-linked navigation categorized cranial structures into three shift groups.[4] Low shift structures included the brainstem and meningeal components. Moderate shift structures included the ventricles, choroid plexus, and septum pellucidum. High shift structures were adjacent to the lesions, blood vessels, and cortex. Postresection brain displacement was measured in 13 patients with intracranial tumor using a US-linked navigation system.[12] The postresection shift was more prominent in patients who received mannitol or in older patients. The location (depth from the cortical surface) of the tumor also seemed to be related to the magnitude of shift. In the present study, significant differences were not found between shift of tumor margin with regard to volume of tumor and rate of tumor removal in patients with gliomas, but the magnitude of shift of tumor margins was significantly greater in patients with superficial gliomas than in patients with deep gliomas.

This study evaluated the brain shift of the tumor margin and specific brain structures in detail using a US-linked navigation system. Few authors have reported detailed changes in brain shift during surgery.[4] This study also demonstrated the usefulness of the US-linked navigation system for brain tumor surgery. The US scanner used was a 2D US scanner. 3D US images may solve the problems with the image quality and orientation experienced with 2D US.[11,24] However, we think that the 2D US images in this US-linked navigation system were useful for evaluation of brain shift and extent of tumor resection.

IV. Conclusions

US-linked navigation (synchronized navigation) provided useful information regarding the degree of the intraoperative brain shift, as well as real-time information about the extent of tumor resection during surgery. This navigation system improves the accuracy and utility of image-guided surgery.

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Commentary

This study clearly shows that the ultrasound (US)-linked navigation system used by the authors was able to evaluate the extent of tumor resection. This was easier for lower grade gliomas with clearcut borders. Compared to preoperative CT or MR imaging introduced in the navigation system, the intraoperative US exploration was able to detect and measure the brain shift occurring during surgical resection. As expected, shift was the more important as the tumor was superficial (cortico-subcortical) and located in front of ventricle(s). As pointed out by the authors, the method does improve accuracy of image-guided surgery from preoperative CT/MR imaging. The next step should be that the computer be able to relocate, i.e., superimpose the volume and borders of the tumor given by CT/MR imaging to the margins of the resection cavity given by the US scanning. Thus the surgeon could better appreciate the extent of resection.

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