Original Articles

Continuous Echo-guided Surgery for Brain Tumor Removal

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In brain tumor surgery, navigation is helpful for precise targeting of deeply seated lesions and important structures, and for performing accurate tumor resection. Intraoperative echo-guided surgery through a cranial window has been used for removal of tumors, arteriovenous malformations, and other pathological structures. The echo probe can be applied intermittently through the cranial window to visualize the operating field. Initially, very good images can be obtained, but during the operation the images deteriorate and become difficult to visualize. To obtain clear echo images without interruption of the surgical procedure, we created another small cranial window at the opposite side of the operating field, into which an echo-guiding probe was inserted. We were then able to produce clear images continuously until the end of the operation. The shifting of intradural structures caused by CSF drainage and/or reduction of the tumor mass was detectable in real time. This method also allowed clear evaluation of the relationship between the tumor and blood vessels. We used this method for 16 cases that involved large and deeply located brain tumors, including meningiomas, gliomas and pituitary adenomas, and were able to perform the required surgery safely, easily, and with a high degree of success. This method for continuous echo-guided surgery has already proved to be useful for the safe removal of brain tumors.

Key words: echo-guided surgery, continuous echo-guide, neuronavigation, tumor removal, neurosurgery

In neurosurgery, the particular, and to some degree unique, anatomy of individual patients is encountered, and targeting specific areas of the nervous system is thus difficult. Intraoperative neuronavigation is one useful tool that may be utilized in order to reach a specific target, as it projects preoperative imaging data of the patient into the operative site, and *vice versa*. In brain tumor surgery, navigation is helpful for the precise targeting of deep-seated lesions and important structures, in defining the extent and location of the corticotomy, the relationship between the tumor and vessels, and in performing an accurate tumor resection. It helps the surgeon to confine the approach to the necessary minimum and to avoid injury to normal nervous structures and vessels, thus enabling less invasive surgery.

A number of neuronavigation systems are currently available^{6, 10, 14, 17}. All of them, however, utilize preoperative information from magnetic resonance image (MRI) and/or computed tomography (CT) scans. Changes to the preoperative data occur intraoperatively in the form of significant shifts of the intracranial structures such as, for example, the brain itself, the brain tumor and the ventricles, especially after the removal of cerebrospinal fluid (CSF) and tumor resection¹⁵. The navigation systems available currently are therefore unable to provide accurate intraoperative information. Recently, some of

the systems are combined with ultrasound to solve this problem, however it is not enough and complicated^{3, 4, 13}. Ultrasound imaging may be used to resolve this problem because: (1) it produces a real-time image, (2) it may be used repeatedly or continuously, (3) it is non-invasive, and (4) it is simple to operate. Intraoperative echo-guiding is also a useful tool with which to establish an individual's anatomy, which is very important when performing operations to resect brain tumors. Echography has been used at the operating field through the cranial window (Fig.1-A)^{8, 11}. Although initially the image it produces is good, it does deteriorate during the procedure. To solve this problem, we began to perform echo-guiding via a small cranial window that is made at the opposite side of the operating field, or a position distant from the point of surgery^{2, 12}. Using this technique, we obtain a continuous, clear image of the entire surgical process (Fig.1-B).

Methods

The candidates for this study were a selection of patients with large and deeply seated brain tumors that would be difficult or complicated to remove because of their location or their complicated relationship with surrounding structures. The echo-guiding equipment that was used was the HDI3000 (Advanced Technology Laboratories, Botnell, WA, USA), from

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Fig. 1 Schemata of methods for echo-guided surgery.

- A : Conventional method of echo examination of the operating field through a cranial window.
The operation is interrupted and the echo probe is applied within the operating field. The echo image is not clear due to irregularity of the dissecting surface, and large amounts of debris and blood, etc.
- B : Our method of continuous echo-guided surgery. The probe is applied at a small cranial window at the side opposite the main cranial window. The procedure can be continued under echo guidance, and the image remains clear until the end of surgery.

which a good B-scope image, color Doppler image, power Doppler image, and a 3D rotating image of the intracranial vessels can be obtained. The frequency at which the probe functions is 3-5MHz and the size of the tip of the probe is 2.0×2.5 cm. The intensity curve of the echo beam is changeable depending on the depth. With the color Doppler image, we can obtain a Doppler sonogram and determine the flow velocity at a selected part. With power Doppler images, we can obtain 3D vascular images within 30s and can easily produce an automatically rotating, 3D animated image. After making a main cranial window through which resection of the brain tumor would be performed, another small cranial window of about 2.5×3.0 cm was made on the opposite side of the operating field to the main cranial window (Fig.1-B) (Fig.2). After exposure of the dura mater, a standard echo examination was performed at the main cranial window, and then a further echo examination was performed through the small burr-hole on the opposite side. Usually a B-scope image, a color Doppler image, a power Doppler image and a three-dimensional (3D) vascular image are examined. The B-scope and color Doppler images are used mainly for navigation. When we want to know more about vessels and their flow velocity, 3D vascular images are examined. The echo probe was attached to the dura mater and it was kept in position by an arm holder that was fixed onto the Mayfield frame throughout the operation (Fig.2); the probe was frequently adjusted by hand as and when it was necessary.

Results

We used this technique for 16 surgical cases, seven with large meningiomas, five with pituitary adenomas, two with astrocytomas, one with metastatic tumors, and one with

Fig. 2 Intraoperative view (A) and the corresponding schema (B). The echo probe is applied at a small cranial window (arrow) created at the side opposite the main cranial window (arrowhead).

Fig. 3 Case 1. Enhanced MRI before surgery shows a large meningioma located in the suprasellar, paracavernous portion and the medial sphenoidal ridge. The tumor invades the cavernous sinus and involves large vessels. (A) axial, (B) sagittal, and (C) coronal views.

craniopharyngioma. Ten males and 6 females and the mean age of the patients was 56 years (32~73-year-old).

Initially, especially before opening the dura mater, the image of the intracranial structures and the tumor were clear. During the tumor dissection, the tip of the dissector or suction tip was seen in real time. Following the tumor dissection, the image of the operating field became obscure and it was not possible to identify the brain structure. However, the remnant of the tumor, which was located at the side of the probe, was clearly visible. An echo artifact (scattering), which looked like a band, was frequently seen from the tip of the dissector and/or suction tube in a direction opposite to the side of operating field; this artifact looked like the dissector, although it came into the field from a

Fig. 4 Echogram obtained via the small cranial window during the operation.

- A : Before opening the dura mater. Coronal section. Shifting and changes in shape of the ventricles (V) due to the tumor (arrowheads and falx are evident).
- B : Same condition. Power Doppler image. The relationship between vessels (internal carotid artery, anterior cerebral arteries, middle cerebral artery) and the tumor or ventricle is evident. Vessels have shifted significantly.
- C : During tumor dissection. The movement and location of the tips of the suction tube and dissector (black arrows) are clearly seen. The change in shape of the tumor (arrowheads) caused by internal decompression and the shift of the ventricle are also clearly visualized.
- D : During tumor dissection. Tumor removal has progressed, and the tips of the suction tube and dissector (black arrows) are seen near the tumor surface. The ventricle has enlarged significantly following decompression.
- E : After removal of the tumor mass, a dead space is seen. The tips of the dissector can be seen at the deepest points of the space (black arrows).
- F : During irrigation of the dead space. Movement of much fine debris is clearly visualized. The tips of the dissector can be seen in the cavity (black arrows). Artificial echo scattering is seen (*).
- G : Shrinkage of the dead space is seen in the supra- and paracavernous portions (arrowheads). The ipsilateral ventricle is also dilated.
- H : After tumor removal. Power Doppler image. Vessels and falx (F) are clearly visualized. The middle cerebral artery has returned to its previous position, but a shift of the anterior cerebral artery is still recognizable. An enlarged ventricle and cistern are also seen.

Fig. 5 Case 1. Enhanced MRI after the operation reveals only a small part of the tumor which involves vessels and invades the cavernous sinus. (A) axial, (B) sagittal, and (C) coronal views.

different angle (Fig.4-C). Fortunately, however, this echo artifact was not visible in the area where we had to continue the dissection. The sinking of the brain and shifting of the remnant of the tumor were clearly visible until the completion of tumor removal. The location of the cerebral vessels and their relationship to the surrounding structures, such as the tumor and brain, were established using the color Doppler and power Doppler images; the 3D vascular image was also examined. The 3D rotating vascular image was helpful for obtaining stereoscopic images of the vessels. Using this method, the size of the vessels seemed to be thicker than the actual size. Both morphological and hemodynamic information were examined at selected parts of the vessels in order to determine their function. It was not necessary to interrupt the operating procedure when these examinations were performed.

Typical cases of a meningioma and an astrocytoma will now be described.

Case 1: A 43-year-old man experienced an epileptic seizure in January 2001. He recovered and showed no neurological deficit. A MRI revealed a large left parasellar and medial sphenoidal ridge meningioma (Fig.3). The tumor involved the internal carotid artery and invaded the left cavernous sinus. On February 2001, tumor removal was performed with the aid of continuous echo-guided surgery. Echography through the small cranial window that was made at the opposite side of the operating field to the main cranial window revealed the relationship between

Fig. 6 Case 2. Enhanced MRI before surgery. The tumor extends to the corpus callosum and the right frontal lobe. A large cystic space is present in the left frontal lobe, caused by frontal lobectomy in the previous operation. (A) Axial, (B) sagittal and (C) coronal views.

the main vessels, such as the left carotid artery, middle and anterior cerebral arteries (Fig.4-A,B). Even after partial removal of the tumor, movement of the tip of a suction tube or a dissector was seen clearly in the operating field, and the remnant of the tumor and its surrounding part were still clearly visible (Fig.4-C,D). During the surgery, we could see the location of the main vessels with the aid of color Doppler and power Doppler images, and/or a 3D vascular image. We were able to proceed with the dissection safely and most of the tumor was removed (Fig.4-E,F,G), although a small part of the tumor was left because of its involvement with the perforating arteries (Fig.5). Using the echo-guiding system we were able to observe the whole process throughout the surgery, and the information regarding the 3D vascular structure and flow velocity of these arteries was quite helpful. The return of the main vessels from the shifted position to the original position was also observed (Fig.4-H).

Case 2: A 31-year-old man experienced loss of consciousness in January 2000 and was transferred to a medical center. A MRI revealed a left frontal lobe glioma, which was removed in February of same year. The nature of the tumor was anaplastic astrocytoma. He underwent additional irradiation (50G; Liniac) and then combined therapy of chemotherapy and interferon in April 2000. However, regrowth of the tumor was observed and the patient requested that the tumor be removed. The patient was referred to our hospital. The MRI showed that a wide cystic space had developed following the right frontal lobectomy and that the recurrent tumor had extended to the opposite side of the frontal lobe through the corpus callosum (Fig.6). However, the

Fig. 7 Echograms obtained during the operation through a small cranial window.

- A : Near-coronal section showing the falx (F) and the margin of the tumor (arrowheads). Movement and the location of the tips of the suction tube and dissector (white arrows) are clearly seen in the operating field.
- B : The tumor mass has been partially removed and the tips of the dissector and the suction tube (white arrows) are seen slightly outside the border line of the tumor (arrow heads) and brain tissue.
- C : There is a wide space after removal of the tumor, and movement of much fine debris (arrow) is clearly visualized upon irrigation of the space with saline.
- D : The dead space has shrunk and its marginal surface is visualized as a white band.
- E : Sagittal section showing the dead space after removal of the tumor including the anterior part of the corpus callosum (CC). The movement of fine debris upon irrigation is clearly seen. The callosomarginal artery (CM) and sulci are visualized.

tumor was still circumscribed within part of the frontal lobe and the corpus callosum. This patient showed no neurological deficits, however since he had a 5-month-old boy he was eager to have the tumor removed as a last resort. Our goal was to operate without producing neurological deficits. In September 2000, we performed the surgery with the aid of continuous echo-guiding. The MRI revealed that both of the pericallosal arteries had been shifted by the tumor. We opened the large cyst, but found that the tumor tissue and brain tissue were coated with gliosis and the borderline between the two was not clear. We made another small cranial window at the right frontal lobe and

applied the echo probe. The orientation of the buried arteries was quite easily established under echo-guidance. The borderline between the tumor and the brain tissue was not clear when viewed through the operating microscope; however, the tumor was echogenic and so we were able to distinguish the borderline clearly using the echo-guiding equipment (Fig.7-A,B). We were confident enough about the location of the tumor that we removed only a small amount of the brain tissue from the surrounding area (Fig.7-C,D,E). Macroscopically, the tumor was almost totally removed; only a slight invasion in the corpus callosum remained (Fig.8), and no neurological deficit

Fig. 8 Case 2. Enhanced MRI after surgery. The tumor mass has been removed and a small remnant is recognizable at the edge of the corpus callosum. During the operation, echo imaging suggested the possible presence of this remnant.

was effected. The patient received gamma knife therapy for the remnant of the tumor.

Discussion

There are currently more than 10 navigation systems available, all of which are based on preoperative information from CT and MRI scans. In these systems, light¹⁰⁾, an electromagnetic complex⁶⁾, and a mechanical arm¹⁷⁾ are used. During surgery, lots of structural changes will occur because of, for example, CSF drainage, tumor removal, swelling, and bleeding. Under these conditions, the preoperative navigation data become inaccurate, and as a consequence the surgeon may lose his or her orientation^{4, 13)}. On the other hand, there is a possibility that these problems could be solved by echo-guiding. If we compare ultrasound navigation to neuronavigators, although neuronavigation based on MRI findings produces superior resolution, ultrasound is superior in that (1) it produces real-time images, (2) it is simple to use, (3) it may be used repeatedly, (4) it can produce 3D images, (5) it is relatively cheap, and (6) it produces anatomically accurate images¹³⁾. Recently, intraoperative echo-guided surgery has been used before. Ultrasound has been used in two different ways. First, through a burr hole to establish orientation when performing, for example a ventriculoperitoneal shunt, ventricle tap, cyst aspiration, or biopsy procedure under echo-guidance^{1, 3, 9, 11)}. Second, it has been applied to surgery for the removal of a tumor, and for tumor remnant check through a bone window^{3, 5, 7, 14, 16)}. For tumor removal, the probe is applied to the operating field through a cranial window (Fig.1-A). Initially, before opening

the dura mater, very good images can be obtained. However, during the operation, images deteriorate because of the irregularity of the brain and/or tumor surface, the presence of floating debris, blood, and swelling. Moreover, the echo examination has to be interrupted when it is most required, because of the necessity of fine dissection, or when bleeding occurs, for example, because the same cranial window is used for the echo examination and the surgery. This means we cannot achieve good images in cases where those images are most needed. This is a significant problem; echography thus has tended to be used at the beginning of surgery, but then dispensed with during surgery, the most important procedures being performed without the aid of echo-guidance.

To solve this problem, we made another small burr hole at the opposite side of the operating field, or at some distance from the first craniotomy (through which the surgery would be performed), through which a probe was applied to the dura mater²⁾. (Fig.1-B). Since the ultrasound images originated from the opposite side of the operating field, we could see clear images not only at the beginning of surgery, but also throughout the entire surgical procedure. We were able to identify the shift of the structures caused by CSF drainage or mass reduction of the tumor in real time and, even if bleeding occurred, for example, the operation and observations could continue uninterrupted. When it was important to be able to establish which vessels were involved with the lesion, it was possible to produce nice 3D images of the vascular structures, and the relationship between the lesion and the vessels could be discerned. The B-scope images were two-dimensional; however, with movement of the probe during scanning, we could obtain a 3D image, and with power Doppler we could obtain a 3D image of the vascular structure.

Although this technique has many merits, there are several problems that have yet to be resolved:

- (1) The size of the probe should be reduced.
- (2) A more flexible and easily controlled probe holder is required; a remote-controlled set-up would be more helpful.
- (3) The power Doppler shows the vessels wider than their actual size; investigations of a new technique that shows vessels at their actual size are progressing.
- (4) The echo artifact that arises from the tip of the probe might lead to a misunderstanding of the actual location of the suction tip.
- (5) Since all parts of the probe are echogenic, not only the tip, this might also lead to a misunderstanding about the position of the suction tip.
- (5) The resolution of this system is not as good as that obtained with MRI or CT images.

In our series, there was no case of arteriovenous malformations, cavernous angiomas, or hemangioblastomas, lesions that would also be good candidates for echo-guided

surgery. In the case of arteriovenous malformation, the hemodynamic information made available using this system would be quite useful. In these cases, it is possible that remnants of these lesions might be left. Echo-guided surgery would be very useful for the detection of these remnants.

Conclusion

To get clear echo images intraoperatively without interruption of the procedure, we made another small cranial window at the opposite side of the operating field, into which the echo-guiding probe was inserted. We were then able to produce clear images continuously until the end of the surgery. The shifting of the intradural structures caused by CSF drainage and/or mass reduction of the tumor was detected in real time. The relationship between the tumor and the blood vessels was also clearly visible using this method, making it useful for surgery of tumors that involve blood vessels. We used this method for 16 cases that involved large and deeply located brain tumors, including meningiomas, gliomas and pituitary adenoma, and we were able to perform the required surgery safely, easily, and with a high degree of success. Although a smaller-diameter probe, a better probe holder and better resolution for this system are currently being developed, this continuous echo-guided surgery has already proved to be quite useful for the safe removal of brain tumors.

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