# Brain Operations Guided by Real-time Two-dimensional Ultrasound: New Possibilities as a Result of Improved Image Quality

**Geirmund Unsgaard, M.D.**
Department of Neurosurgery, University Hospital of Trondheim, and Norwegian University of Science and Technology, Trondheim, Norway

**Aage Gronningsaeter, Ph.D.**
SINTEF Unimed, Trondheim, Norway

**Steinar Ommedal, B.S.**
SINTEF Unimed, Trondheim, Norway

**Toril A. Nagelhus Hernes, Ph.D.**
SINTEF Unimed, Trondheim, Norway

**Reprint requests:**
Geirmund Unsgaard, M.D., University Hospital of Trondheim, 7005 Trondheim, Norway.
Email: geirmund.unsgard@medisin.ntnu.no

**Received,** April 26, 2001.
**Accepted,** April 3, 2002.

**OBJECTIVE:** In 1995, a project was initiated in Trondheim, Norway, to investigate various possibilities for more frequent use of ultrasound in brain surgery. Since that time, the quality of ultrasonic images has improved considerably through technological adjustment of parameters. The objective of the present study was to explore essential clinical parameters required for the successful use of ultrasonic guidance in brain surgery.

**METHODS:** During the study period, several surgical setups designed to optimize the use of intraoperative real-time two-dimensional ultrasonic imaging were explored. These included various positions of the ultrasound probe in relation to both the operation cavity and the lesion, as well as the position of the operation channel in relation to the gravity line.

**RESULTS:** All lesions from the latest period (1997–2001; n = 114) were depicted well by ultrasound imaging, with the exception of two cases. High image quality and direct image guidance of the tool were maintained best throughout the operation by imaging through an intact dura and at an angle relative to a vertical operation channel. All tumor operations were performed without complications, and ultrasound imaging was found to be an important factor in the detection of remaining tumor tissue at the conclusion of surgery. For 14 low vascular tumors, the operation was guided only by ultrasound imaging. No bleeding complications occurred. A method of minimally invasive ultrasound-guided evacuation of hematomas was developed. In 19 patients, the method was found to be efficient (i.e., >90% of the hematoma was evacuated) and without complications, except for one patient who experienced rebleeding.

**CONCLUSION:** With proper planning and surgical setup, ultrasound imaging may provide acceptable image quality for use in image-guided brain operations.

**KEY WORDS:** Hematoma evacuation, Image-guided surgery, Neurosurgery, Real-time two-dimensional ultrasound, Tumor resection

*Neurosurgery 51:402-412, 2002* DOI: 10.1227/01.NEU.0000019873.66709.0D www.neurosurgery-online.com

When ultrasound imaging became commercially available in the 1970s, it was expected to become an important tool in brain surgery. After the initial period of enthusiasm, however, insufficient image quality resulted in disappointment. Since then, significant technological development in ultrasound imaging has been driven by the use of this modality in diagnosis. In 1995, when we recognized the potential of adjusting and adapting ultrasound technology for different clinical applications, we initiated a research program designed to explore the capabilities of ultrasound technology and further optimize the clinical use of this imaging modality in brain surgery (11, 12).

The use of ultrasound guidance in performing brain tumor resections has gained more attention in recent years because of the real-time capabilities of this imaging modality (4, 19). Studies of the use of intraoperative magnetic resonance imaging (MRI) guidance in performing brain tumor resections have indicated an increase in tumor removal as compared with surgery performed without this intraoperative imaging technology (18, 32). As an intraoperative imaging technique, ultrasound may provide an alternative to MRI for delineating tumor tissue and improving the chances of achieving gross total tumor resection (13, 33).

Our first clinical application of two-dimensional (2-D) ultrasound was in a patient with an intracerebral hematoma (28).

Whether spontaneous deep-seated supratentorial hematomas should be evacuated is still controversial (2, 7, 24, 27). The opinion that the operation itself is harmful to normal tissue has led to the use of stereotactic approaches such as one involving use of the Archimedes screw (3) as well as endoscopic aspiration procedures (2). In our initial experiences in the present study, however, dynamic events during evacuation of a hematoma made the real-time imaging capability of ultrasound suitable for guiding these operations. Therefore, we initiated the development of a procedure based on real-time 2-D ultrasound for the evacuation of hematomas.

In all image-guided surgical procedures, the surgeon depends on high image quality. We previously presented alternative technological adjustments of parameters for obtaining high-quality ultrasound images in the brain (11). In the present study, we focused on how clinical arrangements can affect ultrasound image quality and on the practical use of this imaging modality for guiding tumor resection and the evacuation of hematomas. This article summarizes our clinical experiences during 6 years of active use of real-time 2-D ultrasound at our clinic.

## PATIENTS AND METHODS

### Patients

Since 1995, we have performed ultrasound-guided surgery in 156 patients in our clinic. The types of lesions removed from these patients are summarized in *Table 1*. The patients had different brain tumors as well as hematomas and vascular lesions in the brain. Informed consent to use intraoperative ultrasound was obtained from all patients. Postoperative computed tomographic (CT) scans were obtained.

**TABLE 1. Neurosurgery guided by real-time two-dimensional ultrasound as performed to treat various brain lesions, 1995–2001**

| Lesions | No. |
|---|---|
| Hematomas | 19 |
| Glioblastomas | 27 |
| Anaplastic astrocytomas | 8 |
| Low-grade astrocytomas | 18 |
| Metastasis | 22 |
| Meningiomas | 8 |
| Other tumors | 26 |
| Other lesions (cyst abcess) | 13 |
| Vascular lesions | 15 |
| Total | 156 |

### Equipment

Real-time 2-D imaging was performed using a System FiVe high-performance ultrasound scanner (GE Vingmed Ultrasound, Horten, Norway). Scanner parameters for brain surgery applications were optimized as described previously (11). For deep-seated or subcortical lesions, a 4- to 8-MHz phased array probe with optimal image quality at depths of 3 to 6 cm and with a footprint 13 × 17 mm was used. For some of the superficial lesions, a 10-MHz linear array probe with optimal image quality at 2 to 4 cm was tested in addition to the 4- to 8-MHz probe. The ultrasound probe was covered by a sterile condom with sterile gel before it was introduced into the operative field.

### Clinical Setup: Surgical Arrangements

#### *Positioning the Probe*

A challenge that we faced in this study was positioning the probe to obtain the highest possible image quality, both to observe the progression of surgery in real time and to steer the surgical tools directly to the lesion with real-time image guidance. Therefore, we explored various positions of the probe in relation to the resection cavity and the location of the lesion in the brain. The practical way of obtaining alternative setups was to perform an enlarged craniotomy, ensuring space for the probe beside the resection cavity, or to perform a second minicraniotomy (diameter, 3.5 cm) for placement of the probe (*Fig. 1*). Sterile gel was placed between the probe and the dura to ensure satisfactory contact for optimal wave propagation.

#### *Positioning the Patient*

Another parameter that might affect ultrasound image quality is the position of the patient on the operating table. Patient position affects the angle of the resection cavity in relation to the vertical gravity line and hence the amount of air trapped in the cavity during the resection.

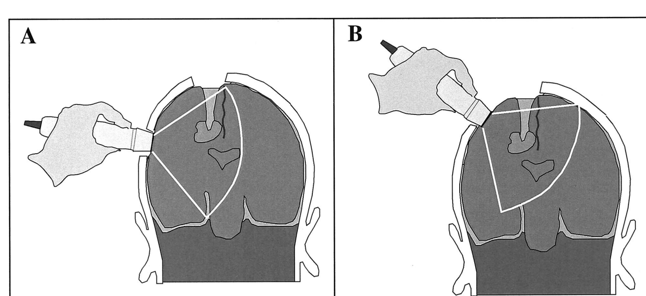



**FIGURE 1.** *Drawing illustrating how image quality and real-time ultrasound guidance may be improved by scanning through an intact dura at an angle of 10 to 90 degrees between the resection cavity and the image acquisition site. This goal is achieved by performing a second minicraniotomy (diameter, 3.5 cm) for insertion of the ultrasound probe (A) or by performing an enlarged initial craniotomy to allow for insertion of the ultrasound probe beside the resection cavity (B). Sterile gel was placed between the probe and the dura to ensure optimal wave propagation.*

### *Additional Items that Cause Reverberation*

Cotton padding and spatulas were removed from the resection cavity during ultrasound imaging. These items cause undesirable echoes, shadows, and reverberation in the images.

## Ultrasound Guidance

### *Open Tumor Resection*

The operation was performed with the microscope inserted through as small an opening as possible in normal tissue. When ultrasound imaging was performed, the resection cavity was flushed with saline, which made it easy to visualize remaining tumor tissue located at the border of the resection cavity and in surrounding areas. This procedure usually was repeated several times during the operation to observe the progress of the resection. Sterile gel was placed between the probe and the dura consistently to obtain optimal conditions for acoustical wave propagation. Tumor material was removed by the use of a Cavitron ultrasonic surgical aspirator (CUSA; Valleylab, Boulder, CO), biopsy forceps, and/or a suction device.

### *Closed Tumor Resection*

Access to the tumor was sometimes obtained through eloquent normal tissue. To reduce harm to normal tissue, some low, vascularized subcortical or deep-seated tumors were resected with only real-time 2-D ultrasound imaging guidance. In these cases, the surgeon was unable to visualize the tumor directly and thus had to trust the accuracy of the ultrasound images as the only available method of guidance. The tumors and the instruments (CUSA, biopsy forceps, and/or a suction device) were imaged simultaneously during the procedure. The tip of the surgical tool could be guided into the lesion with a high degree of precision on the basis of image information on the monitor. None of the tumors in patients who underwent this minimally invasive technique were highly vascularized. Vessels as small as 1 mm in diameter were detected by the use of power Doppler ultrasonography.

### *Evacuation of Spontaneous Deep-seated Hematoma*

After confirmation of the diagnosis by examination of CT or MRI scans, all patients were immediately brought to the operating room. The hematomas were located mostly in the putamen or the thalamus, and they were evacuated during the acute phase. All patients were placed supine with the neck flexed. A vertical operation channel from around the coronal suture to the center of the hematoma was obtained by elevation of the head end of the table. A temporal incision and a parasagittal incision of 5 cm each were made in the skin, and two small craniotomies (diameter, 3.5 cm) were performed. The ultrasound probe was placed into the temporal craniotomy and was affixed with a holder (Martin's arm) to ensure continuous, stable monitoring throughout the procedure. With 2-D ultrasound guidance, a thin, rigid guidewire was inserted through the frontal craniotomy into the hematoma. A slightly conical metal tube (diameter, 8 mm) with a plug was moved over the guidewire to the hematoma, protecting normal brain tissue from instrument manipulation during evacuation. The sucker, biopsy forceps, and CUSA were alternative tools used for the evacuation of the hematoma. The surgical setup for ultrasound-guided evacuation of hematomas is shown in *Figure 2*.

### *Saline Flushing in the Cavity for Observing the Progression of Surgery*

For both closed tumor resection and hematoma evacuation, it was important to observe the progression of the operation carefully. Saline was flushed into the operation cavity, which expanded the cavity and made it easy to identify remaining tumor tissue or hematoma, which appeared in sharp contrast to the saline solution. The movement of natural air bubbles in the saline solution could be observed, which made it easy to identify the resection cavity border.

# RESULTS

## All Lesions Depicted Well by Ultrasound Imaging

### *Ultrasound Imaging before Resection*

In brief, the image modality was useful for locating different brain tumors and hematomas in relation to surrounding anatomic structures. Sample ultrasound images of different lesions and surrounding anatomic structures are shown in *Figure 3, A–F*. These images were acquired after craniotomy was performed but before dura opening. From 1995 to 1996, image quality varied because of experimental setups and technological adjustments. Among patients who underwent surgery from 1997 to 2001, all lesions (n = 114) except two were depicted well by ultrasound imaging.

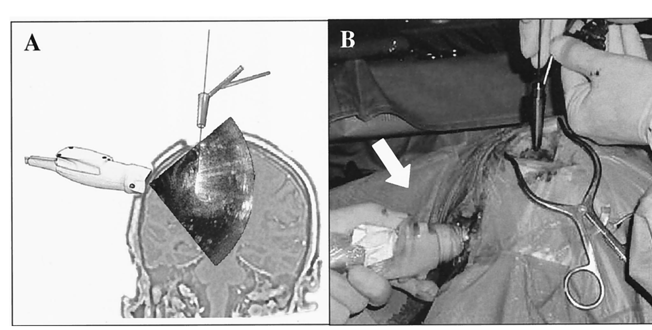



**FIGURE 2.** *Ultrasound images used for guiding a hematoma evacuation.* A, *illustration of the setup, also showing the sector in the brain imaged by real-time ultrasound as it would be shown during the evacuation procedure.* B, *a thin, rigid guidewire is placed into position through a second minicraniotomy (diameter, 3.5 cm) with the use of real-time 2-D ultrasound guidance. The ultrasound probe* (arrow) *is covered by a sterile condom with sterile gel. The conical metal tube (diameter, 8 mm) with a plug is gently placed on top of the guidewire and manipulated until it reaches the hematoma. Then the plug is removed.*

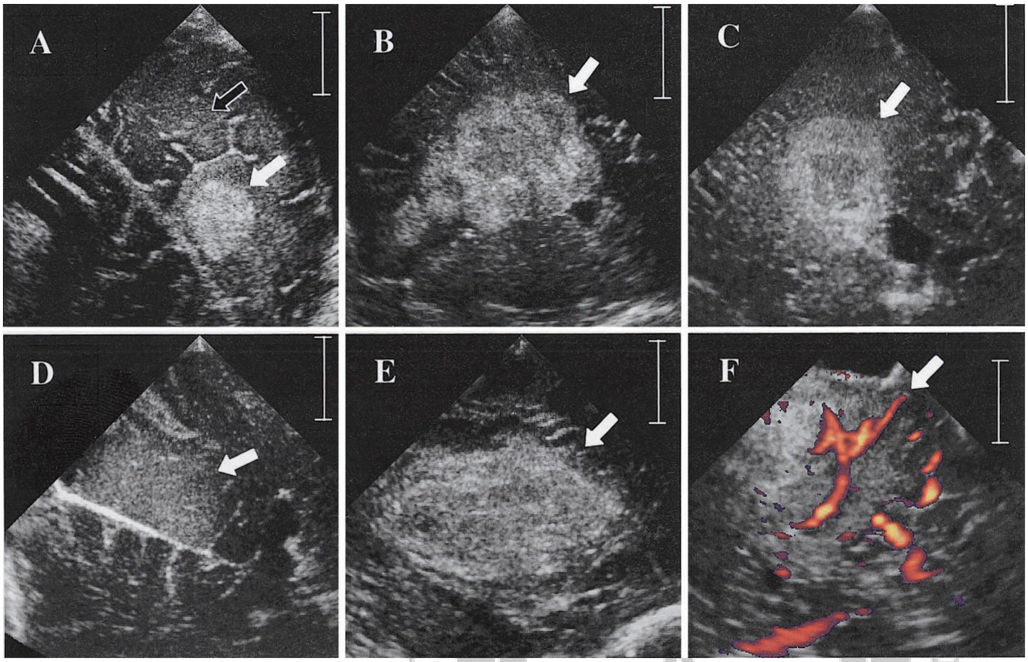


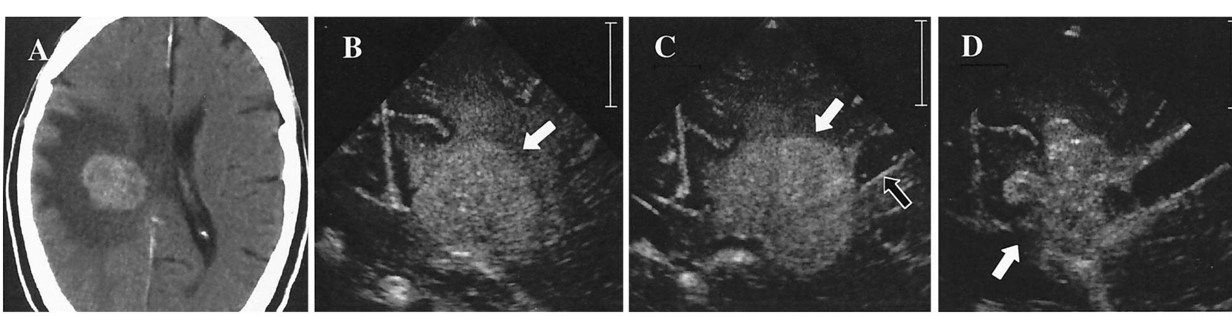

**FIGURE 3.** *Intraoperative images of the lesions that we resected from 1997 to 2001 at our clinic. These lesions (*white arrows*) were depicted well by the use of ultrasound, except in two cases.* A, *metastasis with surrounding edema (*black arrow*);* B, *glioblastoma;* C, *anaplastic astrocytoma;* D, *low-grade astrocytoma;* E, *hematoma;* F, *vessels in a tumor detected with the use of ultrasound power Doppler.* Scale bars, *2 cm.*

### *Ultrasound Image Guidance during the Operation*

Ultrasound was used extensively for guiding the surgical tools to the lesion. An example of an ultrasound-guided metastasis operation from the early phase of our study is shown in *Figure 4*. Ultrasound image quality was maintained throughout the operation and was used both for guiding the surgical tools directly as well as for observing the progression of the procedure in real time.

Real-time ultrasound imaging guidance was especially important in closed tumor operations (n = 14; 8 metastases, 6 gliomas of different grades). A sample intraoperative image obtained in a closed tumor operation is shown in *Figure 5*. No bleeding complications occurred that made it necessary to convert a closed operation into an open procedure. None of the patients with tumors exhibited neurological deterioration. One of the patients (with a metastasis) was refused operation by another senior surgeon because of the tumor's location in an eloquent area of the brain.

For the evacuation of hematomas, the real-time capability of ultrasound was especially important because of the dynamic nature of the procedure. The hematomas were evacuated in a period of seconds, and monitoring in real time was essential to maintain safety during this procedure (*Fig. 6*). In all hematoma patients (n = 19), more than 90% of the hematoma was removed. No bleeding complications occurred during the evacuation that made it necessary to con-



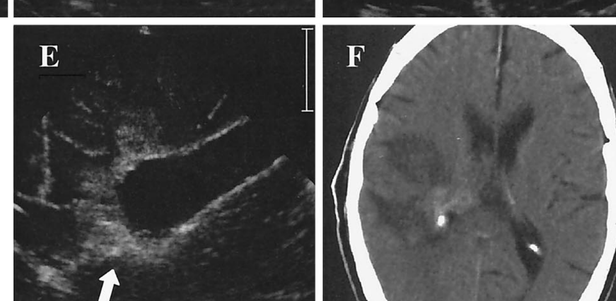




**FIGURE 4.** *Ultrasound images obtained to observe the progression of open tumor resection in a metastasis. These images were obtained in the early phase of the study.* A, *preoperative CT scan.* B, *intraoperative ultrasound image obtained before the dura was opened.* C, *ultrasound image obtained after the operative channel to the lesion was created (*black arrow*).* D, *ultrasound image obtained at midoperation; much tumor tissue is still in the brain.* E, *intraoperative ultrasound image obtained near the end of the operation; some tumor material visible in the image was subsequently removed.* F, *postoperative CT scan showing a small hematoma or possibly some residual tumor tissue in the cavity.* White arrows, *tumor material visualized via ultrasound imaging during the operation;* scale bars, *2 cm.*

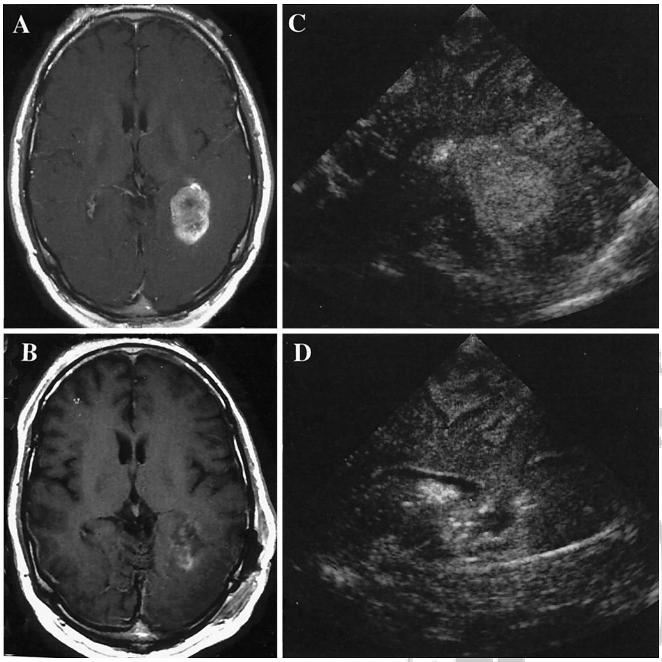



**FIGURE 5.** *Sample intraoperative ultrasound imaging studies used to guide the surgical tools during closed, minimally invasive resection of a metastasis.* A, *preoperative MRI scan;* B, *postoperative MRI scan obtained the day after surgery;* C, *intraoperative ultrasound image obtained before resection;* D, *intraoperative ultrasound image obtained after resection.*

vert an operation to a conventional open procedure. One episode of rebleeding occurred after closure in one of the first patients to undergo this treatment. This hematoma was evacuated with a biopsy forceps that probably tore a small vessel. Of the various instruments that we tested in the evacuation of hematomas in the brain, CUSA was found to be the most suitable because it sucked the hematoma into the middle of the cavity and removed even firm clots. The activated CUSA impaired but did not obscure the real-time 2-D ultrasound image (*Fig. 7*).

### Image Quality and Resection Control

For the majority of the tumor resections performed in this study, ultrasound was important not only for observing the progression of the operation but also for detecting possible remaining tumor tissue at the conclusion of the operation. Such tissue may not be visible with the microscope, and this may affect the outcome of surgery. *Figure 8, A–C*, shows several examples in which ultrasound imaging was used to detect remaining tumor tissue in the cavity wall. The interpretation of the images in the border zone between the glioma and normal tissue required an experienced ultrasound user. During the initial study period, freeze sections were obtained from such volumes, which maintained safety and increased the surgeons' understanding and interpretation of the ultrasound images in relation to the histopathological evaluation of tissue samples. In our clinic, a research project is under way in

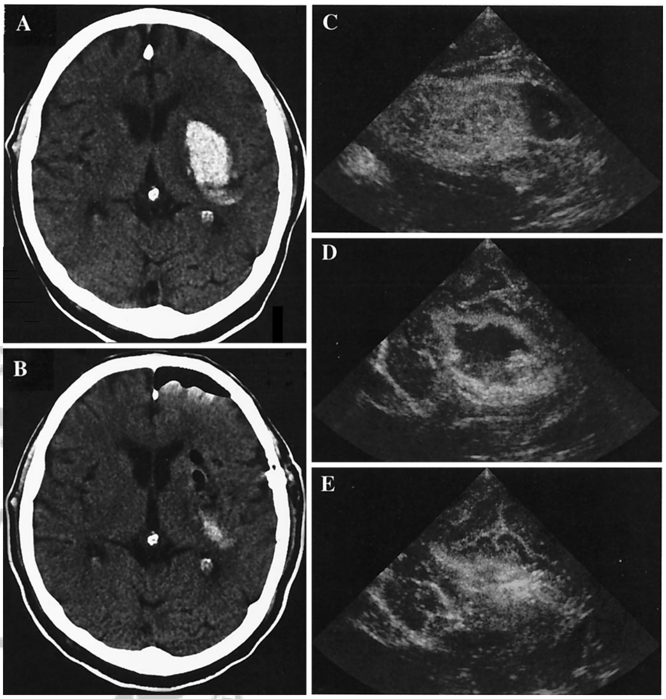



**FIGURE 6.** *Imaging studies obtained in a hematoma evacuation that was performed and guided only by 2-D ultrasound (closed operation).* A, *preoperative CT scan;* B, *postoperative CT scan;* C, *intraoperative ultrasound image obtained before evacuation;* D, *intraoperative ultrasound image obtained during evacuation;* E, *intraoperative ultrasound image obtained after evacuation.*

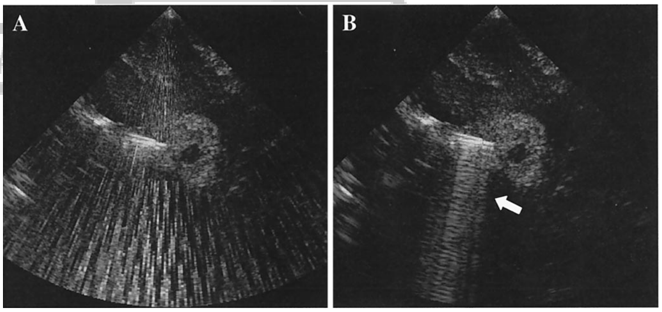



**FIGURE 7.** *The activated CUSA did not obscure the ultrasound images and thus did not decrease the safety of the operation, because it was turned on and off as needed during the procedure.* A, *ultrasound image obtained while the CUSA was activated.* B, *ultrasound image obtained while the CUSA was inactive. Reverberation* (arrow) *caused by the inactivated CUSA makes it possible to interpret the position of the CUSA.*

which this information will be collected systematically and presented, and this study will be published in a later article. In cases in which ultrasound detected remaining tumor material in eloquent areas in the brain, the operations were ended without removal of all tumor tissue.

In patients in whom the cavity wall was manipulated during the resection, we sometimes experienced an increase in the so-called rim effect. In our experience, the rim effect is asso-

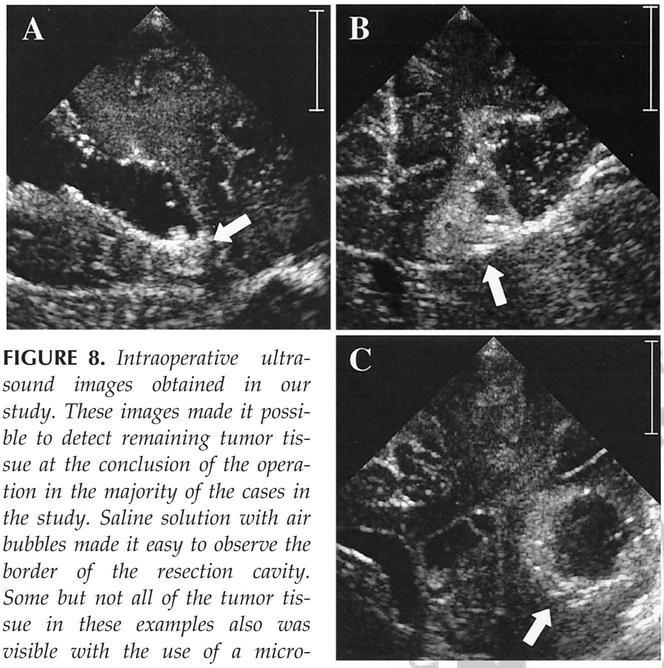



**FIGURE 8.** *Intraoperative ultrasound images obtained in our study. These images made it possible to detect remaining tumor tissue at the conclusion of the operation in the majority of the cases in the study. Saline solution with air bubbles made it easy to observe the border of the resection cavity. Some but not all of the tumor tissue in these examples also was visible with the use of a microscope.* A, *metastasis;* B, *glioblastoma;* C, *anaplastic astrocytoma. Remaining tumor tissue (*white arrows*) was removed after its detection with the use of intraoperative ultrasound imaging.* Scale bars, *2 cm.*

ciated with a rougher cavity wall that provides ultrasound signals that might be misinterpreted as tumor material. If there was a possibility that artifacts in the ultrasound images could have been misinterpreted as tumor material, biopsies were sent for histopathological evaluation before the resection was continued.

In three of the closed tumor operations (n = 14), the resection cavity was opened for safety reasons at the conclusion of the operation for visual inspection, with the focus being on remaining tumor tissue. Residual tumor tissue was detected by the use of the microscope in only one of these cases (a low-grade glioma). In two of the other closed operations (one metastasis and one low-grade glioma), biopsies were performed to verify radicality. For all of the closed operations, no tumor material could be observed on postoperative CT scans, with the exception of two patients in whom deliberate partial resection, as evaluated by ultrasound imaging, was performed. In these two patients with gliomas, the resection was ended before all tumor material was removed, because the tumors were located in especially sensitive areas of the brain.

## Ultrasound Image Quality, Tumor Location, and Surgical Setup

### *Probe Positioning*

In our experience, ultrasound guidance was useful in the majority of the surgical procedures in the study, and image quality was satisfactory for observing the progression of the operation in real time, especially when imaging was performed through an intact dura. The probe position and the frequency level used were chosen carefully and adjusted in accordance with the location of the lesion in the brain. The optimal distance of the 4- to 8-MHz phased array probe from the lesion was 3 to 6 cm. Beyond 3 to 6 cm, the image quality began to decline. Therefore, ultrasound imaging performed with this probe was most suitable for patients with subcortical lesions in the brain. For patients with superficial lesions, a probe with a higher frequency (10 MHz) would improve image quality considerably. An alternative, also tested in the present study, was to use gelatin standoff (1 cm in thickness), which usually made it possible to visualize even superficial tumors with the 4- to 8-MHz probe.

Real-time imaging that ensured satisfactory image quality throughout the operation was performed through an enlarged craniotomy (imaging 10–50 degrees relative to the resection cavity; 47% of cases) or through a second minicraniotomy (imaging 60–90 degrees relative the resection cavity; 53% of cases). In brief, these clinical arrangements were optimal for three reasons. First, imaging through an intact dura and normal brain caused fewer tissue artifacts, acoustic shadows, and reverberations from the operation instruments and the resection cavity wall. Imaging through the resection cavity (approximately 0 degrees) frequently resulted in noise and reverberation from the resection cavity wall, which made it difficult to observe the contour of the lesion deeper in front of the cavity wall (*Fig. 9*). Second, the probe was not in the way of the surgeon, and the assistant (or a mechanical probe holder) could keep the probe in position throughout the operation. Third, the surgical tool could be monitored in real time to ensure safety when the hematoma was evacuated or the tumor tissue was removed in a closed tumor operation. This monitoring is essential because it affords the surgeon the ability to always observe the tip of the instrument during the procedure. Visualization is obtained best by ensuring a probe angle of 60 to 90 degrees relative to the operative channel.

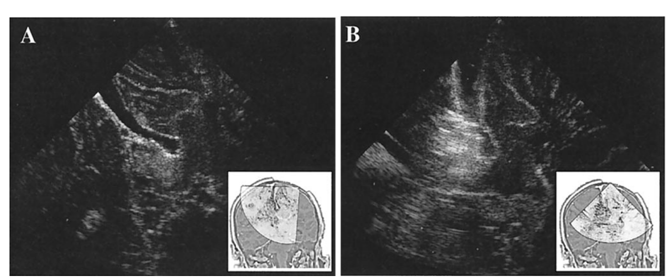



**FIGURE 9.** *Ultrasound images obtained in a patient in whom an enlarged craniotomy was performed. Ultrasound image quality was affected by the position of the probe in relation to the resection cavity and the position of the tumor.* A, *intraoperative ultrasound image showing the view through an intact dura at an angle of approximately 45 degrees relative to the resection cavity.* B, *intraoperative ultrasound image showing the view from the top of the resection cavity. The position of the ultrasound probe relative to the resection cavity is shown in the lower right corners in* A *and* B. *Considerably more noise is observed in* B *than in* A; *thus, the tumor border and remaining tumor tissure are difficult to interpret in* B.

*Operation Channel Positioning*

A vertical operative channel prevented air from becoming trapped in the resection cavity and made it possible to fill the resection cavity completely with water, which was important for obtaining satisfactory images. In all supratentorial lesions, it was possible to position the patient so that the plane of surgical access became vertical.

### Orientation with 2-D Guidance

The use of real-time 2-D ultrasound for guiding surgical tools into position is challenging for inexperienced users of this imaging modality. The orientation problem of the 2-D ultrasound plane is considerable for most surgeons. Up-and-down and right-to-left directionality observed on the monitor normally do not correlate with the directions in which the surgical instruments are moved in the patient (*Fig. 10, A* and *B*). Thus, when real-time 2-D images are used to guide a surgical instrument into the brain, the actual movement of the operative instrument usually cannot be intuited by viewing it on the monitor.

Another problem in the use of 2-D ultrasound for navigating surgical tools into the lesion is the position and orientation or angle of the ultrasound 2-D plane in relation to the tip of the surgical tool. Inexperienced users may misinterpret a small reverberation in the ultrasound image as the tip of the surgical tool, but this reverberation may be caused only by a cross section of the instrument (*Fig. 11, C* and *D*). This misinterpretation may have serious consequences, because the instrument tip may be far from the 2-D image plane and may cause damage to normal brain tissue in the worst-case scenario. In our experience with 2-D ultrasound imaging, the longitudinal reverberation from the tool in the ultrasound image ensures that the tip is properly visualized on the image (*Fig. 11, A* and *B*).

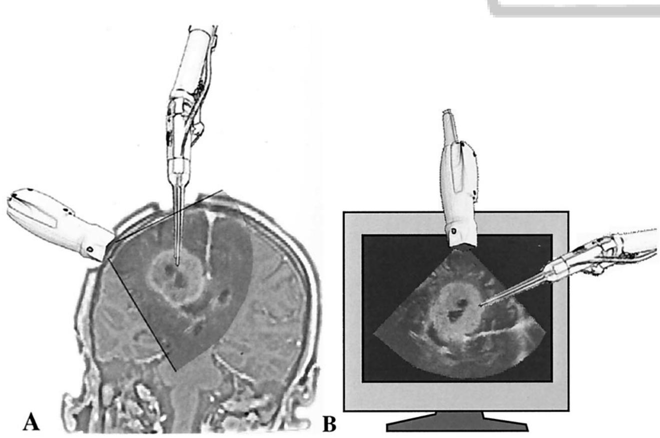



**FIGURE 10.** *Imaging studies illustrating the complex orientation of images in relation to the actual patient position. This complexity makes real-time 2-D ultrasound intraoperative guidance difficult. The surgical tool may be steered from the top* (A)*, but the images displayed on the screen seem to indicate that the tool is inserted from the right* (B)*. Depending on the orientation of the ultrasound probe, the images may even have a mirror effect, making it difficult to observe and guide the surgical tools solely on the basis of real-time imaging information.*

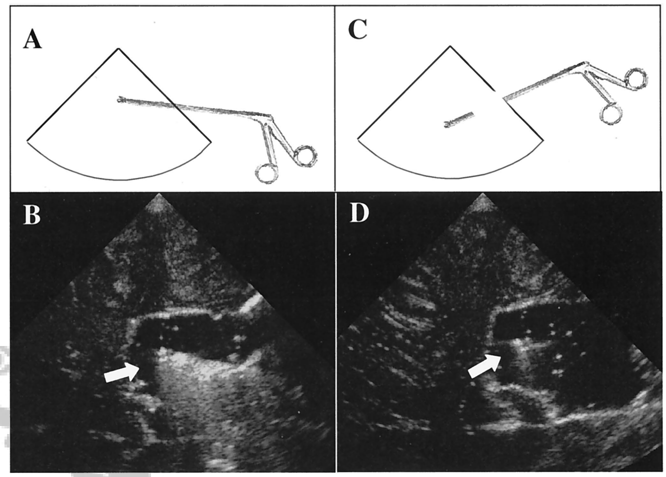



**FIGURE 11.** *Drawings and intraoperative images illustrating that the guidance of surgical tools in a 3-D space on the basis of 2-D images is challenging and demands experience. To safely perform intracranial procedures on the basis of 2-D intraoperative images requires that the tip of the surgical tool always be located in the 2-D image plane* (A)*. This goal is achieved most easily by adjusting the ultrasound image plane so that the longitudinal shadow* (arrow) *created by the surgical tool is displayed in the image* (B)*. If the image shown in* A *is not visualized, as shown in* C*, a smaller shadow* (D, arrow) *created by the cross section of the tool may lead to the surgeon to misinterpret the position of the surgical tool tip in the actual 3-D space. The tip may actually be far from the ultrasound 2-D image plane* (C)*.*

## DISCUSSION

Increased use of ultrasound in brain surgery will depend on the production of high-quality images. In 1990, Auer and van Velthoven (1) reported that all intracerebral lesions could be identified during intraoperative ultrasound investigations. Since then, ultrasound technology has developed considerably, making it possible to adjust parameters and further optimize image quality for brain surgery applications (11).

### Surgical Setup, Tumor Location, and Ultrasound Image Quality

In our study, the surgical setup seemed to be important to maintaining good image quality throughout the operation. By proper planning before surgery, we expect that image quality could be improved considerably with little effort.

*Positioning the Ultrasound Probe*

It may seem controversial to perform an additional mini-craniotomy or even an enlarged craniotomy to allow for intraoperative guidance (9, 13, 19, 26). In the present study, we explored different positions of the ultrasound probe. Although these setups demanded some extra incision and some additional operative time (typically 14 min total, including 7 min each for opening and for closing with CranioFix [Aesculap Co., Tuttlingen, Germany] and an extra minicraniotomy), none of the patients refused or questioned the procedure. The main concerns of the patients and the surgeons were to minimize injury to normal brain and to optimize tumor removal. On the basis of the present study, we are convinced that the extra time and effort as well as the ethical considerations involved in making the additional incision are rewarded by an increase in image quality, which enhances the performance and hence the outcome of surgery.

### *Positioning the Patient*

In the present study, we found that a vertical operative channel prevented trapping of air in the cavity and thus provided optimal conditions for ultrasound imaging. This positioning of the operative channel also minimized the need for spatulas and cotton padding, which frequently are used when the operative channel is not vertical. Our experience demonstrates that if the surgeon is aware of the parameters that affect ultrasound image quality, proper positioning of the patient may minimize potential problems with image quality.

### *Tumor Location*

Imaging from the other side of the midline was tested in only a few cases, but the acoustic signals seemed to be inadequate when the midline structures were passed using the specified probe. In the few cases of posterior fossa lesions, it seemed more difficult to obtain images via ultrasound, possibly because proper positioning of the probe and the patient was difficult or impossible to obtain. Auer and van Velthoven (1) found that image quality in this location was not optimal but that it was suitable for guidance in burr-hole procedures, the evacuation of hematomas, tumor biopsies, and the detection of small subcortical metastases. Despite the limited image quality achieved in this region of the brain in the few cases in the present study, ultrasound was useful to locate and verify proper removal of one exophytic brainstem glioma and one cavernous hemangioma of the brainstem. In summary, ultrasound imaging seems to provide high-quality image information regarding tumor and lesion extension and location, especially in the supratentorial brain. Other experienced users of this imaging modality also have reported similar experiences (1, 6, 9, 19).

## Image Quality, Surgical Performance, and Patient Outcome

The extent to which tumor removal affects survival time has been studied for several years, with conflicting results reported (8, 10, 15, 16, 20, 21, 23, 25). However, recently published studies have demonstrated increased survival time related to the extent of tumor removal (5, 31). In addition, evidence is increasing that the radical resection of gliomas with the use of intraoperative MRI guidance prolongs patient survival time (32). Corresponding patient outcome studies using ultrasound as the intraoperative imaging modality have not yet been presented. Hammoud et al. (13) and Woydt et al. (33), however, demonstrated that intraoperative ultrasound may be an alternative imaging modality to MRI for guidance in surgical procedures, because ultrasound in many cases provides better information than MRI regarding tumor extension and location. In the present study, we found that by optimizing the surgical setup, ultrasound imaging was satisfactory in directly guiding the surgical tools as well as for tumor resection control. Our results reflect many of the same benefits as those reported previously with regard to the use of intraoperative MRI guidance in neurosurgery (18, 32).

At the conclusion of our procedures, we occasionally found that ultrasound imaging reflected a zone of strong signal from the cavity wall in the area of resection that could be misinterpreted as residual tumor tissue. Other investigators previously attributed this rim effect to different causes (33), but we did not consider it a major problem in the present study, and therefore it was not a focus of our work. For inexperienced users of ultrasound imaging technology, however, this signal could lead the surgeon to continue the resection beyond the true borders of the tumor and thus damage normal brain tissue. We found, however, that when ultrasound was used frequently throughout the procedure, the surgeon could observe the progression of the resection in relation to the presumed tumor border and other well-known landmarks such as sulci and ventricles and therefore was able to end the resection at the correct location.

The indications for the evacuation of spontaneous, deep-seated hematomas remains controversial (2, 7, 24, 27). The idea that any potential benefit of hematoma evacuation may be lost because of the harmful effect of an open operation led to the development of stereotactic approaches to remove hematomas (27). Reduced surgical trauma seems to be important (22) for improved patient outcome. The problem with these methods is that the lack of real-time monitoring devices means that the surgeon has limited control during the procedure. In this article, we present a method that is a technological cross between a stereotactic operation and an open evacuation procedure using real-time 2-D ultrasound guidance. The method is also fast. As demonstrated by the present study, the use of ultrasound images might be associated with a tendency to overemphasize residual hematoma as compared with the use of postoperative CT images. This problem probably is attributable to signal from transmuted normal tissue around the hematoma. In our experience, however, because the suction and/or evacuation of a hematoma is a dynamic event that demands only a few seconds, ultrasound imaging seemed to be suitable for intraoperative guidance in these procedures.

## Ultrasound Imaging and Future Technology

In this article, we summarize our experience with using real-time 2-D ultrasound guidance during brain surgery. Despite all of the advantages of this technology, a disadvantage is that safe image-guided surgery (i.e., that provides true imaging of the tip of the surgical tool) may be performed only when the longitudinal view of the tool is displayed in the real-time 2-D image. Furthermore, severe reverberation in the images makes it difficult to interpret information about anatomic structures and lesions located deeper in the brain. In addition, the orientation problem is severe.

Navigational technology and three-dimensional (3-D) imaging data increasingly are being integrated into neurosurgery (11). This technological innovation has been demonstrated to be useful in solving the orientation problem in image-guided surgery and in improving tumor resection and patient outcome (30, 31). These systems do not yet have the real-time capability of ultrasound, however, which is important for guiding surgical tools with a satisfactory degree of safety. Several alternative solutions to integrate 2-D ultrasound and navigational technology have been presented by different groups (4, 11, 14, 17, 19). Although several of these alternatives have proved useful in characterizing brain shift during surgery, the orientation problem with real-time 2-D ultrasound has not been solved, and the brain shift problem remains. We think that by integrating 3-D ultrasound and navigational technology for brain surgery applications as described (11, 29), it is possible to compensate for brain shift by updating the 3-D map to solve both the orientation and brain shift problems.

## CONCLUSIONS

Image quality is critical in the use of intraoperative ultrasound guidance during neurosurgical operations. Ultrasound depicts all brain tumors and hematomas satisfactorily. The surgical setup is important to maintaining the production of high-quality images throughout the procedure. Real-time 2-D ultrasound has been proved useful in the evacuation of deep-seated hematomas; intraoperative guidance of surgical tools during tumor resections; and the identification of residual tumor tissue at the conclusion of surgery, which allows more radical resection to be performed. Real-time 2-D ultrasound has limitations as compared with integrated 3-D neuronavigation solutions, especially regarding the problem of orientation when surgical tools are manipulated in approaching the lesion.

## DISCLOSURE

At the time that this study was initiated, all of the authors were research scientists and had no financial interest in the outcome of the study. Today AG is employed by MISON AS and may benefit in the future successful use of ultrasound in neurosurgery. However, AG was not involved in this study after he became chief executive officer of MISON AS.

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## Acknowledgments

This work was supported by the Research Council of Norway, the Ministry of Health and Social Affairs, GE Vingmed Ultrasound (Horten, Norway), and the Norwegian Cancer Society.


## COMMENTS

The results of this study are valuable in terms of the clinical arrangement in which brain surgery can take better advantage of intraoperative ultrasound imaging. The authors frankly describe the limitations and pitfalls of using this method—namely, surgery performed in the posterior fossa, the misinterpretation of a cross section of the instrument as the instrument's tip, and the rim effect at the cavity wall. Because intraoperative ultrasound may be a less expensive and more versatile alternative to intraoperative magnetic resonance imaging (MRI), we encourage these authors to measure the radicality of tumor resection in future work by means of not only postoperative computed tomography but also early postoperative MRI.

**Johannes Schramm**
**Dirk Van Roost**
*Bonn, Germany*

The authors describe in detail their techniques for the use of two-dimensional ultrasound during surgery performed to remove intracranial lesions. Even with the advent of modern frameless stereotactic guidance systems, intraoperative ultrasound remains the only practical real-time tool available for determining the localization and the extent of tumor or hematoma resection. I have used intraoperative ultrasound imaging on at least a weekly basis for 20 years, and I still find it an invaluable adjunct in the operating room. Even expensive and cumbersome intraoperative MRI and computed tomography do not provide true real-time imaging of surgical instruments.

The authors use a new and somewhat controversial approach to tumor or hematoma resection viewed exclusively via intraoperative ultrasound. Intraoperative imaging is performed by performing a separate craniotomy through which the lesion and the resection can be observed at a 90-degree angle to the surgical approach. This bold, innovative approach may prove to be useful in cases of nonvascular tumors or hematomas. An important point is that if a hematoma is induced during resection, it is readily observable on ultrasound images. The future of intraoperative imaging probably will involve a combination of real-time intraoperative ultrasonic imaging and frameless stereotactic guidance.

**William F. Chandler**
*Ann Arbor, Michigan*

In this article, Unsgaard et al. discuss their experience with ultrasound-guided intracranial surgery. Their method of ultrasound-based neuronavigation has been described previously in *Neurosurgery* (1). In the present article, they convey further information on the basis of their experience with the use of two-dimensional perioperative ultrasound. Unfortunately, this study is descriptive rather than analytical. Therefore, it not possible to draw conclusions with regard to the type of situation in which the use of such a system would be beneficial. Although this article reports a limited amount of new information, it is a useful reminder of the value of intraoperative ultrasound as a neurosurgical tool. Ultrasound may represent an attractive alternative to real-time intraoperative MRI in the future.

**Iver A. Langmoen**
*Stockholm, Sweden*


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Intraoperative ultrasonic imaging has been available in our operating rooms for approximately 20 years. Typically, it has been used to find subcortical tumors before and after dural opening. These authors demonstrate that the method also can be used to monitor the resection of tumors and hematomas. The key seems to be to place the transducer orthogonally or nearly orthogonally to the surgical trajectory, which can be directed through another cranial opening if necessary. The authors also provide some useful technical points to improve the quality of the images, which to date has been a problem with intraoperative monitoring during resection.

**Patrick J. Kelly**
*New York, New York*

*Detail from a jade sculpture of Shou Xing (also see Chen, pages 517–518).*