During the history of stereotaxy, numerous technical improvements have been achieved, with imaging modalities having the most influence on procedural strategies. The advent of open intraoperative MR imaging transforms a blind stereotactic procedure, which is oriented in a supposedly rigid mathematical volume, into a visually controlled one, which can be adapted to dynamic anatomical changes that occur during surgery.

The outstanding features of open intraoperative MR imaging are near-real-time imaging during the operation (meaning a delay of 2–3 seconds between acquisition and display of the image), multiplanar imaging, high image quality with good soft-tissue discrimination, and fusion of the imaging, surgical, and time space (in other words, images can be acquired anytime during a surgical procedure without changing the patient’s position or moving the magnet), making registration procedures unnecessary.

The published articles on stereotactic biopsy procedures, both frame-based and frameless, describe variable morbidity and mortality rates and histological yields, reflecting not only varying amounts of experience and skill, but also differences in patient populations and surgical judgment.

The system used in our study fuses imaging space with surgical and time space, making registration obsolete. In addition, the fusion of these three spaces allows detection of any anatomical changes that might occur during a surgical procedure, potentially making a stereotactic procedure more accurate because a shift of the targeted structure can be accommodated by adjusting the trajectory of the biopsy cannula. During near-real-time imaging, the imaging plane and the trajectory plane are fused by an optical tracking device that visualizes the straight biopsy cannula in its entire length, thus confirming that its cutting window lies within the targeted structure.
Open magnetic resonance imaging–guided stereotactic brain biopsy

The most frequently reported applications of intraoperative MR imaging are for resection control and for neuronavigation in which intraoperative imaging is used in brain tumor surgery. In our hospital this system is used for minimally invasive MR imaging–guided procedures, particularly in combination with endoscopy, such as brain biopsy sampling, abscess evacuation, cyst drainage, and ganglionic hematoma evacuation, which account for 80% of all the procedures performed.

This prospective study was conducted to provide further information based on a larger group of consecutive patients who underwent frameless stereotactic biopsy procedures aided by open intraoperative MR imaging. We analyzed morbidity and mortality rates; histological yield; frequency of hemorrhagic complications seen on routine follow-up CT scans obtained on the 1st postoperative day; and the nature, size, and location of lesions; as well as procedure time. The key characteristics of open MR imaging are discussed with respect to their usefulness in stereotactic procedures. Our experience contributes to the ongoing discussion about the value of this expensive equipment for stereotactic biopsy sampling of brain lesions.

Clinical Material and Methods

Patient Population

During a period of 51 months (July 1996–November 2000), 113 consecutive patients (median age 53 years, range 6 months–78 years) with an intracranial lesion detected on CT or MR studies were chosen to undergo stereotactic biopsy procedures to enable histological characterization of their lesion before therapy. The indications for stereotactic biopsy sampling were as follows: 1) prohibitively high risk of morbidity because of the patient’s age and/or infirmity; 2) deep-seated, cystic, diffuse, or multifocal lesions; 3) locations of lesions in primary functional regions of the brain; and 4) suspected disease entity that would not require cytoreductive treatment for adequate therapy. These patients were offered the option of having the stereotactic biopsy procedure performed using open intraoperative MR imaging as an alternative to conventional frame-based stereotaxy. No patient preferred conventional stereotaxy when offered the two options. Informed consent was obtained according to the regulations of the institutional ethics committee.

The volume was estimated as a spherical structure by multiplying the largest cross-sectional diameters in three planes, multiplied by one sixth of \( \pi \left( \frac{X \times Y \times Z}{6} \right) \). The volume of the lesions ranged from 0.8 to 203 cm³, with a median size of 33.5 cm³ (Fig. 1). Of the 113 patients, 30 (26.5%) presented with lesions in the basal ganglia; 10 had lesions in the central region (8.8%); six in midline structures (5.3%); 23 in the temporal (20.4%), 21 in the frontal (18.6%), 13 in the parietal (11.5%), and seven in the occipital lobe (6.2%); and three in the insular region (2.6%) (Table 1). Fifty-three percent of the lesions were located in the left hemisphere. Although there are no contraindicated locations for brain biopsy procedures in the system we used, there were no patients with lesions in the brainstem or posterior fossa that required biopsy in this series.

Interventional MR System and Data Acquisition

All procedures were performed in an open-configuration, 0.5-tesla superconducting MR imaging system housed in a sterile-procedure room with an MR-compatible respirator and MR-compatible anesthesia monitoring equipment. All standard pulse sequences were available for imaging (T₁- and T₂-weighted, proton density, spin echo, gradient recalled echo, spoiled-gradient recalled acquisition in the steady state, time-of-flight sequence, and so on). The magnet produces a spherical imaging volume 30 cm in diameter at the center of the bore, with linear image acquisition and essentially no warping.

Imaging with this system is achieved in either a standard mode, as with conventional MR systems, or an interactive mode. In the latter case, the system is used as a frameless stereotactic device that allows the surgeon to select and control interactively the location and orientation of the imaging plane. This is achieved using an integrated optical 3D tracking system with specialized image guidance software running on a window-driven interactive computer workstation.

The imaging protocol used in all patients has been previously described. Continuous monitoring at the highest possible spatial resolution and image quality should be adjusted to nearly real-time update frames of the images during the interactive procedure. Our protocol included the following three steps: 1) standard, noninteractive, baseline imaging in which a T₁-weighted 3D radiofrequency fast spoiled–gradient sequence (TR 17 msec; TE 7.3 msec; flip

<table>
<thead>
<tr>
<th>Site of Lesion</th>
<th>No. of Patients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemispheric</td>
<td></td>
</tr>
<tr>
<td>frontal</td>
<td>21 (18.6)</td>
</tr>
<tr>
<td>temporal</td>
<td>23 (20.4)</td>
</tr>
<tr>
<td>central</td>
<td>10 (8.8)</td>
</tr>
<tr>
<td>parietal</td>
<td>13 (11.5)</td>
</tr>
<tr>
<td>occipital</td>
<td>7 (6.2)</td>
</tr>
<tr>
<td>insular</td>
<td>3 (2.7)</td>
</tr>
<tr>
<td>midline</td>
<td>6 (5.3)</td>
</tr>
<tr>
<td>basal ganglia</td>
<td>30 (26.5)</td>
</tr>
</tbody>
</table>

*Table 1: Location of supratentorial lesions in 113 patients undergoing stereotactic biopsy sampling.*

Fig. 1. Histogram showing the distribution of the lesion volume in which a biopsy was obtained. Ccm = cubic centimeters; # = number of.

J. Neurosurg. / Volume 97 / August, 2002
angle 45°; slice thickness 3 mm; in-plane resolution 0.9 × 0.9 mm; NEX 2; 28 slices covering the area of interest) and a T2-weighted fast spin-echo sequence were used (TR 3500 msec; TE 114 msec; slice thickness 4 mm, with 1-mm gap; in-plane resolution 0.86 × 1.14 mm; NEX 2); 2) interactive imaging in which a T1-weighted two-dimensional radiofrequency-spoiled-gradient sequence was used (TR 40 msec; TE 9.4 msec; flip angle 50°; field of view 24 cm; matrix 256 × 128 mm; slice thickness 5 mm; NEX 1), which provided image-update frames every 3 seconds; and 3) control T1- and T2-weighted images obtained at the end of the procedure by using the same protocol as that performed for baseline imaging.

Neurosurgical Procedure

All procedures were performed in the open intraoperative MR imaging suite at the University Hospital, Zürich. Most patients underwent surgery after induction of general anesthesia and were continuously monitored by an anesthesiology team, but the clinical condition of three patients required local anesthesia, with general anesthesia kept on standby. All patients received intravenously administered antibiotic drugs perioperatively. After shaving the region of the presumed surgical site, a flexible transmit–receive surface coil, wrapped in a sterile fashion, was applied around the patient’s head, depending on the location of the lesion. A modified Mayfield clamp, which was attached to the MR imaging couch, was used only in the first 10 patients. In the remaining cases, the patient’s head was placed in a moldable pillow and taped to the couch. Subsequently, the patient was transferred to the imaging room and the couch was docked at the entrance of the magnet. The patient was moved through the bore of the magnet, either a “front-dock” or “side-dock,” into the imaging volume. For lesions requiring a temporal burr hole, patients were transferred into the magnet by the front opening; patients with lesions requiring a frontal paramedian burr hole were transferred into the magnet by the side opening. Whereas two surgeons can work within the magnet’s gaps when the patient is front-docked, only one can work within the magnet with the patient side-docked.

Positioning of the patient inside the magnet was accomplished with the help of a laser cross demonstrating the isocenter of the magnet. The surgical site was brought within the field of view of the tracking system’s optical sensors, which are used for trajectory planning and fusion of the imaging plane with the trajectory plane. An initial standard MR imaging sequence, as described earlier, as well as the interactive images, were displayed for the surgeon on two flat panel monitors (liquid crystal displays) located within the gap of the magnet.

In all cases, the biopsy procedure was performed through the coil draped around the surgical field. The biopsy kit described previously, and all other instruments remaining in the operative field during imaging, were made of composite materials in order to avoid susceptibility artifacts.

For planning the entry point of the trajectory to the target lesion, the three-point light-emitting diode guide was adapted to a real-time trajectory-planning device (Pathfinder) that simulates the 35° moving angle of the Snapper-Stereoguide and marks the skin for accurate burr-hole positioning. The optimal entry point and trajectory to the lesion were determined by showing the trajectory projected within the lesion on two orthogonal planes. The process of trajectory planning was significantly accelerated by using the “fast needle graphics” option, which allows the imager to acquire data continuously and to display them on a previously selected plane or on the last image acquired with the interactive sequence, thus displaying the trajectory with a rate of up to 10 updates per second. After selecting the appropriate trajectory, the patient’s skin was marked, a sterile operational field was prepared, and a 15-mm burr hole was made. The dura mater was detached and the previously described Snapper-Stereoguide was inserted and tightly affixed to the burr hole. The three-point light-emitting diode guide was attached to the Snapper-Stereoguide, the previously planned trajectory was verified, the system was locked into the selected orientation, the depth of the lesion in the planned path was estimated, and an artifact-free, side window cannula biopsy needle, made from carbon fiber–reinforced composite material was advanced in a stepwise fashion along the planned pathway with the aid of continuous near-real-time imaging, visualizing the tip of the biopsy cannula and confirming its position within the targeted lesion.

In contrast-enhancing lesions, serial biopsy samples were obtained from the lateral border of the lesion to its hypointense center. The biopsy material was aspirated using a 5-ml syringe to apply suction to the tissue, while the inner cannula was rotated. This yielded cylindrical tissue pieces of 10 × 1 mm, which were sent for definitive neuropathological studies. No frozen sections and waiting for histopathological results during surgery were necessary because the needle’s position within the target was confirmed by near-real-time imaging.

In patients with diffuse lesions and a preoperative PET study, real-time image fusion was applied to direct the target to the region of highest fluorodeoxyglucose uptake within the lesion. Software has been developed that enables communication with the open MR imager and that presents an advanced image-fusion environment to the surgeon. Previous imaging studies of the patient are initially loaded, for example, a fluorodeoxyglucose-PET study and/or a high-resolution MR image acquired on a high-field system. After the patient has been prepared for the operation, a volumetric data set is acquired, to which the preloaded data sets are geometrically aligned; this procedure takes approximately 20 minutes. During the operation, single-slice images are acquired at arbitrary orientations. Each one is automatically retrieved by the fusion system, together with its slice definition parameters, the matched slice of one of the reference studies is generated, and an image is displayed that shows the fused information. Several variants of fusion possibilities are supported. The surgeon’s interface shows a pixel overlay between the two imaging modalities, where he or she can choose to view the intraoperative MR images only, the PET scan only, or a gradual overlap of both modalities.

Our standard approach was a transgyral one, to avoid sulcal vessels. Perforation of the ventricle was necessary in three cases, but otherwise it was avoided, although intraoperative changes necessitated by cerebrospinal fluid leakage along the trajectory could be accommodated by near-real-time imaging.

After tissue sampling, the biopsy cannula was carefully
Open magnetic resonance imaging–guided stereotactic brain biopsy

Fig. 2. Histogram demonstrating the depth at which biopsy samples were obtained, measured from the dura to the deepest target point.

retracted and the wound was closed. A postprocedural MR protocol in standard imaging mode was performed in all cases to determine the presence or absence of hemorrhage and alterations of the lesion. Further neuroimaging monitoring was performed within 24 hours by using unenhanced contrast-enhanced CT scanning in all cases.

Sources of Supplies and Equipment

The superconducting magnet (Signa SP) was acquired from General Electric Medical Systems, Milwaukee, WI. The MR-compatible respirator (Servo 9000 C) was purchased from Siemens, Erlangen, Germany, and the MR-compatible anesthesia monitoring equipment (MagniStereoguide) from Bruker Medical, Wissembourg, France. The artifact-free biopsy needle, the Pathfinder, and the Snapper-Stereoguide were manufactured by Magnetic Vision GmbH, Rüti, Switzerland. The optical 3D tracking system (Flashpoint 5000) was obtained from Image Guided Technologies, Boulder, CO. The computer workstation (Sun 4/670) was supplied by Sun Microsystems, Mountain View, CA. The Mayfield clamp used early in the study was purchased from Ohio Medical Instruments, Cincinnati, OH.

Results

We performed 114 stereotactic biopsy procedures in all, aided by open intraoperative MR imaging. All biopsy procedures were performed without using fiducial markers or stereotactic registration frames. After the first 10 patients, head fixation in the Mayfield clamp was not used. The depth of the lesions ranged from 10 to 80 mm, with a median distance of 50 mm (Fig. 2). All biopsy samples contained pathological tissue, and in 111 (97.4%) of 114 a specific neuropathological diagnosis was obtained (Table 2). The median time required for the entire procedure, including planning, was 73 minutes (range 27–119 minutes); after the first 20 patients, as experience with the system was gained, the median procedure time was 60 minutes. In two cases (1.8%) a hemorrhage was found on routine follow-up CT scans on the 1st postoperative day; these lesions were both already visible on the immediate postbiopsy MR images. In the first patient a small hemorrhage less than 1.5 cm was confined to the tumor site, and in the other there was evidence of subarachnoid bleeding; there was no postoperative neurological worsening in either case. Both patients manifested severe intraoperative hypertension, which the anesthesia team could not control. Morbidity with neurological worsening was seen in three different patients, it was transient in two (1.8%), whereas the third patient required emergency craniotomy because of an increase in the perifocal edema.

There was one death (0.9%). In this case, after we placed a left parietal burr hole 2.5 cm paramedian to the sagittal sinus, a large venous sinus was opened, resulting in dramatic venous bleeding in this patient. It was temporarily controlled by sealing the burr hole with bone wax; however, intraoperative imaging showed a large developing subdural hematoma. Emergency craniotomy was performed with the aid of the open intraoperative MR imaging to expose and close the lesioned venous sinus, which resulted in more massive bleeding because of the firm attachment of the dura to the inner table of the skull. The lack of a central line and a delay in blood replacement contributed to the fatal result. Coagulopathy after cessation of aspirin therapy 7 days before the biopsy procedure and abusive consumption of alcohol were additional precipitating factors in this patient.

The number of biopsy specimens obtained in each case ranged from one to 10, with a median of four biopsy samples, excluding the abscess cases. Seventy-seven percent of all procedures were performed by the same neurosurgeon (R.L.B.), and the remainder were completed by five different neurosurgeons. We were able to classify intraoperative shift into three categories: 1) brain shift manifesting as displacement of the brain surface; 2) target shift; and 3) midline shift.

The first type, inward shifting of the brain surface, was most prominent in elderly patients with atrophic brains. Outward shifting of the brain surface was seen in patients with large lesions and perifocal edema, in whom the brain was seen bulging into the burr hole. Minimal or no shift was present in cases of small or medium-sized lesions with minimal or no edema. In cases in which this shift was detectable (6%), the lesions ranged between 2 and 5 mm (mean 3 mm).

The second category, shifting of the target, was most common in lesions with a capsule, that is, abscesses, but was also seen in tumors with apparently well-defined mar-

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>No. of Patients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>neoplasms</td>
<td></td>
</tr>
<tr>
<td>high-grade glioma (WHO III–IV)</td>
<td>36 (31.3)</td>
</tr>
<tr>
<td>low-grade glioma (WHO I–II)</td>
<td>35 (30.4)</td>
</tr>
<tr>
<td>lymphoma</td>
<td>14 (12.2)</td>
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<tr>
<td>metastasis</td>
<td>3 (2.6)</td>
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<tr>
<td>not classified</td>
<td>3 (2.6)</td>
</tr>
<tr>
<td>gliomatosis</td>
<td>1 (0.9)</td>
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<tr>
<td>pineoblastoma</td>
<td>1 (0.9)</td>
</tr>
<tr>
<td>craniopharyngioma</td>
<td>1 (0.9)</td>
</tr>
<tr>
<td>dysgerminoma</td>
<td>1 (0.9)</td>
</tr>
<tr>
<td>inflammatory process, abscess</td>
<td>10 (9.6)</td>
</tr>
<tr>
<td>progressive multifocal leukencephalopathy</td>
<td>5 (4.3)</td>
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<tr>
<td>gliosis</td>
<td>4 (3.5)</td>
</tr>
</tbody>
</table>

* No biopsy sample contained normal brain tissue.
gins, that is, high-grade gliomas and metastases, which represent 44% of the patients in this study. This type of shift in patients with brain tumors was seen in 17% of all participants in this series (range 3–9 mm, mean 5.3 mm). It was seen in patients with cystic lesions, mostly abscesses (11% of participants, range 8–17 mm, mean 11 mm). There was no target shifting observed in soft tumors like lymphomas and diffuse infiltrating gliomas (43% of the patients in this study). Most importantly, in four patients with small, solid lesions (approximately 1 cm) in periventricular locations, the entire lesion shifted away from the biopsy trajectory, which had to be adjusted to hit the target eventually.

The third type, midline shift ranging from 3 to 8 mm (mean 3.5 mm), was observed in cystic/necrotic lesions (11% of the patients in this series), which were evacuated during the biopsy procedure.

Intraoperative near-real-time imaging was most useful in 22.7% of cases. These included patients with very small lesions (< 2 cm, 2.6%) and small lesions close to the ventricular systems (3.5%), in which a displacement of the targeted structure was observed and it was thought that without intraoperative imaging the target would have been missed. The near-real-time imaging was also beneficial in patients (2.6% of all cases) in whom a transventricular approach was necessary, and in cystic tumors and abscesses (14%), in which biopsy procedures and palliative drainage were combined.

Discussion

Postoperative Complications

The complication rate is known to depend on various factors: the number of biopsy samples obtained in a patient, the location (in deep-seated lesions fivefold increased) and histological features of the lesion (in malignant tumors fourfold increased), as well as increased intracranial pressure.

The percentage of deep-seated or critically located lesions, such as those in the basal ganglia and midline structures (31.8%), central region (8.8%), and insular region (2.7%), as well as the frequency of high-grade gliomas (31.3%) and lymphomas (12.2%), was in the typical range reported in previous stereotactic biopsy series. The median number of biopsy samples obtained from each patient was four, excluding the abscess cases. The frequency of stereotactic procedures performed using the open intraoperative MR imaging system was 2.2 biopsy procedures per month and six different neurosurgeons were involved, although the majority (77%) of cases were handled by the first author (R.L.B.).

After considering the aforementioned factors, the complication rate in our series was comparable with previously published series, even those originating from centers with a high case load and therefore extensive experience with stereotactic procedures. The rate of hematomas larger than 1 cm in our series was 1.8%, with one case of a silent, small hemorrhage smaller than 1.5 cm and confined to the tumor margins, and another of a mild subarachnoid hemorrhage without neurological deterioration. In both cases a severe and acute intraoperative hypertensive episode occurred, which could not be controlled sufficiently during surgery, and was probably due to ornipressin administration, which has been discontinued since then. The acute hypertensive episodes seem to have a causal relationship with bleeding at the biopsy site, so we strongly discourage continuation of a stereotactic procedure in such a situation. No delayed hemorrhage was detected on routine follow-up CT scans in this present series. In the two patients mentioned, in whom subarachnoid hemorrhage and hemorrhage within the tumor margins occurred and was seen on postoperative CT scans, the lesions were both visible already on the intraoperative MR images. Therefore, it seems rather unlikely that one would find a newly formed hemorrhage that was not detected on the intraoperative MR images.

Morbidity with neurological worsening was seen in three patients with large malignant tumors and increased intracranial pressure, which was transient in two of them (1.8%) after a mild increase of hemiparesis and an increase in the frequency of epileptic seizures postoperatively. In one of these three patients (0.9%), because of an increase in the perifocal edema after the biopsy procedure, emergency craniotomy was necessary. There was one death (0.9%) which occurred in a patient before a biopsy specimen was obtained. There was not a single case of infection.

In previously reported series of CT-guided stereotactic biopsy procedures, morbidity ranged from 0.6 to 7.2%; hemorrhages were the most frequent complication. Transient neurological worsening in the absence of a hemorrhagic complication has been observed to occur due to increased perilesional edema in up to 26% of patients.
with lesions in highly functional areas. In our series, of the 10 patients with lesions in highly functional regions, only one developed an increased edema and had to be transferred to the operating room for tumor decompression after biopsy of a large cystic temporal GBM.

Advantages of Open Intraoperative MR Imaging

One of the prominent characteristics of stereotactic biopsy samples in open intraoperative MR imaging is the fusion of anatomical space, imaging space, and time space, transforming the blind stereotactic procedure into a procedure that is visually controlled by near-real-time imaging. Registration, head frames, and fiducial markers are obsolete. Planning and performing the biopsy procedure becomes a one-step process. In the majority of cases no head fixation with the modified Mayfield clamp was applied, because the skull-mounted Snapper-Stereoguide prevented translation of any movements of the patient’s head to the biopsy cannula. Even if the patient’s head position changed, near-real-time image updates and the fusion of the trajectory plane with the imaging plane would always display the planned trajectory. Visualization of the biopsy cannula within the targeted lesion in all cases led to a reduction in the number of biopsy specimens obtained from the target to a median of four (abscess cases excluded), reducing the potential risk of hemorrhage, according to the report by Sawin, et al.29 As another consequence of the visualization, we could refrain from obtaining frozen sections and waiting for the histopathological result. The demonstration of highly vascularized regions (Fig. 3 left), especially in GBM cases, allowed planning of the trajectory within a less vascularized region of the tumor (Fig. 3 right), and possibly contributed to the rather low rate of hemorrhagic complications. In a subset of patients (22.7%) with cystic tumors, abscesses (Fig. 4), transventricular approaches, and very small lesions (Fig. 5), the dynamic accuracy of the system was believed to be truly helpful in compensating for anatomical changes caused by brain shift and target shift due to pressure of the biopsy cannula on the lesion (Fig. 6).

Additional advantages include the technically intuitive aspects of the procedure described earlier, the speed of completion of the stereotactic procedures, and complication rates and histological yields comparable with the reported results in other groups. The fact that six different neurosurgeons achieved these results may indeed be an important point in the future: if more neurosurgeons are performing fewer procedures, technically intuitive methods will permit a high level of quality in stereotactic biopsy surgery without the need for specially dedicated teams with expertise and knowledge about an unwieldy neurosurgical subspecialty.

Whereas the median procedure time, including planning, was 160 minutes for the first 10 biopsy procedures performed in this environment, the overall time decreased to a median of 60 minutes for the subsequent patients in this study.

Disadvantages of Open Intraoperative MR Imaging

One of the most cited restrictions of this technology is cost effectiveness. In the near future, however, we expect that less costly open intraoperative MR imaging technology will probably be available. Among the costs should be included the development of MR-safe and MR-compatible instruments, which was necessary in our study and which are now commercially available.

The architecture of the double-doughnut imager also has some limitations in terms of access to the patient. This is not
as big a problem in stereotactic procedures as in tumor resections, in which a 270° access is a neurosurgical standard. Another restriction is the impossibility of elevating a patient’s head during a procedure. As mentioned earlier in one fatal case it would have been helpful at least to elevate the patient’s head to decrease venous bleeding. These restrictions have been partially solved in some centers (TM Moriarty, personal communication), where the gantry can be pulled out of the magnet.

Last, although there is no proof of biological effects related to the lengthy exposure of persons working in a magnetic field, this subject is still under investigation.

**Image Quality**

In all cases, image quality with the system running in the standard mode for preoperative planning of the procedure and postoperative control was very good. In most cases the lesions were also clearly visualized in the interactive mode, with an image update every 2 to 8 seconds, but in a few cases the image quality was marginal in terms of difficulties in detecting small nonenhancing lesions. In these cases standard-protocol images were used to confirm the correct position of the biopsy cannula. In several lesions it was possible to visualize the cutting window of the biopsy cannula, which was most helpful in small lesions for rotating the window toward the targeted lesion (Fig. 7).

**Accuracy of the System**

The mean overall procedural linear error of accuracy of the system has been tested and reported earlier to have a mean value of 1.5 mm and a mean euclidean or vectorial error of 1.7 mm. Taking into account the amount of brain shift, reported by several authors, and the associated shift of the targeted structures, the dynamic accuracy of this system is surpassed by no other.

**Neurosurgical Procedure and Instruments**

This method of obtaining biopsy specimens is truly frameless, because we refrained from fixation of the patient’s head in a Mayfield clamp in the majority of cases (91%). In conventional frameless neuronavigation systems in which preoperative images are used, rigid head fixation and tracking without displacement of localizing scalp fiducial markers is essential.

As we reported earlier, a completely artifact-free and disposable set of instruments for stereotactic procedures was developed in our institution by using exclusively composite materials, because MR-compatible metallic instruments produce a considerable image distortion resulting from magnetic susceptibility differences between the needle and the surrounding tissue, and also a corresponding shift of the artifact center away from the actual center of the needle. Because stereotactic procedures should have an overall accuracy in the millimetric range, the size of these artifacts may partially spoil the accuracy of the system and obscure visualization of the target lesion. Using a composite cannula allowed artifact-free visualization of the cannula itself, which was depicted as a linear signal void (Figs. 5 and 6) and of the surrounding tissue next to the cannula. Due to characteristics of the composite materials, the outer diameter of the biopsy cannula used was 3.9 mm. The mean volume added by inserting the cannula into the brain was 2.6 ml, and no complications related to this were observed in the majority of cases, although it may have contributed to neurological worsening in one case, in which multiple biopsy samples were obtained in three different areas of a large tumor. The slightly blunt shape of the tip and the diameter
of the biopsy cannula may contribute to lowering the incidence of hemorrhages by pushing aside small blood vessels and the wall of a ventricle instead of perforating them. This phenomenon was clearly demonstrated during interactive imaging in two cases (Fig. 8).

Freehand brain biopsies, as presented by Hall, et al., are of some concern in our opinion and should be discouraged, because small angular movements by the patient or by the surgeon during the biopsy may result in considerable translational movements in the target area, putting the target region at risk of additional injury. Also, fixation of a stereotactic probe with a Bookwalter arm, as reported by Moriarty, et al., is insufficient in our opinion and may cause injury by the aforementioned mechanism.

The stereotactic biopsy kit used in this series is tightly affixed to the patient’s skull to exclude any transfer of movements of the patient’s head to the biopsy cannula within the brain. This concept allowed us in most cases to use only a band of tape to immobilize the patient’s head and to refrain from use of the Mayfield clamp.

**Histological Yield**

The definition of histological yield is differently applied in the various previously reported studies. Should the yield represent the percentage of successful tissue sampling, rate of recovery of pathological tissue, or the percentage of cases in which a specific and conclusive neuropathological diagnosis was obtained? There is always a small number of cases in all stereotactic series, in which tissue diagnosis is not obtained beyond the nonspecific category “pathological tissue.” This may be partially due to sampling problems, but it also demonstrates the limitations of neuropathological diagnostic capabilities. In our current series there was a patient in whom a craniotomy was performed following the stereotactic biopsy procedure; however, no specific histological diagnosis was possible. This case illustrates that even when a large enough tissue sample is obtained in a technically correct manner, a conclusive neuropathological diagnosis may be difficult or impossible to obtain because of rare tissue characteristics. In another patient with diffuse periventricular T2 signal enhancement and long-lasting epileptic seizures, gliosis was found to be the appropriate diagnosis, whereas in other cases gliosis was not accepted as a specific diagnosis.

In this series none of the biopsy samples yielded normal brain tissue, and in all cases a histological diagnosis of pathological tissue was obtained. A specific histopathological diagnosis was achieved in only 97.4%, however.

The histopathological diagnosis has to be seen in relation to the nature of the lesion, with a decreasing yield for biopsy procedures performed in cases in which a metabolic disturbance is suspected. Other factors increasing the histological yield are the number of biopsy samples obtained in a patient and the lesion size. Increasing the number of biopsy samples also increases the risk of a potential hemorrhage, according to Sawin, et al., whereas other groups question this statement.

**Alternative Open Intraoperative MR Imaging Systems**

Several other open intraoperative MR imaging systems have been reported over the last few years. Most of them require that the patient be moved in and out of the imager, whereas others move the magnet to and from the patient. In the system used in this study no patient transfer was required for image acquisition and there was virtually no delay between the decision to obtain images and the actual process. There is a polarity of high- and low-field-strength open intraoperative MR imaging systems. The system used in this study belongs to the lower-field-strength systems. Higher-field-strength systems have the potential of sequences that allow spectroscopy, functional MR imaging, and in general have shorter image acquisition times. Integration of such systems into a neurosurgical field, however, is more difficult. We also doubt the practicality of intraoperative spectroscopy and functional MR imaging, because these sequences are very sensitive to intraoperative changes and manipulations.

**Conclusions**

Open intraoperative MR imaging transforms a blind conventional stereotactic procedure into a visually controlled stereotactic procedure that is adaptable to dynamic intraoperative anatomical changes. Routine postprocedural MR imaging allows immediate detection of complications, making a follow-up CT scan on the 1st postoperative day obsolete. This largest reported series of intraoperative MR-guided biopsy procedures demonstrates that the advantages of near-real-time intraoperative imaging may include a low incidence of complications, high yield of pathological tissue, and a mean procedure time of 60 minutes, including planning.

**Disclaimer**

The patent for the Snapper-Stereoguide is pending, and none of the authors is benefiting financially from the device at this time.

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