Frameless neuronavigation in intracranial endoscopic neurosurgery

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Objective. Frameless computerized neuronavigation has been increasingly used in intracranial endoscopic neurosurgery. However, clear indications for the application of neuronavigation in neuroendoscopy have not yet been defined. The purpose of this study was to determine in which intracranial neuroendoscopic procedures frameless neuronavigation is necessary and really beneficial compared with a free-hand endoscopic approach.

Methods. A frameless infrared-based computerized neuronavigation system was used in 44 patients who underwent intracranial endoscopic procedures, including 13 third ventriculostomies, nine aqueductoplasties, eight intraventricular tumor biopsy procedures or resections, six cystocisternostomies in arachnoid cysts, five colloid cyst removals, four septostomies in multiloculated hydrocephalus, four cystoventriculostomies in intraparenchymal cysts, two aqueductal stent placements, and fenestration of one pineal cyst and one cavum veli interpositi. All interventions were successfully accomplished. In all procedures, the navigational system guided the surgeons precisely to the target. Navigational tracking was helpful in entering small ventricles, in approaching the posterior third ventricle when the foramen of Monro was narrow, and in selecting the best approach to colloid cysts. Neuronavigation was essential in some cystic lesions lacking clear landmarks, such as intraparenchymal cysts or multiloculated hydrocephalus. Neuronavigation was not necessary in standard third ventriculostomies, tumor biopsy procedures, and large sylvian arachnoid cysts, or for approaching the posterior third ventricle when the foramen of Monro was enlarged.

Conclusions. Frameless neuronavigation has proven to be accurate, reliable, and extremely useful in selected intracranial neuroendoscopic procedures. Image-guided neuroendoscopy improved the accuracy of the endoscopic approach and minimized brain trauma.

Abbreviations used in this paper: CT = computerized tomography; MR = magnetic resonance; STN = Surgical Tool Navigator; STP = stereotactic planning; UITT = universal instrument tracking tool.

Clinical Material and Methods

Patient Population

In a series of 135 patients who underwent an intracranial endoscopic intervention at our institution between May 1996 and October 1999, computerized neuronavigation was used in 44 of them. The mean age of these patients was 31 years (range 1–71 years). There were 29 male and 15 female patients. The diagnoses included noncommunicating hydrocephalus, multiloculated hydrocephalus, arachnoid cysts, intraparenchymal cysts, colloid cysts, intraventricular tumors, isolated fourth ventricles, cavum veli interpositi, and pineal cyst (Table 1). Thirteen third ventriculostomies, nine aqueductoplasties, eight intraventricular tumor biopsy procedures or resections, six cystocisternostomies in arachnoid cysts, five removals of colloid cysts, four septostomies in multiloculated hydrocephalus, four cystoventriculostomies in intraparenchymal cysts, two aqueductal stent placements, and fenestration of one pineal cyst and one cavum veli interpositi were performed. In nine patients, two endoscopic procedures were performed simultaneously: third ventriculostomy and tumor biopsy (in five patients), third ventriculostomy and aqueductoplasty (in three patients), and tumor biopsy
Neuronavigation in intracranial neuroendoscopy

and stent placement (in one patient). The mean operating time was 45 minutes (range 30–160 minutes).

Neuronavigation System

We used the STN, a frameless, armless, image-guided, infrared-based, intraoperative tracking system. This system consists of a workstation, localizer camera, dynamic reference frame, tool box, hand control panel, UITT, and pointer, which are connected by coaxial cable. The tool box allows the simultaneous connection of the dynamic reference frame, hand control panel, pointer, and three UI TTs mounted on various instruments. In cooperation with Carl Zeiss and Karl Storz GmbH & Co., a special optical bridge attached to a UI TT has been developed (Fig. 1). This bridge allows the use of different standard endoscopes and trocars. For each trocar and endoscope, a special tool file exists in the computer. Thus, any trocar and endoscope can be used after selecting the tool in the “tool selection” menu and passing the validation process. These separate tool files enable quick exchange of scopes and trocars while eliminating the need for tool calibration. The system can be operated by the surgeon using the sterilized hand control panel. The recently updated navigation software is the STP software (version 4.0) linked with Zeiss navigation software.

Endoscopic Equipment

We used the Gaab universal neuroendoscopic system, which was developed by the senior author.¹¹ We prefer rigid rod-lens scopes (Hopkins II: 4-mm outer diameter) because of their brilliant optical quality, extreme wide-angle view, and easy guidance. Even in cases of minor hemorrhages that blur the view one can stay oriented, which is extremely difficult with the poor optics of a fiberscope. The endoscopes are inserted via an operating sheath (outer diameter 6.5 mm), which is initially introduced with the aid of a trocar under neuronavigational guidance. The operating sheath allows one to change scopes intraoperatively without reinserting them through brain tissue, thus avoiding unnecessary damage to the surrounding brain. The operating endoscope with angled eyepiece is used for manipulations and tissue removal. For exploration of the aqueduct and fourth ventricle, a 2.5-mm steerable fiberscope is available. Various mechanical instruments such as scissors, hooks, puncture needles, and biopsy and grasping forceps are used for dissection and tissue removal. For hemostasis and dissection, bipolar as well as monopolar diathermy probes and a laser guide that enables the laser fiber tip to be bent are available. We use a neodymium-yttrium-aluminum-garnet laser for these surgical procedures. Balloon catheters are used to enlarge ventriculostomies or for other fenestrations. Irrigation is controlled with the Malis irrigation module.

Neuronavigation Procedures

. After image acquisition and fiducial registration in patients, determination of a straight approach was made. The target and entry points were selected to provide the best surgical access to reach the lesions without damaging important brain structures, such as the fornix or eloquent cortex. For lesions within the third ventricle, the multiplanar-view window was especially useful to find the best entry point. The target point and the foramen of Monro were marked. Then, in the parallel-to-trajectory window, the target–foramen line was extended to the level of the skull and the ideal position of the entry point was defined. With the pointer, the entry point was located on the scalp. Then the patient’s head was prepared and draped. After the skin incision was made, a 10-mm burr hole was placed and the endoscopic trocar was selected in the tool window. Once the dura had been incised and the cortex coagulated, the trocar was introduced according to the preplanned approach, while viewing the computer screen (Fig. 2). Then the trocar was replaced by the diagnostic scope and the ventricles were inspected. After approaching the target under navigational guidance, in most cases, the operation was performed under endoscopic vision. Within cystic lesions without anatomical landmarks, such as intraparenchymal cysts and loculated hydrocephalus, however, navigation was used interactively. While tracking the diagnostic endoscope, the preplanned fenestration site was exactly identified despite a lack of landmarks. After fenestrating the cyst membrane, the endoscope was advanced into the ventricle to verify a sufficient communication with the normal cerebrospinal fluid pathways. With loculated hydrocephalus, the approach trajectory was selected to reach as many loculi as possible with a single pass. Final endoscopic inspection confirmed free communication between all the compartments and the ventricular system. In an isolated fourth ventricle that was approached subocipitally because of bilaterally collapsed frontal horns, aqueductal stent placement was performed with neuronavigational guidance because the aqueduct could not be identified. Details of our procedures of third ventriculostomy, aqueductoplasty, removal of colloid cysts, intraventricular tumor biopsy/resection, and fenestration of arachnoid and other cysts have been reported elsewhere.¹²–¹⁸

Assessment of the Usefulness of Neuronavigation

To assess the need for neuronavigation in determining the location of the burr hole, the entry point was initially selected in a free-hand fashion without neuronavigation according to the surgeon’s choice. Subsequently, the accurate entry point was determined with the aid of neuronavigation. Furthermore, the procedures were divided into operations in which orientation was feasible according to

<table>
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<th>TABLE 1</th>
<th>Summary of diagnoses in 44 patients in whom frameless neuronavigation was performed</th>
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<tr>
<td>Diagnosis</td>
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</tr>
<tr>
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<td>1</td>
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anatomical landmarks and operations in which orientation was difficult because of a lack of clear landmarks, which necessitated interactive image-guided surgery.

Sources of Supplies and Equipment

The optical bridge with the UITT was kindly provided by Karl Storz GmbH, Tuttlingen, Germany, and Carl Zeiss, Inc., Oberkochen, Germany. It was developed by the authors in cooperation with these two companies. The STN intraoperative tracking system was manufactured by Carl Zeiss, Inc. The STP software (version 4.0) and the Zeiss navigation software (STN 1.24) were supplied by Carl Zeiss, Inc. The Gaab universal neuroendoscopic system including the Hopkins II endoscope was acquired from Karl Storz GmbH. The Opmilas YAG-M laser (1.064 µm) was manufactured by Carl Zeiss, Inc. The Malis CMS-II Irrigation Module was purchased from Codman and Shurtleff, Inc., Randolph, MA.

Results

The STN tracking system has proven to be reliable and accurate. In all procedures, the target was actually approached as planned at the workstation. The mean computer-calculated registration accuracy was 1.99 mm, ranging from 0.56 to 3.48 mm. With an earlier software version, four crashes were sustained and rebooting was necessary. However, the recent software version (STP 4.0) has worked with no problems and has been easy to use. Shifting was only of minor importance in two of the intraparenchymal cysts, which partially collapsed after entry. One parenchymal cyst fenestration had to be aborted because of significant bleeding obscuring the visualization of the target. This procedure was continued as an endoscope-assisted microsurgical intervention, and the postoperative course was uneventful. All other interventions were successfully accomplished endoscopically. In all tumor operations, a histological diagnosis was obtained.

The correspondence of the burr hole location chosen by the surgeon with the entry point preplanned with the computer is shown in Table 2. Correction of the entry point was mainly necessary for accurately approaching intraparenchymal cysts, multiloculated hydrocephali, and small arachnoid cysts, as well as passing a small foramen of Monro to reach the posterior third ventricle. Moreover,
Neuronavigation in intracranial neuroendoscopy navigational tracking was helpful in entering small ventricles. Neuronavigational planning of the appropriate approach was also very useful in colloid cysts (Fig. 3). Interactive application of neuronavigation proved to be necessary with all cystic lesions lacking clear anatomical landmarks, such as located hydrocephali, intraparenchymal cysts (Fig. 4), cavum veli interpositi, and one isolated fourth ventricle. In most intraventricular procedures and all procedures involving arachnoid cysts, orientation guided by the anatomical landmarks such as choroid plexus, vessels, and nerves was feasible.

Discussion

Frame-based stereotaxis has been used for a long time for precision insertion of endoscopes into the brain. However, the stereotactic frame and arc are bulky and restrict the freedom of movement of the endoscope. Computerized frameless neuronavigation enables free-hand movement of the endoscope with real-time control of the position of the endoscope tip and of the approach trajectory. Frame-based stereotaxis lengthens the overall operating time when the time needed for frame application and imaging studies is considered. For neuronavigation, the MR imaging is performed on the evening before the day of surgery. Setting up the hardware and planning the approach are done simultaneously with induction of a state of anesthesia. Only approximately an extra 10 minutes is required for patient-to-image registration and determination of the entry point. Thus, neuronavigation can be regarded as almost time neutral in most endoscopic procedures, a finding well known from neuronavigation in open cranial surgery. Furthermore, in cystic lesions lacking anatomical landmarks, neuronavigation even shortens the operating time by diminishing the uncertainty in selecting the correct location for the fenestration.

Application of frameless stereotaxis in neuroendoscopy has recently been reported. However, the role of image guidance in endoscopic procedures remains to be determined. Based on our experience in 255 intracranial endoscopic procedures, including 148 third ventriculostomies, we found that for most endoscopic procedures in hydrocephalic ventricles, a free-hand approach is adequate. The dilated ventricles give enough space for free-hand insertion of an endoscope and maneuvering of the scope for minor position corrections. Orientation within the ventricles is generally easy because of the well-known landmarks such as veins, choroid plexus, and foramen of Monro. However, when the ventricles are small or the posterior third ventricle has to be approached through a narrow foramen of Monro, precise guidance is helpful. Additionally, image guidance is valuable for selection of the best entry point into cystic lesions and for determination of the optimal approach trajectory for the fenestration (for example, cystoventriculostomy). Moreover, preplanning of the approach to colloid cysts has proven to be very useful in providing access to the cyst through the foramen of Monro more anteriorly and as far laterally (approximately 5–6 cm paramedian) as possible without causing damage to the caudate nucleus and fornix. This approach facilitates the visualization of the roof of the third ventricle where the cysts arise and enables a complete endoscopic cyst removal. In none of our image-guided third ventriculostomies have we found neuronavigation to be helpful in selecting the entry point or in intraventricular orientation. We do not believe that stereotactic guidance of third ventriculostomies helps avoid neurovascular injury. The relation of the floor of the third ventricle to the basilar tip can be assessed on sagittal or axial MR images and CT scans. Small perforating vessels can only be identified endoscopically after fenestration of the floor. Therefore, the correct placement of the ventriculostomy, which is determined under endoscopic view, is crucial for avoiding vascular or nerve damage. In all intraventricular tumors and arachnoid cysts, orientation after inserting the endoscope was easy when following the anatomical landmarks, such as choroid plexus, veins, middle cerebral artery, and optic and oculomotor nerves.

In most image-guided endoscopic procedures, only the location of the entry point and the approach trajectory are determined with navigational guidance. The procedure itself is performed under endoscopic visual control. However, with intraparenchymal cysts and multiloculated hydrocephalus, interactive use of the guidance system has emerged as an invaluable aid in maintaining orientation and localizing the appropriate fenestration site. However, cystic lesions may change size and shape after insertion of an endoscope. Therefore, navigation guided by preoperative images is less accurate. To overcome this problem, intraoperative ultrasonography has been used to update the image information. Fusion of preoperative MR images with real-time ultrasound is probably the most promising modality in the near future for dealing with brain shift throughout the procedure. Use of ultrasonic imaging alone to guide an endoscope has not been generally accepted because of the poor resolution, low contrast, and bad signal-to-noise ratio. Intraoperative CT scanning may be an alternative but has not met expectations. In our opinion, intraoperative MR imaging is currently not appropriate for endoscopic purposes because open magnets and MR-compatible equipment require considerable extra cost, which is not justified by the cost/benefit ratio. In our series, brain shifting was of minor importance. All

### Table 2

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<tr>
<th>Procedure</th>
<th>Corrected</th>
<th>Interactive Use</th>
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<td>pineal cyst fenestration</td>
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of our cystoventriculostomies to treat intraparenchymal cysts and cyst fenestrations to treat multiloculated hydrocephalus were accomplished successfully. In all parenchymal cysts, two multiloculated hydrocephali, and one isolated fourth ventricle, we relied on navigational guidance alone in identifying the correct fenestration site because the membranes were very thick and endoscopic orientation was impossible. Some precautions should be taken to prevent cyst changes; these include positioning the patient with the lesion at the highest point. We minimized fluid escape from the lesion after introduction of the endoscopic sheath. The watertight connection of endoscopic sheath and endoscope is of value in maintaining the pressure inside the cyst.
Although MR images have spatial errors because of field distortions and are therefore less accurate than CT scans, MR imaging is considered to be the preferred imaging modality for neuronavigation because it provides an excellent soft-tissue resolution with detailed anatomical delineation of thin membranes, tumors, and other structures. An application accuracy of 3 to 4 mm (not measured in our series, but described with similar neuronavigation systems\textsuperscript{13,16} ) seems to be sufficient for endoscopic purposes. After approaching the target with navigational tracking, minor position corrections can be performed under direct vision. To enhance the application accuracy of the navigation system, the fiducial markers should be placed close to the target and in a manner that the target area is in the center of the space created by these markers.\textsuperscript{28} The camera array should be positioned at a distance of approximately 1.4 m.\textsuperscript{23}

We do not believe that “frameless stereotaxy” or “neuronavigation,” terms coined by Roberts, et al.,\textsuperscript{36} and Watanabe, et al.,\textsuperscript{53} respectively, belong in the category of
“gimmicks and gadgets.” The value of computer assistance in improving the accuracy of certain neurosurgical procedures was shown by Kelly and colleagues as early as in the beginning of the 1980s. Although our assessment of the usefulness of frameless neuronavigation is highly subjective, we strongly suggest that this technology enables a more accurate approach that minimizes brain injury and renders selected procedures less invasive.

Conclusions

Neuroendoscopy has become a well-established technology in neurosurgery, and its use is intended to decrease injury to healthy brain tissue. The combination of neuroendoscopy and neuronavigation improves the accuracy of the endoscopic approach and further minimizes brain trauma while reaching the target via the ideal corridor. For selected cystic lesions, frameless neuronavigation is mandatory to be both successful and truly minimally invasive. The approach to small lateral ventricles or the posterior third ventricle through a narrow foramen of Monro as the bottleneck of the surgical corridor can be accurately simulated before surgery and the exact entry point can be determined. There is no doubt that frameless stereotaxis is a valuable and reliable part of the armamentarium in modern neurosurgery. However, the neurosurgeon should not blindly rely on modern technology. The option offered by the computer should be seriously assessed by the surgeon to avoid experiences like that of a BMW driver who was pulled out of a river because his navigation system could not distinguish between a bridge and a ferry.

Disclosure

The senior author is a consultant with Karl Storz GmbH.

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