BrainLab VectorVision Neuronavigation System: Technology and Clinical Experiences in 131 Cases

Hartmut K. Gumprecht, M.D., Darius C. Widenka, M.D.,
Christianto B. Lumenta, M.D.

Department of Neurosurgery, Academic Hospital München-Bogenhausen,
Technical University of Munich, Munich, Germany

OBJECTIVE: The BrainLab VectorVision neuronavigation system was used in 131 cases of different brain pathological conditions. The neuronavigation system was used without problems in 125 cases. These cases included 114 microsurgical operations, 4 endoscopic procedures, 4 frameless stereotactic biopsies, and 3 catheter placements.

METHODS: The BrainLab VectorVision neuronavigation system is an intraoperative, image-guided, frameless, localization system. The system consists of a computer workstation for registration of images and physical spaces, an intraoperative localization device, and a computer image display. The system provides real-time responses regarding the locations of surgical instruments. VectorVision is based on passive reflections of infrared flashes. Universal adapters with reflective markers for surgical instruments, endoscopes, and the operating microscope are used.

RESULTS: In six cases, the system could not be used because of system failure or mishandling. In 125 neurosurgical cases, the neuronavigation system was useful, with a target-localizing accuracy of 4 ± 1.4 mm (mean ± standard deviation). For small cerebral lesions, we never performed an exploration with negative results.

CONCLUSION: The BrainLab neuronavigation system has been shown to be very helpful and user-friendly for routine neurosurgical interventions. Its advantage lies in its mobility, based on wireless reflective adapters for surgical instruments, endoscopes, and the operating microscope. (Neurosurgery 44:97–105, 1999)

Key words: Cerebral lesion, Frameless stereotaxy, Neuroendoscopy, Neuronavigation

Exact targeting of small brain lesions, even in subcortical and deeply located brain areas, is still a challenge to neurosurgeons. Information from two-dimensional images must be transferred to the three-dimensional spaces of the brain. Neuronavigation began with the introduction of stereotactic techniques for calculation of defined targets within three-dimensional space. With the development of detailed imaging techniques, stereotactic neurosurgery is now widely used for the treatment of small and deeply located pathological lesions in the brain (13, 15, 16, 19). Frame-based techniques are very exact, even for deeply located lesions. On the other hand, the frame and the stereotactic arc are bulky and may interfere with the surgical exposure and approach. These systems do not provide intraoperative feedback regarding anatomic structures encountered in the surgical field. Several investigators have developed frameless stereotactic systems. Meanwhile, many sophisticated neuronavigation systems are available. The working principles are based on ultrasonic impulse detection (1, 20, 21), articulated mechanical arms (7, 17, 26), and optical detection of infrared flashes (4, 23–25).

One of the newest neuronavigation systems is the BrainLab VectorVision (BrainLab USA, Moorestone, NJ), an intraoperative, image-guided, frameless, armless localization system that is based on passive reflections of infrared flashes. In this article, we report the technical application of and our experiences with the BrainLab system for 131 patients harboring different brain pathological conditions.

COMPONENTS OF THE VECTORVISION

Workstation (*Fig. 1*)

The computer system is based on alpha technology, i.e., very fast Complex Instruction Set Computing and Reduced Instruction Set Computing technology. The special software requires Windows NT. In our department, we use a computer with a 433-MHz alpha processor, Windows NT 4.0, and a 4-MB Matrox Millennium graphics card.

Camera system

Two cameras, arranged in a predefined position, are attached to the trolley. The cameras are mounted on the camera holder, 100 cm from each other. The positional angles of the two cameras are variable. The distance to the operating field should be within 90 to 200 cm, depending on the adjusted angles of the cameras. The optimal working distance is pro-

FIGURE 1. BrainLab VectorVision workstation.

vided by the computer after calibration of the cameras. The calibration procedure is simply managed by moving a calibration rod in front of the cameras. Infrared light-emitting diodes (LEDs) are positioned around the cameras, detecting the positions of objects. The cameras are connected to the video controller box, which converts the analog signals from the cameras into digital data. The physical characteristics of the cameras are given in *Table 1*. The two-dimensional positions of the projections observed by each camera are extracted and transferred to the workstation through a serial interface.

Reflective marker system

The infrared flashes are reflected by passive marker spheres. The spheres are 8 mm in diameter. The markers are covered with a glass-bead coating. The spheres must be gas-sterilized, and they can be used more than 10 times before damage to the coating occurs. The reflective markers are simply screwed onto different adapters.

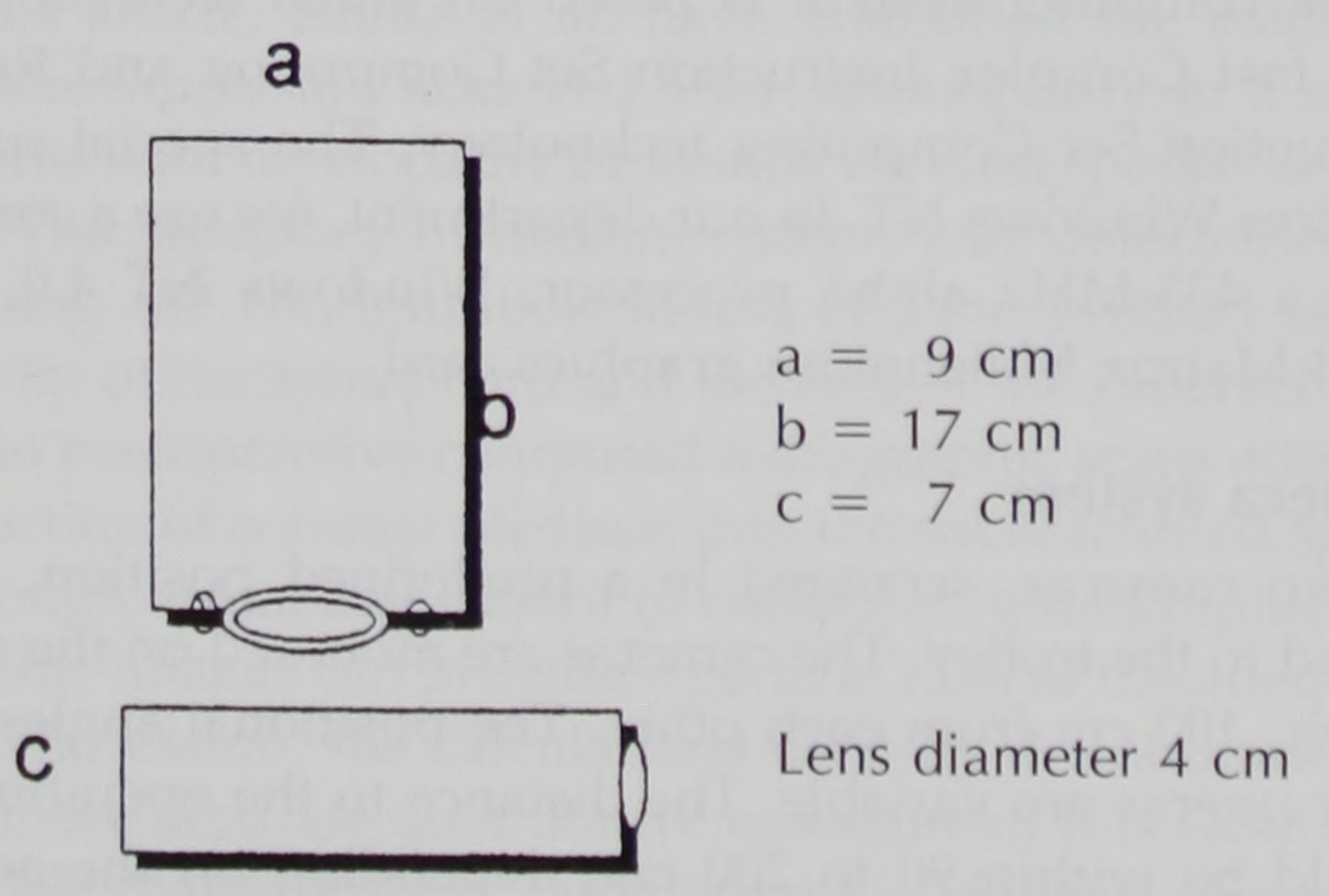

FIGURE 2. Physical characteristics of the cameras.

Adapters with reflective marker spheres

A special pointer tool, equipped with two highly reflective markers, is used for registration of the patient. To achieve real-time imaging of patient head movement during surgery, a star-shaped tool is fastened to the Mayfield headrest as a rigid reference point. To guarantee exact navigation, this so-called "Mayfield adapter" must remain in the same position, with respect to the head of the patient, throughout the operation. The Mayfield adapter consists of two pieces (*Fig. 3*). The upper part, i.e., the star-shaped piece with the reflective markers, can be detached from the lower part, which can be clamped to the Mayfield headrest in a very stable position. The upper part can be replaced in the same position as before because of a key-type mechanism with 0.1-mm precision. The instrument adapters are tools with different geometric configurations to distinguish the instruments that are used simultaneously during surgery. The adapters can be attached to the preferred surgical instruments and to the endoscope or to any tool required for surgery (*Fig. 4*). The Mayfield adapter wears a calibration cone at the junction of the three arms. This cone is used for calibration of the various instruments and the microscope (*Fig. 5*). By tipping of the instrument into the calibration cone, the software is supplied with the offset of the tip, relative to the attached reflective marker.

Skin fiducials

For preoperative computed tomographic (CT) scanning, skin fiducials are glued to the head of the patient using

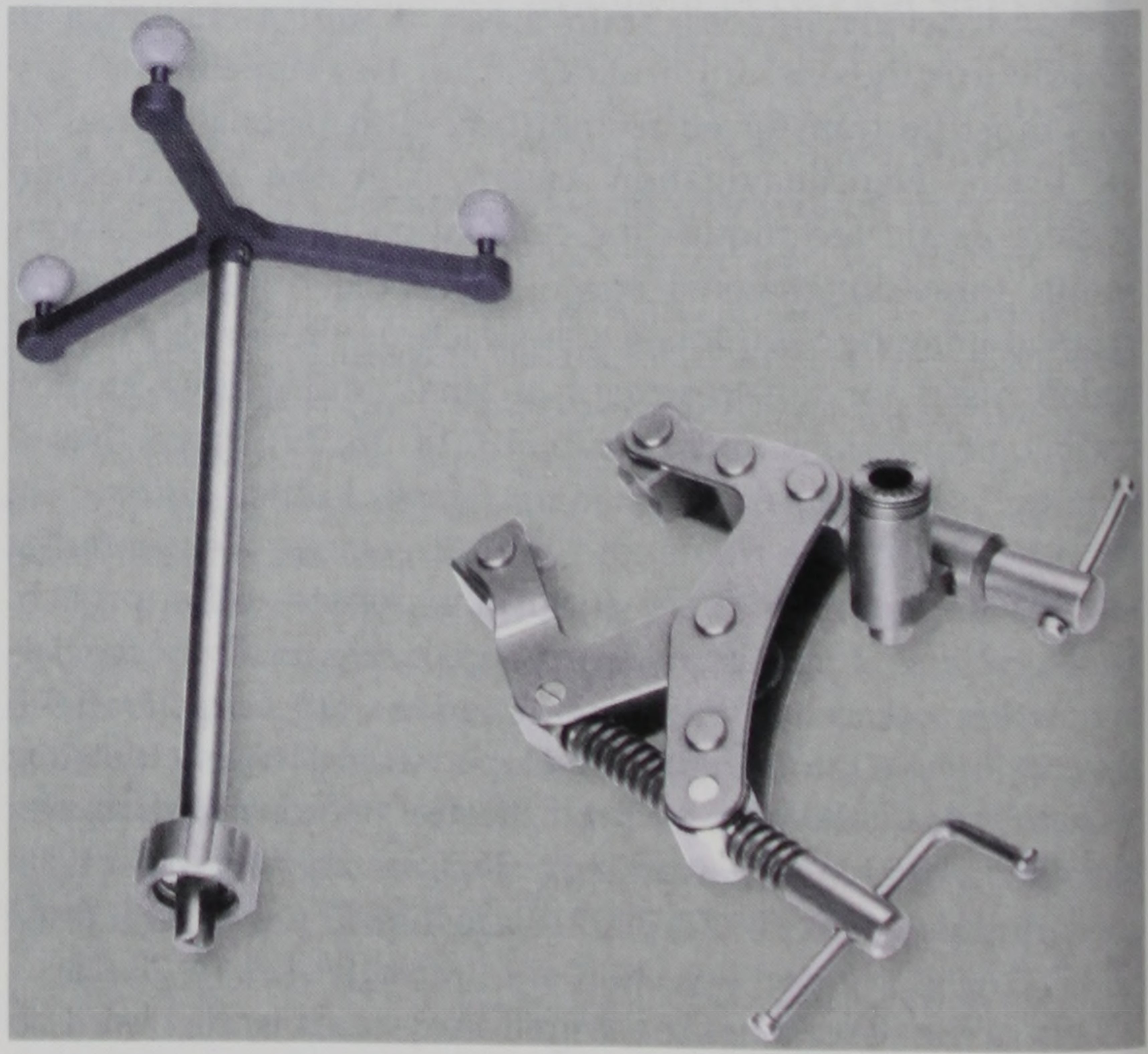

FIGURE 3. Mayfield adapter.

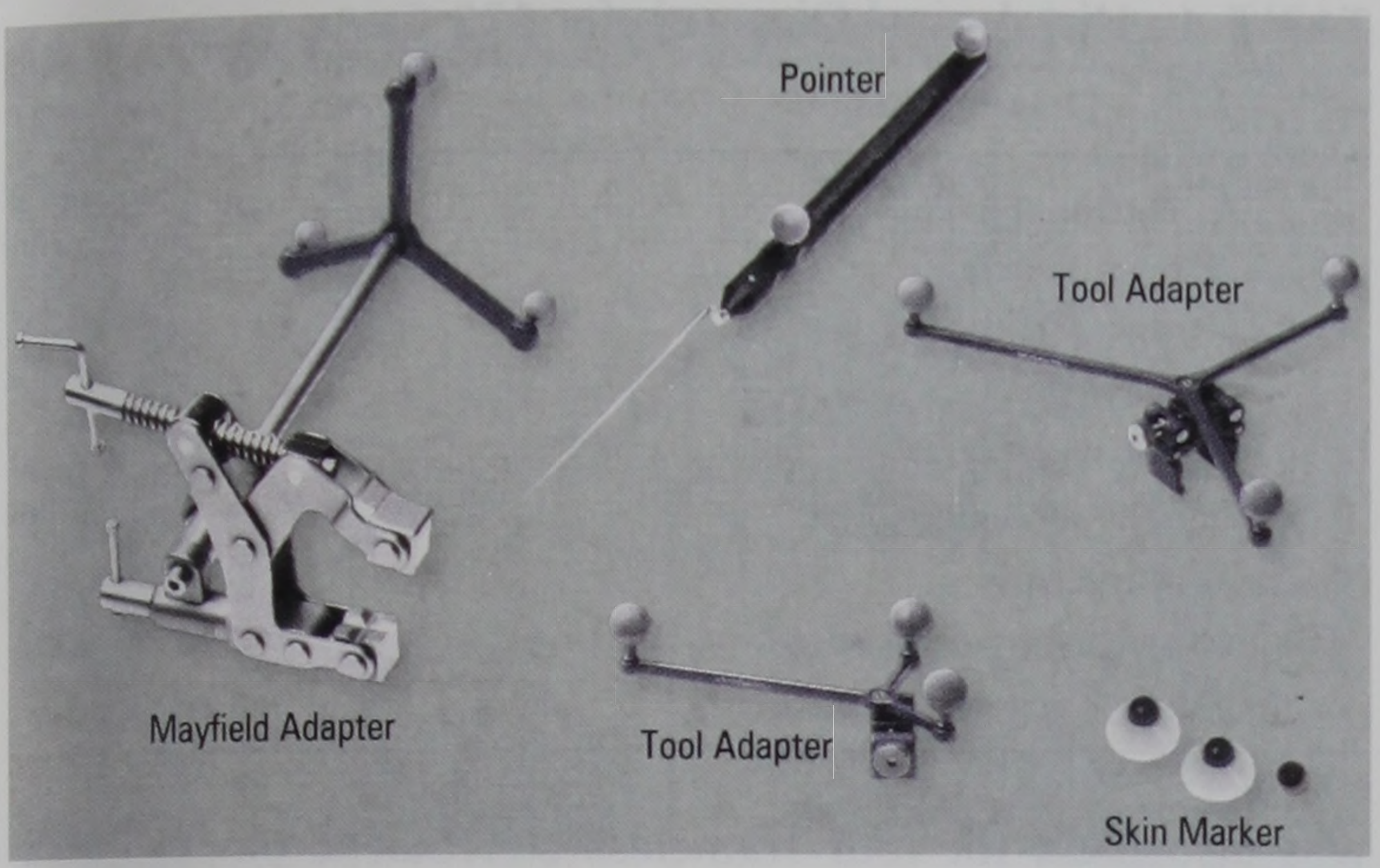

FIGURE 4. Neuronavigation tools.

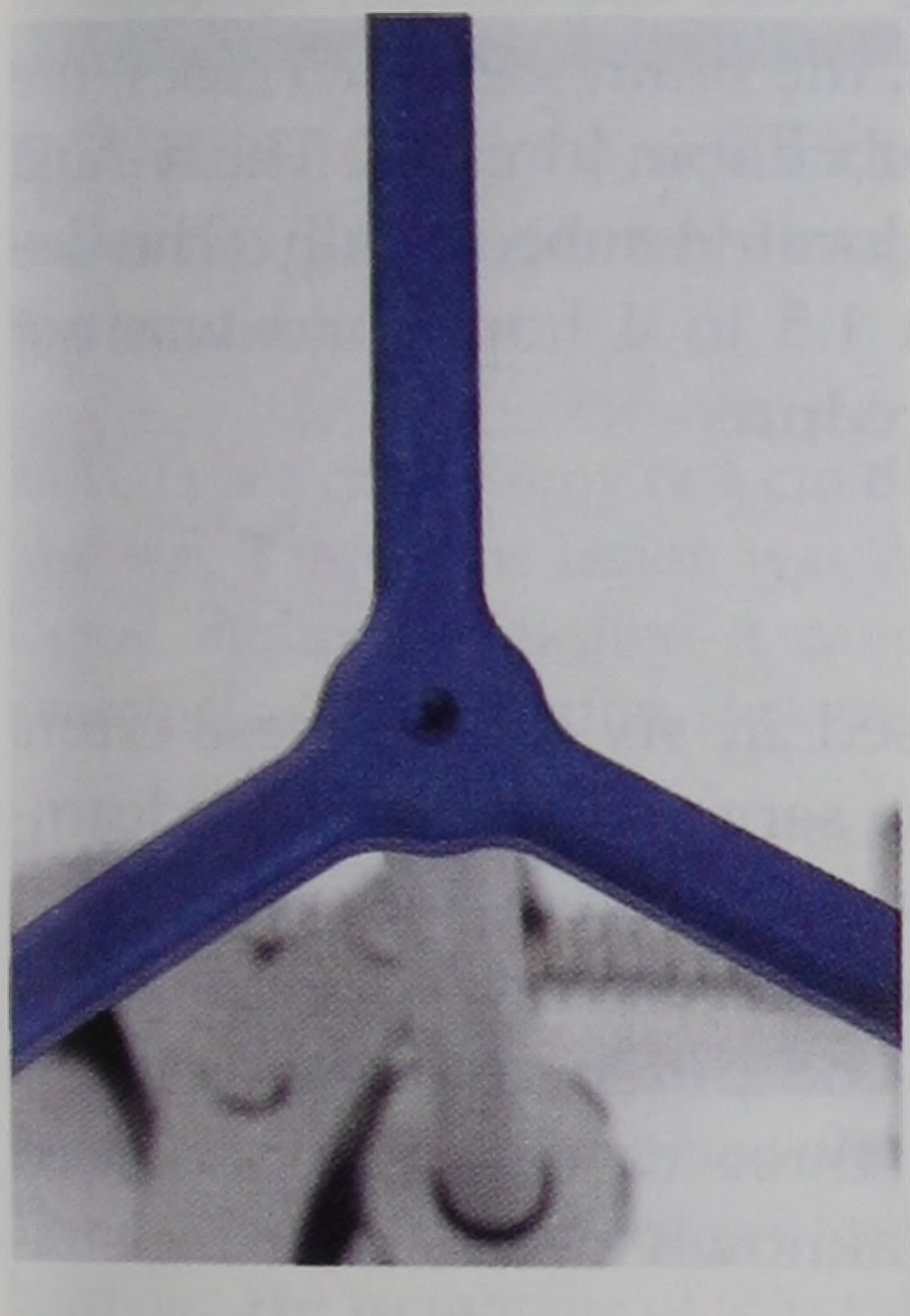

FIGURE 5. Calibration cone of the Mayfield adapter (see text under heading "Adapters with reflective marker spheres" for description).

double-adhesive tape. These fiducials consist of a plastic socket and two different aluminum markers. The spherical markers are for CT imaging, and the hemispherical markers are for intraoperative referencing. The markers can be screwed into the plastic bases.

Microscope interconnection

The Möller-Wedel Co. (J.D. Möller Optische Werke GmbH, Wedel, Germany) offers a serial computer interface for microscopes that enables connection to the BrainLab neuronavigation system. The microscope is fitted with a special adapter equipped with reflective marker spheres. The microscope is calibrated by focusing the calibration cone of the Mayfield adapter at maximum zoom. Similar to the instrument calibration described above, the focal length is determined. For this maneuver, a crosshair ocular piece is recommended. The microscope can then be used as a pointer. This function can be used with microscopes other than Möller instruments. However, the robotic functions, with tool- and target-tracking, provided by the software can only be used with the Möller VM 900 microscope.

PREOPERATIVE PREPARATION

Using all available imaging data (magnetic resonance imaging [MRI], CT scanning, and angiographic data), the surgical approach and the position of the patient during surgery must be considered. Three to five fiducials are glued to the head of the patient. More than five fiducials do not increase the accuracy, in our experience. CT scanning with 2- to 3-mm slices is performed. Contrast medium is used if necessary. The data are archived on a magnetic optical disc. To avoid movements of the glued skin markers, we prefer to perform the imaging procedures when the patient is awake, in the morning on the day of surgery. After the imaging procedures, the patient is transported to the operating room; during initiation of anesthesia, the data are transferred to the computer workstation. This procedure requires only minutes. The CT images are displayed on the computer screen and the lesion is delineated. Reconstruction in a triplanar format (transverse, coronal, and sagittal), as well as three-dimensional reconstruction, is performed, and a plan for the optimal surgical approach can then be developed. If necessary, MRI scans that have been acquired earlier can be combined with the CT images. The cameras are calibrated. The patient is positioned for surgery, with the head secured into the Mayfield headrest. The spherical markers are replaced by the conical markers. The marker registration can be performed under either sterile or nonsterile conditions.

Registration under sterile conditions

After preparation of the skin with sterile solution, the surgical site is covered with sterile foil. The fiducials are included in the draping. This foil secures the fiducials in their positions, and draping is continued. The Mayfield adapter is attached to the headrest, and the cameras are brought into position. An unobstructed view for the cameras must be provided throughout the procedure. The skin fiducials are digitized by touching the pointer to each of the conical markers. The registration requires less than 1 minute.

Registration under nonsterile conditions

The new Mayfield adapter is more compact than the prototypes and is made of two pieces, as described above. With this newly designed Mayfield adapter, we prefer registration under nonsterile conditions. After the patient is positioned for surgery, the left part of the Mayfield clamp is covered with a sterile drape. The sterile adapter is attached to this area. The patient undergoes registration using the nonsterile pointer. The skin incision is outlined on the scalp after determination of the approach. The sterile upper part of the adapter is detached, and the patient undergoes draping as usual. After complete draping, the upper part of the adapter is replaced.

Registration accuracy

The mean reference accuracy, given as a computer-calculated value, is 1.4 mm, with a minimum of 0.7 mm, a maximum of 3.2 mm, and a standard deviation of 0.51 mm, as measured in 125 cases.

Re-registration

After skin incision and craniotomy, the skin markers are displaced and not usable for re-registration. The software provides an option for intraoperative re-registration using the "Restore" button in the main VectorVision menu. This procedure restores the initial registration of the patient, which was kept in the computer memory. This option can be used if the power support is accidentally uncoupled. If relative movement between the head and the Mayfield adapter occur, small-twist drill trephinations drilled earlier can be used for re-registration.

Surgical procedure using the neuronavigation system

All instruments being used must be equipped with reflective marker tools. They are digitized by touching them to the calibration cone of the Mayfield adapter. The microscope is also referenced by focusing the calibration cone.

By defining the borders of the lesion, the most minimal craniotomy can be performed. The tips of the instruments can be virtually prolonged, and thus the depth of the lesion, as well as the direction of the approach, can be displayed on the computer screen.

Intraoperative accuracy check and application accuracy

The intraoperative accuracy is confirmed using skin fiducials, the bone surface, small burrholes drilled into the cranium, and the tumor margin before removal. The skin fiducial used for accuracy checks is positioned on the scalp, where it does not move after skin incision and wound stretching. A few (two or three) 1-mm burrholes are drilled into the bone. When the pointer is moved into a burrhole, the corresponding position on the CT scan is displayed on the computer screen and sketched in color, to record this position for error measurement. During surgery, the pointer is moved into the burrholes and the distance to the formerly marked target is measured. The discrepancy between the tumor margin in the operating field and the margin demonstrated on the computer screen is measured for accuracy (before tumor removal). The average target-localizing error, measured in 125 cases, was 4 mm, with a maximum of 6 mm, a minimum of 1.5 mm, and a standard deviation of 1.4 mm.

PATIENTS

From May 1996 through October 1997, 131 patients with different brain pathological conditions underwent surgical treatment in our department using the VectorVision neuronavigation system. In the beginning, we experienced function errors in six cases because of mistakes during CT imaging, system failures, or failures in handling the system. In 125 cases, the system worked adequately. VectorVision was used in four cases of endoscopic surgery and in one case for catheter placement into slit ventricles. In two cases, catheters were properly placed into cerebral cysts. In 114 cases, the neuronavigation system was used for microsurgical treatment of different brain pathological conditions (*Table 1*). The system was also used for four frameless stereotactic biopsies. The lesions ranged from 0.57 to 96 cm^3 in volume, with a mean size of 25.4 cm^3. The locations were the cranial base in 22 cases, the cerebellum in 4 cases, the brain stem in 3 cases, the ventricle in 4 cases, and the cerebrum in 91 cases. Thirty-nine of the 91 cerebral lesions were located subcortically. The duration of surgery ranged from 1.5 to 4 hours and was not affected by the navigation procedure.

TABLE 1. Histological Diagnosis for 125 Cases

Diagnosis	No. of Cases
Gliomas	48
Meningiomas	29
Metastatic tumors	21
Angiomas	6
Radionecrosis	3
Cystic lesions	3
Melanomas	2
Craniopharyngiomas	2
Miscellaneous	11

RESULTS

The system could not be used in six cases. These errors occurred in the beginning of the series, when we were learning how to work with this navigation system; the system itself was a prototype. In one case, the mode of CT scanning was changed during scanning. The computer could not read the data from the optical disc. In three cases, we experienced computer malfunctions from unknown causes after registration. The first Mayfield adapter was very small. There was one piece for the left side and another for the right side of the Mayfield clamp. One piece was inadequately fixed and fell during surgery in one case. In another case, the computer was accidentally disconnected from the power supply, and a re-registration mode was not available at that time.

After we became more familiar with the system and the software and hardware were improved, the navigation system worked well in 125 neurosurgical cases. The overall intraoperative accuracy, including the mechanical precision of the system, was a mean of 4 ± 1.4 mm. In most cases, the size of the craniotomy could be kept quite small (3–5 cm in diameter). We never performed an exploration with negative results. In 108 cases, the lesion was removed completely, as confirmed by postoperative MRI performed within 48 hours. In seven cases, only partial removal was achieved because the tumors were very large and had infiltrated eloquent regions or the brain stem.

ILLUSTRATIVE CASE REPORTS

Patient 1

Figure 6 presents the neuronavigation workstation image for a 70-year-old female patient. She was admitted to our department experiencing seizures and dizziness. Her clinical condition was good (Karnofsky index, >70%), and she was considered for surgery. Using the neuronavigation system, the lesion (2.4-cm^3 volume) was re-

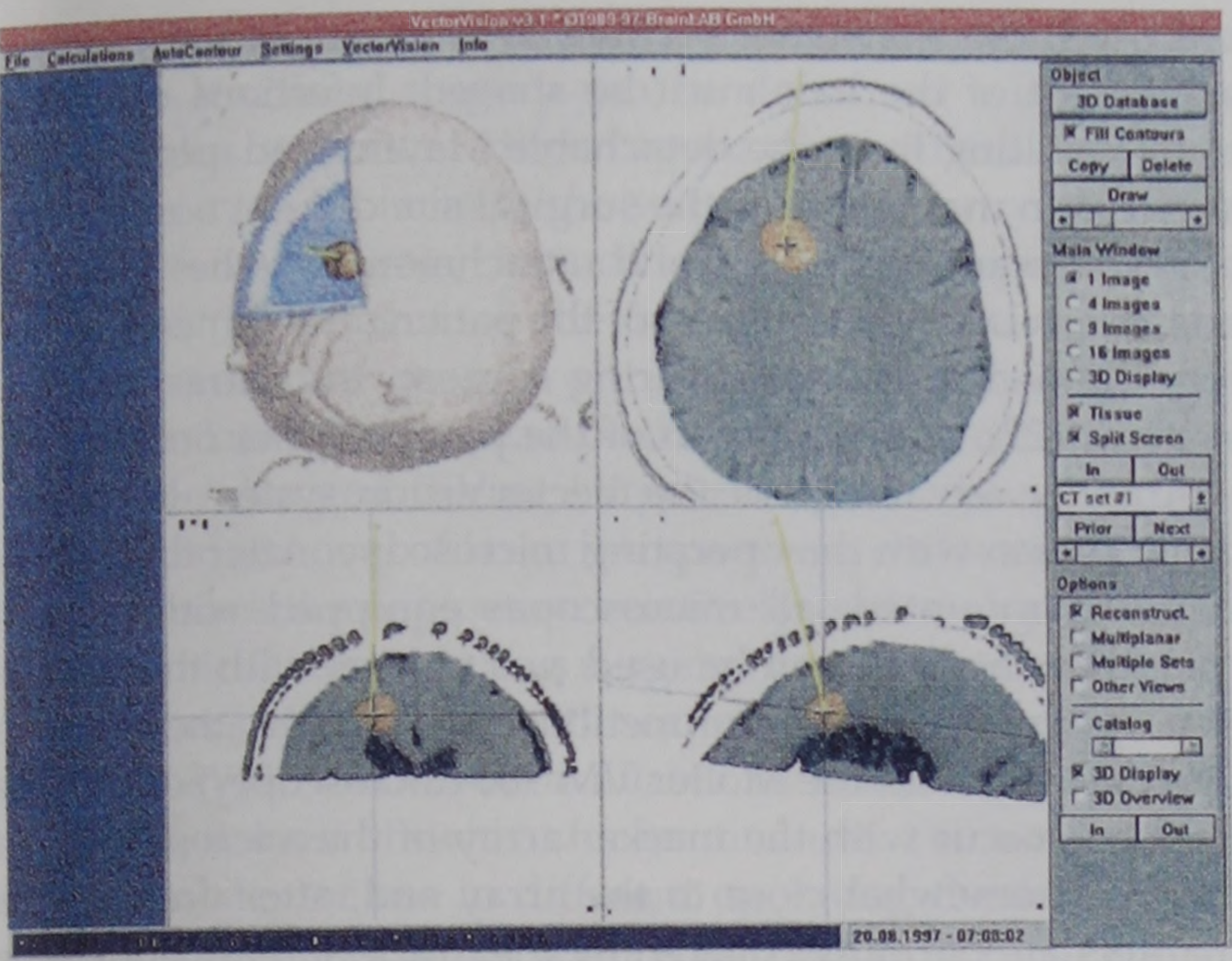

FIGURE 6. Case of a small cavernoma (2.4-cm^3) removed under navigation control (image from the navigation workstation).

moved via a craniotomy of 4-cm diameter. The maximum error in this case was 3 mm. The lesion was completely removed, and the histological findings indicated a cavernoma. The patient exhibited no neurological deficits after surgery.

Patient 2

A cystic lesion was diagnosed in a 22-year-old male patient experiencing headaches and dizziness. The lesion was surgically treated using the endoscope combined with the neuronavigation system (*Fig. 7*). The endoscope was guided precisely into the lesion via a 1-cm occipital burrhole. The membrane of the cystic process was completely removed. An arachnoid cyst was histologically diagnosed. Headache and dizziness improved after surgery.

Patient 3

The third patient was a 39-year-old female patient who was admitted with headache, double vision, and slight facial paralysis. The neuroradiological images demonstrated a contrast medium-enhancing lesion in the petroclival region. The patient underwent surgery. By using the navigation system for planning and performing the far-lateral approach, the lesion (World Health Organization Grade I meningioma) was removed completely (*Fig. 8*). The accuracy was 2 mm.

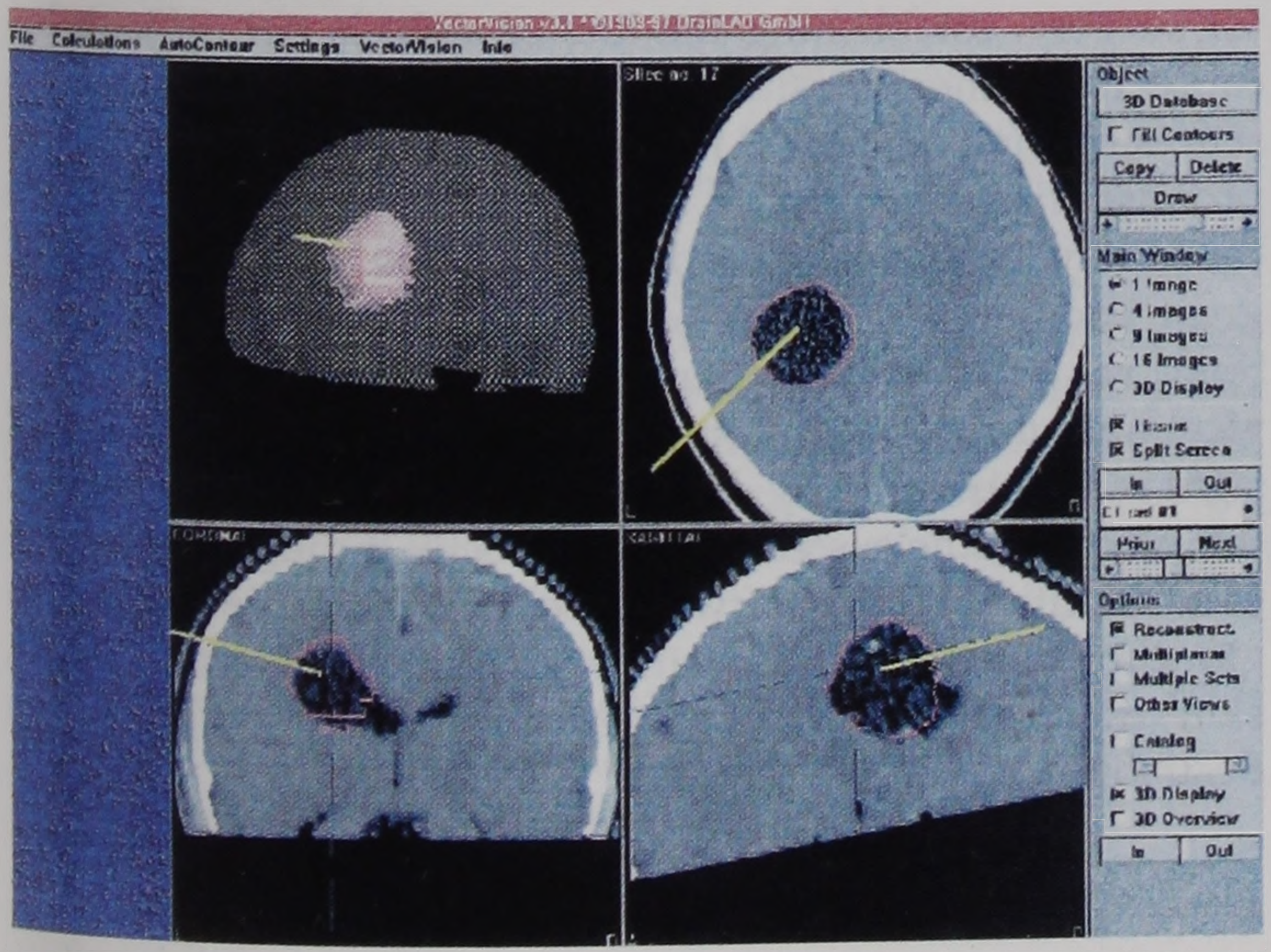

FIGURE 7. Case of an arachnoid cyst that was removed endoscopically with the guidance of the neuronavigation system (image from the navigation workstation).

DISCUSSION

Stereotactic surgery has been used for decades. Horsley and Clark (8) first reported stereotactic operations in animals in 1908. Almost 40 years later, Spiegel et al. (26) introduced the stereotactic method into clinical use. The use of stereotactic techniques increased with the advent of CT scanning and MRI. Kelly and colleagues (10–14) developed special computer software for volumetric removal of tumors. Based on that work, stereotactically guided neurosurgery became a helpful tool for the surgical treatment of lesions in eloquent regions. Those authors combined a microscope, a laser, and the Todd-Wells stereotactic system for the surgical procedures. Several authors have described their stereotactic techniques, often combined with other useful methods such as ultrasonography and intraoperative neurophysiological mapping techniques (5, 15, 16). In 1986, Roberts et al. (21) reported the development of a frameless, computer-based system for the integration and display of CT image data with the operating microscope. Ultrasonic pulses emitted by spark gaps on the microscope were received by microphones. The time delay from emission to detection of the ultrasonic signals was used to determine the position of the spark gaps. Barnett et al. (1) gave an account of a navigation system using ultrasonography and a sonic wand, and they described their results with 48 procedures. The problem with ultrasonography is that ultrasonic noise and drafts in the operating room may interfere with this technique (23). Watanabe et al. (27) described a navigation technique based on an operating arm. Several other authors reported their developments and experiences with arm-based navigation systems (3, 6, 7, 17). The disadvantage of articulated arms may be the awkwardness of continuous interactive tracking of surgical instruments. A frameless, armless, navigational system was described by Kato et al.

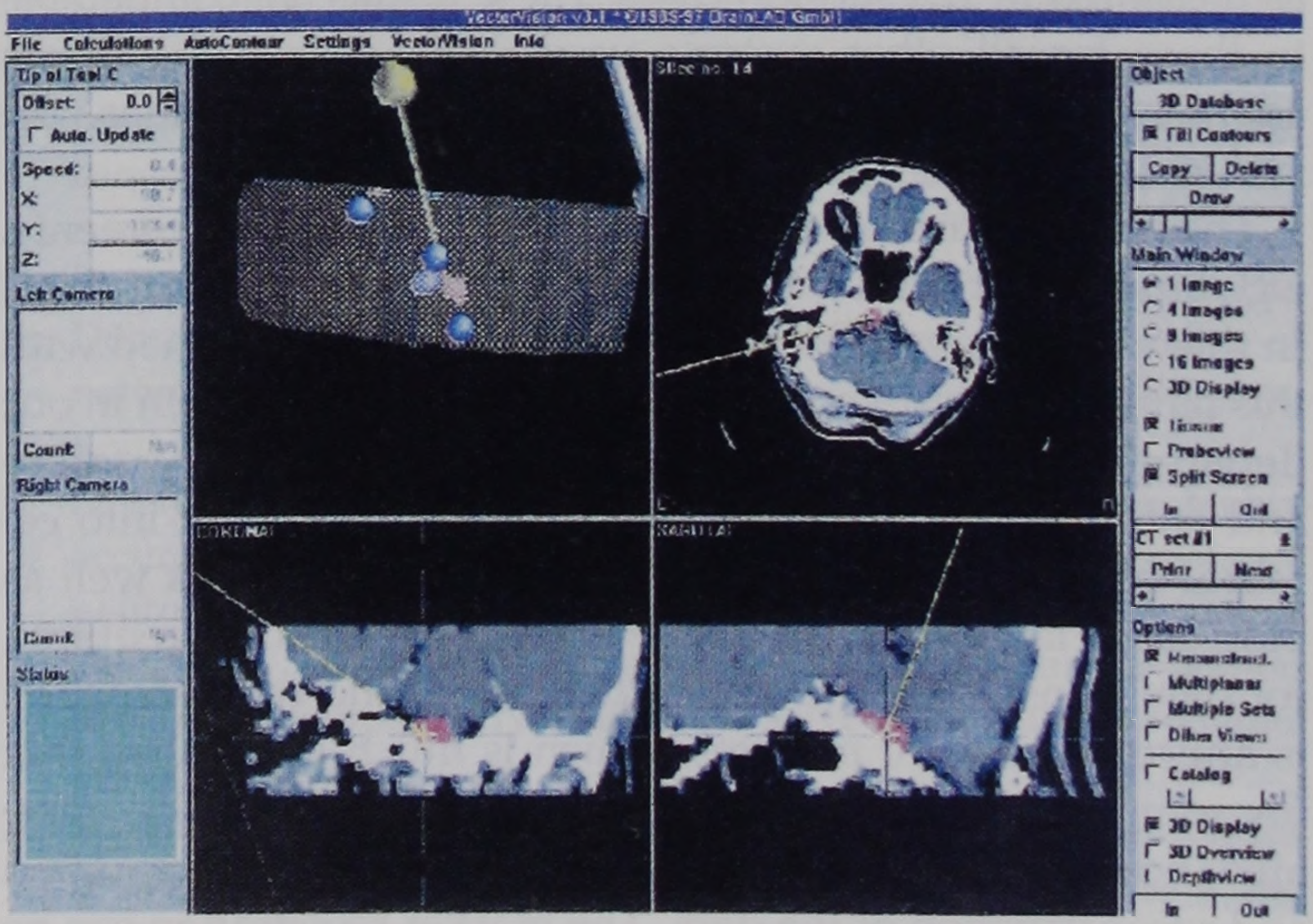

FIGURE 8. Case of a petroclival meningioma (image from the navigation workstation).

(9). The system was based on a three-dimensional digitizer that used a magnetic field to determine the spatial position of the instruments. Four skin fiducials were used to translate the spatial data of the probe onto preoperative CT or MRI scans of the patient. Methods of optical tracking have become available for use in frameless stereotaxy (2, 4, 11, 22). LEDs are detected by cameras.

A frameless stereotactic system with real-time tracking of patient head movement was described by Ryan et al. (23). An imaging procedure (CT scanning or MRI) with fiducials was not necessary. The registration was performed retrospectively by surface matching, using an algorithm to register the MRI scans with the anatomic features of the patient. A dynamic reference frame with LEDs was attached to the head of the patient, and table fixation was not necessary. Other systems operate on the base of LED-prepared instruments detected by two or more cameras (3, 22). In contrast to those "active" LED systems, the BrainLab VectorVision is based on passive reflection of infrared flashes. The most important factor for neuronavigation systems is accuracy. Precision is derived from the accuracy of the digitizer (tested on a phantom), the registration accuracy (which includes the errors of CT scanning and fiducial marker registration), and the target-localizing accuracy after brain shifting resulting from positioning, mannitol application, and cerebral spinal fluid drainage. High accuracy values can be achieved with implantable markers or frames. Galloway and Maciunas (3) reported an intrasurgical precision of 1.665 ± 0.43 mm using an arm-based system in conjunction with a stereotactic frame. With frameless systems and external skin markers, the precision decreased. Kato et al. (9) achieved an average registration accuracy of 1.7 mm and a mean intraoperative precision of 4 mm using a magnetic field and skin markers. Barnett et al. (1) described a target-localizing accuracy of 4.8 ± 2.1 mm using the sonic wand. Similar results were achieved by other authors (4, 6, 22, 23, 27). The digitizer accuracy of the BrainLab system, tested on a phantom, was less than 0.5 mm and was similar to that of other systems (1, 23, 28). The registration accuracy was 1.4 mm (with a standard deviation of 0.5 mm) and the target-localizing precision was 4 ± 1.4 mm, as measured in 125 surgical cases. These results are comparable to those for all other systems used. With universal wireless adapters of different sizes and geometric configurations, the system has various applications.

The adapters are simply screwed onto surgical instruments, e.g., bipolar forceps, suction tubes, endoscopes, and catheters. In this way, many surgical procedures can be performed with this navigation system. We use the VectorVision system in our department for operations other than brain tumor surgery and endoscopic procedures, e.g., catheter placement into cerebral cysts and puncture of very small ventricles, as well as biopsies of larger (>2-cm diameter) lesions. The time required for data transfer, delineation of the lesion, and reconstruction is approximately 10 minutes, which is much faster than that for some other systems (18). The system can be easily operated; no specially trained technician is needed for preparation and reconstruction of the data. The marker registration can be performed in a sterile or nonsterile fashion; the two methods have advantages and disadvantages. If straight skin incisions are used, the nonsterile method is superior, because only a small part of the hair must be shaved. Infectious complications resulting from the detachable Mayfield adapter or nonsterile skin markers near the surgical site did not occur in our series. Because of the solid attachment of the Mayfield adapter, relative to the head of the patient, the cameras can be repositioned at any time during surgery. In contrast to other systems (22), re-registration of the patient is not necessary.

Another advantage of the VectorVision system lies in the combination with the operating microscope. After the marker frame is mounted, all microscopes equipped with a serial computer interface can be used as a pointer with the navigation system. The robotic functions provided by the software operate only with the Möller VM 900 microscope. Some problems can occur with the marker array of the microscope. The frame is somewhat close to the array and, after draping, the markers are partially covered by the drape and are not visible for the cameras. Another criticism involves the calibration mode, because the visual focus of the surgeon is used for this maneuver. This subjective procedure can decrease the accuracy of the calibration and should be eliminated by developing a method of calibration that is independent of individual focus. The accuracy measurements in this series were obtained only by using the pointer tools. Nevertheless, the use of the microscope navigation function is helpful, based on our experiences.

The navigation system is very useful for planning the surgical approach. The skin incisions and craniotomies are smaller than without the system. Using virtual planning of the trajectory, we never performed an exploration with negative results. The system is also very useful for surgical treatment of cranial base lesions. In this area, the shift is not important and does not decrease the accuracy. Even for large cranial base lesions (for example, olfactory groove meningiomas), the navigation system proved to be helpful for determination of the position within the tumor and for calculation of the distances to important structures. In our experience, with proper arrangement of the cameras and the other equipment needed for surgery, establishing the line of sight is not difficult because the camera position can be changed if anything obscures the line of sight. Although blood and other fluid compromise the reflectivity of the marker spheres, this does not cause any problems. The distance to the operating field is great enough that the spheres are not dewed with blood. Spurious reflections from environmental factors, such as surgical instruments or draping, were not noticed. If the line of sight is not obscured by draping, instruments, or the hands of the surgeons, the system works perfectly throughout the procedure. Although the software provides an image fusion program for CT, MRI, and positron emission tomographic data, skin fiducials for MRI, which are not yet available, are desirable.

CONCLUSIONS

The BrainLab VectorVision neuronavigation system has proven to be a helpful tool for surgical treatment of different brain pathological conditions. The additional time required for preparation is approximately 20 minutes; on the other hand, the length of surgery can be decreased with smaller craniotomies and more direct approaches. The advantages over other systems include the wireless adapter connections to various instruments, including the microscope and the endoscope. Movement of the head of the patient can be tracked in real time because of rigid fixation of the reference markers, relative to the head of the patient; the camera position can be changed during surgery without re-registration. After partial removal of large intraparenchymal tumors, brain shifting makes the navigation relatively useless. Updating of the anatomic features during surgery, using ultrasonography or intraoperative CT or MRI scanning, can overcome this difficulty. With soon-to-be-available ultrasound integration, the system is most attractive for routine use. The workstation is fully mobile, for use in different operating theaters. However, for biopsies of small lesions and surgical treatment of small, deeply located, thalamic lesions, where a precision of 1 to 2 mm is required, we prefer the frame-based stereotactic approach. Disadvantages include the aforementioned microscope adapter and calibration mode, as well as the lack of MRI-compatible skin fiducials. The VectorVision neuronavigation system also provides a software package for spinal navigation, which was not the subject of this article.

ACKNOWLEDGMENTS

The authors have no financial interest in the instrumentation described in this article.

MRI-compatible fiducials have become available.

Received, September 10, 1997.
Accepted, August 21, 1998.
Reprint requests: Christianto B. Lumenta, M.D., Department of Neurosurgery, Academic Hospital, München-Bogenhausen, Englschalkingerstraße 77, 81925 München, Germany.

REFERENCES

1. Barnett GH, Kormos DW, Steiner PC, Weisenberger J: Use of a frameless, armless stereotactic wand for brain tumor localization with two dimensional and three-dimensional neuroimaging. **Neurosurgery** 33:674–678, 1993.
2. Bucholz RD: Three-dimensional intraoperative ultrasonography using an optical digitizer. Proceedings of the American Association of Neurological Surgeons Meeting, Boston, MA, 1993, p 148.
3. Galloway RL, Maciunas RJ: An articulated localizing arm for neurosurgical use, in Maciunas RJ (ed): *Interactive Image-Guided Neurosurgery*. Park Ridge, American Association of Neurological Surgeons, 1993, pp 159–168.
4. Germano IM: The Neurostation system for image-guided, frameless stereotaxy. **Neurosurgery** 37:348–351, 1995.
5. Giorgi C, Ongania E, Casolino SD, Riva D, Cella G, Franzini A, Broggi G: Deep seated cerebral lesion removal, guided by volumetric rendering of morphological data: Stereotactically acquired clinical results and technical considerations. **Acta Neurochir Suppl (Wien)** 52:19–21, 1991.
6. Golfinos JG, Fitzpatrick BC, Smith LR, Spetzler RF: Clinical use of a frameless stereotactic arm: Results of 325 cases. **J Neurosurg** 83:197–205, 1995.
7. Guthrie BL, Adler JR Jr: Frameless stereotaxy: Computer interactive neurosurgery. **Perspect Neurol Surg** 2:1–22, 1991.
8. Horsley V, Clarke RH: The structure and the function of the cerebellum examined by a new method. **Brain** 31:45–124, 1908.
9. Kato A, Yoshimine T, Hayakawa T, Tomita Y, Ikeda T, Mitomo M, Harada K, Mogami H: A frameless, armless navigational system for computer-assisted neurosurgery. **J Neurosurg** 74:845–849, 1991.
10. Kelly PJ: Computer assisted stereotaxis: A new approach for the management of intracranial intra-axial tumors. **Neurology** 36: 535–541, 1986.
11. Kelly PJ: Volumetric stereotactic surgical resection in intra-axial brain mass lesions. **Mayo Clin Proc** 63:1186–1198, 1988.
12. Kelly PJ: Volumetric stereotaxis and computer assisted stereotactic resection of subcortical lesions, in Lunsford LD (ed): *Modern Stereotactic Neurosurgery*. Boston, Marinus Nijhoff, 1988, pp 169–184.
13. Kelly PJ: Stereotactic imaging, surgical planning and computer assisted volumetric resection of intracranial lesions: Methods and results. **Adv Tech Stand Neurosurg** 17:77–118, 1990.
14. Kelly PJ, Alker GJ Jr, Goerss S: Computer-assisted stereotactic microsurgery for the treatment of intracranial neoplasms. **Neurosurgery** 10:324–331, 1982.
15. Lerch KD, Schaefer D, Palleske H: Stereotactic microresection of small cerebral vascular malformations (SCVM). **Acta Neurochir (Wien)** 130:28–34, 1994.
16. Lumenta CB, Gumprecht HK, Leonardi MA, Gerstner W, Brehm-Häuser B: Three-dimensional computer-assisted stereotactic-guided microneurosurgery combined with cortical mapping of the motor area by direct electrostimulation. **Minim Invasive Neurosurg** 40:50–54, 1997.
17. Mösges R, Schlöndorff G: A new imaging method for intraoperative therapy control in skull base surgery. **Neurosurg Rev** 11:245–247, 1988.
18. Nabavi A, Manthei G, Blömer U, Kumpf L, Klinge H, Mehdorn HM: Neuronavigation. **Radiologe** 35:573–577, 1995.
19. Patil AA: Free-standing, stereotactic, microsurgical retraction technique in key hole intracranial procedures. **Acta Neurochir (Wien)** 108:148–153, 1991.
20. Reinhardt HF, Zweifel HJ: Interactive sonar-operated device for stereotactic and open surgery, in Gildenberg PL (ed): *Stereotactic and Functional Neurosurgery*. Basel, S. Karger, 1990, pp 393–397.
21. Roberts DW, Strohbein JW, Hatch JF, Murray W, Kettenberger H: A frameless stereotactic integration of computerized tomographic imaging and the operating microscope. **J Neurosurg** 65:545–549, 1986.
22. Roessler K, Ungersboeck K, Dietrich W, Aichholzer M, Hittmeir K, Matula C, Czech T, Koos WT: Frameless stereotactic guided neurosurgery: Clinical experiences with an infrared based pointer device navigation system. **Acta Neurochir (Wien)** 139:551–559, 1997.
23. Ryan MJ, Erickson RK, Levin DN, Pelizzari CA, Macdonald RL, Dohrmann GJ: Frameless stereotaxy with real-time tracking of patient head movement and retrospective patient-image registration. **J Neurosurg** 85:287–292, 1996.
24. Smith KR, Frank KJ, Bucholz RD: The Neurostation: A highly accurate, minimally invasive solution to frameless stereotactic neurosurgery. **Comput Med Imaging Graph** 18:247–256, 1994.
25. Spetzger U, Laborde G, Gilsbach JM: Frameless Neuronavigation in modern neurosurgery. **Minim Invasive Neurosurg** 38:163–166, 1995.
26. Spiegel EA, Wycis HT, Marks M, Lee AJ: Stereotaxic apparatus for operations on the human brain. **Science** 106:349–350, 1947.
27. Watanabe E, Mayanagi Y, Kosugi Y, Manaka S, Takakura K: Open surgery assisted by the Navigator, a stereotactic articulated, sensitive arm. **Neurosurgery** 28:792–800, 1991.

28. Zinnreich SJ, Tebo SA, Long DM, Brem H, Mattox DE, Loury ME, Kolk AV, Koch WM, Kennedy DW, Bryan N: Frameless stereotaxic integration of CT imaging data: Accuracy and initial applications. **Radiology** 188:735–742, 1993.

COMMENTS

Gumprecht et al. summarize their experience using the BrainLab VectorVision neuronavigation system in 131 cases. Among the many unique features of the BrainLab system is the fact that it uses passive reflection of infrared flashes from reflectors placed on surgical instruments, which are triangulated by linear charge-coupled device camera arrays. Currently, this is one of few systems that use passive optical tracking. The Northern Digital Polaris system currently being used with the Sofamor Danek StealthStation also uses a passive reflective infrared system. The VISLAN system and the Utah MachineVision method use two-dimensional video and pattern recognition, to cite two examples.

The authors state an application accuracy of 4.0 ± 1.4 mm for this system. This illustrates the current lesser accuracy of passive reflective infrared systems, a limitation that is counterbalanced by their flexibility, simplicity, and utility. The suggestion that, during surgery, blood and other fluids might compromise the reflectivity of the spheres used and might therefore decrease the accuracy, as well as the utility, of these systems remains to be more thoroughly evaluated. The experience of the authors attests to the facile integration of interactive image-guided technology into neurosurgical practice once that technology becomes transparent, robust, and cost-effective.

Robert J. Maciunas
Rochester, New York

In this report, Gumprecht et al. describe their experience using a passive, infrared, surgical navigation system (BrainLab VectorVision). The principle advantage of this approach is that it allows the use of wireless instrumentation as the pointing devices for surgical navigation. The system performed well in the vast majority of more than 100 cases, with a variety of surgical procedures. Although reflective spheres are, in theory, less robust than active, light-emitting diode (LED) systems, the overall accuracy of approximately 4 mm was apparently sufficient for the applications undertaken by the authors. Environmental interferences, such as reflections, were apparently minimal problems and can plague even LED-based systems.

The input device (three-dimensional digitizer) sections of surgical navigation systems have continued to evolve. It is doubtful that the LED-based systems that are currently so prevalent will be the preferred approach a decade hence. The passive infrared approach using reflective spheres is one step toward "true machine vision." The promise of machine vision is that it would allow the surgeon to select an unmodified instrument, which would be recognized by the machine from its database of instrument geometries, and to proceed to use it with little or no thought to the process of active or passive infrared transmission.

Perhaps the most important point of this article is the candid disclosure by the authors of several cases, early in their experience, in which difficulties were encountered. To some extent these problems were the result of the early device being a prototype system but there were also hardware and software problems, which can arise with any of these surgical navigation systems and reflect the so-called "learning curve." For these reasons, I think that it is very important that, when surgeons first obtain such a system, they use it solely as an adjunct to conventional techniques and they learn to operate the system before undertaking cases in which they must rely on the system to accomplish a surgical goal.

Gene H. Barnett
Cleveland, Ohio

Systems for frameless stereotactic neuronavigation include multijointed encoder arms, ultrasonic three-dimensional digitizer systems, magnetic field digitizers, robotic systems, and infrared flash/camera systems. All have minor problems. With active or passive infrared systems, there is the line-of-sight requirement, which can create problems. However, these are useful systems that are reasonably accurate when combined with a dynamic reference system.

This article describes a passive infrared/camera digitizer system, which has shown its usefulness in more than 100 cases in the experience of the authors. I am pleased that the authors quote their application accuracy and not the benchtest accuracy of the system. An application accuracy of 4 mm is less than one would expect with a stereotactic frame but is within the range of the accuracies of other frameless stereotactic systems. Accuracy in this range is adequate for most tumor treatments and is certainly better than most neurosurgeons can achieve with freehand techniques. The authors make the very valid point that stereotactic localization allows neurosurgery to be less invasive.

Patrick J. Kelly
New York, New York

This article describes the BrainLab VectorVision frameless stereotactic system and presents early but considerable clinical experience. This system includes a camera-based digitizer that uses reflective spheres rather than LEDs, resulting in elimination of the electrical wires needed for the latter. This makes it easier to set up and less intrusive (despite the reflective spheres being larger than LEDs), i.e., steps in the desirable direction of transparency to the surgeon. Overall, this is a digitizing technology roughly comparable to other systems.

It is not immediately clear how the accuracy data presented should be interpreted. The registration accuracy described by the authors might be a root mean square or similar value, reflecting the geometric consistency between the fiducial array in the imaging study and that detected by the digitizer in the operating room. If so, it is only an indirect measure of potential accuracy (it is possible for fiducial positions nearly identical to one another in scale and orientation but translated with respect to one another to produce very low values but be associated with inaccurate registration). It was also not explicitly stated whether the skin fiducial used as a test marker is an independent marker, i.e., not itself used for the registration that it is being used to assess. The use of new points (repre-