Computer Aided Surgery

ISSN: 1092-9088 (Print) 1097-0150 (Online) Journal homepage: https://www.tandfonline.com/loi/icsu20

Development of an Endoscopic Navigation System Based on Digital Image Processing

M. Scholz, W. Konen, S. Tombrock, B. Fricke, L. Adams, M. von Düring, A. Hentsch, L. Heuser & A. G. Harders

To cite this article: M. Scholz, W. Konen, S. Tombrock, B. Fricke, L. Adams, M. von Düring, A. Hentsch, L. Heuser & A. G. Harders (1998) Development of an Endoscopic Navigation System Based on Digital Image Processing, Computer Aided Surgery, 3:3, 134-143, DOI: 10.3109/10929089809149841

To link to this article: https://doi.org/10.3109/10929089809149841

Biomedical Paper

Development of an Endoscopic Navigation System Based on Digital Image Processing

M. Scholz, M.D., W. Konen, Ph.D., S. Tombrock, B. Fricke, M.D., L. Adams, Ph.D., M. von Düring, M.D., A. Hentsch, M.D., L. Heuser, M.D., and A.G. Harders, M.D.
Department of Neurosurgery (M.S., A.G.H.), Center for Neuroinformatics (W.K., S.T.), Institute of Neuroanatomy (B.F., M.D.), and Institute of Radiology and Nuclear Medicine (A.H., L.H.), Ruhr University Bochum, Bochum, Germany, and Philips Medical Systems, Eindhoven, The Netherlands (L.A.)

ABSTRACT **We developed a new system to couple the endoscope to an optical position measurement system (OPMS) so that the image frames from the endoscope camera can be labeled with the accurate endoscopic position. This OPMS is part of the EasyGuide Neuro navigation system, which is used for microsurgery and neuroendoscopy. Using standard camera calibration techniques and a newly developed system calibration, any 3-dimensional (3-D) world point can be mapped onto the view from the endoscope. In particular, we can display the coordinates of any anatomical landmark of the patient as it is viewed from the current position of the camera. This and other image-processing techniques are applied to the labeled frame sequence in order to offer the neurosurgeon a variety of control modules that increase the safety and flexibility of neuroendoscopic operations. Several modules, including a new motion alarm system and the "tracking" and "virtual map" modules, were tested in a human cadaveric model using the frontal and occipital approaches. A failure rate of 8.6% was experienced during testing of the first version of the software, but the second version was 100% successful. Thus, an endoscopic navigation system based on digital image processing has been developed that could be a revolutionary advance in image-guided surgery.** Comp Aid Surg 3:134–143 (1998). ©1998 Wiley-Liss, Inc.

Key words: **neuronavigation, neuroendoscopy, image-guided surgery, virtual endoscopy**

INTRODUCTION

Many publications describing the use of image data in computer-assisted surgery (CAS) deal primarily with the registration of preoperative 3-dimensional (3-D) data [i.e., from computed tomography (CT) and magnetic resonance imaging (MRI)] with the intraoperative situation and position.[4] Frameless and armless navigation systems for microsurgery of brain tumors are used routinely today,[1,8] and the integration of a navigation system with a microscope has also been developed and is in routine use.[7] In this kind of operation the control of the position data by the navigation system is recommended, and this can easily be done by manual calculation with the CT topogram as described in detail by Seeger.[18] The tumor is projected slice by slice into the CT topogram, then its relation to

Received September 23, 1997; accepted September 17, 1998.
Address correspondence/reprint requests to: Dr. Martin Scholz, Department of Neurosurgery, Ruhr University Bochum, Knappschaftskrankenhaus, In der Schornau 23–25, 44892 Bochum, Germany. E-mail: Martin.Scholz@rz.ruhr-uni-bochum.de.

natural anatomic landmarks (i.e., the porus acusticus externus, bregma, protuberantia occipitalis externa, and glabella) is calculated and then measured on the patient's head.

In most navigation systems a connection with the endoscopic image data is not possible. Furthermore, intraoperative tissue displacement caused by loss of cerebrospinal fluid or by surgical reduction of a space-occupying lesion is not taken into account. A possible approach to real-time neuroendoscopic navigation is based on the application of intraoperative open MRI, and basic research in this area has been undertaken with human cadavers at Ruhr University Bochum.[16] The main difficulties encountered are electromagnetic artifacts caused by the monitor and the endoscope system and material artifacts of the endoscopic instruments. In addition, the required MR compatibility can be attained only with a complete rearrangement of the whole operating room, including the endoscopy system and endoscopic instruments.

In specialized centers the guidance of the endoscope is based on X rays and intraventricular application of a contrast medium.[2] The combination of a frameless navigation system with an ultrasound device in the endoscopic tip is another development intended to improve orientation in endoscopic operations.[15] The EasyGuide™ Neuro system (Philips) is one of the latest generation of neuronavigation systems that use a high-precision optical position measurement system (OPMS) suitable for microneurosurgery[19] and neuroendoscopy.[17] It has also been used in combination with intraoperative CT to update and recalibrate the preoperative image data.[13] The high precision of the OPMS was the major reason we chose this system for our study.

In neuroendoscopic interventions there are several problems that must be overcome, including loss of visibility as a result of bleeding, difficulties in orientation with respect to pathologic anatomy, the lack of a rear view behind the endoscopic tip (with the consequent danger of tissue damage resulting from movement in that direction), and a restricted visual field when close to the observed object. During neuroendoscopy the endoscopic picture appears on the screen, but it is lost in the next instant unless it is recorded on tape or by photography. Gunkel et al.[6] described a navigation system based on preoperative CT data that is able to insert a preoperatively defined path into the live-video data of the endoscope. However, in this system the endoscopic picture itself is not analyzed. Image analysis may provide different options for the neurosurgeon with the use of the modern techniques of neuroinformatics. The new aspect of the system described here is the combination of an endoscopic navigation system with a new image-guided control system based on video data to increase the safety and flexibility of neuroendoscopic interventions. The video data are digitalized by a frame grabber and used in different image-control modules. These modules offer the options in the following eight subsections.

Motion Alarm System

The main danger of endoscope holders is tissue damage arising from loss of fixation of the endoscope. In our system an automatic image-control module monitors the stationary endoscope and gives an alarm if there is any movement in the observed image. Thus, the light-emitting diodes (LEDs) at the endoscope can be switched off and the navigation system used for another instrument without removing the endoscope from the operating field. This may be useful if endoscope-assisted microsurgical procedures are being performed.

Landmark Location and Tracking

This module allows a given landmark in the endoscopic image to be marked, tracked automatically while the endoscope is moving, and relocated from any point, even if it is outside the endoscopic view. For example, during the inspection of an arachnoidal cyst, the optimal fenestration point can be marked as an "optimal image" and linked with CT position data. After further exploration of the cyst, this point can be easily found again by following overlaid arrows in the system. This is especially helpful for orientation in very large and homogenous surroundings with only a few anatomic structures for reference. When marking two landmarks it is also possible to measure distances in a no-touch mode, such as the size of a previously performed fenestration or a partial tumor resection.

Virtual Map

This module allows automatic storage in map form of endoscopic images obtained from various positions during inspection of the ventricular system. All these views come from the same patient and are stored each second during the endoscopic exam. If the direct view is lost (e.g., due to bleeding, a defect in the light source or camera system, or pollution of the endoscopic tip) the corresponding virtual images can be retrieved from the computer, thus helping the neurosurgeon to maintain a visual impression of the operating field. The system offers

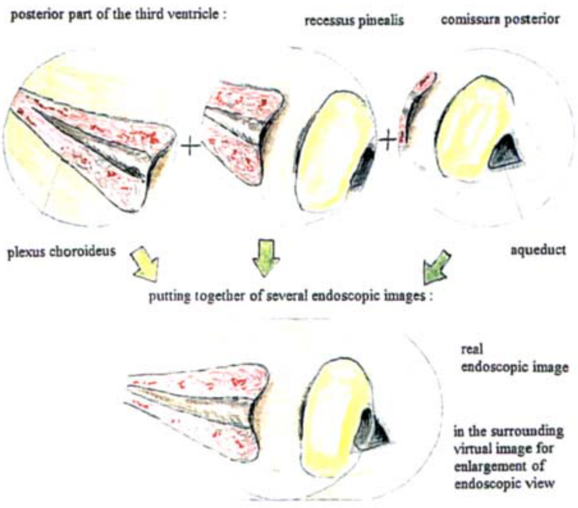

Fig. 1. Schematic example of a virtual visual field enlargement performed by fusion of several endoscopic images.

the closest image present in the data base; interpolation methods are not used. If the actual position is too far from a previously passed position and a virtual image cannot be calculated, an alarm sounds and a red blank warns the neurosurgeon of the situation.

Virtual Background for Bleeding

In current neuroendoscopic operations the surgeon can manage bleeding that causes a complete image loss ("red-out") only by rather ineffective indirect methods such as rinsing. If this is not effective the reverse movement of the endoscope carries the risk of severe tissue destruction. The function of virtual background in the case of red-out allows the calculation of a virtual image based on actual endoscope position data and previously stored endoscopic images. A red detector can help to find the source of bleeding by comparing the image showing the bleeding to previously stored images showing a dry surgical field; this may allow safe navigation and perhaps intervention (coagulation), even in the case of complete failure of the sensor.

Virtual Visual Field Enlargement

During lateral movement of the endoscope, several images from it are fused to give one general view, offering better orientation and providing an overview for the neurosurgeon. Figure 1 gives an example of such a virtual visual field enlargement.

Virtual Reverse Movement

During reverse movement of the endoscope there is the danger of vessel injury because of the restricted visual field. The "virtual reverse movement" function offers a virtual image sequence beginning at the actual endoscope position, which is comparable to a real reverse movement. Dangerous situations can thus be recognized and avoided prior to actual movement of the endoscope. For example, an approach through the foramen Monroi to the floor of the third ventricle can be complicated by fornix damage at the edge of the f. Monroi if the endoscope is tilted too severely. The virtual reverse movement function can prevent such a potentially fatal complication by permitting optic measurement of the f. Monroi area and further calculations (Fig. 2).

Recalibration by 3-D Position Measurement of Anatomical Landmarks

One major problem affecting the precision in conventional navigation systems is displacement of brain tissue as a result of cerebrospinal fluid loss or intraoperative reduction of space-occupying lesions. Preoperative CT data cannot solve this problem; however, once we have a calibrated endoscope, the endoscopic video data can be used for on-line recalibration inside the brain in order to overcome this difficulty. One or more distinctive

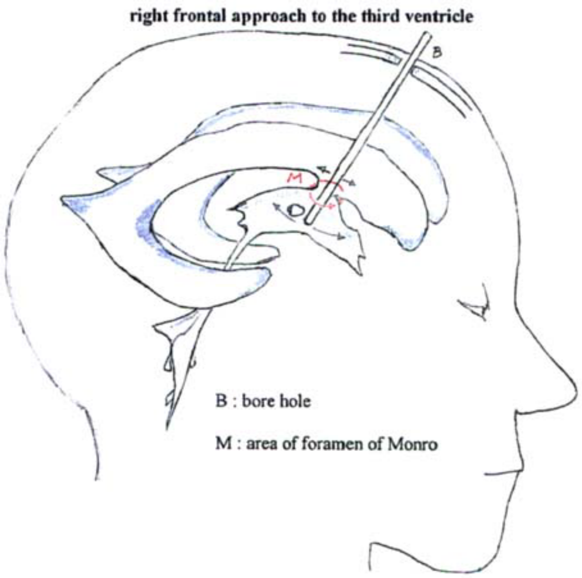

Fig. 2. Calculation of the size of the foramen of Monroi in order to allow safe movement of the endoscope at the floor of the third ventricle without damaging fornical structures.

landmarks are marked by the neurosurgeon in a video frame, and subsequent automatic tracking establishes their 3-D coordinates. If necessary, the preoperative data can then be recalibrated. The achievable precision of the recalibration is within the precision range of the navigation system (e.g., EasyGuide Neuro). No exact model for tissue motion has been found so far, although it is thought that brain tissue displaces more markedly in cortical areas than, for example, in the region of the brain stem. In addition, there are presumably significant individual and age-dependent differences related to the amount of water in the brain that must also be taken into account.

Aiming

This module permits a return to a previously marked anatomic structure by robot steering under the automatic control of the endoscopic image data. It is possible to set up a data base of anatomical landmarks to allow automatic patient-independent identification of these landmarks. Robot steering in the operating room is only possible with automatic visual control.

MATERIALS AND METHODS

A special device with three infrared LEDs was mounted on a rigid endoscope (Wolf, 5.9-mm outer diameter) at a distance of 18 cm from the tip (Fig. 3). A color charged-coupled device (CCD) camera (Wolf, CCD Endocam 5500) at the rear end of the endoscope captures the image from the tip through a special lens system (380-mm distance from tip to rear). The positions of the LEDs are measured continuously by the OPMS, which is part of the EasyGuide Neuro navigation system. The OPMS basically consists of a stereo camera rig stationed in the operating room. The system determines the 6 degrees of freedom of the rigid endoscope within the coordinate system of the camera rig. The OPMS data are transferred via serial interface to the PC at a rate of 8 Hz (eight position data sets per second) and a serial line communication at 14,400 baud. The video output of the endoscope camera is connected to a TV monitor and a PC frame grabber; this allows live display of the color image on the PC's VGA monitor with the option of overlaying certain cursor marks. The procedure of Tsai[21] was used for camera calibration, which provides a versatile and robust estimation of the camera parameters.

A basic feature of the calibrated system is its ability to establish the 3-D coordinates of an anatomic landmark in the patient using standard triangulation techniques.[13] It was found that small movements of the endoscope (e.g., 2–3 mm looming movements) are sufficient for good accuracy. Thus, even the small maneuvering space available during an operation is adequate for obtaining the 3-D information. In automated mode the landmark, once selected, is automatically tracked until views from sufficiently divergent angles are obtained. In all cases, no greater movements are required than those that are usual during operative navigation. Knowing the camera positions from the OPMS, we obtain the 3-D representation in the OPMS system using standard triangulation techniques.[14] The accuracy of the different calibration procedures was measured during laboratory investigations, and the technical aspects of our work are described in more detail in an earlier report.[12]

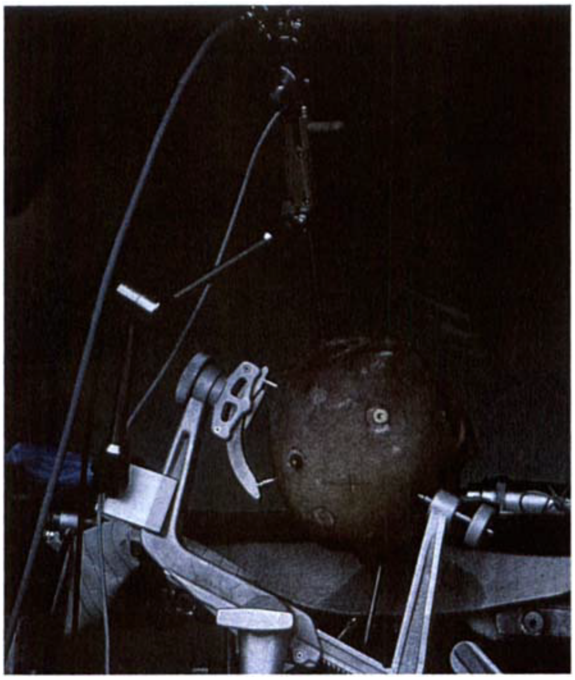

Fig. 3. Experimental arrangement of a human cadaveric head fixed with the Mayfield clamp. The endoscope with the triangular-shaped LEDs is inserted via an occipital approach.

Although not specified in a standard protocol, it has been determined that if the position of the endoscopic LEDs is not changed, one initial calibration process (of approximately 25-min duration) is sufficient for several operations. The neurosurgeon can proceed in the normal manner recommended for endoscopic operations, inspecting the ventricular system if necessary and then navigating to the target of choice. During this time sufficient images are stored to enable the modules to function. There are no problems responding to changes in the head's position during surgery because the position of the Mayfield clamp can be registered by a specially developed LED rig.

In our preclinical study the first three modules described (the alarm system, tracking, and virtual map modules) were tested in a formalin-fixed human cadaveric head using a right and left frontal and occipital approach. During all experiments a neurosurgeon and a programming engineer were both present to evaluate the system, and possible improvements to the software were discussed afterward. The alarm system was tested during fixation of the endoscope with a special holding device (Magic Arm, Philips) in three different situations: movement of the endoscope, small vibration of the endoscope, and change in lighting conditions.

The tracking module was tested on different anatomic landmarks with strong contrast (plexus choroideus) and poor contrast (corpora mammillaria), and the accuracy of landmark detection was observed. During tests of the virtual map module special movements without a direct endoscopic view were undertaken by the neurosurgeon that were based solely on the virtual images. The engineer controlled the path of the endoscope by comparing virtual and real images.

A physical evaluation of the system's precision was also performed in the laboratory in the form of 810 tests of the modules' landmark tracking and measurement abilities. We used a tripod-mounted endoscope directed onto special graph paper in a bath of Ringer's solution for these tests as shown in Figure 4.

Fig. 4. a: Experimental setting for testing of the module's accuracy: the endoscope is directed at special graph paper in a bath of Ringer's solution. **b:** Example of experimental distance measurement.

RESULTS

A good calibration for the wide-angle and radially distorted endoscopic lens system was obtained (0.2-mm accuracy). We coupled the endoscope to an OPMS that tracks its 3-D location in space. The system allows the direct overlay of 3-D points or arbitrary 3-D structures onto the live camera image with high accuracy (0.7–0.8 mm). Conversely, landmarks in the camera image can be tracked when the endoscope is moving and their 3-D data can be obtained and reported to other systems. During the cadaver experiments and phases of software improvement particular care was taken to ensure that every module could be initiated with only one or two clicks of the computer mouse.

We conducted 35 cadaver experiments with the system; Table 1 summarizes the results. Even the initial software revision gave good results in nearly all the experiments undertaken, although failure occurred in 3 out of 35 experiments (8.6%). Failures of the system were due to incorrect landmark tracking. After the subsequent second revision of the software, a 100% success rate was achieved. The software changes were of a mathematical nature and involved optimization of camera calibration and the intrinsic calibration of the system.

The alarm system module (Fig. 5) effectively controls the endoscopic view and reacts if the endoscope is moved, but a mere change in light intensity does not result in an alarm. Similarly, rhythmic vibrations of ventricular contents, which can sometimes be observed in neuroendoscopic interventions, can be detected and do not produce a false alarm either.

The tracking module [Fig. 6(a–c)] is available in two different forms: the first requires two

Table 1. Results of Preclinical Cadaver Experiments

Modules tested	Anatomic details	No. experiments	No. failures and cause	Failure analysis and remedy
Alarm system	Foramen monroi	6	1-fast change in light	Not necessary
	infundibulum	3	intensity	
Tracking	Infundibulum corpora	8	1-slipping of arrow in up	Successful
	mammillaria artificial	1	and down movement	improvement of
	piece of brain edge of	1	(first software version)	software
	f. monroi plexus	2		
	choroideus	6		
Virtual map	Floor of III, ventricle–	4	1-rotation of endoscope	Successful
	lateral ventricle lateral	4	not detected (first	improvement of
	ventricle–infundibulum		software version)	software
Total number		35	3	

mouse clicks on the same landmark from different points of view, and the second requires only one mouse click and permits automatic tracking during slow movement of the endoscope. The surgeon simply points initially at the landmark, then the system tracks it while the endoscope is moving until some stopping criterion is met; then it finally reports the 3-D coordinates and displays the overlay mark. A fast tracking algorithm was implemented that uses template matching in a 2-D logarithmic search fashion.[10] If the landmark is outside the endoscopic view, an arrow shows its direction; if the landmark is behind the endoscopic tip, the arrow appears yellow; if it is in front, it appears red. Furthermore, the width of the arrow increases as the landmark moves off into the distance and shrinks when the landmark is brought closer to the endoscopic tip. This was clearly demonstrated in the cadaveric model. The landmark was also found again following a long inspection of the ventricular system.

Fig. 5. Image analysis with movement detection by the alarm system.

The accuracy of tracking (as determined by experiments in a bath of Ringer's solution) in our laboratory was 0.3–0.7 mm. The accuracy of measurement was registered under laboratory conditions as 0.15–0.5 mm. With longer distances the error is comparable to that reported for the OPMS.

In the cadaver tests the virtual map module enabled the surgeon to navigate the endoscope without direct visualization. This was simulated while navigating the endoscope in slow motion (e.g., from the floor of the third ventricle through the foramen of Monroi to the lateral ventricle and back) [Fig. 7(a–c)]. Virtual gray scale images gave enough information to allow the neurosurgeon adequate endoscopic navigation in what would previously have been a dangerous situation without any direct sight. When the neurosurgeon rotates the endoscope around its axis such that the endoscopic image undergoes a frontoparallel rotation, the virtual image is rotated correspondingly as well. A special alarm system was developed that gives information as to whether the actual endoscopic position is near any previously passed area. A red error bar beneath the virtual image signals the distance of the actual position from the closest stored position, and a small coordinate system shows the direction of the error. The further the neurosurgeon moves away from previously stored positions, the larger the error bar becomes. Thus, a large red sign warns the neurosurgeon of a dangerous situation.

The status of the other five modules described is as follows: the virtual background in case of red-out module is now developed and has recently been successfully evaluated in the laboratory. Animal experiments with rats have been approved and will be conducted in the near future. The virtual reverse movement and aiming modules are developed at the software level, and attempts are being made to combine the latter module with robot steer-

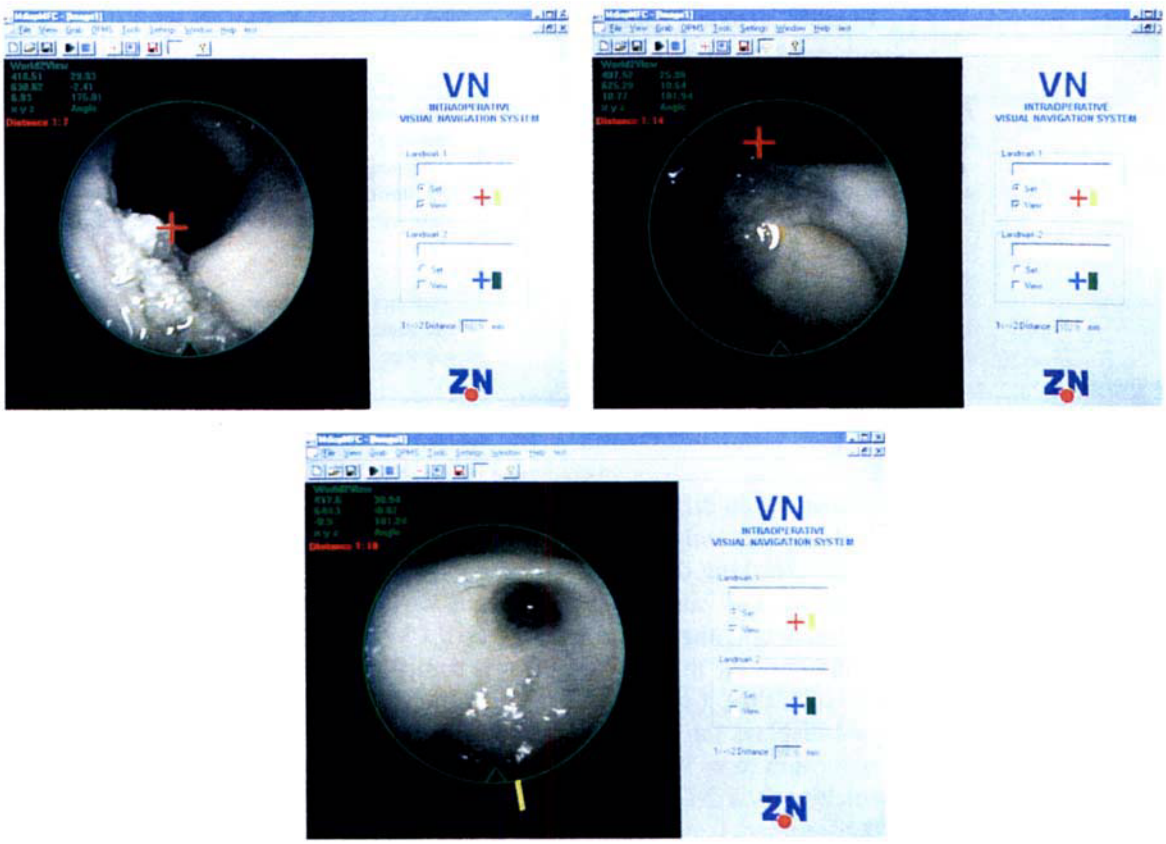

Fig. 6. **a:** Marked anatomic landmark (plexus choroideus) at the edge of the foramen of Monroi and **b, c:** tracking of this landmark during movement.

ing. The most difficult modules to develop from the neuroinformatic point of view are the modules for virtual field enlargement and 3-D recalibration by position measurements. The first can be demonstrated at the software level, but it is difficult to optimize for clinical needs. As for the second, it is questionable whether position measurements alone are sufficient for 3-D recalibration and a combination with other real-time imaging techniques (e.g., 3-D ultrasound) would be more encouraging.

DISCUSSION

In the last few years navigational information sources such as MR or CT have been introduced into the operating room, and they offer the neurosurgeon more safety in the planning and performance of procedures. Navigation systems can also be used in neuroendoscopic interventions.[17]

The next step in CAS involves the image analysis itself (i.e., the digitized image processing within the endoscopic images). Visual control systems that store images combined with their 3-D address can offer surgeons new solutions in difficult and dangerous intraoperative situations. As has been shown in our study, such a system can successfully work with a high degree of precision in endoscopic surgery.

In the ARTMA navigation system[6] the endoscopic position is measured by Hall sensors and is used to overlay certain preoperatively defined structures in the live endoscopic image. However, no camera calibration has been undertaken in this approach, so the achievable accuracy is fairly limited and does not allow the determination of the depth of an intraoperatively marked point from different camera views.

Bricault et al.[3] developed a new method of computer-guided transbronchial biopsy that involves the fusion of image data from CT slices and bronchoscopic video sequences. The basis of this system is a special segmentation process using mathematical morphology operators to analyze the video sequence and localize the bronchoscopic camera within the tracheobronchial tree. Different kinds of rigid endoscopes and navigation systems

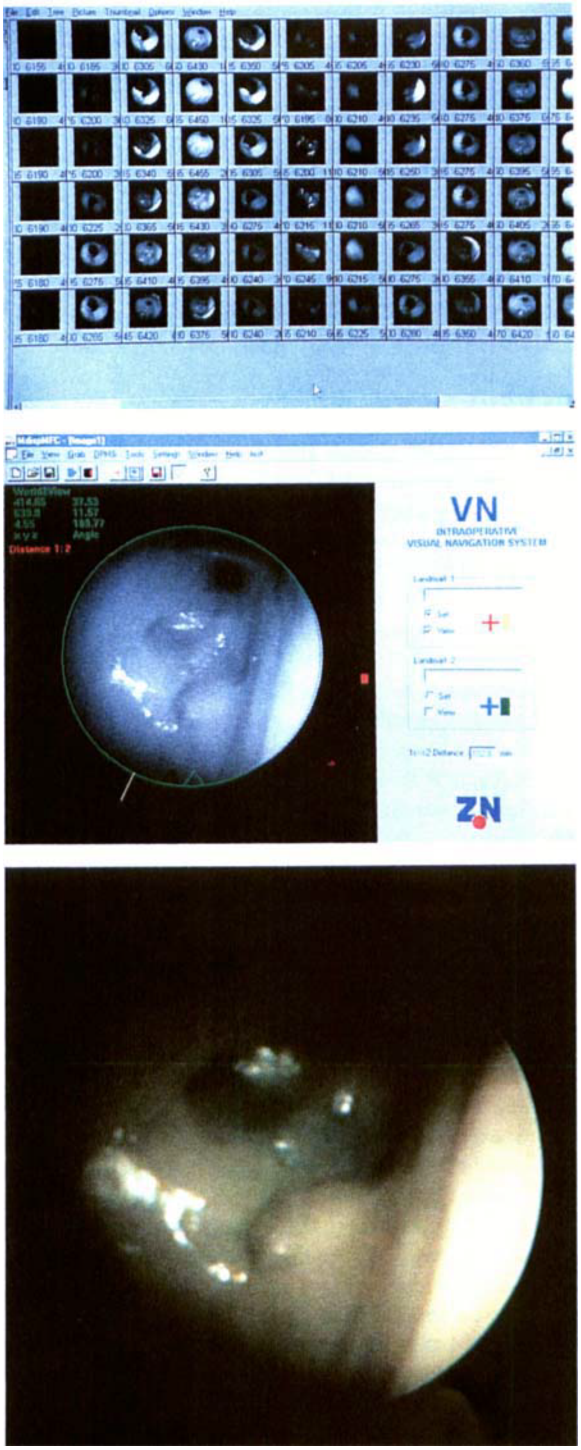

Fig. 7. **a:** Virtual map with stored images from the computer's hard disk. Comparison between **b:** the virtual image (black and white) and **c:** the real endoscopic image.

can also be used with the camera and system calibration described here.

It is questionable whether navigation systems with preoperative data sets can give enough information in every intraoperative situation, especially during loss of cerebrospinal fluid or tumor resection. Recalibration with intraoperative CT data can be a solution, but it is time consuming and requires further X-ray exposure. If CT recalibration is used in endoscopic neuronavigation, the endoscope has to be removed and then reinserted; this may result in additional damage to brain tissue. Intraoperative MRI would be an interesting alternative if compatible instruments were developed. Additionally, in MR-guided interventions of the future an OPMS will be needed to find the exact position inside the magnet and to give information to newly developed visual control systems. We believe that this combination has the greatest potential.

In our visual navigation system the 3-D world points come directly from the OPMS, which sends measured position data to the visual navigation computer. In clinical practice it is also possible for the OPMS (equipped with specially developed software) to transfer position data to the visual navigation system and the conventional navigation system with a CT or MR data base. The very localized original image information provided by the system cannot be offered by CT or MR and, if bleeding occurs, the neurosurgeon needs exact endoscopic images.

The question remains as to how the neurosurgeon can assimilate all the new information presented by the navigation system and the visual control system. This remains to be tested in clinical practice. One may argue that too much information may lead to a new form of overstimulation for the neurosurgeon, although, in practice, the operator only looks at the screen of the navigation system in case of difficulties. The visual control system works in the same way: if the neurosurgeon has reached the area of intervention (e.g., a small intraventricular tumor), the visual control system can give support in case of red-out or if measurement of the tumor margins is to be performed visually. We believe that after a short training period the additional display of CT images and information from the visual control system will not disturb the surgeon. The situation is similar to that of a pilot flying a plane where many of the instruments in the cockpit support additional safety options and are used only if they are needed. Such instruments or modules have to be easy to manage and must be able to withstand unintentional misuse. For this reason the close collaboration between the surgeons and programming engineers at a very early stage of module development is highly recommended, as demonstrated in our study.

The term "virtual endoscopy" was previously reserved for special diagnostic procedures using patient-specific high-resolution digital images with a helical CT scan or MRI.[11] Individual organs can be graphically isolated or "segmented" into fully interactive 3-D reconstructions on a computer monitor. Applying sophisticated flight-tracking programs, the organs can then be "flown through," giving a view nearly identical to endoscopy. One major disadvantage of this procedure is the possibility of introducing artifacts. With the newly developed virtual map module another form of virtual endoscopy is possible based on previously stored real endoscopic images. Coupling the system to MR or CT data obtained in real time to allow projection of radiologic information (e.g., 3-D reconstructed tumor margins) into the endoscopic image would be a possible future application of this system, as would its use in a variety of computer- or robot-guided aiming processes[5]: if the endoscope is to be navigated by a robot, only direct visual control is sufficiently safe.

A more philosophical question is whether robots are really needed in neurosurgery in the first place. Jacobs et al.[9] showed that laparoscopic procedures in particular could be enhanced by a robotic system working in conjunction with video analysis. The Automated Endoscope System for Optimal Positioning (AESOP) robot makes possible the elimination of the camera person, returns control of the camera and operative field to the operating surgeon, and enhances human performance. Similarly, Taylor and colleagues[20] developed a system that includes a robot for holding a camera or other laparoscopic instruments, which are linked to control, image-processing, and display functions. This LARS system is also capable of processing images from the camera to obtain geometric information about the patient's anatomy, which may then be used to assist targeting of the camera or other instruments held by the robot. The possibility of adding the robot's own position measurement to that of the optical system would certainly increase the safety of such systems.

In summary, we showed that advanced image-processing techniques can be successfully applied to endoscopic surgery. The visual control system presented here could also be a revolutionary step in image-guided surgery in other disciplines that use endoscopy, such as otorhinology and maxillofacial surgery. It is our belief that advanced image-processing methods will play an increasingly important role in endoscopic surgery where the surgeon faces new challenges due to continuing miniaturization and thus needs new tools for improved navigational support.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Ruhr University of Bochum for Interdisciplinary Research (Forum). The study was performed with the approval of the Ethics Commission of the Ruhr University Bochum (No. 844).

REFERENCES

1. Barnett GH, Kormos DW, Steiner CP, Weisenberger J (1993) Use of a frameless, armless stereotactic wand for brain tumor localization with two-dimensional and three-dimensional neuroimaging. Neurosurgery 33: 674–678.
2. Bauer BL, Hellwig D (1994) Minimally invasive endoscopic neurosurgery—A survey. Acta Neurochir 61(Suppl):1–12.
3. Bricault I, Ferrettio G, Cinquin P (1995) Computer-assisted bronchoscopy: Aims and research perspectives. J Image Guided Surg 1:217–225.
4. Cinquin P, Bainville E (1995) Computer assisted medical interventions. IEEE Eng Med Biol.
5. Finlay P (1993) Neurorobot—A fully active system for assisting in neurosurgery. Ind Robot 20(2):28–29.
6. Gunkel AR, Freysinger W, Thumfart WF, Truppe MJ (1995) Application of the ARTMA image guided navigation system to endonasal sinus surgery. In Lemke HU, Inamura K, Jaffe CC, and Vannier MW (eds): Proceedings of the Computer Assisted Radiology Conference (CAR '95), Berlin, June 21–24, 1995. Berlin: Springer, pp 1147–1151.
7. Harders AG, Hardenack M, Schmieder K, Scholz M, Seeger W (1995) Mikrochirurgische Planung und Durchführung bei Großhirngliomen und erste Erfahrungen mit dem Mehr-Koordinaten-Manipulator MKM. In Moskopp D (ed): Moderne Verfahren zur Optimierung der Behandlung von Hirntumoren. Aachen, Germany: Shaker (Berichte aus der Medizin).
8. Horstmann GA, Reinhardt HF (1994) Micro-stereometry, a frameless computerized navigating system for open microsurgery. Comput Med Imaging Graph 18: 229–233.
9. Jacobs LK, Shayani V, Sackier JM (1997) Determination of the learning curve of the AESOP robot. Surg Endosc 11:54–55.
10. Jain AK (1989) Fundamentals of Digital Image Processing. Englewood Cliffs, NJ: Prentice–Hall, pp 404–406.
11. Kay CL, Evangelou HA (1996) A review of the technical and clinical aspects of virtual endoscopy. Endoscopy 28:768–775.
12. Konen W, Scholz M, Tombrock S, Tölg S, Brauckmann M, Adams L (1997) An image based navigation

support system for neuroendoscopic surgery. In Ahlers R (ed): Symposium Bildverarbeitung 1997. Esslingen, Germany: Technical Akademie Esslingen.

13. Koos WT, Roessler K, Matula C, Czech T, Schindler E (1997) Combination of intraoperative computed tomography (CCT) and image-guided neurosurgery. In Proceedings of the 11th International Congress of Neurological Surgery. Italy: Monduzzi Editore, pp 1585–1590.
14. Longuet-Higgins HC (1981) A computer algorithm for reconstructing a scene from two projections. Nature 293:133–135.
15. Ohira T, Kawase T, Ohtani M (1995) Significance of navigation in endoscopic operations for deep-seated brain tumors with a frameless navigator and an endoscopic ultrasound. In Abstract Book: Neuroendoscopy from the Satellite Symposium of the 10th European Congress of Neurosurgery EANS, May 4–6, 1995.
16. Scholz M, Deli M, Wildförster U, Wentz K, Recknagel A, Preuschoft H, Harders A (1996) MRI-guided endoscopy in the brain: A feasability study. Minim Invasive Neurosurg 39:33–37.
17. Scholz M, Koch R, Hentsch A, Tschelishvilli I, Konen W, Hardenack M, Fricke B, von Düring M, Heuser L, Harders AG (1997) Endoskopische Neuronavigation. Eine präklinische Studie mit dem EasyGuide Neuro system. Endosk Heute 3:299–305.
18. Seeger W (1979) Microsurgery of the Brain. Anatomical and Technical Principles. I. New York: Springer–Verlag, pp 48–53.
19. Spetzger U, Laborde G , Gilsbach JM (1995) Frameless neuronavigation in modern neurosurgery. Minim Invasive Neurosurg 38:163–166.
20. Taylor RH, Funda J, Eldridge B, Larose D, Gomory S, Gruben K, Talamini M, Kavoussi L, Anderson J (1996) A telerobotic assistant for laparoscopic surgery. In Taylor RH, Lavallée S, Burdea GC, Mösges R (eds): Computer-Integrated Surgery: Technology and Clinical Applications. Cambridge, MA: MIT Press, pp 581–592.
21. Tsai RY (1987) A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses. IEEE J Robot Automation 3:323–344.