Experience With Various 3-Dimensional Navigation Systems in Head and Neck Surgery

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Objective: To evaluate the benefits and difficulties encountered when using various 3-dimensional (3-D) navigation systems in head and neck procedures.

Design: Five different navigation systems were used for preoperative planning and intraoperative 3-D navigation in procedures at the paranasal sinuses, the frontal and lateral skull bases, and the petrous bone.

Intervention: Intraoperative 3-D localizing systems (position-sensitive mechanical arms, infrared cameras, etc) demand reliable patient fixation on the operating table. We achieved this by developing a noninvasive head holder. Other systems allow patient movements by using magnetic digitizing technology (ARTMA System) and sophisticated programming.

Results: Having surpassed an initial learning curve, we now achieve an accuracy of 1 to 2 mm regularly. Especially in paranasal and frontal basal surgery, all navigation systems used provide valuable positioning information during surgery. In particular for revision or tumor surgery, decisive benefits resulted from use of these systems: shorter overall operation time; safer manipulation near delicate structures; and reliable identification of the skull base even in patients with bleeding, scarring, or missing anatomical landmarks.

Conclusions: We performed approximately 250 operations with different systems and introduced navigation at the lateral skull base and the petrous bone with mechanical, optic, and magnetic digitizers. In these anatomical areas, navigation was used successfully; the technical challenge is greatest at the lateral skull base, however.


Among others, Schlöndorff et al1 introduced 3-dimensional (3-D) navigation to otolaryngology in 1987 with a position-sensitive articulated arm. A successor thereof was the ISG Viewing Wand, which was for sometime considered the criterion standard in 3-D navigation. After initial scepticism of otolaryngologists, 3-D navigation emerged as an accepted and useful technique in nasal, paranasal, and skull base surgery. Minimally invasive surgery has gained enormous popularity because delicate structures at risk can be identified safely even when reliable landmarks are missing (tumors, revision, bleeding, etc).1,2 We have gained experience with different 3-D navigation systems in approximately 250 operations mainly at the paranasal sinuses and the frontal and lateral skull bases. We report some aspects of our work with 3-D navigation systems, emphasizing those that are crucial to obtaining optimal intraoperative results.

VBH AND SANDSTRØM HEAD HOLDER

The cardinal factor for image-guided surgery is reliable intraoperative patient fixation in those systems requiring it (e.g., ISG Viewing Wand, ISG/ELEKTA free-hand, Zeiss STN, Zeiss MKM, and Philips Easy Guide). The VBH head holder has provided superior patient fixation and flexibility in ear, nose, and throat surgery and for computer-assisted interstitial brachytherapy. The Sandstrøm head fixation device3 could not achieve the same accuracy in terms of repositioning; its construction is inappropriate for external approaches to the paranasal sinuses and the frontal and lateral skull bases, and the fixation can lead to pressure ulceration in the region of the outer ear or the nasion and cause considerable pain. Therefore, we use the VBH head holder almost exclusively.

The ISG Viewing Wand has given us reliable results for a long time. However,
MATERIALS AND METHODS

IMAGING

We use 3-D computed tomographic and magnetic resonance (CT/MR) imaging as described by Freysinger et al.6

PATIENT FIXATION

Various options are available for intraoperative patient fixation to the operating table for navigation: tape fixation, the Vogele-Bale-Hohner (VBH) head holder (Medical Intelligence, Schawbmünchen, Germany), and the Sandstrøm headset (Carl Zeiss, Oberekochen, Germany). The most important factor affecting patient-image registration is reliable patient fixation that still provides full access to the operating field and is noninvasive. Classic stereotactic frames are not desirable, and therefore we developed a noninvasive head holder, the VBH head holder. It consists of a headrest, hydraulic fixation elements, and an individual upper dental cast. The patient rests on a head plate and the dental cast is inserted, which is secured by underpressure and mounted to the fixation elements. The mouthpiece can carry registration elements. A counterfixation at the patient's occiput completes immobilization: it is firm and reliable but not invasive. Its variability supports all operations9,10 as well as computer-assisted interstitial brachytherapy.10 Preoperative 3-D imaging is done with the dental cast registration rods assembly in place, permitting creation of a “virtual patient” for preoperative planning and simulation. Figure 1 illustrates the VBH head holder.

THE SANDSTRØM HEAD FIXATION DEVICE

Another option for patient fixation is the Sandström head fixation device. This is also noninvasive and consists of an adjustable U-shaped carbon fixation element running across the head; its ends fit into the outer ear canals with plastic “olives.” A V-shaped aluminum alloy element locks into the first element and provides counterfixation by resting on the nasion.12 The patient is fixated by tightening screws on both sides of the frame and locking the holder to the headrest plate (Figure 2). Counterfixation is provided by a strap running across the back of the head.

PATIENT-IMAGE REGISTRATION

A set of well-defined landmarks, either anatomical or fiducial, is matched with identical points in the images. Accuracy is affected by a variety of factors tentatively known as theoretical resolution of the 3-D digitizer; actual touching and correlating of landmarks with the stylus; skin shift; motion artifacts during imaging; movement of fiducial markers, the patient, or the operating table; and combinations thereof.

3-D NAVIGATION SYSTEMS

ISG Viewing Wand

The Viewing Wand (ISG Technologies, Mississauga, Ontario) mainly consists of a position-sensitive mechanical measuring arm with a localizing stylus of varying shapes at the end. The arm has 6 degrees of freedom and can be moved inside the operating field. The joints’ positions are converted to position and orientation in space, which are shown as crosshairs in the preoperative CT/MR images. This allows searching of preplanned paths or identification of anatomical structures during surgery.13,14 To improve functionality we added tools,13,14 thus providing straight and bent probes, suction devices, power instrumentation, needles, cannula, etc. Other than for ear, nose, and throat surgery, we have successfully used this system for interstitial brachytherapy to place low radiation in optimal preplanned positions inside inoperable tumor masses of the head and neck region.10

Philips Easy Guide, Zeiss STN, and ISG/ELEKTA Free-hand

These systems (Philips Easy Guide [Philips, Eindhoven, the Netherlands], Zeiss STN [Carl Zeiss], and ISG/ELEKTA free-hand [ELEKTA, Stockholm, Sweden]) use pointers that are equipped with infrared light-emitting diodes. The position and orientation of the light-emitting diodes are detected with 2 or 3 infrared cameras close to the operative field, and the position of the probe is indicated as crosshairs in the 3-D data sets. These systems require stable intraoperative patient fixation, and the registration procedures are nearly identical. We have used these systems in procedures at the paranasal sinuses, the frontal skull base, and the petrous bone (Figure 3).

ARTMA System

This virtual patient system (ARTMA, Vienna, Austria) is considerably different from the latter, apart from the fact that it uses magnetic digitizing. Sensors fixed to the instrument, the endoscope (microscope), and the patient provide 3-D data for navigation. In addition—and this is the unique feature of this navigation system—the positions, access paths, and additional graphical structures can be visualized on the live video. This allows us to directly superimpose 3-D information into the video sequence. For example, a predefined path can be shown by a sequence of colored frames, similar to a tunnel, floating as permanent information over the video and the data set at the same time, guiding the surgeon to the planned target. To that end, digital photographs of the patient (lateral and frontal views), the medical image data sets (2-dimensional and 3-D) are registered to the patient. The optical function of the endoscope (microscope) has to be determined, and thereafter navigation is possible: pathways are faded into the live video, and navigation in CT/MR is possible.16 The intraoperative setup with the tracked endoscope and the patient is shown in Figure 4.

Zeiss MKM System

The Zeiss MKM system (Carl Zeiss) is mainly designed for neurosurgical and otologic operations. The microscope is mounted on a high-precision robotic arm. The patient is rigidly mounted to the operating table, where the reference emitter of the digitizer is mounted too. This emitter is referenced with the robotic arm. The position of the focal point inside the patient can be displayed relative to the patient’s 3-D image data sets after a standard patient-image registration procedure. The Zeiss MKM system can superimpose contours, targets, or diagnostic images to the microscopic view, showing the actual position of the autofocal point inside the patient.
technological advances have provided other newer 3-D digitizing systems that are used. The arm must be mounted properly to the operating table to provide access to the whole surgical field. In addition, “working around corners,” which is frequent in sinus surgery, is awkward.17 We have reached an accuracy of less than 2 mm regularly in all operations, and the intraoperative preparation and registration time—including patient fixation—has been shortened to 15 minutes on average. In operations at the lateral skull base, the Viewing Wand’s probes are too bulky and working with the arm under the microscope unwieldy, although we were able to achieve superior accuracy, even down to CT resolution.18 Figure 5 shows the application in a girl with a tumor in the retromaxillary region and the pterygopalatine fossa.

Another important aspect for working with a 3-D localizer is that the surgeon has to change from the monitor (binoculars) that he or she is working with to the computer monitor. This is especially critical during navigated microscopic ear surgery in which the surgeon touches an anatomical structure with the stylus and then looks away to the monitor for verification with the crosshairs.2,3,11,18 This is obviously inconvenient and risky because inadvertent movements might violate delicate structures unintentionally.

PHILIPS EASY GUIDE, ZEISS STN AND MKM, AND ISG/ELEKTA FREE-HAND

These systems provide patient-image registrations similar to those of the Viewing Wand (<2 mm) but are more convenient by providing navigation with infrared-tracked tools. It is crucial to position the infrared camera during surgery so that an unobstructed view is established throughout surgery. One must ensure that the suc-
tion-irrigation endoscope with videocamera, video rack, irrigation unit, navigation unit, sterile draping, instruments, and surgeon and nurse not be in the line of sight. We found the ideal positioning for endoscopic sinus and frontal skull base procedures as follows: the camera is opposite the surgeon, who looks in the face of the patient, at the patient's head. Right-handed surgeons move the stylus with the right hand under video endoscopic control (left hand) so that the camera can detect the diodes.

In the lateral skull base and the petrous bone, sufficient accuracy down to 1 mm was possible with the microscope. However, current probes are still too bulky to provide convenient navigation. Similar precautions as those mentioned for the Viewing Wand apply here too; moreover, the length of the stylus might be problematic when a focal distance of 200 mm is used. Sometimes the stylus simply cannot be introduced into the operating field, eg, deep in the petrous bone or the cerebellopontine angle.

The user interface is important because the surgeon needs a software structure that simplifies the reading and matching of landmarks to the imaging data and immediately informs and warns him or her of possible errors and system failure. In this respect, the Zeiss STN system currently seems most advanced. The pointer of the Philips system is equipped with many light-emitting diodes so that it can be detected by the camera from practically all working positions and, despite its linear form, perform real-time multiplanar reformatting.

Zeiss MKM is suitable for operations at the petrous bone and the lateral skull base, for open procedures at the frontal skull base, and, of course, for neurosurgical procedures. It is not useful for endonasal procedures because it is difficult to work under microscopic view and navigate inside the nose. Because the angle of view often has to be changed in these procedures, the robotic arm is too slow and immobile to allow proper surgical handling. The MKM has its domain in cases in which microscopic preparation is performed and the approach is minimized as much as possible. The surgeon gets relevant spatial information and the position of the autofocus point relative to the CT image faded into his or her view. Therefore, the surgeon need not look away at the monitor. In the meantime, the quality of the graphic overlay has improved in sharpness and contrast. The surgeon can now perform the registration without technical assistance simply by touching keys on a steriley draped microscope, easing registration. Accuracy with the MKM reaches 1 mm and therefore approaches the resolution of the CT scan.

ARTMA SYSTEM

This system uses magnetic digitizing, and the patient need not be fixed on the operating table, which is advantageous. Because magnetic fields penetrate the whole operating field, a direct view from light-emitting diodes to a camera is not necessary. So the surgeon never interferes with the “measuring beam” of systems with optical detection. This system has another feature: it connects the live video with the patient’s images and provides graphical structures (lines, pathways, etc) to guide the surgeon in the live video. These structures show the spatial position of the region of interest or a preplanned path. In addition, these structures can be changed, modified, and readadapted on the basis of identified landmarks in the video or the CT or from outside the operating theater by a supervisor or “master surgeon” in the sense of telepresence. The system offers many options for the field of telemedicine and telesurgery. We have already successfully transferred and modified surgical 3-D navigation data via the Internet and ISDN. This system is powerful and has several promising features. Permanent system development has decisively improved handling, accuracy, and convenience. Currently, accuracy lies in the range of 1 to 4 mm for endoscopic and microscopic operations of the head and neck region. Having previously used the ARTMA System mainly in endoscopic sinus operations, we now have successfully used it in operations at the petrous bone. In Figure 6, the system is used in a case of endocrine ophthalmopa-
thy in which an endoscopic endonasal decompression of the orbit and the optic nerve was performed.

APPLICATION AT THE FRONTAL AND LATERAL SKULL BASES

For navigation at the midface, the paranasal sinuses, and the frontal skull base, one can use a variety of anatomical landmarks, fiducial markers, or markers of the head fixation system, which mostly yield satisfactory registration results. In the petrous bone or the lateral skull base, the patient's face and the available landmarks are covered and not available for intraoperative registration. On the other hand, well-defined landmarks are rare at the lateral aspect of the skull. This complicates the situation, and registration is prone to errors. We solved this problem by introducing landmarks in this region using the head holder to avoid implantation of screws.

GENERAL ASPECTS

Minimally invasive procedures in the region of the paranasal sinuses, the frontal skull base, the petrous bone, and toward the brain bear a distinctive risk for violating delicate structures. The advantage of 3-D navigation is obvious provided that some key requirements are satisfied.21,22 Only then can these techniques successfully support the surgeon and help minimize the potential risks. Successful system use requires intensive cooperation with the radiology department to achieve 3-D data sets that comply with all requirements of navigation, especially for otolaryngological operations.23 Every 3-D navigation system available today cannot simply be “switched on and used for exact navigation” like an ordinary surgical tool. The systems are still too complicated, and the possibilities for pitfalls and consecutive inaccuracy are numerous. Our practical experience has clearly shown that “good results” (ie, high accuracy) and ease of use are only possible if the user faces the problem of navigation as a whole, especially failures. This starts with adapting head fixation for imaging, registration, and, finally, navigation itself. All systems that we have used up to now are still “2-person systems,” that is, intraoperative technical assistance is still necessary.

FAILURE DETECTION

Although the software of all systems we have used so far has been steadily improved, there still is demand for an immediate failure detection, eg, inadvertent patient movement. The surgeon has to be aware of this possibility and has to repeatedly check the registration’s validity during surgery by touching well-defined landmarks in the operating field to ensure that they are still identical to the corresponding location in the images. Whenever in doubt, the registration needs to be verified or redone. If this is not possible, the operation must be continued “classically.”

CONCLUSIONS

We have used various 3-D navigation systems in about 250 operations. We believe that computer-assisted navigation significantly improves safety and orientation in minimally invasive procedures at the paranasal sinuses, the frontal skull base, the petrous bone, and the lateral skull base. Different optical 3-D digitizing systems regularly achieved an accuracy of 1 to 2 mm provided that a reliable patient fixation is used if necessary. We now routinely use these systems during surgery for endonasal procedures. For microscopic operations at the frontal skull base, the petrous bone, and the brain, the Zeiss MKM system offers valuable intraoperative support by superimposing spatial information into the microscopic images. The ARTMA System, using magnetic digitizing technology, offers a range of additional measuring options for endoscopic and microscopic procedures, including the possibility of teleteaching and telesurgery. In conclusion, all systems must become simpler to use to become efficient tools for everyday surgery.

REFERENCES


