The Journal of Otolaryngology, Volume 30, Number 1, 2001

Review Article

Stereotactic Computer-Assisted Navigational Sinus Surgery: Historical Perspective and Review of the Available Systems

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Intraoperative image guidance in functional endoscopic sinus surgery (FESS) has gained increasing acceptance since its introduction some 6 years ago.[1,2] It is now used regularly in over 100 centres across the United States and Europe. The close proximity of the sinuses to the orbital and cranial cavities demands a high degree of surgical precision and provides little room for error regarding anatomic relationships. The optic nerves, cavernous sinuses, and internal carotid arteries lie close to the sphenoid sinuses. Major complications of carotid rupture and death have been reported during sinus surgery.[3–5] These demands can be particularly challenging when operating on a patient with poor anatomic landmarks as a result of extensive disease or previous sinus procedures, as is often the case. Knowledge of surrounding anatomy not visible to the endoscopic surgeon but available on the patient's medical images would make the technique significantly safer and allow for more complete surgery with better long-term outcomes.

The first practical surgical application of stereotaxis and guidance originated in Russia in the late 19th century.[6,7] With the discovery of x-rays in 1895, the mathematical foundation for the calculation of computed tomographic images was laid as early as 1917.[8] By 1973, computers were powerful enough to allow for the development of computed tomography (CT), which opened the door to modern-day intraoperative navigation and orientation.[9,10] Early real-time intraoperative guidance systems used a stereotactic frame that required fixation of the patient's head during surgery with cranial screws.[11] The first frameless computer-assisted system for intraoperative navigation in the sinuses was developed by ISG Technologies (Mississauga, ON). This system uses an articulated mechanical arm or viewing wand to hold a probe used for anatomic localization.[6,12] This system, although a great advancement in sinus surgery, was felt to be awkward to use and time consuming.[13,14] It also required the patient's head to be immobilized during surgery, which made the system impractical to use. The introduction of the InstaTrak™ image guidance system (Visualization Technologies Inc., Boston, MA) allowed for a user-friendly, less cumbersome, frameless, wandless system that did not require articulated arms or head immobilization.

At the Georgia Nasal and Sinus Institute, over 95% of all sinus cases are revision surgeries, and the InstaTrak image guidance system is commonly used in over 100 cases per year.[15] The electromagnetically based InstaTrak system has been used for both revision and nonrevision FESS as well as for pituitary and other skull base procedures.[16] Since the introduction of the InstaTrak system 5 years ago, several other image guidance systems have become available to the sinus surgeon. At present, there are two different tracking technologies that are commercially available to the sinus surgeon: the electromagnetically based (InstaTrak) and the optically based (Landmarx™ from Xomed Industries, Jacksonville, FL, and VectorVision2™ from BrainLAB Inc., Munich, Germany) systems. We present our experience with the InstaTrak system and briefly review the two other nonelectromagnetically based systems that are now available on the market.

Electromagnetic System (InstaTrak)

The InstaTrak system uses an electromagnetic tracking technology attached to standard aspirators that include the straight, the long straight, the 45° and the 90° aspirators or to other FESS instrumentation (Fig. 1). Intraoperatively, the location of the aspirator tip in the context of the patient's anatomy is presented on a computer screen (Fig. 2). A Sun SPARC Station 5 running the Solaris operating system (Sun Microsystems, Palo Alto, CA) pro-

Received 07/07/99. Received revised 05/07/00. Accepted for publication 27/07/00.

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Presented at the Canadian Society of Otolaryngology—Head and Neck Surgery, 53rd Annual Meeting, Halifax, NS, June 1999.

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vides the real-time position of a suction (or other) instrument on preoperative CT images. Two electromagnetic sensors are used to provide positional information on the CT images. One sensor is incorporated into the standard aspirator or instrument and the second is located on a headset that the patient wears during both the preoperative CT scan and the surgical procedure (Figs. 3 and 4). The headset compensates for head movement during the procedure and is a means for automating registration. Registration is the process of creating a correlation between the position of the instrument in the surgical field and the corresponding location on the CT images. An automated registration method uses the position of the headset to create this correlation without manual intervention. The sensors are registered to show the position of the instrument tip with respect to the three orthogonal CT images of the patient (see Fig. 2). The tip location appears as a set of crosshairs on the display screen that moves through the CT image data in accordance with the movement of the pointer during surgery.[17,18] The newest system, the InstaTrak 3000, allows for the use of two localizing instruments simultaneously. This newer unit also allows for surface calibration, thereby allowing the surgeon to place the headset over the chin instead of the nasion intraoperatively when an external surgical approach is necessary.

The presence of metallic objects in the operative field interferes with functioning of the electromagnetic radiofrequency-based system. A double mattress on the operating table is usually used to avoid interference. Also, a significant amount of metallic hardware on the facial skeleton from previous fracture reconstruction will result in loss of visualization of the affected region intraoperatively. Strategic placement of anaesthesia and other metallic operating room equipment avoids interference with the tracking ability of the system.

The manufacturer has recently introduced attachments that can be used to localize the tip of the Xomed XPS™ straightshot débrider (Jacksonville, FL) and surgical instruments during computer-assisted FESS. A prospective study comparing the InstaTrak's localization accuracy of the Xomed XPS straightshot débrider with the presently available suction tips was carried out at the Georgia Nasal and Sinus Institute for a total of 20 consecutive patients undergoing stereotactic computer-assisted navigational (SCAN) sinus surgery. The mean localization of the straightshot débrider across 20 patients was 1.06 mm, compared with 0.89 mm for the 0° aspirator and 1.05 mm for the 45° aspirator. We found that the accuracy of the new attachment for the XPS débrider was as good as, if not better than, the standard aspirator(s) for most anatomic positions.[19] This study was carried out to confirm our personal impression that the accuracy of the InstaTrak remained acceptable when attachments other than the standard aspirators were used for localization.

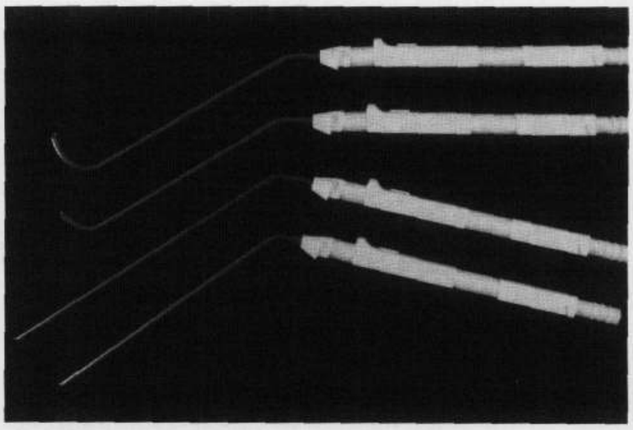

Figure 1 Aspirators used during tracking for the electromagnetically based InstaTrak system.

The manufacturer also recommends the use of one headset for each patient undergoing SCAN sinus surgery. The recommendation is for the same headset to be used during scanning and surgery for maintenance of acceptable accuracy. A study was therefore carried out to determine if a headset other than the one used during CT scanning could be used intraoperatively with an acceptable level of accuracy and if the same headset could be used for more than one patient without a loss in accuracy. We found the accuracy of the instrumentation in localizing the different internal anatomic landmarks using generic research headsets (not used during CT scanning) to be no different when compared with the patients' own headset (used during CT scanning). We also found that the level of accuracy remained unchanged when a headset was used in up to five cases.[19] Contrary to manufacturer recommendations, our study showed that headsets were interchangeable and reusable without a loss in accuracy.

The ConneCTstat™ workstation (Visualization Technologies Inc.) has recently been introduced for use in the clinic. It is a desktop computer designed to accept network transfer of CT data from standard CT scanners supporting DICOM 3 output. It can be used by the surgeon to scroll through images in all three orthogonal planes in an office setting as soon as data are transferred from the CT scanner. It allows the surgeon to review the scan with the patient prior to surgery and can be very effective in preoperative planning. It can also be used as a powerful radiologic and anatomic teaching tool for medical students and residents.

Optical Systems

Landmarx™

The Landmarx system (Xomed Industries) uses an infrared tracking system to locate the real-time position of surgical instruments on the patient's preoperative CT scan. The instrument tip is depicted by

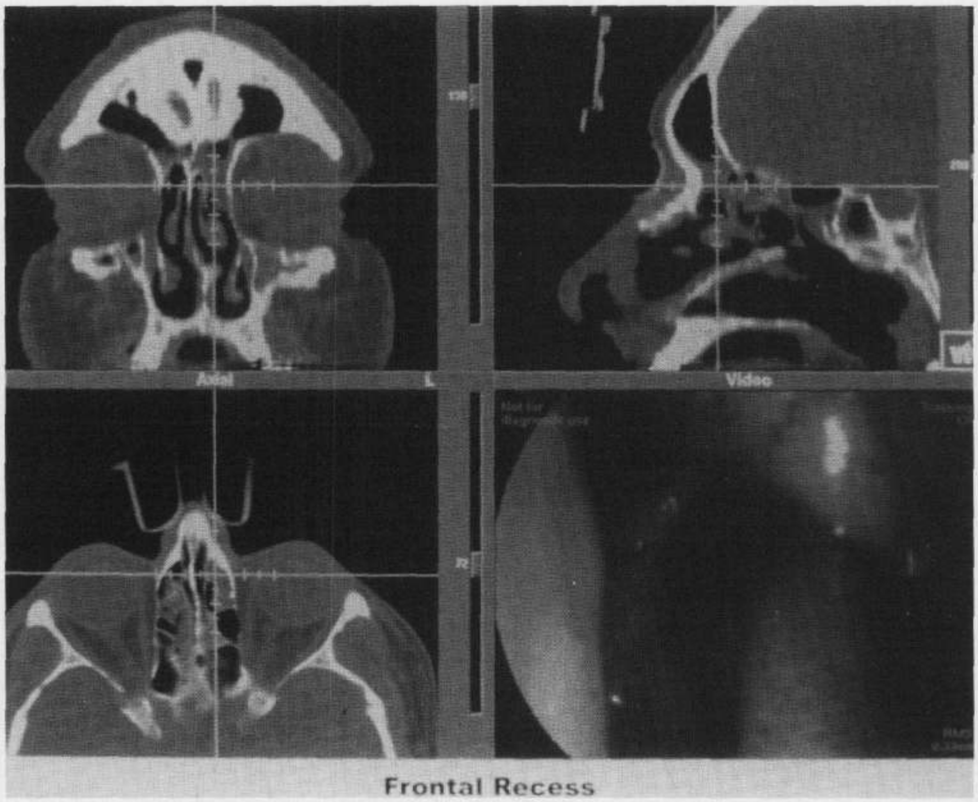

Figure 2 Intraoperative monitor view of the InstaTrak system showing localization of the instrument tip on all three orthogonal planes.

crosshairs on a video display of a reformatted three-dimensional image, as well as axial, coronal, and sagittal CT views. The optical sensor is an array of three infrared cameras attached to an articulating arm attached to the main body of the computer tower. Optimal resolution is obtained by positioning the cameras approximately 6 feet from the head of the operating table. The cameras coordinate the position of light-emitting diodes (LEDs) that are attached to a straight probe or standard sinus instruments to a separate set of LEDs mounted to a headset worn by the patient during surgery to monitor head movement. An optical digitizer and Silicon Graphics Indy Workstation (Palo Alto, CA) is used to process the information. It is important to note that rotation of the operating instrument will interfere with tracking when a direct line of sight between the cameras and the LEDs on the instrumentation is not maintained.

Calibration of the surgical handpiece is carried out by placing the tip of the instrument in a divot on the headset LED array while the foot pedal is depressed. For registration, anatomic surface fiducials are correlated with corresponding points on the CT images. The location of these surface fiducials on the patient's face is touched with the tip of the straight probe while depressing the foot pedal. During surgery, the location of the instrument tip is displayed on the CT images whenever the foot pedal is depressed. When the foot pedal is released, the current location of the instrument is frozen on the computer display.

The Landmarx system allows for loading of 1- to 3-mm axial scans and reformatting of the coronal and

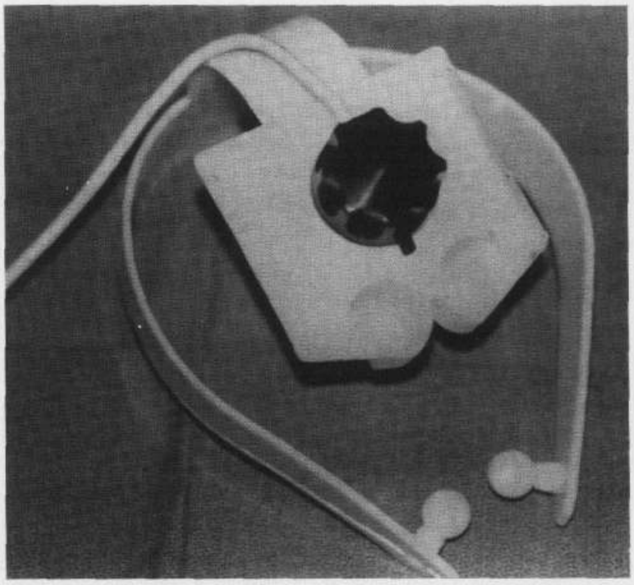

Figure 3 Electromagnetic sensor incorporated into the Instatrak headset.

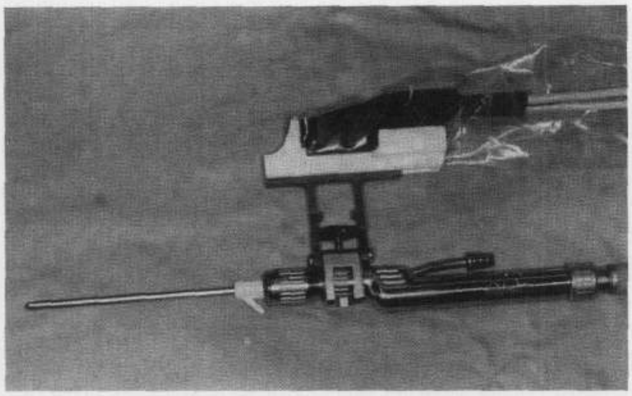

Figure 4 Electromagnetic sensor attached to the Xomed XPS Straightshot débrider for intraoperative tracking.

sagittal scans in the operating room. This eliminates the need to have reformatting done on a separate workstation or via the radiology department. The patient is not required to wear a headframe during CT since registration is carried out using surface fiducials on the patient's face. The headframe is held in place by a band across the brow during surgery and is sterilizable and reusable. An advantage of the Landmarx headframe is that it allows access to the frontal sinus for trephination-type external procedures and for procedures in the medial canthal or auricular regions.

VectorVision²™

The VectorVision² system from BrainLAB Inc. (Munich, Germany) is the newest optically based computer-assisted navigation system being introduced to the market for sinus surgery. It follows the same basic principle as the Landmarx system with regard to an optical sensor involving cameras that monitor LED-type spherical receivers attached to surgical instrumentation, with a few differences. The receivers attached to the instrumentation are wireless "passive" markers that can be clamped onto any surgical instrument. Because these receivers are spherical in shape, they allow the instrument to rotate up to 250° without losing the ability to track. The system also allows for the use of four different instruments to be attached for tracking simultaneously. In addition, it has the ability to identify the physical diameter of the instrument while tracking. Therefore, it allows the entire instrument to appear as an outline on the computer screen when being used. The different instruments appear on the screen in different colours for ease of differentiation intraoperatively. The software is a Windows NT-based system that allows for snapshots of the computer image to be stored and used for manipulation, as well as for Microsoft Powerpoint™ presentations. This system requires the patient to wear a headframe during CT scanning, which allows automatic registration in the operating room. It also allows for the use of a docking station notebook computer that allows the surgeon to review the CT images prior to surgery. The cost for the "watered-down" sinus surgical system is expected to be about US$125,000.

Discussion

Computer-assisted navigation for sinus surgery is becoming increasingly popular for revision procedures and for skull base procedures such as repair of cerebrospinal fluid leaks and pituitary surgery. The technology is extremely useful for patients who have had previous sinus surgical complications or in cases where the disease has destroyed the lamina papyracea or skull base. We use computer-assisted navigation for all of our cases, including primary cases. We believe that it results in more complete surgery with a reduction in the risk of surgical complications. It is exceedingly valuable in detecting potentially risky anatomic sites and in helping prevent orbital and intracranial complications during surgery. We also believe that these patients have a reduced rate of revision surgery than patients who have not had computer-assisted navigation during surgery.[20]

Image guidance systems are now available in over 150 institutions in the United States, Europe, and Japan and are often being employed for primary FESS cases. Both the electromagnetic and the optically based systems are relatively easy to use and reliable for sinus surgery. Anatomic localization is found to be accurate to less than 2 mm for both systems.[17,19] Both systems compensate well for head movement, making head fixation unnecessary. Each system now provides the ability to use more than one instrument for tracking at any one time, and the VectorVision² allows for four instruments, including the endoscope, to be tracked simultaneously during surgery.

The InstaTrak system uses a radiofrequency signal for localization. Metallic objects in the surgical field can distort this signal. This is avoided by placing the patient on two mattresses to avoid interference from the metal operating table. Instrument tables and anaesthesia equipment also have to be positioned appropriately from the surgical field to avoid interference with the radiofrequency signal.

The optically based systems require a clear line of sight between the infrared camera and the LEDs on the surgical instrument to function correctly. The instruments have to be held with the LEDs uncovered and pointed in the direction of the camera during tracking. This system does not allow for the placement of equipment (or personnel) between the patient's head and the camera. The VectorVision² allows the instruments to be rotated up to 250° without losing tracking ability.

All systems require additional operating room time for equipment set-up and operation. Metson et al.[18]

compared the InstaTrak system versus the Landmarx system and found that the InstaTrak system took 17 minutes longer for set-up. However, the InstaTrak was the first system they used and therefore required more time to get used to. They felt that an additional 20 to 30 minutes per case was required when first learning to operate either system, but once the staff became familiar with the equipment, this time could be reduced to less than 10 minutes. We have been using the InstaTrak system for 4 years, and our set-up time ranges between 5 and 10 minutes per patient.

The cost of these systems is comparable but significant at present. The systems range from US$120,000 to about 150,000. However, they allow the sinus surgeon to carry out more complete surgery with an increased margin of safety. It is important to realize, however, that the systems can, on occasion, be inaccurate by as much as 5 mm. Stereotactic computer-assisted navigation should never substitute for adequate surgical training and thorough understanding and knowledge of the variable and complex sinus anatomy that exists between patients.

Conclusion

The computer-assisted navigational systems discussed here have become increasingly available to the sinus surgeon over the last 5 years. They have become the standard of care in many advanced sinus centres for revision and difficult sinus surgery and for skull base procedures. They provide accurate information regarding anatomic localization during sinus surgery and consequently allow the surgeon to carry out more complete surgery with increased confidence. As a consequence, complication rates during these procedures are anticipated to decrease with an increase in patient safety. These systems, however, are not a substitute for adequate training and knowledge of sinus anatomy.

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