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Review Article

Three-dimensional computed-aided endoscopic sinus surgery

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Abstract
Three-dimensional computer-aided surgery adds a 'third-dimension' to endoscopic sinus surgery. The images it provides have the potential to provide the surgeon with further information that might result in safer and more effective surgery with less surgical morbidity. The gold test, as yet untested, will be whether the technique leads to fewer revision procedures and complications as a result of more complete and safe initial surgery. Its greatest asset lies in reinforcing the surgeons' estimate of an instrument's position in a difficult anatomical area. It can augment the learning curve and enhance teaching and training in endoscopic sinus surgery but it is not a substitute for a thorough knowledge of paranasal sinus anatomy.

Key words: Paranasal Sinuses; Surgical Procedures; Operative; Endoscopy; Image Interpretation, Computer-Assisted

Introduction

Computer-aided (image-guided) surgery has become a valuable tool for the rhinologist in endonasal endoscopic sinus surgery. The term computer-aided surgery originally coined in Aachen, Germany is now used worldwide to refer to intra-operative navigation systems in general.[1] In the past it has been referred to as computer-assisted or augmented surgery. These terms have now been superseded by computer-aided surgery since the use of the computer neither truly assists nor augments surgery but aids the surgeon through a complex procedure.

History of computer-aided systems

Computer-aided systems were first used in neurosurgery during operative procedures to destroy discrete parts of the cerebrum to help alleviate pain and reduce tremor. They calculated the trajectory of planned surgery but did not show the actual position of surgical instruments, that is the hallmark of modern day systems.[2,3] These early systems utilized a stereotactic frame fixed to the patient's head with cranial screws. Fixation of the head with immobile frames is not suitable for endoscopic sinus surgery because movement of the head is often required to obtain access to deeper structures.[4] Therefore, in endoscopic sinus surgery, frames have been replaced by moveable headsets.

Computer-aided surgery in rhinology

With modern optical technology the surgical view of the intranasal and intrasinus anatomy has improved. However, it is not stereoscopic and distorted anatomy or intra-operative bleeding can reduce visibility. That endoscopy reduces the depth of perception is attributed as a major contributing factor to the orbital and central nervous complications that can occur.[5]

The development of computer-aided surgery has become popular as it adds a 'third dimension' (in addition to computed tomography (CT) and endoscopic views) allowing the surgeon to point to a specific structure in the surgical field using an instrument and to view its location on the CT images preloaded into a computer and displayed on a monitor.[6] The first reported use of computer-aided surgery in rhinology was from the Aachen University of Technology in Germany in 1986 using a passive robot arm.[5] Since then many new systems have been developed which will be described later.

Principles of computer-aided endoscopic sinus surgery

The principle of computer-aided systems is to provide the surgeon with a direct interactive link with the pre-operative CT (or magnetic resonance (MR)) images.[7] This is achieved by reformatting patient specific CT (or MR) images acquired pre-

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operatively and displaying them on screen from a variety of planes (coronal, sagittal and axial). During the operation the system tracks the position of specialized surgical instruments in or on the patient anatomy and continuously identifies and updates these positions on the pre-operative images, thus allowing safer, precise and more complete surgery to be performed.

To ensure optimum benefit from these systems certain principles should be adhered to. These include that:

(1) the surgeon should spend time studying the pre-operative CT scans on the computer in order to develop a three-dimensional map of the patient's sinus anatomy,
(2) precise surgical dissection is of prime importance, and
(3) the navigation system should not be an excuse to 'point and hunt' for a structure but to help the surgeon confirm the position of the instrument.[6]

Criteria for computer-aided surgery systems

Roth *et al.*[8] presented some important criteria for the computer-aided systems in use for endoscopic sinus surgery.

(1) An intra-operative accuracy of 2–3 mm should be achieved,
(2) the need for two pre-operative CT scans should be abolished by the use of surface marking registration methods,
(3) head movements should be compensated and updated for by the computer,
(4) instruments that are used such as suction devices and dissecting tools should have sensors attached to allow them to be used as probes, and
(5) the devices should be user-friendly to eliminate the need for a technician in theatre.

At the current time of writing nearly all, if not all, of the modern day systems fulfil the above criteria and further technological advances continue to be made.

Indications for computer-aided endoscopic sinus surgery

Computer-aided endoscopic sinus surgery can be used for a range of operations but it is by no means necessary for all endoscopic sinus procedures. There are certain areas, however, where its use is particularly advantageous over conventional endoscopic techniques.

Anatomically, computer-aided surgery is most useful in potentially risky sites to help prevent orbital and intracranial complications. These areas include the frontal recess, determining the height of the skull base and in particular the cribiform plate, the proximity of the lamina papyracea, and localizing structures in the lateral wall of the sphenoid. It is particularly valuable in undertaking median drainage procedures when the frontal recesses are stenosed.

In terms of disease pathology computer-aided surgery has special value where the normal anatomy is distorted, complex or where there has been previous surgery. This includes severe sinonasal polyposis, allergic fungal sinusitis, chronic invasive fungal sinusitis and some sinonasal tumours.[6] Other applications include optic nerve or orbital decompression, skull base tumours, drainage of orbital abscesses, and for choanal atresia in paediatrics.[2]

A relative indication is its benefit in helping the trainee and to build up a concept of the three-dimensional relationships of the sinuses.

Steps in computer-aided endoscopic sinus surgery

Although systems vary slightly in their mechanism of action there are several sequential steps that need to be followed in computer-aided endoscopic sinus surgery. These are:

(1) pre-operative work up,
(2) modelling,
(3) positioning in theatre,
(4) registration,
(5) a method of localization, and
(6) display on a screen.[1,9,]

Pre-operative procedure

Patient selection is paramount and a thorough history, physical examination and a course of medical treatment should ensure that computer-aided surgery is used optimally. If a decision is made to use computer-aided surgery, then a CT (or MR) scan is performed pre-operatively. Axial slices of 1 mm thickness at 1 mm intervals are used to scan an area from the base of the maxillary sinuses to the superior margin of the frontal sinuses. Some systems require a headframe to be worn in this pre-operative CT scan. The radiology technician then transfers this CT data onto a magnetic optical disc or digital audiotape that can be directly transferred to the computer in the operating room.[9]

Modelling

This is the computer process of reformatting the pre-operative axial image data to form a three-dimensional reconstruction of the patient anatomy in the three primary orthogonal planes (coronal, sagittal and axial). CT seems to be the imaging modality that presents least problems for current computer technology whilst MR reconstruction is associated with problems due to distortion of magnetic field lines.[1] The surgeon should study the CT scans and the computer modelled three-dimensional images to ensure the 'road-map' of the patient's individual sinus anatomy is embedded in his mind prior to operating.

Positioning of the patient, surgeon and equipment

The patient is placed supine on the operating table and the headset applied. During surgery the surgeon faces the computer workstation monitor and observes the CT projections and endoscopically

FIG. 1
Theatre set-up with an optical (LandmarX®) system.

navigated pictures (Figure 1). The equipment is positioned so that assistants do not obstruct the view of the monitor or in the optical systems the line of sight between the sensors and the camera.

Registration

This is the process of aligning the pre-operative CT scan images with the patient prior to operating. This is a necessary step in all computer-aided surgery systems and the accuracy of the system is dependent on how closely the two align.

There are essentially three methods of registration: headset registration, fiducial markers and surface registration. Headset registration requires the use of the same headset for both the pre-operative CT scan and the procedure. The placement of the headset at surgery leads to automatic registration. The design of the headset ensures best possible reproducibility. Fiducial registration entails placing optical or ferrous markers on the patient before the CT scan that are used as registration points in the operating theatre. However, this means that the fiducial markers remain on the patient between the CT scan and surgery and this is usually only feasible if the scan is organized for the same day or the day prior to surgery. This often entails a second pre-operative scan as the initial scan does not have the fiducial markers in place. Albritton *et al.*[10] has recently described the use of a malleable registration mask with 10 nickel fiducial markers that is applied to the patient's face.

Most optical systems now use natural landmarks and perform 'surface registration' (LandmarX, StealthStation, VectorVision systems), which allows pre-operative scanning without any headset or patient-mounted fiducials. This involves the surgeon touching a finite number of discrete points on the patient with a probe and registering the corresponding points on the three-dimensional model depicted on the computer display.[7,9] Four to six points are usually chosen and may include the tragi, lateral orbital rims and lateral canthi, medial canthi, the deepest part of the glabella, the columellar-labial angle, and the nasal alar rims. Surface registration must be conducted carefully as the accuracy of the match between the surface contact points on the patient and the corresponding points on the computer model determines the accuracy range of the registration.

Once registration has occurred the surgeon should perform an anatomical check with known structures to evaluate positional accuracy and estimate target error. The probe localizes to the respective area on the three-dimensional image and thus provides visual confirmation of the correlation between the actual and displayed position. Each instrument used must be registered and verified before use.

Method of localization

This refers to the system that is used to translate the position of a probe in the surgical field into coordinates on the preloaded pre-operative CT/MR images displayed on the computer monitor. The critical component of this localization system is the digitizing sensor or tracker. Four different types of tracking technology have been used. These are optical, electromagnetic, electromechanical and sonic. At present, however, optical and electromagnetic systems are the only two in widespread use.

Optical. In recent years these have become the most popular systems for computer-aided endoscopic sinus surgery. Various systems exist such as the LandmarX®, (Xomed Corporation, Jacksonville, FL) (Figure 1), StealthStation® (Sofamor Danek, USA) and VectorVision® (Brain LAB, Germany). There are two types of optical tracking systems: active and passive. In the active system (LandmarX) the headframe and the instrument have infrared emitting diodes that are detected by an array of two cameras. These utilize a number of infrared imaging diodes (three to five) attached to the operating probe or instrument in a distinctive geometric pattern. This system needs the hand held instrument to be connected by a wire to the generator. Knowledge of their relative positions to each other and the cameras thus determines the probe position.[1–3]

The passive system (BrainLAB) depends on three diode markers attached to the instrument being detected passively by the infrared cameras. A three-camera array system positioned at six feet from the headset detects the position of these diodes. The headset which is not worn during the pre-operative scan, contains a sterile virtual keyboard which is used intra-operatively. This virtual keyboard allows the surgeon to remain independent of a computer operator by inputting commands directly into the computer without disturbing the surgical field.[11] The headset also contains diodes and is therefore crucial for registration of each instrument. The cameras are equipped with infrared filters and so stray light has negligible influence on the system calculations.

The disadvantage with this system is that a clear line of sight must be maintained between the instrument sensor, the headset and the camera array. It is vital that the headframe does not slip during the procedure. At present the range of

FIG. 2
Theatre set-up with an electromagnetic (InstaTrak®) system.

instruments available do not have infrared imaging diodes placed in a variety of positions that enable them to be used and detected by a camera in one position. This particularly applies to instrumenting in the frontal recess. This means that the camera and stand have to be moved in order for the signal to be detected.

Electromagnetic. The principle of electromagnetic systems is localization by the detection of ferromagnetic probes within a magnetic field. The most widely used electronic system is the InstaTrak® (VTI Inc, Boston, MA) (Figure 2). This consists of a headframe with an electromagnetic transmitter (Figure 3), detachable probe with an electromagnetic receiver in its handle, and a computerized control system with a high-resolution monitor. When the receiver is brought into the magnetic field a voltage is induced within the coils of the magnetic field generator and the strength of the voltage will depend on the orientation of the receiver within the magnetic field. A plastic headset is worn by the patient during the pre-operative CT scan and the surgery. The headset produces a constant co-ordinated reference for the patient (by virtue of several metal balls incorporated into the headset) and is also a means of registration.

FIG. 3
InstaTrak® headset with electromagnetic field generator.

The presence of any other ferromagnetic object such as aluminium in the surgical field can destabilize and distort the magnetic field although this is unusual. The exact same headframe needs to be worn for the pre-operative CT scan and the operative procedure. This system is easy to use and is widely accepted.

Electromechanical. These stereotactic systems rely on detectors located within the joints of a table-mounted, position-sensitive, articulated multijoint robot arm. An example of such a system is the ISG Viewing Wand (ISG Technologies, Ontario, Canada).[9] The position in space of the tip of a probe or instrument connected to the arm is calculated from the arm geometry and information from the joint detectors.[1] Problems with this system are that movement of the patient's head affects registration and hence the head has to be immobilized. The device is also bulky and space consuming in the operating theatre.[7]

Sonic. These systems are not used much today. Their mechanism of action is based on measuring the time for sound emitted from several locations to be absorbed by several microphones. Problems with this system are that temperature differences and humidity affect the speed of sound, and echoes, airflow and convection currents may diminish the reliability of the system.[1,2]

Display

The working computer display screen for computer-aided endoscopic sinus surgery is divided into four quadrants. Three quandrants simultaneously show greyscale two-dimensional coronal, sagittal and axial sectional images reconstructed from the pre-operative CT scan.[7,9] The tip of the probe or surgical instrument with markers (Figure 4) is depicted by crosshairs on the images. The fourth quadrant can be used either as an onscreen control panel, for display of the endoscopic views (Figure 5), or in more recent systems the three-dimensional reconstructed models (Figure 4).

Discussion

Image-guidance for endoscopic sinus surgery affords a 'third dimension', providing depth to the two-dimensional view through the endoscope. It is for this reason that the use of computer-aided systems for endoscopic sinus surgery is becoming more widespread. The various systems differ in certain aspects, however they all share some common features.

Accuracy

Much has been written on the accuracy in millimetres of these three-dimensional navigation systems. Cartellieri *et al.*[12] reviewed five 3D-navigation systems and reported that system precision on the screen unpredictably varied between 0 and 5 mm during surgery. Inaccuracies can originate from the CT scan and its reconstruction, the tolerances of the

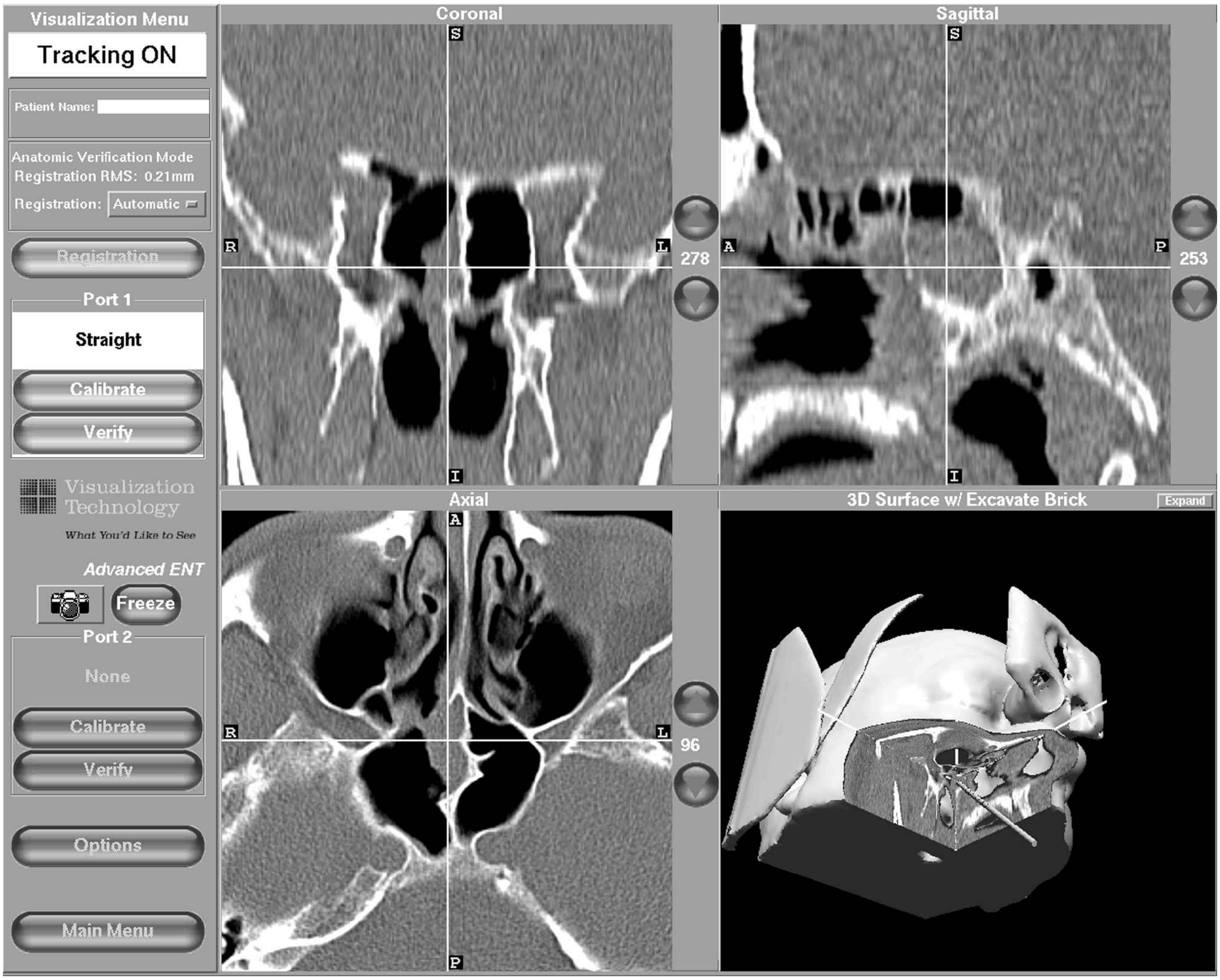

FIG. 4
On screen 3-dimensional model and CT images in three planes.

sensor device, the ability of the surgeon to place the probe on an exact point, mathematical round-off errors, patient motion, and in electromagnetic systems through interference by surrounding ferromagnetic structures.[5] This reinforces the fact that the success of the operation still depends primarily on the skill and experience of the surgeon and cannot be replaced by technology, and further that the operating surgeon must estimate registration accuracy on several occasions during the procedure.[6] However, generally accepted figures suggest an accuracy range of 0.5 to 3 mm with a mean of approximately 1 mm, which is a standard of precision acceptable for clinical use.[12]

Operative time

Metson *et al.*[13] showed that using the image – guided system over conventional endoscopic sinus surgery increased operative time and this was cited as the major disadvantage by 71 per cent of surgeons. Operative times were initially longer but as surgeons became familiar with the technology the increase in operating time was shown to fall from 15–30 minutes to five to 15 minutes. The registration period, and the increased tendency to authenticate the surgical position, contributes to most of this increase in time but attempts to cut corners during registration can compromise accuracy and hence a balance between the two has to be reached. Registration time is negligible and automatic with systems using the headframe during CT scanning. Optical systems using surface registration need more preparation time but this time is not wasted as it is crucial in order to increase accuracy that will in turn give the surgeon added confidence and increase the speed of the procedure.

Economic factors

Computer-aided endoscopic sinus surgery is more costly than traditional endoscopic techniques. In addition to the computer system, there are the costs of the optical discs, prolonged anaesthetic time and possibly the need for a larger operating room. Older CT systems required two scans, one for the initial

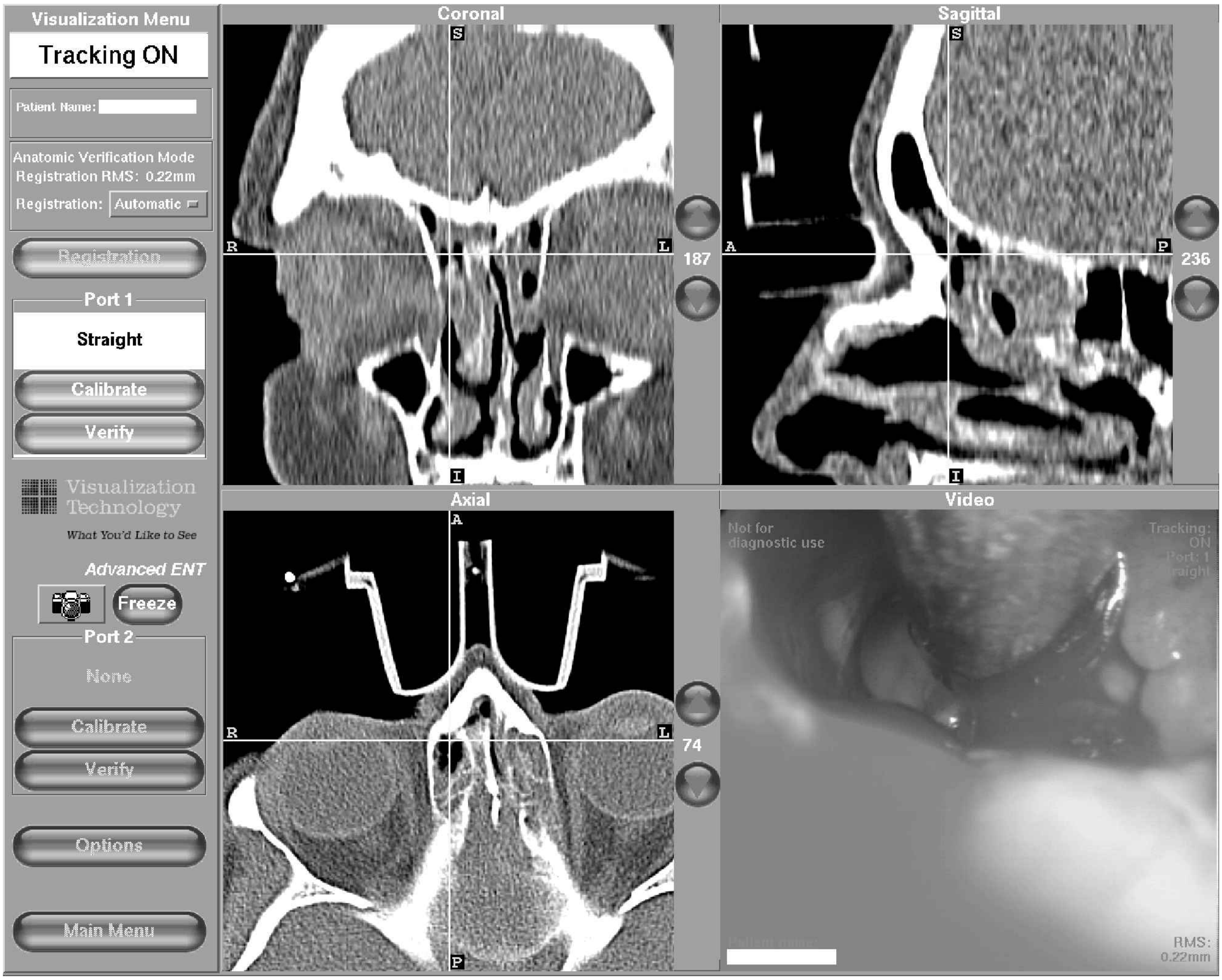

FIG. 5

A computer display showing an endoscopic image and CT images in three planes.

diagnostic purposes and then one for use with the computer-aided system. Newer systems now require just one scan. A cost analysis by Gibbons *et al.*[14] showed that computer-aided endoscopic sinus surgery provided significant benefits for the patient despite being more expensive and hence was 'cost-effective'. Taking the above into consideration and given the higher precision of surgical dissection and improved surgeon confidence, many authors believe that these high initial costs of 3D navigation systems are justified in the long term.[15]

Anaesthetic and surgical access

Traditionally in Europe, endoscopic sinus surgery has been performed under general anaesthesia. Most current optical and electromagnetic systems allow movement of the patient to be detected by the system. This allows the option of surgery being performed under local anaesthetic, that will eliminate the risk of general anaesthesia and also have economic benefits.[2]

Some systems use a headframe (e.g. InstaTrak®) that covers a portion of the medial orbit and frontal regions. This can compromise an external approach if required. Other techniques such as the malleable registration mask suffer from the same disadvantage.[10]

Complication rates and blood loss

A major advantage is the improvement in three-dimensional positioning that leads to an increase in the surgeon's confidence.[13] Intra-operative blood loss and complication rates however, have not been shown to be reduced using computer-aided systems. The added confidence should allow more radical dissection, that might theoretically reduce the possibility of recurrent disease. However, excessive confidence has the potential to lead to larger surgical procedures and increase the potential for complications. If the crosshair is not in agreement with the probed structure, the surgeon should rely on his own experience and recheck the accuracy of the system using the defined anatomical structures.

Operating-theatre space and software

In the optical system the camera must be a certain distance (usually six feet above the head of the table) for optimum function. The surgeon must realize that computer-aided technology is susceptible to problems that may afflict any computer, such as software bugs and hardware failure. It is therefore of utmost importance that surgeons are familiar with the technology they are using so that they may recognize these problems early and act to rectify them quickly.[6]

Teaching

Computer-aided systems allow medical students and junior trainees to appreciate paranasal sinus anatomy in a manner not experienced previously. Being able to visualize the endoscopic view and the CT image on the same monitor provides an excellent teaching tool for surgeons in training and helps the supervising surgeon to identify what step the trainee is doing.

The future

The claim that computer-aided systems in endoscopic sinus surgery are 'real-time' is at present, inaccurate. Computer-aided surgery relies on pre-operative imaging data rather than intra-operative imaging and hence does not reflect or compensate for tissue changes, volume shifts or dissection during surgery.[6] The future of computer-aided endoscopic sinus surgery is for simultaneous or periodic real-time imaging using intra-operatively acquired MR images to reflect these changes in anatomy.[16] At the time of writing real-time image-guided neurosurgical procedures are being undertaken in MR scanners. However, recent work suggests that there remains more work to be done before the use of this application becomes more widespread.

Cartellieri *et al.*[17] performed intra-operative CT on six patients undergoing computer-aided endoscopic sinus surgery. Several problems were encountered that included the need for more operating theatre space and for radiologists or technicians in theatre, the use of the scanning table as an operating table, the prolonged exposure of the patient to radiation, and the fact that in small sinus cavities it was difficult to differentiate soft tissue from liquids. They concluded that although better precision was achieved, the use of three-dimensional navigation systems in combination with intra-operative CT could not be recommended for standard endoscopic sinus surgery at the current time.[17,18]

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