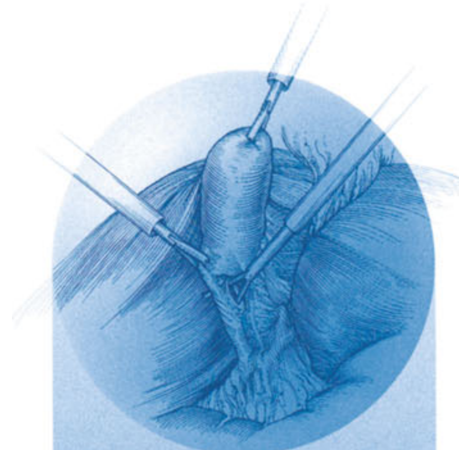
Virtual reality for image-guided surgery

Joachim Kettenbach
Karl Landsteiner University of Health Scien…

Ferenc A Jolesz
Harvard Medical School

Ron Kikinis
Harvard Medical School

William E. Lorensen
General Electric



CHAPTER 20

Virtual Reality for Image-guided Surgery

Ferenc A. Jolesz
Ron Kikinis
William M. Wells III
William E. Lorensen
Joachim Kettenbach

Recent advances in medical imaging techniques have led to an escalation in the use of image-based information by radiologists, clinicians, and surgeons. The increased availability of imaging modalities is of considerable use to the physician; however, these methods are still inherently limited because they provide images with information limited by the physical characteristics of the imaging device. Although the direct interpretation of images is sufficient, some situations require postprocessing for the extraction and use of the anatomic and physiologic information inherent in the three-dimensional medical images. This chapter reviews some applications that would benefit from improved use of effectively processed medical images.

DISEASE DIAGNOSIS

Early detection is often the key to effective treatment. Images of internal organs provide evidence of particular diseases that are manifested through structural or functional changes. The high resolution and high contrast available with ultrasound, CT, and magnetic resonance imaging (MRI) aid the diagnosis of a wide range of problems. Diagnosis can be improved not only with computerized tools that can highlight such diseases in single images, but also with methods that allow accurate comparison among images.

TREATMENT MONITORING

By taking multiple images of a subject over time, the physician can effectively track progress or regress of a medical condition and quickly determine the impact of treatment regimens. By using initial images as a baseline, such follow-up examination results in interpretations that are more specific to the disease process.

MULTIMODALITY INFORMATION INTEGRATION

Because different imaging modalities highlight different tissue types and different physiologic functions, it is often useful to fuse information from different imaging devices, such as blood vessels from angiograms, soft-tissue structures from MRI, bones from CT, or metabolic activity from single-photon emission CT (SPECT) or positron emission tomography. Differing resolutions, aspect ratios, possible distortions, and differences in coordinate frames pose difficult problems in interpreting these combined images.

AUGMENTED INTRAOPERATIVE VISUALIZATION

Visualization during surgery is incomplete because the surgeon cannot see the anatomy beyond the exposed surfaces. For example, conventional craniotomy is markedly

D. C. Brooks (ed.), *Current Review of Minimally Invasive Surgery*

constrained by the relatively small area of exposed brain surface, which lacks spatial clues that surgeons would need to comprehend all of the relevant anatomy. Such limitations of direct surgical visualization have several consequences. First, localization is not accurate and is even more compromised within the parenchyma. Second, the definition of exact trajectories for targeting is impossible without image guidance. Third, if the anatomic and pathologic boundaries are not clear (and thus accurate tumor localization is not possible), normal tissue has to be removed to ensure complete resection.

In many procedures, the surgeon has a limited view of the operating field and cannot visualize structures beyond the exposed surfaces. In minimally invasive surgeries, particularly during endoscopic procedures, the surgeon is also confronted with difficult hand-eye coordination problems because he or she is looking at a camera's view of the surgical field with a totally different reference frame than his or her own. In other cases, procedures are complicated by the similarity in visual appearance of different tissues (*eg*, tumor and healthy tissue), although such tissues have high contrast in some medical images. The best examples are breast cancer and brain glioma, which can be difficult to distinguish from normal tissue. Better use of the three-dimensional imaging can improve surgical visualization and help the surgeons overcome the limitations of existing procedures. In particular, enhanced reality visualization, in which the surgeon's field of view is augmented with additional structural information, can provide useful guidance in planning and executing the surgery.

INSTRUMENT TRACKING

Another application for bringing the imaging into the surgical process is to track the positions of surgical instruments and relate their location relative to images acquired preoperatively. For example, the correct placement of biopsy needles and minimally invasive surgical tools such as laparoscopes and remote cutting tools is problematic if they are out of the visual field. By tracking the three-dimensional position of these instruments, the position of the instrument can be shown on scans of the patient, such as MRI or CT.

INTRAOPERATIVE GUIDANCE

Because of the unavoidable changes of anatomy and tissue position during surgery, preoperatively acquired images have substantial limitation in guiding procedures intraoperatively. Real-time imaging or frequent image updates can provide the necessary corrections for these displacements. Intraoperatively acquired images can also be used for warping and fusing preoperative images to the shape of organs as they change during the surgical procedure. With the development of intraoperative MRI we can now combine the advantages of diagnostic imaging (definition of tumor margins, delineation of anatomy), real-time treatment monitoring (frequent image updates during open surgeries or real-time temperature-sensitive imaging of thermal ablations), multimodality image registration (with the possibility of elastic warping to the actual anatomic boundaries), visualization of the surgical field (in combination with enhanced reality display from three-dimensional images), and instrument guidance (intraoperative tracking and interactive scanning).

To fully use the information available from medical images, and to optimally provide those to the diagnostic radiologist, surgeon, or clinician, we need to 1) extract the structural and functional information of particular relevance, and 2) provide that information in an effective manner. To achieve this desired goal, several key issues must be resolved, including image segmentation, image registration, and visualization.

Image segmentation

Segmentation converts the medical images into anatomically, functionally, or surgically identifiable structures that are more readily useful to the operator. This procedure involves the classification of particular tissue types, such as bone, fat, vessel, white matter, gray matter, or tumor. Such classification is based on the ability to discriminate among tissue types as well as anatomic knowledge of tissue structures and relationships. By providing automated tools for segmentation, we gain the ability to transform the raw image data into three-dimensional structures that more directly relate to the patient's anatomy.

Image registration

Registration involves the alignment of various image data sets (*eg*, MRI and CT scans) such that correspondences among them can be more easily identified. In this process, raw image data or the segmented images are transformed into new reference frames in which the geometric relationship between these structures is appropriate for the task. Such transformations are required for fusing information from multiple imaging modalities or mapping functionally, anatomically, or pathologically defined three-dimensional structures to the anatomy of the patient. The key problem in registration is to transform the segmented structures to new reference frames that best use the extracted information. This may mean registering multimodal inputs to a common coordinate frame, such as merging magnetic resonance angiographic data, MRI soft tissue reconstructions, and functional MRI inputs into a common coherent whole. Additionally, it may mean registering such a fused model of the patient's anatomy to the actual position of the patient, for use in image-guided surgery.

Visualization

Visualization is the display of transformed information to the observer in a useful manner. This term refers to the three-dimensional rendering and display of structures using interfaces through which the medical personnel can readily view and interpret the processed data. Image analysis tools must work synergistically with the clinician, providing sufficient interactivity, response, and feedback capabilities. The process of visualization and display are part of almost every use of computers in medicine, from inspection of an MRI series on an interactive console to the measurement of a patient's temperature or blood pressure. Visualization uses image processing, computer graphics, and interactive tools to separate relevant from extraneous information. The results of the visualization process can be computer-generated images, animated movies, or dynamic models with which the viewer can interact. No matter what form the processed data is in, the purpose of its presentation is to help the researcher, scientist, or physician better understand his or her data.

Although considerable progress has been made in these areas, all suffer from several drawbacks. In general, all of these methods are computationally expensive, and generally all still require some level of user interaction or guidance. The former problem will be alleviated to some extent by improvements in computational hardware, as well as by algorithm refinement. At the same time, however, better, more automated methods will also address this shortcoming. The ultimate goal is to provide fully automated methods for extracting important structural and functional information from the images, and to do this one must provide means for incorporating anatomic and other global knowledge into the process.

Although considerable progress has been made in combining computer vision techniques with medical image analysis methods, we are still not at the stage of providing fully automatic, rapid, accurate, and easily used tools for clinical applications.

The goal of image processing and virtual reality displays is to make the presentation of images easier by taking the raw imaging data, segmenting out relevant structures, and then generating three-dimensional computer-based reconstructions. This work has several potential applications:

- Making the work of radiologists more efficient by condensing information from several slices into one image rendering
- Facilitating the communication with referring physicians and enhancing their ability to translate imaging information into a surgical scenario
- Assisting surgeons in planning for surgical intervention
- Assisting in the follow-up
- Assisting in the investigation of pathology by revealing the subtle differences present in magnetic resonance or CT examinations that may not be apparent without processing

Although tissue specificity mostly depends on tissue characterization with a given physical system (*ie*, CT or MRI), anatomic specificity is primarily determined by postprocessing techniques. The development of methodology is primarily driven by specific medical questions. Nevertheless, all tools can be used for multiple purposes and build an integrated environment for medical image analysis.

COMPUTER-BASED IMAGE GUIDANCE

Image guidance, in general, can reduce the inherent invasiveness of surgery and improve localization and targeting by intraoperative imaging via ultrasound or, more recently, MRI. Alternatively, intraoperative image guidance can be based on previously acquired images using reference frames attached to the patient (frame-based stereotaxy), or images that have been registered to the patient (frameless stereotaxy). In the latter case, computers can navigate the operator through three-dimensional coordinates and thus fulfill the need for enhanced visibility during interventional radiologic and minimally invasive surgical procedures.

Image-derived information for treatment can be applied to every stage of the therapeutic process. The increasing demand for refinement of imaging and image representation for surgery requires unique methods for data acquisition, processing, and display, and the full understanding of the process of imaging and its applications to therapy. Image-based modeling requires computerized image-processing methods (segmentation, registration, and display) and image integration techniques, replacing the mental process of generating three-dimensional representations of the patient's anatomy. Although advanced imaging modalities and information processing or display methods are widely used in planning, monitoring, and guiding various therapies, these imaging techniques could be integrated into interventional and surgical procedures.

SURGICAL PLANNING AND SIMULATION

For full comprehension of image-based information, surgeons prefer appropriately rendered and interactively displayed three-dimensional data that resemble the visual information seen during surgical exploration. Automation of image processing, however, makes these novel approaches more and more feasible and practical. Depending on the particular application, preoperative planning implies not only image reconstruction, but also integration of various displays, image manipulation, and visualization tools that help simulate and plan an intervention.

The role of surgical planning in tumor surgery is to define the safest possible approach with the least possible damage to normal tissue. In this trajectory-optimization process, alternative navigational paths and movements through the physical space are tested and analyzed using a preoperative model. In craniofacial and orthopedic surgical applications, the role of surgical planning is the optimal execution of preoperative plans [1–6]. Further expansion of surgical planning and simulation techniques into other surgical fields requires more complex methods (*eg*, elastic warping) and more information about shape, position, and orientation that may correct or account for unavoidable tissue deformations and organ shifts during surgery [7]. Establishing a simulated procedural environment is also a critical step for creating an image-based virtual reality environment that allows the user to actively enter the three-dimensional environment and perform simulated procedures within it.

INTRAOPERATIVE IMAGE GUIDANCE USING PREOPERATIVE IMAGES

Surgery today relies conceptually on the same principles that it did 3000 years ago: the surgeons use their hands to directly control instruments and their eyes to observe feedback on the effect of their manipulations. Accordingly, surgeons need access to the site of an operation for both visualization and manipulation. The evolving modern trend in surgery is the development of minimally invasive approaches, in which the damage caused by accessing the surgical site is reduced. Rigid or flexible long-necked instruments are introduced into the target areas through natural openings or small incisions. These instruments typically carry some form of visualization equipment and provide some way to introduce instruments for procedures.

A skillfully prepared, geometrically correct preoperative plan and a well-developed simulation of the procedure are, in fact, components of an executional operational model that can be implemented in the operating room. Intraoperative image guidance is based on functional integration of the previously acquired and processed three-dimensional information and the corresponding anatomy of the patient within the same frame of reference. During the actual surgery, an interactive real-time display can demonstrate the otherwise hidden anatomic information that has been generated by a single modality or composed from multimodal volumetric images [7–10,11••,12]. Trajectories from the preoperatively prepared executional plans and models can also be exhibited (Fig. 20-1).

Intraoperative guidance requires matching of the two frames of reference. The actual coordinates within which the models exist must be mapped or registered into the physical space of the patient. Links between these two components are realized by combining image-to-patient registration and by tracking instruments within the operational field. These are the key ingredients of frameless stereotactic targeting methods, which capitalize on the interactive control of image planes and exploit the full information content of perceived three-dimensional space.

Patient-to-model registration is substantially different from multimodality coregistration. Image fusion requires matching all image-based geometric data in a single, unique coordinate system. The matched data coexist within a single virtual database, but for image-guided procedures they have to be registered into the physical space of the patient, too. In addition, these data should be overlaid or projected to the patient's exposed surface if surgical guidance is necessary. Various methods exist for patient-to-model registration. In the original, frame-based stereotactic method, three-dimensional points (of the physical frame) are matched with two-dimensional points (seen on the images). Alternatively, surface points are matched with selected anatomic landmarks or external fiducial markers visible on both the images and on the patient. In these methods, the registration process requires pointers attached to position-sensing devices that establish the relationship between the reference frame of the patient and the images.

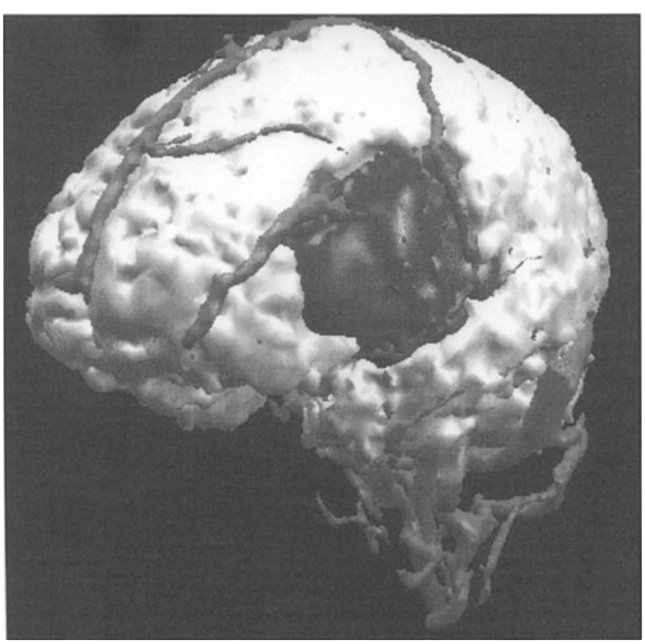


Figure 20-1 A three-dimensional reconstruction of a 37-year-old woman with an astrocytoma of the left frontal-temporal cortex. The tumor is in *green* and the blood vessels in *red*. (*See* Color Plate.)

Other registration techniques match visible anatomic objects, features, or shapes represented on both the patient and the reconstructed images. Video camera–based methods detect visible features on the patient (ear, nose, eyes) appearing on both the reconstructed surfaces and on the video images [13]. Readjusting them to inner surfaces of the organs as they become exposed during surgery can refine skin surface–based registrations. For example, video registration can be improved by matching cortical vessels, visible on the surface of the exposed brain and on three-dimensional reconstructions based on magnetic resonance angiograms [14•]. Currently, we use laser scanning to obtain digitized surfaces and subsequently match three-dimensional curves with three-dimensional curves obtained with automated methods [15••].

To improve accuracy, the various registration methods can be combined. Multimodality data from MRIs, magnetic resonance angiography, SPECT, or positron emission tomography scans and spatially recorded functional physiologic and preoperative surgical planes can be registered to the patient in order to integrate all the available information intraoperatively [9,10].

Reliable and completely automated registration methods can integrate the image-based information with the patient's anatomy. Nevertheless, intraoperative three-dimensional position sensing and tracking is essential to account for the inevitable movements of the patients and the actual path of the surgical instruments. Without establishing the correspondence between the actual position of surgical instruments, anatomic landmarks, and image-derived three-dimensional anatomy, geometric accuracy is impossible and precise plans cannot be executed consistently. After initial registration, patient motion can be tracked by reregistration of the updated images if real-time imaging is available. In computer-assisted surgery, in which only previously acquired images are used, so-called navigational systems establish the relationship between the surgeon's movements and the image-based information within the physical space of the patient [16–22]. Using intraoperative two- and three-dimensional displays or virtual or enhanced (augmented) reality representations, navigation within the patient's body can be guided by both direct visibility and by the images themselves.

To follow the movements of the surgeon's hand or instruments, the position and orientation of passive mechanical arms can be continuously detected at the articulations by encoders [23]. Alternatively, various three-dimensional position sensors can be mounted on the patient or standard surgical tools [24,25••]. These noncontact devices can be used for tracking patient or physician movements or the path of rigid surgical instruments. Optical and ultrasound digitizers cannot transmit through the tissues; therefore, for detecting positions deep inside the body, they have to be placed on the proximal end of rigid instruments. Conventional electromagnetic sensors can be detected through the body, but cannot fit within needles or endoscopes unless they are miniaturized. Currently, a small-scale version of electromagnetic sensors has become available that can be attached to the tip of flexible catheters and inserted into the working channel of endoscopes (Acker and Jimenez, Paper presented at the Fourth Congress of Neurosurgical Surgeons, Montreal, 1996). The tracking technology, using single or multiple sensors, permits the use of instruments such as pointers or tracing tools and enables the physician to outline regions or define trajectories.

The most important aspect of the sensor technology and tracking is interactivity. Conventional stereotactic frames impede freedom of motion and use calculations instead of displays to define positions. In interactive frameless stereotaxy, the computer displays the position and the motion of the instruments accurately and immediately in correct orientation with respect to image-defined anatomic boundaries. Repetitive display of target, trajectory, and volume information allows interaction with the surgical plan and monitoring of the progress of the procedure.

Most of the navigational systems developed in the past decade are relevant only for interactive image-guided neurosurgery and endoscopic sinus surgery. The use of preoperative images for intraoperative image guidance is limited by the potential intraoperative changes in the anatomy. If the navigation is solely based on preoperative images, intraoperative tissue distortions, shifts and displacements (due to retraction of tissues, removal of tumor masses, loss of cerebrospinal fluid, hemorrhage, or edema) cause substantial errors. Modeling of elastic deformations and correction of the images is possible, but only within a limited range; beyond that, intraoperative imaging becomes necessary.

INTRAOPERATIVE IMAGE GUIDANCE USING MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging, because of its high tissue contrast and spatial resolution as well as multiplanar and functional imaging capabilities, has the most appeal for monitoring and controlling therapy. Open configuration magnets, which permit full access to the patient and are equipped with instrument tracking systems, provide an interactive environment in which biopsies, percutaneous or endoscopic procedures, and minimally invasive interventions or open surgeries can be performed. In addition, various thermal ablations with image-based control of energy deposition can be performed to exploit the intrinsic sensitivity of MRI to both temperature and tissue integrity.

Magnetic resonance imaging provides images that are reflective of regional differences in proton concentrations and the physicochemical environment of protons (*eg*, water protons show different magnetic resonance behavior from protons in larger molecules such as lipids, proteins, and so on; protons in hydration water show different magnetic resonance behavior than protons in unbound water). Pathologic changes in tissue composition often alter the proton distribution and can therefore be highlighted by MRI. Therefore, tumoral infiltration, edema, and bleeding can be distinguished from the surrounding healthy tissues.

More specific tissue characterization is being achieved by exogenous administration of MRI contrast agents. Gadopentate dimeglumine (Gd-DTPA) is a compound containing a paramagnetic ion (gadolinium) and a macromolecular chelating moiety (DTPA). The gadolinium ion modulates the magnetic resonance signal whereas the macromolecule moiety limits the molecule distribution in brain tissue to areas of disrupted blood-brain barrier. Postprocessing techniques enable the integration of this information into quantitative tissue characterization maps.

As the computer becomes a more integral part of the surgical process, the need to provide information to the surgeon in a convenient and intuitive way becomes greater. Nowhere is this relationship more obvious than in the interventional MRI system, in which image information acquired by MRI and augmented and annotated by computer data is a powerful tool for intraoperative planning and guidance.

In 1989, the magnetic resonance division of the Department of Radiology of Brigham and Women's Hospital and Harvard Medical School initiated a project to develop magnetic resonance–guided interventional procedures [26,27••,28,29,30••]. The components of this project included 1) the development of a new kind of MRI scanner, providing access to the patient during imaging; and 2) development of the computerized processing methods necessary for efficient presentation and analysis of data generated in such an environment.

General Electric Medical Systems (Milwaukee, WI) participated in the project by building an open magnet, called the SIGNA SP, for surgical applications. The SIGNA SP is a complete environment, including magnetic resonance–compatible instruments, magnetic resonance–compatible anesthesia, monitoring equipment, and so on. The first machine was installed at Brigham and Women's Hospital in March 1994. Since then, several surgical applications have been tested on it, including biopsies, ear, nose, and throat endoscopic procedures [25••,31,32], and open brain surgeries [33,34••].

Near real-time MRI imaging or frequent image updates during interventional and surgical procedures provide updates about patient anatomy or the changing position of movable organs, depicts the position of instruments, and without registration establishes the necessary relationship between the patient and the images. Advances in MRI with high-performance computing now permits the combination and integration of near-real time, high contrast and spatial resolution volumetric images with frameless stereotactic, interactive localization methods while performing image-guided therapy.

During the development of interventional MRI, several obstacles hindered the evolution of MRI-guided interventions. Its value for guiding biopsies of tumors best detectable by MRI was apparent, but the closed magnets—conventional at the time—made it a cumbersome procedure to perform. The incompatibility of the electromagnetic environment, the inaccessibility of patients within the magnets, and the expense of MRI impeded the widespread acceptance of MRI for percutaneous procedures. Advances in low-field open-configuration magnet design and recognition of the potential of MRI for monitoring and controlling thermal ablations and other percutaneous therapies initiated this new direction in interventional radiology. Because of the lack of direct visualization of thermal ablations, a three-dimensional imaging technique must be used to monitor these processes. Using temperature-sensitive MRI sequences during therapy, the progress of heat deposition and the resulting tissue alterations can be observed [35].

This unique potential of MRI provided the impetus for a mid-field open-configuration magnetic resonance system. The goal was to develop a new generation of imaging systems providing relatively unlimited access to the patient, near real-time monitoring, localization, targeting, interactive scanning, magnetic resonance–compatible instruments, and equipment necessary for an magnetic resonance–based interventional suite or operating room. An underlying promise of this project has been that MRI coupled with direct visualization can realize many interventional and surgical procedures better than either could do alone. A further premise is that such a combination of MRI and invasive procedures meets the present trend toward safe and accurate, image-guided minimally invasive therapies [36].

The configuration of magnet determines the scope and the ease with which interventional or intraoperative imaging can be performed. Most of the percutaneous procedures and open surgeries, however, require freehand techniques based on hand-eye coordination and need close and direct contact with the patient's exposed anatomy. The horizontal gap configuration does not permit open procedures and makes more complicated percutaneous procedures difficult to perform. Only the vertical gap allows the physician to enter between the two components of the magnet and directly manipulate the patient's anatomy. This configuration allows the use of endoscopes, laparoscopes, and operating microscopes (Fig. 20-2).

Figure 20-2 Performance in the open-magnet system. For surgery or interventional procedures, the open-magnet design permits direct clinical access to the patient and simultaneous interactive control of the magnetic resonance imaging process.

The SIGNA SP interventional MRI system and the interventional-surgical suite in which it resides combines these key enabling technologies: superconductive magnetic resonance system, flexible transmit and receive coils, computer workstations, position sensors, intraoperative display, and audiovisual equipment [26,27••]. The facility is equipped with magnetic resonance–compatible anesthesia delivery and monitoring devices and instruments for biopsies, thermal ablations, endoscopies, and open surgical procedures. It incorporates and integrates functions related to imaging, image guidance, and therapy. The high-technology environment and its components represent a cross-fertilization between interventional radiology, minimally invasive therapy, and image-guided, computer-assisted surgery. Although the initial application domain included primarily percutaneous biopsy, the capability ultimately evolved into a broad range of interventional and surgical applications in which the combination of direct imaging and real-time image guidance was consolidated.

The most important characteristic of the interventional MRI system is the ability to interactively use imaging to localize, target, and monitor the procedure. The operator can define scan planes and their location as needed. This capability is similar to what can be done using sonography. The interactive image plane selection and definition implemented in the General Electric interventional MRI system (Flashpoint Scan Plane Pointer) uses an optical tracking system (light-emitting diodes localized by infrared-sensitive video equipment). This method has some aspects in common with frameless stereotactic or navigational systems. In particular, it provides direct control of scan plane location, orientation, and angulation with enough flexibility and convenience to perform freehand procedures and enough accuracy for stereotactic biopsies [26,27••]. The system is capable of capturing images along interactively defined coordinates to obtain geometrically correct information about the patient's anatomy and the location of instruments. This system has provided localization and targeting of brain biopsies even in extremely high-risk areas. Application of interactive MRI scan plane selection for performing biopsies of abdominal organs and other body parts also introduced the concept of frameless stereotaxy into the field of cross-sectional interventional radiology [29,37,38].

Interactive image-guidance within the interventional MRI system using optical or other tracking systems can be applied to a wide variety of interventional and surgical procedures. In all imaging modes, the information is acquired according to the position and orientation of the sensors and three orthogonal planes generated within a moving frame of reference. The most straightforward mode is interactive scanning, in which the operator intuitively moves the device in order to obtain a comprehensive view of the scanned three-dimensional volume. This mode resembles sonography except that the three orthogonal planes can be displayed without changing the actual position of the probe. In the localizing mode, the probe is used as a virtual pointer with a computer-displayed icon that can point to or outline an anatomic object within the body. This mode can also be used to trace contours of organs or margins of lesions or to obtain points or surfaces from inside the body for registration.

Using the targeting mode for biopsy, the tip or the shaft of a virtual needle is displayed on three orthogonal planes showing the expected path of the needle as an annotation. If the predicted position of the tip and the planned trajectory is acceptable by the physician, the real needle or probe can be advanced into the target. Using the tracking mode, the trail of instruments or the motion of body parts can be followed and displayed on the image [33].

For interactive image guidance, the images must be generated and displayed quickly enough to be used without disrupting or slowing down the procedure and before considerable changes occur within the operational field. The definition of real-time imaging or dynamic image update is relative and contingent on the time constants of the procedures or processes being imaged. Imaging needle placement may require update of multiple slices or planes. Monitoring thermal ablation of a tumor should incorporate a volume (several slices). Most localization, targeting, tracking, and monitoring requirements can be satisfied by the commonly available fast imaging techniques (fast spin echo, gradient echo). Several novel imaging techniques offer improved temporal resolution achieved by less redundant spatial encoding and without considerably affecting spatial resolution and signal-to-noise ratio. Magnetic resonance fluoroscopy and other dynamic imaging approaches are also available to use preexisting information for adaptive encoding of changing image data [39–42,43••,44].

MONITORING AND CONTROL OF MAGNETIC RESONANCE–GUIDED ABLATION THERAPY WITH INTERVENTIONAL MAGNETIC RESONANCE IMAGING

The greatest potential of MRI is in monitoring and delivering thermal energies using various thermal probes (*eg*, laser, radiofrequency, microwave, focused ultrasound, cryoprobe). This is a particularly important application of MRI guidance because achieving the full potential of these techniques requires not only good localization and targeting but also quantitative spatiotemporal control of energy deposition, which in turn requires monitoring of the thermal changes and the resulting tissue alterations.

Based on our extensive experience in thermal imaging and magnetic resonance–guided thermal ablations [41,42,43••,45,46], we have developed a computer-assisted monitoring technique based on temperature-sensitive MRI for interstitial laser therapy. Clinical applications involving tumor ablation in the brain and liver have already been initiated. The interventional MRI system was used to guide and monitor the accurate placement of the laser source (needle with optical fiber) at the targeted lesion. Newly developed software in the imaging system and the research workstation enabled rapid (27 to 221 ms) and on-line temperature image reconstruction. In the highlighted brain tumor case, subtraction images from T_1-weighted scans and proton chemical shift images clearly showed the signal intensity peak at the tip of the laser guide. The preliminary study indicated that the presented system design is feasible for real-time and on-line monitoring of interstitial laser therapy.

INTRAOPERATIVE MAGNETIC RESONANCE IMAGING FOR OPEN SURGERIES

The simultaneous combination of direct vision and beyond the surface imaging is possible within a unique environment incorporating both the operating room and a MRI scanner. This integrated system allows more accurate localization and targeting during surgery. Definition of histopathologically correct tumor margins, comprehension of the full extent of disease processes, and accurate definition of anatomic landmarks may improve surgical efficiency and diminish the invasiveness. Complete resection of tumors, decreased vulnerability of surrounding tissues, and avoidance of critical structures should improve clinical outcome and reduce complication rates. By merging MRI with frameless stereotaxy, navigational tools, and multimodality image fusion, the combination of all available spatial information with real-time image update became possible. Use of this composite information during open procedures may revolutionize minimally invasive therapy and will lead to the development of new surgical strategies and approaches.

Our early neurosurgical experience based on close to 100 cases illustrates most of the anticipated benefits of intraoperative MRI [34••,38]. Interactive localization and targeting have not only provided on-line planning of optimal trajectories for biopsies, but also real-time image feedback during the needle advancement and tissue sampling (Fig. 20-2). Using this method, lesions within deep and high-risk regions (*eg*, hypothalamus, pineal region, or brainstem) have been biopsied [38]. Unavoidable hemorrhagic complication was immediately recognized, localized, and treated surgically by open craniotomy within the magnet. Intraventricular, relatively mobile and unstable targets have been reached safely, and cystic structures in various locations have been drained under continuous image control. The potential advantages of precise localization and optimized access route have also been demonstrated by combining an operative microscope with MRI-guided resection of deep-seated small tumors and cavernous hemangiomas. Surgical removal of extra-axial tumors may benefit from the delineation of surrounding, directly invisible anatomy.

When viewing the exposed brain surface without imaging, the neurosurgeon cannot define the spatial extent of the tumor, and even after surgically entering the brain tissue, the tumor is indistinguishable from normal cerebral tissue in most patients. Preoperative image data may help to demonstrate the extent of the tumor in some instances. During resection of large, deep tumors, however, brain structures may move and become deformed, negating the value of preoperative images. Using intraoperative optical tracking and refreshing the volumetric images, surgeons are able not only to locate the tumor margins, but completely resect the tumor while preserving the integrity of surrounding normal brain. Similar methods can be applied to resection of other intraparenchymal tumors such as breast cancer or soft tissue sarcoma, in which the margins are difficult to define with the naked eye.

Multimodality representation of morphology can be integrated from previous CT or MRI along with functional physiologic data (transcranial magnetic stimulation, magnetic resonance angiography, and functional MRI) and metabolic information (SPECT). These combined data can then be coregistered with intraoperative real-time MRI data. The resulting composite provides the surgeon the most comprehensive view of the operative field and helps not only to plan but also to execute the procedure. Coregistration of CT, magnetic resonance angiography, and MRI is especially helpful in skull-base surgery. The combination of functional MRI with cortical physiology is invaluable for executing surgical resection without sacrificing critical brain functions. SPECT registration to intraoperative MRI distinguishes metabolically active tumor parts from necrotic areas.

VIRTUAL ENDOSCOPY

Conventional endoscopic procedures demonstrate inner surfaces of hollow organs using direct visualization or video-assisted technology. The operator interactively explores the organs by navigating within them. Endoscopy is useful for the diagnosis of mucosal or epithelial lesions but provides minimal or no information about the extent of disease within or beyond the wall of the viewed organ. Another shortcoming of endoscopy is the lack of sufficient information in localizing lesions relative to surrounding anatomy.

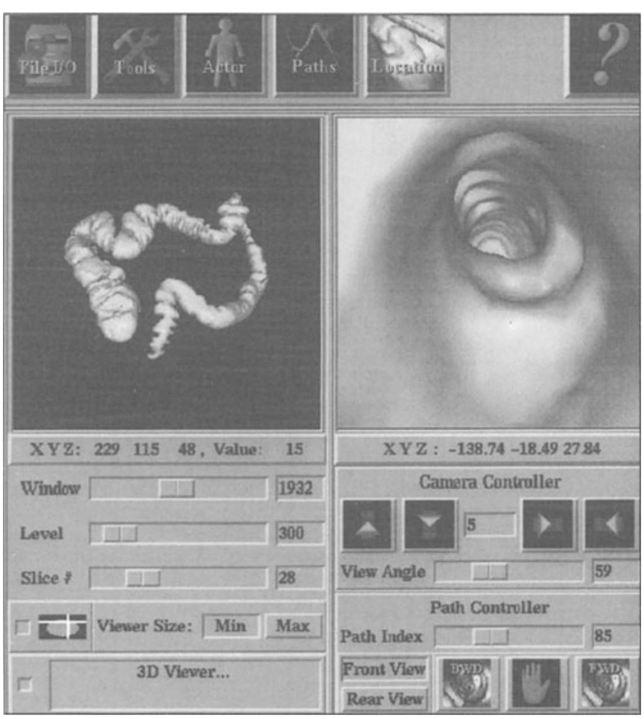


Figure 20-3 A virtual colonoscopy. **Left**, Global view. The program indicates the corresponding virtual camera position with the green line and also has the ability to display the corresponding computed tomographic slice. **Right**, The camera view is displayed. The control panel, on the lower portion of the screen, allows for adjustment of the view (lens) angle, camera direction, zoom, and more. (*See* Color Plate.)

Cross-sectional imaging has a lower resolution than endoscopy, but it is noninvasive and shows the anatomy beyond the wall. Nevertheless, cross-sectional CT or MRI does not allow contiguous viewing of the inside of the organs. Computerized image processing can render cross-sectional images into three-dimensional displays showing not only the outside configuration of organs, but also their inner surfaces. CT or MRI images can demonstrate the mucosal surfaces and can provide information on pathologic processes that go through and beyond organ walls. These images can also correct localization in relationship to surrounding anatomy.

Virtual endoscopy [47–50,51••] (Geiger and Kikinis, Paper presented at the Computer Vision, Virtual Reality and Robotics in Medicine, Nice, France, 1995) yields endoscopy-like visualization using cross-sectional imaging. Virtual endoscopy allows the contiguous exploration of surfaces and therefore improves diagnosis; it is also a navigational tool that can help the endoscopist during diagnostic or therapeutic procedures. Interactive virtual endoscopy displayed during endoscopic procedures can assist in the localization of the lesion, in determining its extent, and ultimately complement visualization during the invasive biopsy or surgical procedure performed with endoscopy (Figs. 20-3 and 20-4).

Virtual-reality techniques and visualization method may improve this new method. Endoscopic viewing is not restricted to the inner surfaces. The viewer may visualize through the walls and see the extent of lesions beyond it. The operator can also see the adjacent anatomic structures, which can assist in tumor staging and developing minimally invasive surgical strategies.

Correct localization and orientation relative to surrounding anatomy is also an important feature of virtual endoscopy. Complementing real endoscopy with virtual images, however, requires knowledge of the endoscope's location within the patient. Various tracking devices or sensors (mechanical, optical, or electromagnetic) can be attached to the endoscopes, or smaller sensors can be introduced into the working channels of endoscopes. Alternatively, endoscopic procedures can be performed within

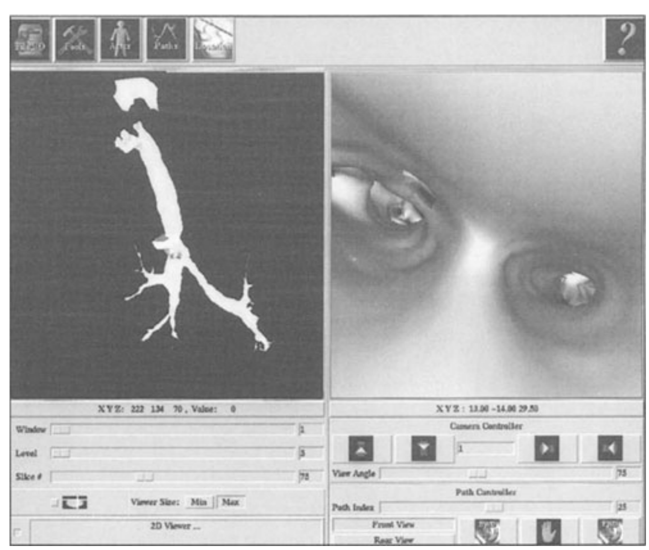


Figure 20-4 A virtual endoscopy of the trachea. **Left**, Global view with a virtual camera displaying the view direction. **Right**, Camera view looking at the carina and the right and left main stem bronchus. (*See* Color Plate.)

open interventional MRI systems. With this setting, the position of the endoscope defines the location of three orthogonal image planes. The magnetic resonance images are displayed simultaneously on two adjacent monitors or in a multiwindow-format display. This combination of endoscopy and cross-sectional imaging can also be achieved with virtual endoscopic presentation, which is based on previously acquired images. These images can be updated with real-time MRI obtained intraoperatively.

Virtual endoscopy is applicable for education and training. Because the endoscopic views are very different from the typical anatomic presentation seen in cross-sectional images or in an anatomy atlas, the virtual models are very useful for training endoscopists. Inexperienced users can learn the endoscopic anatomy and the correlated surrounding volumetric anatomy.

CONCLUSIONS

Full integration of advanced imaging in surgery will result in fundamental changes in therapeutic strategies and approaches. Advances in technology have already resulted in sweeping changes in diagnostic radiology, and more widespread use of modern therapeutic devices, computers, and advanced imaging technologies will have a far-reaching effect on surgery as well. Medical imaging can supplement the surgeon's visual field by providing intraoperative views of otherwise hidden structures.

The concept of image guidance demands a strategic shift in the focus of medical imaging from diagnosis to treatment. Continuous commitment from imaging experts, interventionists, and surgeons is necessary to expedite technologic development in our rapidly changing health care environment. Image-guided therapy offers the possibility of improving safety, efficacy, and cost-effectiveness of existing procedures, and it may result in new procedures that cannot be established outside of this environment.

REFERENCES AND RECOMMENDED READING

Recently published papers of particular interest have been highlighted as:

- • Of interest
- •• Of outstanding interest

1. Vannier MW, Marsh JL, Warren JO: Three dimensional CT reconstruction images for craniofacial surgical planning and evaluation. *Radiology* 1984, 1:179–184.
2. Cutting C, Bookstein EL, Grayson B, *et al.*: Three-dimensional computer assisted design of craniofacial surgical procedures: optimization and interaction with cephalometric and CT-based models. *Plast Reconstr Surg* 1986, 77:877–887.
3. Altobelli DE, Kikinis R, Mulliken JB, *et al.*: Computer-assisted three-dimensional planning in craniofacial surgery. *Plast Reconstr Surg* 1993, 92:576–585.
4. Jolesz FA, Kikinis R, Cline HE, Lorensen WE: The use of computerized imaging and image processing for neurosurgical planning. In *Astrocytomas*. Edited by Black PMcL, Lampson LA. Cambridge: Blackwell Scientific Publications; 1993:50–56.
5. Vogl TJ, Assal J, Bergman C: Three-dimensional MR reconstruction images of skull base tumors. *J Magn Reson Imag* 1993, 3:357–364.
6. Hu XP, Tan KK, Levin DN, *et al.*: Three-dimensional magnetic resonance images of the brain: application to neurosurgical planning. *J Neurosurg* 1993, 72:433–440.
7. Chernoff DM, Silverman SG, Kikinis R, *et al.*: Three-dimensional imaging and display of renal tumors using spiral CT: a potential aid to partial nephrectomy. *Urology* 1994, 43:125–129.
8. Zhang J, Levesque MF, Wilson CL, *et al.*: Multimodality imaging of brain structures for stereotactic surgery. *Radiology* 1990, 175:435–441.
9. Holman BL, Zimmerman RE, Johnson KA, *et al.*: Computer-assisted superimposition of magnetic resonance and high-resolution technetium-99m HMPAO and thallium-201 SPECT images of the brain. *J Nucl Med* 1991, 32:1478–1484.
10. Levin DN, Hu XP, *et al.*: The brain: integrated three-dimensional display of MR and PET images. *Radiology* 1989, 172:783–789.
11.•• Wells MW, Viola P, Atsumi H, *et al.*: Multimodal volume registration by maximation of mutual information. *Medical Image Analysis* 1996, 1:35–51.

A new technique is presented to register volumetric medical images such as MRI, CT, or positron emission tomography. This is achieved by adjustment of the relative position and orientation until the mutual information between the images is maximized. No reprocessing or segmentation is required because the algorithms are quite general and can foreseeably be used with a wide variety of imaging devices.

12. Kelly PJ, Kall B, Goerss S: Functional stereotactic surgery utilizing CT data and computer generated stereotactic atlas. *Acta Neurochir Suppl (Wien)* 1984, 33:577–583.
13. Gleason PL, Kikinis R, Altobelli D, *et al.*: Video registration virtual reality for nonlinkage stereotactic surgery. *Stereotact Funct Neurosurg* 1994, 63:139–143.
14.• Nakajima S, Atsumi H, Moriarty TM, Kikinis R, Jolesz, Black PML, *et al.*: Use of cortical surface vessel registration for image-guided neurosurgery. *Neurosurgery* 1997, 41:403–409.

Three-dimensional modeling and video registration using cortical surface vessels is practical and improves two-dimensional projection accuracy significantly over skin registration in neurosurgery.

15.•• Grimson WEL, Ettinger GJ, White SJ, *et al.*: An automatic registration method for frameless stereotaxy, image-guided surgery, and enhanced reality visualization. *IEEE Trans Med Imag* 1996, 2:129–140.

An automatic technique for registering segmented MRI or CT reconstructions (with any view of the patient on the operating table) was developed to help surgeons plan the exact location of incisions, to define the margins of tumors, and to precisely identify locations of neighboring critical structures. The method enables a visual mix of live video of the patient with the segmented three-dimensional MRI or CT model, supporting enhanced reality techniques for planning and guiding neurosurgical procedures, and interactive viewing of extracranial or intracranial structures nonintrusively. Extensions of the method include image-guided biopsies, focused therapeutic procedures, and clinical studies involving change detection over time sequences of images.

16. Kosugi Y, Watanabe E, Goto J, *et al.* An articulated neurosurgical navigation system using MRI and CT images. *IEEE Trans Biomed Eng* 1988, 35:147–152.
17. Kato A, Yoshimine T, Hayakawa T, *et al.*: A frameless, armless navigational system for computer assisted neurosurgery. *J Neurosurg* 1991, 74:845–849.
18. Roberts DW, Strohbehn JW, Hatch JF, *et al.*: A frameless stereotactic integration of computerized tomographic imaging and the operating microscope. *J Neurosurg* 1986, 65:545–549.
19. Koivukangas J, Louhisalmi Y, Alakuijala J, Oikarinen J: Ultrasound-controlled neuronavigator-guided brain surgery. *J Neurosurg* 1993, 79:36–42.
20. Kall BA, Kelly PJ, Goerss SJ: The computer as a stereotactic surgical instrument. *Neurol Res* 1986, 8:201–208.

21. Apuzzo ML, Sabshin JK: Computed tomographic guidance stereotaxis in the management of intracranial mass lesions. *Neurosurgery* 1983, 12:277–285.
22. Zamorano L, Jiang Z, Kadi AM: Computer-assisted neurosurgery system: Wayne State University hardware and software configuration. *Comput Med Imaging Graph* 1994, 18:257–271.
23. Zinreich SJ, Tebo SA, Long DM, *et al.*: Frameless sterotactic integration of CT imaging data: accuracy and initial applications. *Radiology* 1993, 188:35–42.
24. Mosges R, Klimek L: Computer-assisted surgery of the paranasal sinuses. *J Otolaryngol* 1993, 22:69–71.
25.•• Fried MP, Kleefield J, Gopal H, *et al.*: Image-guided endoscopic surgery: results of accuracy and performance in a multicenter clinical study using an electromagnetic tracking system. *Laryngoscope* 1997, 107:594–601.

The InstrTrak System, an electromagnetic tracking system, includes an automated registration technique for endoscopic sinus surgery. Advantages of this are elimination of the redundant CT scan, compensation for head movement, and the ability to use interchangeable instruments.

26. Schenck JF, Jolesz FA, Roemer PB, *et al.*: Superconducting open configuration MRI system for image-guided therapy. *Radiology* 1995, 195:805–814.
27.•• Silverman SG, Collick BD, Figueira MR, *et al.* Interactive MR-guided biopsy in an open-configuration MR imaging system. *Radiology* 1995, 197:175–181.

Magnetic-resonance–guided biopsy with a frameless stereotactic technique is safe and accurate. Image feedback is near real time, and the procedure is interactive.

28. Jolesz FA: Interventional magnetic resonance imaging computed tomography and ultrasound. *Acad Radiol* 1995, 2:S124-S125.
29. Jolesz FA, Kahn T: Interventional MRI: state-of-the-art. *Appl Radiol* 1997, 26:8–13.
30.•• Jolesz FA: Image-guided procedures and the operating room of the future. *Radiology* 1997, 204:601–612.

This paper highlights the concept of image-guided therapy and the genuinely interdisciplinary approach of radiology in this emerging field.

31. Fried MP, Hsu L, Topulos GP, Jolesz FA: Image-guided surgery in a new magnetic resonance suite: preclinical considerations. *Laryncoscope* 1996, 106:411–417.
32. Fried MP, Kleefield J, Jolesz FA, *et al.*: Intraoperative image guidance during endoscopic sinus surgery. *Am J Rhin* 1996, 10:337–342.
33. Moriarty TM, Kikinis R, Jolesz FA, *et al.*: Magnetic resonance imaging therapy: intraoperative MRI. *Neurosurg Clin North Am* 1996, 44:323–331.
34.•• Black PM, Moriarty T, Alexander E III, *et al.*: Development and implementation of intraoperative magnetic resonance imaging and it neurosurgical applications. *Neurosurgery* 1997, 41:831–845.

Intraoperative MRI allows lesions to be precisely localized and targeted, hence the progress of a procedure can be immediately evaluated. This eliminates errors that can arise during frame-based and frameless stereotactic surgery when anatomic structures alter their position because of shifting or displacement of brain parenchyma but are correlated with images obtained preoperatively.

35. Jolesz FA, Shtern F: The operating room of the future: report of the National Cancer Institute workshop. Imaging-guided stereotactic tumor diagnosis and treatment. *Invest Radiol* 1992, 27:326–328.
36. Silverman G, Jolesz, Newman RW, *et al.*: Design and implementation of an interventional MR imaging suite. *AJR Am J Roentgenol* 1997, 168:1465–1471.
37. Alexander E, Kikinis R, Jolesz F: Intraoperative magnetic resonance imaging therapy. In *Image-Guided Neurosurgery: Clinical Applications of Interactive Surgical Navigation.* Edited by Barnett GH, Roberts D. St. Louis: Quality Medical Publishers; 1998: in press.
38. Alexander E, Moriarty TM, Kikinis R, Jolesz FA: Innovations in minimalism: intraoperative MR. *Clin Neurosurg* 1996, 43:338–352.
39. Matsumoto R, Oshio K, Jolesz FA: Monitoring of laser and freezing-induced ablation in the liver with T1-weighted MR imaging. *J Magn Reson Imag* 1992, 2:555–562.
40. Matsumoto R, Mulkern V, Hushek SG, Jolesz FA: Tissue temperature monitoring for thermal interventional therapy: comparison of T1-weighted MR sequences. *J Magn Reson Imag* 1994, 4:65–70.
41. Bleier AR, Jolesz FA, Coheu MS, *et al.*: Real-time magnetic resonance imaging of laser heat deposition in tissue. *Magn Reson Med* 1991, 21:132–137.
42. Matsumoto R, Selig AM, Colucci VM, Jolesz FA: Interstitial Nd:YAG laser ablation in normal rabbit liver: trial to maximize the size of laser-induced lesions. *Lasers Surg Med* 1992, 12:650–658.
43.•• Cline HE, Hynynen K, Watkins RD, *et al.*: Focused US system for MR imaging-guided tumor ablation. *Radiology* 1995, 194:731–737.

A focused ultrasound system, implemented into an MR-scanner, has been used for image-guided tumor ablation in real time.

44. Duckwiler G, Lufkin RB, Teresi L, *et al.*: Head and neck lesions: MR-guided aspiration biopsy. *Radiology* 1989, 170:519–522.
45. Cline HE, Hynynen K, Hardy CJ, *et al.*: MR temperature mapping of focused ultrasound surgery. *Magn Reson Med* 1994, 31:628–636.
46. Kettenbach J, Silverman SG, Hata N, *et al.*: Monitoring and visualization techniques for MR-guided laser ablations in open MR-system. *J Magn Reson Imag* 1998, in press.
47. Vining DJ, Shifrin RY, Grishaw EK, *et al.*: Virtual colonoscopy [abstract]. *Radiology* 1994, 193:446.
48. Davis CP, Ladd ME, Romanowski BJ, *et al.*: Human aorta: preliminary results with virtual endoscopy based on three-dimensional MR imaging. *Radiology* 1996, 199:37-40.
49. Lorensen WE, Jolesz FA, Kikinis R: The exploration of cross-sectional data with a virtual endoscope. In *Interactive Technology and the New Health Paradigm.* IOS Press; 1995:221–230.
50 Virtual bronchoscopy: Relationships of virtual reality endobronchial simulation to actual brochoscopic findings. *Chest* 1996, 109:549-553.
51.•• Jolesz FA, Lorensen WE, Shinmoto H, *et al.*: Interactive virtual endoscopy. *AJR Am J Roentgenol* 1997, 169:1229–1235.

Merging of real and virtual endoscopy data may provide a more effective diagnostic workup. Knowledge of the location can be accomplished with sensors attached to the endoscope.