Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Image-Guided Interventions: Technology Review and Clinical Applications

Kevin Cleary[1] and Terry M. Peters[2]

[1]Imaging Science and Information Systems (ISIS) Center, Department of Radiology, Georgetown University Medical Center, Washington, DC 20007; email: cleary@georgetown.edu

[2]Robarts Research Institute, University of Western Ontario, London, Ontario, Canada N6A 5K8; email: tpeters@robarts.ca

Annu. Rev. Biomed. Eng. 2010. 12:119–42

First published online as a Review in Advance on April 20, 2010

The *Annual Review of Biomedical Engineering* is online at bioeng.annualreviews.org

This article's doi: 10.1146/annurev-bioeng-070909-105249

Copyright © 2010 by Annual Reviews. All rights reserved

1523-9829/10/0815-0119$20.00

Key Words

tracking, registration, visualization, neurosurgery, orthopedics, cardiac interventions, thoracoabdominal interventions, NOTES

Abstract

Image-guided interventions are medical procedures that use computer-based systems to provide virtual image overlays to help the physician precisely visualize and target the surgical site. This field has been greatly expanded by the advances in medical imaging and computing power over the past 20 years. This review begins with a historical overview and then describes the component technologies of tracking, registration, visualization, and software. Clinical applications in neurosurgery, orthopedics, and the cardiac and thoracoabdominal areas are discussed, together with a description of an evolving technology named Natural Orifice Transluminal Endoscopic Surgery (NOTES). As the trend toward minimally invasive procedures continues, image-guided interventions will play an important role in enabling new procedures, while improving the accuracy and success of existing approaches. Despite this promise, the role of image-guided systems must be validated by clinical trials facilitated by partnerships between scientists and physicians if this field is to reach its full potential.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Contents

HISTORICAL REVIEW 120
IMAGE-GUIDED SYSTEM WORKFLOW AND COMPONENTS 121
Tracking 121
Registration 123
Visualization 124
Software 126
APPLICATIONS 128
Image-Guided Neurosurgery 128
Orthopedics 130
Cardiac Interventions 132
Thoracoabdominal Interventions 133
NATURAL ORIFICE TRANSLUMINAL ENDOSCOPIC SURGERY 135
CONCLUSIONS 137

HISTORICAL REVIEW

In this review, to emphasize the markedly less invasive nature of image-guided interventions, we use the term image-guided intervention rather than image-guided surgery to describe any procedure that is performed without the traditional surgical access. Within this context, modern image-guided intervention techniques have been employed for approximately 20 years, and all use some form of preoperative data, usually in the form of tomographic images combined with some technology to relate these images to the patient. These latter components include the localization and tracking of the position of surgical tools or therapeutic devices, the registration of the patient to the preoperative data, the display of the position of the tools within the volume defined by the preoperative data, and the assessment of any differences between the preoperative data and the intraoperative reality. The first steps in the use of imaging to guide surgical procedures were taken more than 100 years ago, when in 1895, a mere eight days after Roentgen's first paper on X rays was published, a surgeon in Birmingham, England, used the new technique of X-ray imaging to guide the removal of an industrial sewing needle from a woman's hand (1). Barely a month later, John Cox, a professor of physics at McGill University in Montreal (2), successfully removed a bullet from a victim's leg by using the radiograph that had been made of the limb. In 1908, 12 years after the first reported procedure, Horsley & Clarke (3) reported a device that introduced several concepts that are now central to modern image-guided intervention. They affixed a frame to a monkey's head and aligned it using external markers (the auditory canals and orbital rims), which allowed them to assign the Cartesian coordinate system defined by the frame to the animal's brain. This device was termed the stereotactic frame, and it established a concept that is still in use 100 years later. Although the principles of image-guided intervention can be applied to any part of the body, in practice their use was confined to neurosurgery for most of the previous century, as, unlike many other parts of the body, the skull provides a rigid stable frame.

In the latter part of the twentieth century, two events were responsible for catapulting stereotactic surgery into the mainstream of neurosurgical practice. The first was the introduction of computed tomography (CT) scanning in the early 1970s, and the second was the appearance of the personal computer in 1981. Whereas a number of neurosurgery systems had used computers, most notably in the work by Shelden et al. in 1980 (4), they required either customized computer

CT: computed tomography

systems or massive amounts of data reduction, usually performed at the console of the tomographic imaging system. One of the first PC-based systems with the capability to plan stereotactic procedures from CT, magnetic resonance imaging (MRI), or digital subtraction angiography was developed by Peters et al. (5, 6). The increase in computing power triggered one of the most important changes in how data were handled, which was crucial to the advent of image-guided intervention. Before CT, images were both recorded and displayed on photographic film, whether the procedure involved plain film X rays, angiograms, or ultrasound (US) imaging. The use of CT enabled the images to be intrinsically represented as numbers that were converted to gray levels on film or on a cathode-ray display.

MRI: magnetic resonance imaging

US: ultrasound

The first attempt to move beyond the constraints of the stereotactic frame resulted in frameless stereotactic systems as reported by David Roberts's lab at Dartmouth (7, 8). Using a spark-gap sonic localization system attached to the operating microscope, Roberts and his colleagues were able to locate the target within the operative field on a single, but dynamically updated, tomographic image. As computational and display technology improved, Galloway and colleagues (9, 10) developed an articulated arm designed exclusively for neurosurgery, and they were able to display the surgical position simultaneously on three dynamically updated orthogonal CT planes (9).

To overcome the intrusive effects of articulated arms, researchers developed various tracking technologies. We describe these in the following section.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

IMAGE-GUIDED SYSTEM WORKFLOW AND COMPONENTS

As noted above, the rapid development of computing power and the improvements in imaging modalities in the 1990s allowed concomitant growth in the field of computer-aided surgery. Several systems became commercially available and soon evolved into the standard of care for certain neurosurgical procedures. **Figure 1** depicts a typical image-guided neurosurgery platform that employs optical tracking to relate instruments to the patient image. The clinical applications of this technology subsequently expanded into trauma and orthopedic surgery.

The following sequence of steps is typical for image-guided interventions using computer assistance:

1. Preoperative images are acquired (typically tomographic images).
2. The surgical instruments are tracked using a localizer.
3. The patient anatomy is registered to the preoperative image.
4. The position of the surgical instruments is displayed on this image relative to the patient anatomy.
5. The physician uses this virtual display to manipulate the instruments to accomplish the procedure.
6. A confirming image is obtained upon procedure completion.

In the sections below, we briefly describe some of the component technologies critical to an image-guided system, namely tracking devices, registration, visualization, and software.

Tracking

Tracking devices, also known as localizers, are an essential component of any image-guided intervention system. The continued improvements in tracking devices have contributed greatly to the development of new image-guided systems. These devices are used to track the positions of instruments relative to patient anatomy. Early tracking devices were essentially mechanical digitizers (10); optical tracking systems were then quickly adopted because of their high accuracy and large field of view. However, optical tracking systems require that a line of sight be maintained between

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.



Figure 1

StealthStation® S7™ image-guided system with optical tracking and surgical displays. Courtesy of Medtronic Navigation.

the tracking device and the instrument to be tracked, which is not always convenient and precludes the tracking of instruments inside the body. This challenge led to the development of electromagnetic tracking systems, which have no line-of-sight requirement and are able to track instruments such as catheters and the tips of needles inside the body. **Table 1** lists several tracking systems in use today for image-guided interventions. The different types of tracking systems described are (*a*) optical videometric, (*b*) optical active and passive infrared, and (*c*) electromagnetic.

Optical videometric. These systems identify marker patterns on video-image sequences obtained using one or more calibrated video cameras. The marker patterns on crash-test dummies fall into this category. Among the commercially available systems that use such markers is the MicronTracker (Claron Technology Inc., Toronto, Canada), which has a form factor as small as 157 × 36 × 47 mm.

Table 1 Tracking systems in use today for image-guided interventions

Technology	Product	Company	Location
Optical videometric	MicronTracker	Claron Technology Inc.	Toronto, Ontario, Canada
Optical active and passive infrared	Polaris	Northern Digital Inc.	Waterloo, Ontario, Canada
Electromagnetic	Aurora	Northern Digital Inc.	Waterloo, Ontario, Canada
Electromagnetic	microBIRD	Ascension Technology Corp.	Burlington, Vermont, USA

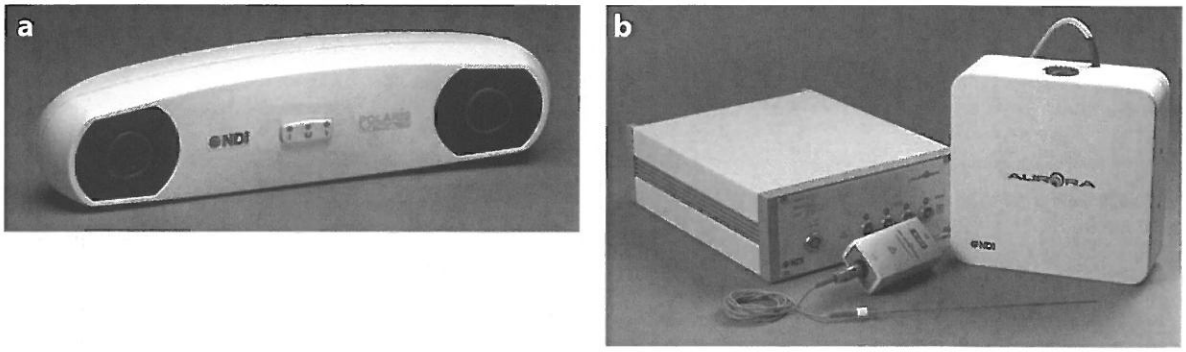


Figure 2

(*a*) Polaris Vicra® optical tracking system. (*b*) Aurora® electromagnetic tracking system. Courtesy of Northern Digital Inc.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Optical active and passive infrared. Two types of infrared trackers exist: active and passive. Both are used widely in clinical applications. In the active optical trackers, light emitting diodes (LEDs) operating in the near-infrared (IR) range are used as markers, tracked by either two planar or three linear charge-coupled device (CCD) units that form the camera module. The passive optical trackers are similar in principle to videometric systems, but they work in the near-IR range. Instead of active markers, retro-reflective spheres are illuminated by the tracking system in the near-IR spectrum. The pattern of the reflective markers, which must be unique for each tracked probe, is identified through CCD cameras. One big advantage of these systems is that they are wireless. The Polaris® System from Northern Digital Inc. (Waterloo, Canada) combines both active and passive infrared in a single tracking system (see **Figure 2*a***). A recent article comparing optical and electromagnetic tracking systems noted some additional advantages of optical tracking such as higher accuracy (11).

Electromagnetic. These systems localize small electromagnetic field sensors (solenoids) in a pulsed magnetic field of known geometry. Recent developments in this technology have enabled extremely small sensor coils (less than 0.5 mm in diameter and 8 mm in length) to be embedded in surgical instruments for tracking inside the body. Whereas these systems are sensitive to metal objects in the environment, which can distort the electromagnetic field and diminish accuracy, recent systems are more robust and can better withstand such disturbances. Furthermore, special geometries have been created that can work in the operating room environment.

Many researchers have studied the accuracy attainable with these systems, and methodologies for characterizing accuracy have been reported (12). The potential use of electromagnetic tracking in the clinical environment and factors to be considered have also been assessed by Yaniv et al. (13). Products commercially available today that researchers can integrate into image-guided systems include the Aurora from Northern Digital Inc. (see **Figure 2*b***) and the microBIRD from Ascension Technology Corp. (Burlington, Vermont).

Registration

Registration, an essential component for all image-guided systems, is the process of bringing two coordinate systems into spatial alignment. In the most common clinical scenario, preoperative images must be registered (aligned) with the patient on the procedure table. Registration can be broadly classified into two types: rigid registration or nonrigid registration. In commercial

image-guided systems only rigid registration is used, whereas nonrigid registration has been applied in some research systems and continues to be a major topic of discussion at conferences such as the Medical Image Computing and Computer Assisted Intervention (MICCAI) meeting. A good early overview of medical image registration can be found in Reference 14.

Rigid registration has been studied extensively over the past several decades. In rigid registration, only translations and rotations of the data sets to be registered are allowed, and deformations are not considered. The major use of rigid registration is in the clinical scenario mentioned above, whereby preoperative images such as CT images are acquired before the start of a procedure and these images are registered with the patient. Because both data sets are three-dimensional, this process is considered to be a 3D-to-3D image registration. The most commonly used 3D-to-3D rigid registration method is paired-point registration, in which anatomic points or fiducial markers from the patients are matched to corresponding points in the preprocedure image (15). The concept of target registration error was later introduced by Fitzpatrick et al. to quantify how accurately targets can be identified based on the preoperative images (16).

In clinical practice, the use of rigid-body models has proven successful in many applications, particularly when the anatomical structures of interests are bony landmarks such as the spine or are surrounded by a rigid enclosing structure such as the brain. However, it is also clear that for many surgical or interventional procedures, as in the abdomen, the rigid-body models are not sufficient; in these cases, nonrigid (deformable) models are required. Thus, in recent years, there has been a focus on nonrigid registration to enable the use of image guidance for these procedures.

Nonrigid registration methods in current use are also 3D-to-3D registration techniques, which typically attempt to deformably register a preoperative image to the patient anatomy. Although this is an area of active research, currently available nonrigid registration techniques lack the robustness required for clinical practice and have only been applied in very limited trials to date. A recent review article focusing on oncology/cardiology and PET/CT scanning discussed some of the issues involved in these techniques (17). One of the critical issues for deformable registration is validation, because choosing a gold standard can be difficult. The accuracy of deformable registration has been investigated for radiotherapy using a deformable phantom (18) and for breast images using finite element methods (19).

Visualization

Visualization of data in image-guided procedures constitutes a vital link in the procedural chain. The surgeon no longer needs to navigate with respect to a single radiograph or CT/MRI image; he or she now has access to a wealth of 3D (and even 4D) data, often complemented with images from various modalities. When images from multiple modalities are being displayed, it is important that they be presented unambiguously to the user. Because the human visual system is not used to interpreting real-world data in this manner, this is not a trivial task.

3D rendering. Today, the acquisition of three-dimensional data from medical imaging modalities is the norm rather than the exception. Indeed, a single standard MRI or CT image volume today can consist of more than 500 MB of data. Such data volumes create major constraints with respect to transmission, storage, and display of the images. One can display these data by scrolling through the stack of slices in orthogonal or even arbitrary directions (multiplanar reformatting), extracting surfaces from the structures in the images and displaying groups of polygonal surfaces (surface rendering), or computing rays through the volumes to produce a projection image (volume rendering). Volume rendering is associated with interactive tools such as clipping planes and with transfer functions to assign colors to the displayed voxels. It is generally considered to be the most

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.



Figure 3

Two views of a single frame of a dynamic volume rendered magnetic resonance (MR) image of a heart. In the images, various components have been classified with a color-coding scheme. Images courtesy of Qi Zhang, PhD, Robarts Research Institute.

appropriate volume visualization technique because it does not suffer from data misclassification as part of the segmentation stage and because it retains all the original data in the rendered image. However, interactive volume rendering is computationally expensive, and only the recent introduction of inexpensive graphics processing units has enabled the widespread use of volume rendering in medical image visualization. Today, large, dynamic volumetric data sets, such as the one shown in **Figure 3**, can be manipulated freely in real time (20).

Virtual reality. Virtual reality (VR) techniques have been employed in surgical training for more than a decade and have become particularly important in the training for laparoscopic surgical procedures (21). In recent years, VR techniques and augmented reality (AR) approaches that register and fuse VR images with those of the real world have been used in visualization and guidance environments for image-guided interventions.

Although a virtual environment that is perfectly registered with the underlying anatomy can be directly employed for image guidance in theory, registration is never perfect in practice, particularly in dynamic environments. It is often desirable to register the virtual image to its real counterpart to detect any registration errors and to give the virtual image additional context. Examples of AR systems in image-guided intervention include the integral videography system described by Liao et al. (22, 23), which creates a "pseudo hologram" by presenting multiple views of an object to the observer via an array of "fly's-eye" lenses. The effect is the creation of a 3D image, fixed in space, which is independent of viewer pose. Under appropriate viewing conditions, the image can be overlaid in space to coincide with the underlying anatomy. Less sophisticated systems employ a head-mounted stereoscopic display either with the images fused with the directly viewed scene (24) or with a video image of the scene obtained with stereo cameras attached to the display (25). Fischer et al. recently described an innovative approach for guiding needle biopsy that employs a 2D planar image (from CT or MR) registered with the patient while the patient was in the scanner (26). An alternative biopsy guidance system is the "sonic flashlight" proposed by Stetten et al. (27), which overlays a virtual US planar image on the patient's anatomy. A significant

VR: virtual reality

AR: augmented reality

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

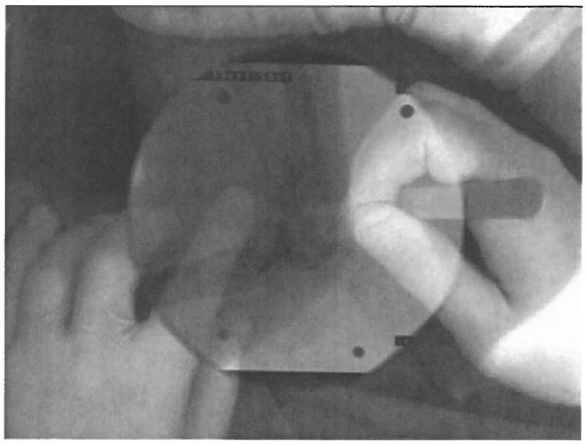


Figure 4

Fused image that combines a direct video view of a patient's elbow with the registered X-ray image of the humerus, radius, and ulna bones. Image courtesy of Nassir Navab, PhD, Technical University of Munich.

benefit of the 2D AR schemes used in Fischer's and Stetten's approaches is that the virtual image is fixed in space, and tracking of the observer's viewpoint is not required. In the area of cardiac interventions, Linte et al. (28) demonstrated the value of registering intraoperative US images with preoperative anatomical models and representations of tracked instruments during intracardiac interventions. Vosburgh and colleagues (29, 30) described a similar approach for visualizing intraoperative laparoscopic US and video images within the context of preoperative models and intraoperative laparoscopic images. Finally, a very practical application of AR has been demonstrated by Navab et al. (31), who developed an X-ray C-arm system equipped with a video camera. The video images the surface of the body with the same pose as the X-ray system, producing a fused image showing the patient surface, registered and fused with the radiograph. Because the video and radiographic axes are prealigned, no specific image registration is necessary. **Figure 4** illustrates the utility of combining the visible surface of an organ—the elbow, in this case—with the registered X-ray image. **Figure 5** gives an example, also from Navab's laboratory, in which a virtual model of the ankle derived from a CT volume is registered with the direct view.

Software

Reliable software is a critical component of image-guided surgical applications, and software development is typically the most labor-intensive and time-consuming phase in developing an image-guided system. The software must integrate information from tracking systems, correlate the data with the relevant images, and display real-time updates of the instruments and patient. Moreover, because the software is used in life-critical applications, it must be carefully designed to ensure ease of use, robustness, and stability (32).

Open source software has become increasingly popular in the research domain because it enables common infrastructure to be shared and enables multiple research groups to avoid "reinventing the wheel." The term open source refers to software whose source code is made freely available and therefore can be modified as needed for new applications. Whereas researchers can choose from several license models, many prefer the Berkley Software Distribution (BSD) license model because it allows the software to be used for any purpose whatsoever, with no obligation to distribute the source code of derivative works (38). The rationale is that this encourages the

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

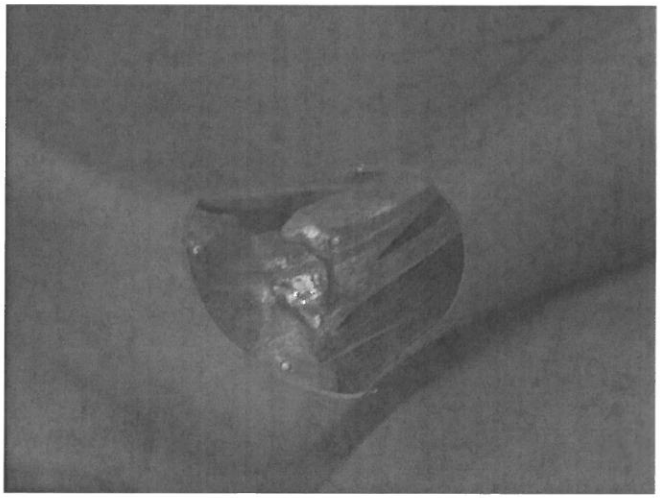


Figure 5

An example of a virtual model of the ankle computed from a computed tomography (CT) volume and registered to a direct view observed through a head-mounted display. The resulting image combines the natural view of the patient's foot with a model representing the underlying anatomy. Image courtesy of Nassir Navab, PhD, Technical University of Munich.

widest possible use of the software and enables companies to develop products based on open source software while retaining their proprietary rights.

Several research groups worldwide have developed open source packages applicable for image-guided interventions. We list three of the major developments here:

1. 3D Slicer from Brigham and Women's Hospital, Boston: **http://www.slicer.org** (see **Figure 6**)

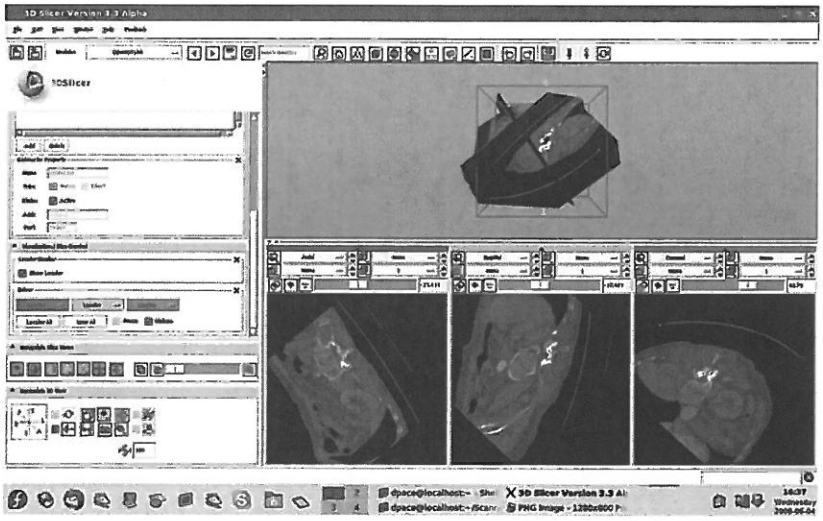


Figure 6

3D Slicer user interface showing three orthogonal planes and corresponding axial, sagittal, and coronal views. Image courtesy of Ron Kikinis, MD, and Nobuhiko Hata, PhD, Brigham and Women's Hospital.

2. Medical Imaging Interaction Toolkit (MITK) from the German Cancer Research Center, Heidelberg: **http://www.mitk.org**
3. Image-Guided Surgery Toolkit (IGSTK) from Georgetown University, Washington, DC: **http://www.igstk.org**

MITK: Medical Imaging Interaction Toolkit

IGSTK: Image-Guided Surgery Toolkit

VTK: Visualization Toolkit

ITK: Insight Segmentation and Registration Toolkit

NOTES: Natural Orifice Transluminal Endoscopic Surgery

3D Slicer is a multiplatform, free, open source software program for visualization and image computing. The software runs on Windows, Macintosh, and Linux platforms, and it provides functionality for segmentation, registration, and three-dimensional visualization of multimodal image data, as well as advanced image-analysis algorithms for diffusion tensor imaging, functional MRI, and image-guided therapy.

The MITK is also multiplatform and free for development of interactive, medical image-processing software. Like 3D Slicer and the IGSTK, it is based on the Visualization Toolkit (VTK) and Insight Segmentation and Registration Toolkit (ITK). (For more information on ITK, visit **http://www.itk.org/**.) The developers have just released an image-guided therapy module (MITK-IGT) to support medical tracking systems and the development of image-guided therapy applications (39).

The IGSTK, which was developed specifically for image-guided interventions, contains the basic components to develop an image-guided application. The toolkit is based on a state-machine architecture and supports several tracking systems, including models from Northern Digital, Ascension, Claron, and Atracsys (Renens, Switzerland) (32).

Recently, these developers and others have considered developing a Common Toolkit (CTK) for medical image analysis and visualization. Two coordinating meetings have been held to date (October 2009), and discussions so far have focused on identifying and supporting common components within these toolkits. Regardless of which direction this initiative takes, it seems clear that using open source to develop these systems can enable researchers to more quickly create robust clinical applications as well as create a sense of community for the field as a whole.

APPLICATIONS

Although many organs in the body are potential targets for image-guided intervention, to achieve a balance between breadth and detail, we focus here on a subset of these targets. In addition to the areas mentioned below, much has been written on image-guided interventions in the kidney, liver, and prostate (33–35). Furthermore, the radiation therapy and radiosurgery (36, 37) communities are increasingly employing imaging to aid interventional procedures, using methodologies that closely parallel those described in this article. We discuss below the clinical-application areas of neurosurgery, orthopedics, cardiology, and abdominal interventions, followed by the new area of Natural Orifice Transluminal Endoscopic Surgery (NOTES).

Image-Guided Neurosurgery

Computer-assisted neurosurgery has been practiced for more than 25 years, and its success has made it the standard of care in most centers (40). It has led to greater standardization in craniotomies for tumor resection, and it has enabled a number of procedures that previously required a craniotomy to be performed via a burr- or twist-drill hole. Functional neurosurgery, particularly the implantation of deep brain stimulators, has become common for movement-disorder surgery (41), whereas epilepsy surgery has benefited from the integration of surface and deep-brain electroencephalography (EEG) data with preoperative images (42).

Over the years, most of the attention on deep-brain interventions has centered on the placement of electrodes inside the brain to detect epileptogenic foci and the placement of ablation or

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

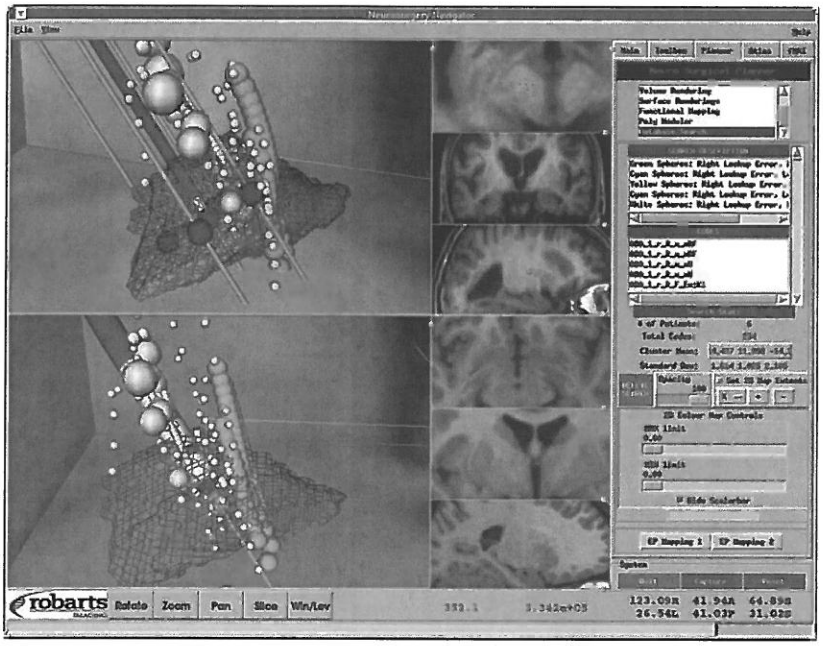


Figure 7

Deep-brain neurosurgery planning platform that employs measurements from an electrophysiological database, represented in a standard magnetic resonance imaging (MRI) brain space (*bottom*), which have been nonrigidly mapped to a patient MRI brain (*top*). The images show the locations of stimulus and response measurements that have been recorded from previous patients, and which are now mapped to the current patient. The colored spheres represent the nature and extent of previous surgical patients' responses to electrical stimuli and/or electrical recordings evoked by external stimulus; these patients' information is stored within the database. This information is used to guide the surgeon to the appropriate target for placement of a deep brain–stimulating electrode. Image courtesy of Ting Guo, PhD, Robarts Research Institute.

stimulation probes to treat Parkinson's disease (41, 43). For the most part, image guidance for this type of neurosurgery is achieved through optically tracked tools and preoperative images registered to the patient in the operating room. Unfortunately, structures within the deep brain such as the thalamus, globus pallidus, and subthalamic nucleus cannot be readily visualized on standard diagnostic MRI images (44). To overcome this problem, researchers have recently employed electrophysiology databases for Parkinson's disease surgery (see **Figure 7**).

These databases record the locations of successful stimuli applied to previous patients—data that can significantly enhance the ability of the surgeon to "hit" the correct targets with minimal passes of an electrophysiological electrode. This approach has demonstrated a significant advantage over methods that linearly map standard brain atlases to the individual patient. This new method creates a standardized database by performing a nonrigid mapping to a standard brain template of each patient's brain, together with the coordinates and descriptions of various stimulus and response measurements. This evolving database can be similarly warped to a new patient to indicate the appropriate regions to target (41).

Image guidance is also important for tumor surgery, but unlike the implantation of an electrode, tumor surgery requires a craniotomy. Unfortunately, under these conditions, the pressure equilibrium inside the cranial vault is changed, and significant brain shift may occur (45). This

means that the position of the tumor as indicated on the preoperative scan no longer represents the actual position of the lesion, which may have shifted up to 20 mm (46). This observation led to the conclusion that surgeries of this nature can only be performed accurately under real-time image guidance, and numerous reports have been published on procedures guided by intraoperative US, intraoperative MRI, or a combination of intraoperative US registered to preoperative MRI (45). One approach has been to combine the real-time ability of US with the rich anatomical information of MRI by identifying landmarks in both modalities and performing a nonrigid image registration between the two image volumes (47, 48). There has been some activity in the field of specialized intraoperative MR scanners in which the surgeon performs the procedure simultaneously with imaging. The most striking example of this approach is the discontinued GE Signa SPS "double-donut" 0.5 Tesla MR scanner (49), which permitted the surgeon to stand between the two halves of the magnet to allow imaging while surgery was taking place. In general, there has been a tendency to move away from specialized surgical MRIs in favor of standard magnets that can be located inside the operating room and that can image the patient in a standard manner at various times during the surgical procedure (50).

One of the most innovative image-guided neurosurgery applications is the neuroArm, an MR-compatible robot designed by Dr. Garnette Sutherland at Foothills Hospital in Calgary, Canada (51). The neuroArm comprises two remote 7-degrees-of-freedom, MR-compatible slave manipulators on a movable base designed to hold a variety of surgical tools. This system is integrated with a ceiling-mounted MR scanner that can be moved in and out of the operating field (i.e., the magnet is brought to the patient, rather than the patient being moved to the magnet every time imaging is required). A unique aspect of this robotic system is that haptic-feedback facilities have been incorporated into the system design. Haptic feedback can potentially complement the visual-feedback experience in an image-guided system, although van der Meijden (52) recently pointed out that except for some specialized tasks such as knot tying, there are few studies that have unequivocally demonstrated the benefits of haptics in image-guided interventions. Although CT also has a potential role in guiding many neurosurgical procedures, it has the disadvantage of exposing both the patient and surgical team to radiation; therefore, it is currently not widely used for this purpose.

Orthopedics

Like neurosurgery, orthopedics is a clinical field in which there has been extensive use of image guidance. The annual Computer Assisted Orthopaedic Surgery conference is the most widely attended specialty conference in the image guidance field. Orthopedics is a natural application for image guidance because most procedures are performed on bones, so rigid-body models are a good fit. However, despite more than a decade of development, the use of image guidance has not been widely adopted by orthopedic surgeons, and the value of image-guided systems for orthopedics is still a subject of debate. Although navigation may increase the accuracy of these procedures, several factors have slowed its widespread use, including the additional time required, the expense to purchase image-guided systems, and health-insurance reimbursement issues (53). The major clinical applications of image guidance in orthopedics have been pedicle-screw insertion, hip replacement, knee replacement, and fracture alignment.

Pedicle-screw insertion. Historically, this was one the first areas for image guidance. The placement of a pedicle screw requires precision to align the screw along the pedicle of the vertebral body and to avoid complications such as impingement on the spinal canal. Among the early pioneers in this area was a group from Grenoble, France, who evaluated navigation assistance for screw

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

placement in the thoracic and lumbar spine with good results (54). Since then, pedicle-screw insertion has been an active application area, and commercial systems for pedicle-screw placement are available from both Medtronic, Inc. (Minneapolis) and BrainLAB AG (Feldkirchen, Germany). Two systems are available from Medtronic: the StealthStation® TREON™, for navigation based on tomographic images such as CT or MRI, and the StealthStation ION™, for navigation based on fluoroscopy images. BrainLAB offers similar products, including its VectorVision® navigation software for spinal applications.

In the most comprehensive analysis conducted to date, 130 studies involving more than 37,000 pedicle-screw placements were analyzed (55). Overall, 90.3% of the screws placed using conventional techniques were considered accurately placed, whereas 95.2% of the screws placed using navigation were considered accurately placed. Therefore, it appears that navigation provides more accurate placement, and it may also result in less radiation exposure for the surgeon who regularly does these procedures.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Hip replacement. Hip replacement is one of the most commonly performed orthopedic procedures, and it was one of the earliest procedures to which image-guided systems were applied. Although robotic systems are not covered in this review, it should be noted that one of the early applications of computer-aided surgery was the development of a robotic system for hip replacement, in which the cavity was milled under computer control by a robot holding a milling tool (56). At approximately the same time, navigation systems for hip replacement based on CT images began to appear, including the HipNav system to plan and verify the alignment of the acetabular and femoral components during the procedure (57). Commercial navigation systems for hip-replacement procedures are now available, such as the Stryker Hip Navigation system with the OrthoMap software package.

Another advantage of navigation systems for hip replacement is that they may allow for a less invasive approach to the procedure. These approaches are technically more demanding and offer the surgeon less visibility and access than traditional procedures, but image guidance can provide assistance via improved visualization. A randomized trial comparing the image-guided, minimally invasive approach with the traditional procedure is ongoing (58).

Knee replacement. Another common orthopedic procedure is knee replacement, particularly primary total knee replacements, which now surpass hip replacement in total procedure volume. A robotic solution has been proposed for knee replacement, whereby the active-constraint robot (ACROBOT) performs accurate milling of the surgical site (59) and works synergistically with the surgeon to precisely complete the procedure. As for hip replacement, there are commercial systems available for knee replacement, such as Aesculap AG's OrthoPilot® system (Tuttlingen, Germany). A case-controlled study of computer-assisted surgery versus manual total knee arthroplasty was recently published by Stulberg and colleagues (60).

Fracture alignment. Fracture alignment is the process of placing bone fragments back in place and securing them so that the bone can heal properly. For fractures of bones such as the femur, both fluoroscopy and CT-based systems have been developed to aid in fracture repair. One of the early systems by Joskowicz and colleagues (61) was for long-bone fracture surgery and named FRACAS (fracture computer-aided surgery). The goal was to reduce the surgeon's cumulative exposure to radiation as well as the surgical complications associated with alignment and positioning errors of bone fragments, nail insertion, and distal screw locking. The authors used fluoroscopic images to register the bone models (created from preoperative CT imaging) to the intraoperative situation and to verify that the registration was maintained.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Cardiac Interventions

In addition to MRI's traditional diagnostic role, recent developments in cardiac MRI now allow images to be used in guiding therapeutic interventions. Some groups have focused on the role of MRI as a real-time imaging modality to guide the therapy (62), whereas others have adopted the approach of registering intraoperative information such as electrophysiology data (63), fluoroscopy, and US (28) with preoperative images of the patient. Techniques such as XMR that combine an X-ray angiographic system coaxially arranged with an MR system in the operating room (64) allow fluoroscopic images to be readily registered with MR images of the subject during the same surgery or imaging session. Such systems are now being installed in a number of institutions. An exciting extension to the XMR technique has been the development of so-called closed-bore XMR systems (CBXMR), in which the X-ray system is integrated within the MR imager. Although this configuration presents a great number of technical challenges, this system can acquire radiographic and MR images simultaneously (65, 66).

Unfortunately, all these approaches demand a high degree of sophistication and expense and thus are unlikely to propagate to the majority of cardiac patients. Some groups have proposed US as the sole imaging modality (67), whereas others register preoperative images with intraoperative US. In the latter case, the US image is used to register the preoperative images to the patient in addition to serving as an intraoperative guidance modality (28, 68).

Stem cell implantation therapy. A growing potential application for image-guided intervention in the heart is in the field of stem cell therapy for treatment of cardiac restoration following injury. Although still at some distance from clinical acceptance, Rickers et al. (69) have demonstrated the feasibility and safety of myocardial injections in animal models under MR fluoroscopic guidance. Rickers's group showed that the intramyocardial distribution of injected dye, which was guided using the intraprocedural images, correlated well with the degree of gadolinium enhancement that indicated the extent of the disease. Their early results demonstrated that myocardial perfusion reserve and regional wall motion improved in the stem cell–treated group compared with the control group. Similar results have also been demonstrated by Rodriguez-Porcel et al. (70), who performed their procedures under US guidance.

Ablation therapy. One of the most widely performed intracardiac procedures is catheter ablation for the treatment of rhythm disorders, particularly atrial fibrillation. Catheter ablation delivers energy, which is typically radiofrequency (RF) or cryogenic, to destroy or electrically isolate the cardiac tissue responsible for the arrhythmia. In this context, image guidance fulfills dual roles: It serves as an electrophysiological mapping system to study the site of arrhythmia mechanisms, and it assists in the therapy itself. One of the better known systems (CARTO XP from Biosense Webster, Inc. of Diamond Bar, California) achieves this by tracking the location of a dual-purpose mapping/ablation catheter tip. The advantage of having one tracked catheter is that it can easily be returned to targeted ablation-therapy sites identified during the mapping procedure. Rettmann et al. (71) from the Mayo Clinic have described a proposed architecture for image-guided cardiac ablation therapy, while Wilson et al. (72) described a method for mapping the electrophysiology data acquired from such interventions onto a dynamic model of the beating heart.

Coronary artery bypass grafting. Coronary artery bypass grafting (CABG), traditionally performed via a full sternotomy and cardiopulmonary bypass, has been achieved in a minimally invasive fashion over the past decade with the da Vinci robot (73). To date, most of these procedures have been performed under stereoscopic endoscope control, with little effort put into the

integration of imaging information from other sources. Whereas work by Falk and colleagues (74) fused preoperative information about the locations of target vessels with the intraoperative environment, this approach has failed to become integrated into the surgical workflow. Although not strictly image-guided, a novel ongoing project that aims to improve the user interface of da Vinci–assisted cardiac procedures is that proposed by Mylonas et al. (75), who track the gaze of the operator to assist in the on-target placement of the robot end-effectors.

Intracardiac procedures. Recent improvements in cardiac MRI have greatly enhanced the role of MRI in both diagnostic and interventional applications. Rickers et al. (76) were the first to demonstrate the use of real-time MRI to guide the placement of an atrial septal defect (ASD) closure device. They were followed in 2007 by Guttman and colleagues (62), who described an interactive imaging/control interface to an MR scanner that could actively guide the placement of an aortic valve introduced into the left atrium via the apex of the heart.

MR imaging can provide exquisite images for interventional procedures, but it is an expensive technology unlikely to be adopted universally in operating rooms. Therefore, Vasilyev et al. (77, 78) employed 3D US alone to guide the placement of mitral valves and ASD closure devices within the beating heart. Linte et al. (28, 68) have taken this approach a step further by registering intraoperative US with preoperatively acquired image data, together with representations of tracked tools to provide a VR environment from which to guide intracardiac interventions. In the report by Vasilyev's group, access to the mitral valve was via an incision in the apex, with the seal around the introducing instrument ensured by a purse-string suture. In Linte's study, multiple instruments required inside the chamber were introduced through the Universal Cardiac Introducer (UCI) (79), a Dacron pouch sutured to the left atrial appendage.

Beating-heart, intracardiac procedures promise significant benefits for patients, but the fast motion of the heart poses serious challenges to surgeons. Yuen et al. (67) describe a new 3D, ultrasound-guided motion-compensation system (3DUS) that synchronizes instrument motion with the heart. This is achieved via a real-time 3DUS tissue tracker that is integrated with a 1-degree-of-freedom actuated surgical instrument and a real-time 3DUS instrument tracker. Initial studies have demonstrated that such a motion-compensation device can increase the success rate of surgical-anchor implantation in a simulated mitral annuloplasty procedure.

Thoracoabdominal Interventions

Image-guided interventions of the thorax and abdomen have been slow to emerge, in part because of the difficulty in dealing with the deformable nature of the organs in this anatomical region. In fact, current work is still based on rigid-body models, although deformable models are beginning to make progress for these interventions (80). The progress in tracking technologies—particularly the development of small, electromagnetically tracked sensors—has enabled the tracking of instruments inside the body, which has led to clinical studies for organs such as the lung, liver, and kidney. Because the lung is the most common site for biopsy, this review focuses on that organ.

Bronchoscopic biopsy. Bronchoscopy, the examination of the endobronchial airways with an optical camera, can be used as both a diagnostic and therapeutic tool. The bronchoscope also has a working channel through which instruments can take tissue samples or deliver therapy. The concept of navigated bronchoscopy was first introduced by Solomon et al. (81) based on an electromagnetic tracking system from Biosense Webster. The system included a 1.5-mm-diameter, 6-degrees-of-freedom position sensor, which was placed at the tip of the flexible bronchoscope. Three external electromagnetic emitters enabled tracking within a 20-cm cube. The researchers

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

developed a graphical user interface (GUI) that included a standard four-quadrant view and showed the position of the bronchoscope tip within the airway. Both animal and human studies were completed using rigid-body registration, which produced a registration accuracy of approximately 5 mm. These developments demonstrated the feasibility of using image-guided navigation in the thoracoabdominal region.

GUI: graphical user interface

Clinical evolution. Bronchoscopy is the one thoracoabdominal procedure in which a commercial guidance system has gained some success, namely the inReach™ System from superDimension, Inc. (Minneapolis). The system was FDA approved in November 2005 for guiding endoscopic instruments in the pulmonary tract. It is a traditional image-guided system consisting of a tracking device, tracked instruments, and a computer-based display.

The tracking system, which is proprietary, is based on a 1-cm-thick, 47 × 56–cm localization board that is placed beneath the patient (82). The board emits low-frequency electromagnetic waves that are detected by a sensor probe of approximately 1 mm in diameter and 8 mm in length. The sensor probe is incorporated into the tip of a flexible catheter 130 cm in length and 1.9 mm in diameter, which can be inserted into the working channel of the bronchoscope. The registration technique is based on anatomical branch points within the bronchial tree, as the system does not use artificially placed fiducials. The goal for registration error is less than 5 mm; if this is not attained, the vendor recommends that the registration process be repeated. Eighty-nine patients were biopsied using the superDimension system (83), resulting in a diagnostic yield of 67%, which was considered clinically acceptable. The system had the benefits of reducing radiation exposure from fluoroscopy and decreasing procedure time by allowing the clinicians to navigate quickly to the lesion.

Lung biopsy by transthoracic approach. An image-guided navigation system for biopsy of abdominal organs has been developed by the Computer Aided Interventions and Medical Robotics (CAIMR) research team at Georgetown University. This system, based on the open source software package IGSTK described earlier, is being used in an Institutional Review Board–approved clinical trial for CT-guided biopsy of suspicious lung nodules using a percutaneous approach. The workflow is as follows:

1) Fiducials are placed on the skin encircling the desired skin-entry point.
2) A CT scan is performed and sent to the navigation system using the Digital Imaging and Communications in Medicine (DICOM) protocol.
3) The image-guided system and electromagnetic tracking device are set up in the CT room.
4) The patient anatomy is registered to the CT scan using paired-point registration.
5) The virtual image overlay is enabled and a path to the lesion is planned using the GUI.
6) The needle is placed using only the image overlay.
7) A confirming CT scan is obtained.
8) If the physician is satisfied with the needle placement, the biopsy is performed in the usual manner.
9) If the physician is not satisfied, the image-guided system is removed and the procedure continues as a standard CT-guided biopsy.

A photograph of the CT room and image-guided system is shown in **Figure 8**. To date, four patients have been enrolled in the clinical trial. The physician was satisfied with the needle placement from the virtual image overlay in three patients. In the fourth patient, the needle placement missed the lesion but was sufficiently close to allow the physician to reposition it easily using standard techniques. These preliminary results show the feasibility of using the system in image-guided lung biopsy. Similar systems have been developed by other researchers, including

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

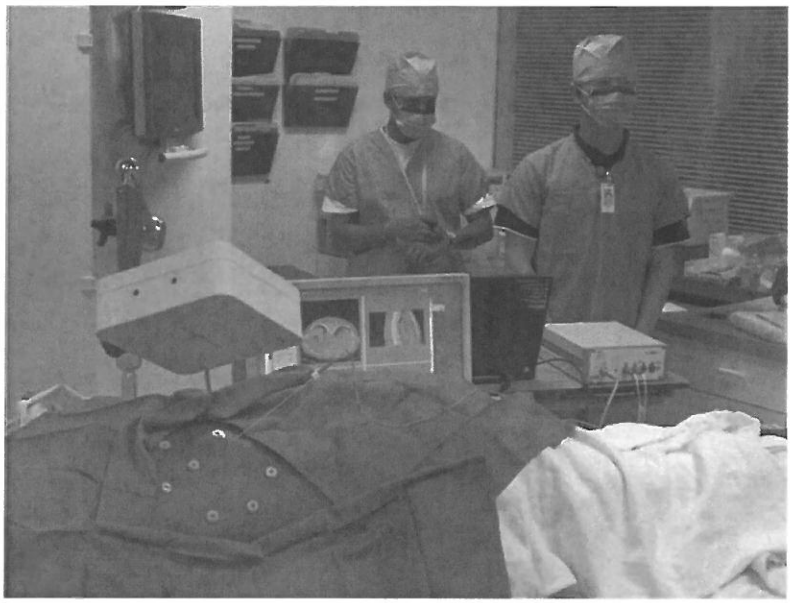


Figure 8

Lung biopsy using open source image-guided system Image-Guided Surgery Toolkit (IGSTK). Patient is lying prone, computed tomography (CT) gantry is to the left. The Aurora electromagnetic tracking system, tracked needle, graphical user interface (GUI), and assistants are shown. Photograph courtesy of Filip Banovac, MD, Georgetown University Medical Center.

the CAPPA system from CAS Innovations (now part of Siemens) and the PercuNav™ system from Traxtal Inc. (now part of Philips).

NATURAL ORIFICE TRANSLUMINAL ENDOSCOPIC SURGERY

Many minimally invasive surgery procedures are achieved using laparoscopic techniques, in which instruments are inserted into the body via a cannula containing a laparoscopic camera alongside the instrument and illumination channels. In 1989, the demonstration of a laparoscopic cholecystectomy by Jacques Perissat (84) in France revolutionized the surgical approach for this procedure. This was followed in 1991 by Clayman et al. (85), who described using a similar approach for laparoscopic nephrectomy. Such techniques have now become widespread and have recently been integrated with robotic procedures, as first described by Cadiere et al. (86) in their 2001 report of a robot (da Vinci)-assisted laparoscopic cholecystectomy. In 2000 and 2001, the same platform was employed to perform a radical prostatectomy (87, 88). Today, in the United States, the robot-assisted procedure for a radical prostatectomy is now more popular than the open approach. The surgical world now finds itself on the threshold of the next revolution in minimally invasive surgery, which is Natural Orifice Transluminal Endoscopic Surgery, or NOTES (89). In this type of procedure, incisions in the abdominal wall are eliminated because they are replaced by access via the mouth, rectum, or vagina (see NOTES sidebar).

NOTES offers several advantages over traditional surgical techniques in that it has the potential to minimize many incision-related complications such as wound infections, incisional hernias, postoperative pain, and adhesions. It also may be used during surgery for morbidly obese patients or

NOTES

Perhaps the most challenging new application for image-guided intervention will be in the field of Natural Orifice Transluminal Endoscopic Surgery, or NOTES, in which miniature instruments and video cameras are introduced into the body cavity via the mouth, rectum, or vagina. The objective is to reach the internal organs without leaving any scar, which in turn is expected to speed healing time and reduce patient trauma. However, performing procedures under such conditions brings a number of challenges. For example, how do surgeons know what they are looking at in the video image transmitted from the surgical site, and how can the location of a tumor embedded within an organ be identified? Because the tube through which the instruments are introduced is flexible, even determining which way is up can be problematic. Fortunately, techniques and instrumentation already developed for image-guided, minimally invasive interventions can potentially provide many of the answers. They can do so by accurately tracking the endoscopic camera and miniature surgical manipulation devices in space using miniature electromagnetic trackers and by accurately registering and fusing preoperatively acquired images of organs with the endoscopic images and with intraoperative images such as ultrasound.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

those with obstructive carcinomas, in which access to the intraabdominal organs via the abdominal wall is difficult and presents an increased risk of wound-related complications.

To date, most procedures have been performed in animal studies via transgastric, transcolonic, transvaginal, and transvesical approaches. In 2006, the Natural Orifice Surgery Consortium for Assessment and Research (NOSCAR) identified a number of potential barriers to the safe clinical implementation of NOTES (90, 91), including access to the peritoneal cavity, closure of the intestine, difficulty with spatial orientation, development of suturing and anastomotic devices, management of intraperitoneal complications, prevention of infection, development of a multitasking platform, unexpected physiological events, compression syndromes, and training. Although some of these challenges seem daunting, many of them may be addressed through the use of image guidance to increase safety and efficacy.

One of the most challenging issues encountered in NOTES procedures is determining the orientation of the endoscope image (92, 93). Because NOTES is performed with a flexible endoscope, there is no natural correlation between the ultimate pose of the camera and the operating instrument. This limitation even exists with rigid instruments, although the problem has been addressed to some extent by the da Vinci robot (94). Understanding the orientation of the endoscope within the body therefore presents a significant challenge.

When NOTES is being performed via transgastric access, some structures may lie behind the instrument (e.g., spleen, liver) and may only be visualized by the scope after it is retroflexed, which results in an inverted image. The only way to overcome this limitation is to perform real-time tracking of the endoscope camera (and associated instruments) and to represent them relative to a reference coordinate system. Such tracking of the endoscope tip, with the ability to display both the location and orientation of the scope, would be a significant advantage during NOTES. Image-registration techniques have been used to achieve this goal and have been shown to improve task performance in both laparoscopy and endoscopy (30, 95).

Image guidance also has the potential to assist with NOTES through registration of the preoperative (e.g., CT or MRI) and intraoperative (US) images with the view seen through the NOTES endoscope. Similar registration techniques have demonstrated enhanced interpretation of endoscopic US images in robot-assisted laparoscopic procedures (96), whereas AR techniques are designed to allow surgeons to "see through" structures to identify anatomy and pathology (97).

CONCLUSIONS

The field of image-guided interventions is still evolving as medical imaging and computing power continue to improve, enabling the development of new image-guided systems. The core component technologies of tracking systems, registration methods, visualization techniques, and software are becoming established while continuing to evolve. Although systems for many clinical areas have been developed, most are still in the prototype stage, and only limited clinical trials have been conducted so far. As surgery continues to move toward minimally invasive interventions, image-guided systems will increasingly be used to improve the precision and quality of medical procedures. Research groups are encouraged to form multidisciplinary partnerships between scientific and clinical personnel to move this technology from the laboratory to the hospital to improve patient care.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

SUMMARY POINTS

1. Image-guided interventions, which have evolved over the past 20 years, provide virtual image overlays based on preoperative and intraoperative images to assist the physician in successful completion of minimally invasive procedures.
2. The tremendous advances in medical imaging and computer power have enabled the development and advancement of this field.
3. Component technologies important for image-guided interventions include tracking systems, registration methods, visualization techniques, and software.
4. The development of miniaturized electromagnetic tracking systems, in which tracking sensor coils can be embedded in the tips of surgical instruments such as catheters and needles, has allowed new opportunities for image-guided interventions.
5. Several open source software toolkits have been developed by the image-guided intervention research community, and the use of such resources helps further build the community while enabling the researcher to rapidly prototype new platforms.
6. Image-guided interventions are being developed for several clinical areas including neurosurgery, orthopedics, cardiac interventions, and thoracoabdominal interventions, among others. Although these systems are believed to be beneficial, validation is still an issue, and randomized clinical trials are needed to fully evaluate the impact of this technology.
7. The development of flexible endoscopic instruments for evolving surgical procedures such as NOTES will provide a new venue for image-guided interventions.
8. Multidisciplinary partnerships between scientific and clinical personnel are essential to move the field forward.

FUTURE ISSUES

1. Most of the research to date has been based on rigid-body assumptions, which do not typically produce a good model of the anatomy, particularly with regard to soft tissue or nonbony structures. Therefore, deformable models and nonrigid registration will be important research topics for the future.

2. Validation is a critical issue and will become more important as deformable models and nonrigid registration techniques evolve. Rigorous validation techniques must be developed in this field.
3. Improvements in component technologies such as tracking also are necessary. Real-time surface tracking of both external and internal organs using lower-cost technologies is required, while continuing improvements in miniaturization and robustness of electromagnetic tracking can be expected. However, a system with the accuracy of optical tracking that can operate inside the body remains elusive.
3. Visualization methods will continue to improve, and real-time visualization using graphics processing units should become commonplace. Information overload and the presentation to the surgeon of unfamiliar, fused data sets will increase the need for research in human factors and human-computer interfaces specific to image-guided interventions.
4. Common software modules will continue to be needed so that researchers do not have to reinvent the wheel and so that newly developed techniques can be widely disseminated. Software architectures and standards implementations can help in this regard.
5. Continued improvements in medical imaging, including further development of 3D ultrasound, will allow for integration of real-time imaging so that a true and accurate operative picture can be provided to the interventionalist at all times.

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

DISCLOSURE STATEMENT

K.C. has received research support from Siemens Medical Solutions. T.M.P. has received research funding from Northern Digital Inc. during the past three years.

ACKNOWLEDGMENTS

Parts of this review are based on a recent book that we edited, *Image-Guided Interventions: Technology and Applications*, which in turn was based on a workshop held at the 2005 Engineering in Medicine and Biology Society (EMBS) meeting in Shanghai, China. We also acknowledge the tremendous editorial assistance provided to us by Jackie Williams.

LITERATURE CITED

1. Burrows E. 1986. *Pioneers and Early Years: History of British Radiology*. Alderney, UK: Colophon
2. Cox J. 1896. The new photography, with a report of a case in which a bullet was photographed in the leg. *Montreal Med. J.* 24:661–65
3. Horsley V, Clarke RH. 1908. The structure and functions of the cerebellum examined by a new method. *Brain* 31:45–124
4. Shelden CH, McCann G, Jacques S, Lutes HR, Frazier RE, et al. 1980. Development of a computerized microstereotaxic method for localization and removal of minute CNS lesions under direct 3-D vision. Technical report. *J. Neurosurg.* 52:21–27
5. Peters TM, Clark J, Pike B, Drangova M, Olivier A. 1987. Stereotactic surgical planning with magnetic resonance imaging, digital subtraction angiography and computed tomography. *Appl. Neurophysiol.* 50:33–38
6. Peters TM, Clark JA, Pike GB, Henri C, Collins L, et al. 1989. Stereotactic neurosurgery planning on a personal-computer-based work station. *J. Digit. Imaging* 2:75–81

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

7. Friets EM, Strohbehn JW, Hatch JF, Roberts DW. 1989. A frameless stereotaxic operating microscope for neurosurgery. *IEEE Trans. Biomed. Eng.* 36:608–17
8. Roberts DW, Strohbehn JW, Hatch JF, Murray W, Kettenberger H. 1986. A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope. *J. Neurosurg.* 65:545–49
9. Galloway RL Jr, Edwards CA, Lewis JT, Maciunas RJ. 1993. Image display and surgical visualization in interactive, image-guided neurosurgery. *Opt. Eng.* 32:1955–62
10. Maciunas RJ, Galloway RL Jr, Fitzpatrick JM, Mandava VR, Edwards CA, Allen GS. 1992. A universal system for interactive image-directed neurosurgery. *Stereotact. Funct. Neurosurg.* 58:108–13
11. Glossop ND. 2009. Advantages of optical compared with electromagnetic tracking. *J. Bone Jt. Surg. Am.* 91(Suppl. 1):23–28
12. Nafis C, Jensen V, von Jako R. 2008. Method for evaluating compatibility of commercial electromagnetic (EM) microsensor tracking systems with surgical and imaging tables. *Proc. SPIE* 6918:691820
13. Yaniv Z, Wilson E, Lindisch D, Cleary K. 2009. Electromagnetic tracking in the clinical environment. *Med. Phys.* 36:876–92
14. Hajnal JV, Hill DLG, Hawkes DJ, eds. 2001. *Medical Image Registration*. Boca Raton, FL: CRC. 392 pp.
15. Arun K, Huang T, Blostein S. 1987. Least-squares fitting of two 3-D point sets. *IEEE Trans. Pattern Anal. Mach. Intell.* 9:698–700
16. Fitzpatrick JM, West JB, Maurer CR Jr. 1998. Predicting error in rigid-body point-based registration. *IEEE Trans. Med. Imaging* 17:694–702
17. Slomka PJ, Baum RP. 2009. Multimodality image registration with software: state-of-the-art. *Eur. J. Nucl. Med. Mol. Imaging* 36(Suppl. 1):S44–55
18. Kashani R, Hub M, Balter JM, Kessler ML, Dong L, et al. 2008. Objective assessment of deformable image registration in radiotherapy: a multi-institution study. *Med. Phys.* 35:5944–53
19. Schnabel JA, Tanner C, Castellano-Smith AD, Degenhard A, Leach MO, et al. 2003. Validation of nonrigid image registration using finite-element methods: application to breast MR images. *IEEE Trans. Med. Imaging* 22:238–47
20. Zhang Q, Eagleson R, Peters TM. 2007. Rapid voxel classification methodology for interactive 3D medical image visualization. *Med. Image Comput. Comput. Assist. Interv.* 10(Pt. 2):86–93
21. Albani JM, Lee DI. 2007. Virtual reality-assisted robotic surgery simulation. *J. Endourol.* 21:285–87
22. Liao H, Dohi T, Iwahara M. 2007. Improved viewing resolution of integral videography by use of rotated prism sheets. *Opt. Express* 15:4814–22
23. Liao H, Iwahara M, Koike T, Hata N, Sakuma I, Dohi T. 2005. Scalable high-resolution integral videography autostereoscopic display with a seamless multiprojection system. *Appl. Opt.* 44:305–15
24. Birkfellner W, Figl M, Matula C, Hummel J, Hanel R, et al. 2003. Computer-enhanced stereoscopic vision in a head-mounted operating binocular. *Phys. Med. Biol.* 48:N49–57
25. Vogt S, Khamene A, Niemann H, Sauer F. 2004. An AR system with intuitive user interface for manipulation and visualization of 3D medical data. *Stud. Health Technol. Inform.* 98:397–403
26. Fischer GS, Deguet A, Csoma C, Taylor RH, Fayad L, et al. 2007. MRI image overlay: application to arthrography needle insertion. *Comput. Aided Surg.* 12:2–14
27. Stetten G, Cois A, Chang W, Shelton D, Tamburo R, et al. 2005. C-mode real-time tomographic reflection for a matrix array ultrasound sonic flashlight. *Acad. Radiol.* 12:535–43
28. Linte CA, Moore J, Wiles AD, Wedlake C, Peters TM. 2008. Virtual reality-enhanced ultrasound guidance: a novel technique for intracardiac interventions. *Comput. Aided Surg.* 13:82–94
29. Estepar RS, Stylopoulos N, Ellis R, Samset E, Westin CF, et al. 2007. Towards scarless surgery: an endoscopic ultrasound navigation system for transgastric access procedures. *Comput. Aided Surg.* 12:311–24
30. Vosburgh KG, San Jose Estepar R. 2007. Natural Orifice Transluminal Endoscopic Surgery (NOTES): an opportunity for augmented reality guidance. *Stud. Health Technol. Inform.* 125:485–90
31. Navab N, Heining S-M, Traub J. 2010. Camera Augmented Mobile C-arm (CAMC): calibration, accuracy study and clinical applications. *IEEE Trans. Med. Imaging.* In press, doi:10.1109/TMI.2009.2021947
32. Enquobahrie A, Cheng P, Gary K, Ibanez L, Gobbi D, et al. 2007. The image-guided surgery toolkit IGSTK: an open source C++ software toolkit. *J. Digit. Imaging* 20(Suppl. 1):21–33

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

33. Benincasa AB, Clements LW, Herrell SD, Galloway RL. 2008. Feasibility study for image-guided kidney surgery: assessment of required intraoperative surface for accurate physical to image space registrations. *Med. Phys.* 35(9):4251–61
34. Cash DM, Miga MI, Glasgow SC, Dawant BM, Clements LW, et al. 2007. Concepts and preliminary data toward the realization of image-guided liver surgery. *J. Gastrointest. Surg.* 11(7):844–59
35. Polascik TJ, Mayes JM, Mouraviev V. 2008. From whole-gland to targeted cryoablation for the treatment of unilateral or focal prostate cancer. *Oncology* 22(8):900–6; discussion 906–7, 914
36. Dawson LA, Jaffray DA. 2007. Advances in image-guided radiation therapy. *J. Clin. Oncol.* 25(8):938–46
37. Romanelli P, Schweikard A, Schlaefer A, Adler J. 2006. Computer aided robotic radiosurgery. *Comput. Aided Surg.* 11(4):161–74
38. Rosen L. 2005. *Open Source Licensing: Software Freedom and Intellectual Property Law*. Upper Saddle River, NJ: Prentice Hall PTR
39. Neuhas J, Kast J, Wegner I, Baumhauer M, Seitel A, et al. 2009. Building image guided therapy applications with the Medical Imaging Interaction Toolkit. *Int. J. Comput. Assist. Radiol. Surg.* 4(Suppl. 1):S108–9
40. Maciunas RJ. 2006. Computer-assisted neurosurgery. *Clin. Neurosurg.* 53:267–71
41. Guo T, Finnis KW, Parrent AG, Peters TM. 2006. Visualization and navigation system development and application for stereotactic deep-brain neurosurgeries. *Comput. Aided Surg.* 11:231–39
42. Noachtar S, Borggraefe I. 2009. Epilepsy surgery: a critical review. *Epilepsy Behav.* 15:66–72
43. Obeso JA, Rodriguez MC, Gorospe A, Guridi J, Alvarez L, Macias R. 1997. Surgical treatment of Parkinson's disease. *Baillieres Clin. Neurol.* 6:125–45
44. Finnis KW, Starreveld YP, Parrent AG, Sadikot AF, Peters TM. 2003. Three-dimensional database of subcortical electrophysiology for image-guided stereotactic functional neurosurgery. *IEEE Trans. Med. Imaging* 22:93–104
45. Comeau RM, Sadikot AF, Fenster A, Peters TM. 2000. Intraoperative ultrasound for guidance and tissue shift correction in image-guided neurosurgery. *Med. Phys.* 27:787–800
46. Hartkens T, Hill DL, Castellano-Smith AD, Hawkes DJ, Maurer CR Jr, et al. 2003. Measurement and analysis of brain deformation during neurosurgery. *IEEE Trans. Med. Imaging* 22:82–92
47. Gobbi D, Lee B, Peters TM. 2001. Correlation of pre-operative MRI and intra-operative 3D ultrasound to measure brain tissue shift. *Proc. SPIE* 4319:264–71
48. Reinertsen I, Descoteaux M, Siddiqi K, Collins DL. 2007. Validation of vessel-based registration for correction of brain shift. *Med. Image Anal.* 11:374–88
49. Kettenbach J, Wong T, Kacher D, Hata N, Schwartz RB, et al. 1999. Computer-based imaging and interventional MRI: applications for neurosurgery. *Comput. Med. Imaging Graph.* 23:245–58
50. Foroglou N, Zamani A, Black P. 2009. Intra-operative MRI (iop-MR) for brain tumour surgery. *Br. J. Neurosurg.* 23:14–22
51. Sutherland GR, Latour I, Greer AD. 2008. Integrating an image-guided robot with intraoperative MRI: a review of the design and construction of neuroArm. *IEEE Eng. Med. Biol. Mag.* 27:59–65
52. van der Meijden OAJ, Schijven MP. 2009. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surg. Endosc.* 23:1180–90
53. Jackson DW, Simon TM. 2008. History of computer-assisted orthopedic surgery (CAOS) in sports medicine. *Sports Med. Arthrosc.* 16:62–66
54. Merloz P, Tonetti J, Pittet L, Coulomb M, Lavallee S, Sautot P. 1998. Pedicle screw placement using image guided techniques. *Clin. Orthop. Relat. Res.* 354:39–48
55. Kosmopoulos V, Schizas C. 2007. Pedicle screw placement accuracy: a meta-analysis. *Spine* 32:E111–20
56. Paul HA, Bargar WL, Mittlestadt B, Musits B, Taylor RH, et al. 1992. Development of a surgical robot for cementless total hip arthroplasty. *Clin. Orthop. Relat. Res.* 285:57–66
57. Jaramaz B, DiGioia AM 3rd, Blackwell M, Nikou C. 1998. Computer assisted measurement of cup placement in total hip replacement. *Clin. Orthop. Relat. Res.*: 354:70–81
58. Reininga IH, Wagenmakers R, van den Akker-Scheek I, Stant AD, Groothoff JW, et al. 2007. Effectiveness of computer-navigated minimally invasive total hip surgery compared to conventional total hip arthroplasty: design of a randomized controlled trial. *BMC Musculoskelet. Disord.* 8:4
59. Davies BL, Rodriguez y Baena FM, Barrett AR, Gomes MP, Harris SJ, et al. 2007. Robotic control in knee joint replacement surgery. *Proc. Inst. Mech. Eng. H* 221:71–80

60. Stulberg SD, Yaffe MA, Koo SS. 2006. Computer-assisted surgery versus manual total knee arthroplasty: a case-controlled study. *J. Bone Jt. Surg. Am.* 88(Suppl. 4):47–54
61. Joskowicz L, Milgrom C, Simkin A, Tockus L, Yaniv Z. 1998. FRACAS: a system for computer-aided image-guided long bone fracture surgery. *Comput. Aided Surg.* 3:271–88
62. Guttman MA, Ozturk C, Raval AN, Raman VK, Dick AJ, et al. 2007. Interventional cardiovascular procedures guided by real-time MR imaging: an interactive interface using multiple slices, adaptive projection modes and live 3D renderings. *J. Magn. Reson. Imaging* 26:1429–35
63. Bertaglia E, Bella PD, Tondo C, Proclemer A, Bottoni N, et al. 2009. Image integration increases efficacy of paroxysmal atrial fibrillation catheter ablation: results from the CartoMerge Italian Registry. *Europace* 11:1004–10
64. Rhode KS, Sermesant M, Brogan D, Hegde S, Hipwell J, et al. 2005. A system for real-time XMR guided cardiovascular intervention. *IEEE Trans. Med. Imaging* 24:1428–40
65. Bracken JA, Komljenovic P, Lillaney PV, Fahrig R, Rowlands JA. 2009. Closed-bore XMR (CBXMR) systems for aortic valve replacement: x-ray tube imaging performance. *Med. Phys.* 36:1086–97
66. Brzozowski L, Ganguly A, Pop M, Wen Z, Bennett R, et al. 2006. Compatibility of interventional x-ray and magnetic resonance imaging: feasibility of a closed bore XMR (CBXMR) system. *Med. Phys.* 33:3033–45
67. Yuen SG, Kesner SB, Vasilyev NV, Del Nido PJ, Howe RD. 2008. 3D ultrasound-guided motion compensation system for beating heart mitral valve repair. *Med. Image Comput. Comput. Assist. Interv.* 11(Pt. 1):711–19
68. Linte CA, Wierzbicki M, Moore J, Little SH, Guiraudon GM, Peters TM. 2007. Towards subject-specific models of the dynamic heart for image-guided mitral valve surgery. *Med. Image Comput. Comput. Assist. Interv.* 10(Pt. 2):94–101
69. Rickers C, Gallegos R, Seethamraju RT, Wang X, Swingen C, et al. 2004. Applications of magnetic resonance imaging for cardiac stem cell therapy. *J. Interv. Cardiol.* 17:37–46
70. Rodriguez-Porcel M, Gheysens O, Chen IY, Wu JC, Gambhir SS. 2005. Image-guided cardiac cell delivery using high-resolution small-animal ultrasound. *Mol. Ther.* 12:1142–47
71. Rettmann ME, Holmes DR III, Cameron BM, Robb RA. 2009. An event-driven distributed processing architecture for image-guided cardiac ablation therapy. *Comput. Methods Programs Biomed.* 95:95–104
72. Wilson K, Guiraudon G, Jones DL, Peters TM. 2009. Mapping of cardiac electrophysiology onto a dynamic patient-specific heart model. *IEEE Trans. Med. Imaging* 28(12):1871–80
73. Falk V, Jacobs S, Gummert JF, Walther T, Mohr FW. 2003. Computer-enhanced endoscopic coronary artery bypass grafting: the da Vinci experience. *Semin. Thorac. Cardiovasc. Surg.* 15:104–11
74. Falk V, Mourgues F, Adhami L, Jacobs S, Thiele H, et al. 2005. Cardio navigation: planning, simulation, and augmented reality in robotic assisted endoscopic bypass grafting. *Ann. Thorac. Surg.* 79:2040–47
75. Mylonas GP, Darzi A, Yang GZ. 2006. Gaze-contingent control for minimally invasive robotic surgery. *Comput. Aided Surg.* 11:256–66
76. Rickers C, Jerosch-Herold M, Hu X, Murthy N, Wang X, et al. 2003. Magnetic resonance image-guided transcatheter closure of atrial septal defects. *Circulation* 107:132–38
77. Vasilyev NV, Martinez JF, Freudenthal FP, Suematsu Y, Marx GR, del Nido PJ. 2006. Three-dimensional echo and videocardioscopy-guided atrial septal defect closure. *Ann. Thorac. Surg.* 82:1322–26
78. Vasilyev NV, Novotny PM, Martinez JF, Loyola H, Salgo IS, et al. 2008. Stereoscopic vision display technology in real-time three-dimensional echocardiography-guided intracardiac beating-heart surgery. *J. Thorac. Cardiovasc. Surg.* 135:1334–41
79. Guiraudon GM. 2005. *U.S. Patent No. US-2005-0137609-A1*
80. Hawkes DJ, Barratt D, Blackall JM, Chan C, Edwards PJ, et al. 2005. Tissue deformation and shape models in image-guided interventions: a discussion paper. *Med. Image Anal.* 9:163–75
81. Solomon SB, White P Jr, Acker DE, Strandberg J, Venbrux AC. 1998. Real-time bronchoscope tip localization enables three-dimensional CT image guidance for transbronchial needle aspiration in swine. *Chest* 114:1405–10
82. Schwarz Y, Greif J, Becker HD, Ernst A, Mehta A. 2006. Real-time electromagnetic navigation bronchoscopy to peripheral lung lesions using overlaid CT images: the first human study. *Chest* 129:988–94
83. Eberhardt R, Anantham D, Herth F, Feller-Kopman D, Ernst A. 2007. Electromagnetic navigation diagnostic bronchoscopy in peripheral lung lesions. *Chest* 131:1800–5

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

84. Perissat J, Collet DR, Belliard R. 1989. Gallstones: laparoscopic treatment, intracorporeal lithotripsy followed by cholecystostomy or cholecystectomy—a personal technique. *Endoscopy* 21(Suppl. 1):373–74
85. Clayman RV, Kavoussi LR, McDougall EM, Soper NJ, Figenshau RS, et al. 1992. Laparoscopic nephrectomy: a review of 16 cases. *Surg. Laparosc. Endosc.* 2:29–34
86. Cadiere GB, Himpens J, Germay O, Izizaw R, Degueldre M, et al. 2001. Feasibility of robotic laparoscopic surgery: 146 cases. *World J. Surg.* 25:1467–77
87. Abbou CC, Salomon L, Hoznek A, Antiphon P, Cicco A, et al. 2000. Laparoscopic radical prostatectomy: preliminary results. *Urology* 55:630–34
88. Abbou CC, Hoznek A, Salomon L, Olsson LE, Lobontiu A, et al. 2001. Laparoscopic radical prostatectomy with a remote controlled robot. *J. Urol.* 165:1964–66
89. Coughlin G, Samavedi S, Palmer KJ, Patel VR. 2009. Role of image-guidance systems during NOTES. *J. Endourol.* 23:803–12
90. Rattner D. 2006. Introduction to NOTES white paper. *Surg. Endosc.* 20:185
91. Rattner D, Kalloo A. 2006. ASGE/SAGES Working Group on Natural Orifice Translumenal Endoscopic Surgery. October 2005. *Surg. Endosc.* 20:329–33
92. Spaun GO, Zheng B, Martinec DV, Cassera MA, Dunst CM, Swanstrom LL. 2009. Bimanual coordination in natural orifice transluminal endoscopic surgery: comparing the conventional dual-channel endoscope, the R-Scope, and a novel direct-drive system. *Gastrointest. Endosc.* 69:e39–45
93. Swanstrom L, Swain P, Denk P. 2009. Development and validation of a new generation of flexible endoscope for NOTES. *Surg. Innov.* 16:104–10
94. Blavier A, Gaudissart Q, Cadiere GB, Nyssen AS. 2006. Impact of 2D and 3D vision on performance of novice subjects using da Vinci robotic system. *Acta Chir. Belg.* 106:662–64
95. Vosburgh K, Stylopoulos N, Thompson C, Ellis R, Samset E, San Jose Estepar R. 2006. Novel real time tracking interface improves the use of laparoscopic and endoscopic ultrasound in the abdomen. *Int. J. Comput. Assist. Radiol. Surg.* 1:282–84
96. Leven J, Burschka D, Kumar R, Zhang G, Blumenkranz S, et al. 2005. DaVinci canvas: a telerobotic surgical system with integrated, robot-assisted, laparoscopic ultrasound capability. *Med. Image Comput. Comput. Assist. Interv.* 8(Pt. 1):811–18
97. Lerotic M, Chung AJ, Mylonas G, Yang GZ. 2007. Pq-space based non-photorealistic rendering for augmented reality. *Med. Image Comput. Comput. Assist. Interv.* 10:102–9

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Annual Review of Biomedical Engineering
Volume 12, 2010

Contents

microRNA: A Master Regulator of Cellular Processes for Bioengineering Systems
Wei Sun, Yi-Shuan Julie Li, Hsien-Da Huang, John Y-J. Shyy, and Shu Chien 1

Biomechanics of Pressure Ulcer in Body Tissues Interacting with External Forces during Locomotion
Arthur F.T. Mak, Ming Zhang, and Eric W.C. Tam 29

Microrobots for Minimally Invasive Medicine
Bradley J. Nelson, Ioannis K. Kaliakatsos, and Jake J. Abbott 55

Mesenchymal Stem Cells as Therapeutics
Biju Parekkadan and Jack M. Milwid 87

Image-Guided Interventions: Technology Review and Clinical Applications
Kevin Cleary and Terry M. Peters 119

Systems Biology through Mouse Imaging Centers: Experience and New Directions
R. Mark Henkelman 143

Protein Engineering in the Development of Functional Hydrogels
Scott Banta, Ian R. Wheeldon, and Mark Blenner 167

Microfluidic Platforms for Single-Cell Analysis
Richard N. Zare and Samuel Kim 187

Topography, Cell Response, and Nerve Regeneration
Diane Hoffman-Kim, Jennifer A. Mitchel, and Ravi V. Bellamkonda 203

Mechanisms of Defibrillation
Derek J. Dosdall, Vladimir G. Fast, and Raymond E. Ideker 233

Microfluidic Technologies for Temporal Perturbations of Chemotaxis
Daniel Irimia 259

Microscopic Imaging and Spectroscopy with Scattered Light
Nada N. Boustany, Stephen A. Boppart, and Vadim Backman 285

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.

Characterization of Biological Processes through Automated Image Analysis
Jens Rittscher 315

Sickle Cell Biomechanics
Gilda A. Barabino, Manu O. Platt, and Dhananjay K. Kaul 345

Osteocyte Mechanobiology and Pericellular Mechanics
Christopher R. Jacobs, Sara Temiyasathit, and Alesha B. Castillo 369

Muscle and Joint Function in Human Locomotion
Marcus G. Pandy and Thomas P. Andriacchi 401

Indexes

Cumulative Index of Contributing Authors, Volumes 3–12 435

Cumulative Index of Chapter Titles, Volumes 3–12 439

Errata

An online log of corrections to *Annual Review of Biomedical Engineering* articles may be found at http://bioeng.annualreviews.org/

Annu. Rev. Biomed. Eng. 2010.12:119-142. Downloaded from www.annualreviews.org
by University of Oslo - Medical Library on 11/18/13. For personal use only.