Image-Guided Surgery and Emerging Molecular Imaging

Advances to Complement Minimally Invasive Surgery

Christopher R. Mitchell, MD, S. Duke Herrell, MD*

KEYWORDS

• Image guidance • Robotics • Surgical navigation • Molecular imaging • Urologic surgery

KEY POINTS

- Image-guided surgery and molecular imaging remain areas of intense basic science and clinical research.
- Image-guided surgery technologies have become standards of surgical care in other specialties, including neurosurgery and orthopedics, but remains in its infancy in urologic and other soft tissue–based surgical specialties.
- Current research endeavors into the combined application of image-guided surgery and robotic urologic surgery presents the unique challenges of soft tissue registration, tissue deformation, operative navigation, and incorporation into the surgical work flow.
- Although progress has been made, continued collaboration between engineers and surgeons is required to achieve the ultimate goals of improved ease and accuracy of performing surgery leading to improved patient outcomes.
- The incorporation of molecular imaging into minimally invasive surgery remains in the early stages of development, however, is likely to continue to increase in importance with development of molecular markers specific to urologic malignancies.

INTRODUCTION

With recent advances in imaging and surgical instrumentation, there has been transition away from traditional open surgery toward new minimally invasive approaches. Open surgery has its distinct advantages in providing the surgeon with unrestricted visual, force, and tactile feedback, often at the expense of large incisions and surgical trauma. The emergence of robotic surgery with mechatronically enhanced or robotic-assisted instruments has significantly improved the capabilities of the minimally invasive surgeon, allowing surgical procedures to be carried out with unprecedented accuracy and efficiency. However, one of the drawbacks of minimally invasive surgery is the lack of haptic sensing and feedback to assist with tissue discrimination. Accordingly, extensive work is being done in the area of image guidance to thereby integrate enhanced visual information to improve ease, accuracy, and surgeon comfort with performing complex robotic surgeries.

Department of Urologic Surgery, Vanderbilt University Medical Center, A1302 Medical Center North, Nashville, TN 37232-2765, USA
* Corresponding author.
E-mail address: duke.herrell@vanderbilt.edu

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Traditional approaches to surgery, both open and robotic, are planned preoperatively using high-fidelity axial medical imaging, such as computed tomography (CT) and magnetic resonance imaging (MRI). These images are typically reviewed off-line and often only as a 2-dimensional (2D) display of the 3-dimensional (3D) anatomy. The surgeon then uses innate knowledge of human anatomy combined with the ability of the human brain to align objects in 3D space in what is referred to as *mental coregistration* of the imaging onto the body and organs. This, in essence, serves as a road map of anatomic relationships to facilitate the proposed surgery. Conversely, image-guided surgery (IGS) provides in situ, real time covisualization of either preoperative or intraoperative data along with the actual anatomy, and the imaging is displayed in a spatially accurate manner coordinated (registered) to the actual anatomy. Thus, the overall goals of IGS are to provide a fully planned procedure before its execution, integrate either real-time intraoperative imaging or preoperative imaging for enhanced accuracy, and to track anatomic changes and tissue deformation during surgery.[1] In the most simplistic form, image guidance is used to improve the surgeon's awareness of both the anatomy of the target organ and its relationship with surrounding structures. This review explores recent advances in IGS and emerging molecular imaging technologies aimed to improve accuracy, precision, safety, and surgeon confidence during urologic robotic surgery.

GENERAL PRINCIPLES OF IGS

IGS can be divided into 2 broad categories, which either utilize preoperatively obtained images or intraoperative, real-time imaging. In the first method, preoperatively obtained images for a specific patient are actively integrated into the workflow and visual display for the operation. Therefore, the images are used to map surgical position and orientation rather than functioning simply as a reference atlas. The second method involves active intraoperative imaging with real-time production of imaging (ie, fluoroscopy, ultrasound, CT, MRI) and requires operating room–based imaging modalities, special instrumentation, and ancillary personnel. With intraoperative CT or MRI, the obvious drawbacks of increased cost and personnel and the limited availability of these imaging modalities within the operating room setting, will likely restrict development and widespread adoption of techniques within this realm of IGS. Thus, most research has focused on using preoperative imaging to create an augmented reality with these images superimposed onto the surgical field of view. Imaging is registered with the patient's intraoperative anatomy to actively display organ, instrumentation, and vital structure location. This type of surgical navigation presents a unique set of challenges to overcome, which primarily involves concepts such as image registration, tracking, and deformation adjustment.

Registration

Central to any IGS system is the process of registration, that is, determining the mathematical relationship between objects in the preoperative images and their physical locations in the operating room. Basic registration is premised on aligning imaging and anatomy in a 3D coordinate space system.[2] A 3D-rendered surface allows for easier understanding of the spatial relationship between a surgical target and other structures the surgeon may wish to avoid. Registration may be done based on anatomic landmarks (points) or markers (fiducials) inserted before image acquisition that can be seen precisely on the imaging study and also identified within the patient in the operating room. Using high-speed computer algorithms, rigid 3D point-to-point alignment is performed. Thus, subsurface anatomy and location of important surrounding structures can be displayed to the surgeon on a video screen or as a virtual overlay on to the patient (ie, augmented virtual reality). The most common example of rigid fiducial-based registration is found with image-guided brain and spine interventions, in which the bony structure's relationships to the vital other structures is available to the surgeon before bringing the patient to the operating room. However, abdominal organs pose a particular challenge, as they are not accessible preoperatively for placement of fiducials and also lack easily identifiable landmarks that can function as points. Therefore, most work with registration for soft tissue applications has been based on surface registration, whereby a captured topographic surface (physical space) is then matched to a surface that has been extracted from preoperative images (image space). With this technique, large numbers of surface point coordinates are captured by sweeping a tracked tool over the surface of the target organ or assembling a surface using a reflected laser beam geometry captured from a laser range scanner.

Localization and Tracking Techniques

Localization is the process by which the surgeon is able to identify and display surgical tool tip locations within the viewing field and in relationship to the registered imaging and vital structures, which are commonly not yet encountered. This

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