ROBOTICS in UROLOGIC SURGERY

JOSEPH A. SMITH JR. • ASHUTOSH K. TEWARI

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This text is dedicated to the robotic surgical teams at Weill Cornell Medical College and Vanderbilt University, which have contributed to the success of the programs and to helping provide the best possible results for our patients.

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PREFACE

Urology has long been recognized as a speciality that embraces technologic advances. From the earliest cystoscopes and resectoscopes to flexible ureteroscopes to extracorporeal lithotripsy to laparoscopy, urologists are at the forefront in adapting and applying surgical technology. It is not surprising, then, that use of surgical robots to date has been dominated by urologists. Over the past decade, minimally invasive approaches have virtually revolutionized surgery, both within urology and in other disciplines. Robotic surgery has accelerated these changes and seems likely to have an even greater impact in the future.

Without question, robotic-assisted laparoscopic prostatectomy is the procedure that has firmly established the role of robotic-assisted surgery. Already, robotic-assisted laparoscopic prostatectomy is the dominant form of surgical treatment for carcinoma of the prostate in the United States, and its use is rapidly expanding worldwide. However, the realm of robotic-assisted surgery has expanded well beyond radical prostatectomy within the domain of urology. Robotics is impacting virtually every aspect of urologic surgery, including kidney removal and reconstruction, bladder removal, female urology, and pediatric urology. Furthermore, it is not difficult to envision changes in both the robotic instrumentation and its applications, which will permit new opportunities, some that could be anticipated and others completely unforeseen.

Introduction of robotics into a surgical practice creates challenges for both the clinician and the hospital. Training, economics, and the logistics of forming an appropriate surgical team must all be considered. Sometimes difficult decisions about whether and how to incorporate robotics into a surgeon's practice must be made. The initial enthusiasm for any new technology must be tempered by an objective analysis of comparative outcomes and patient-focused results.

Even though robotic surgery has been introduced into urology relatively recently, there is a need for a comprehensive text on the subject. In fact, it is the very newness of the topic that increases the significance of a book that dispassionately addresses the current but rapidly evolving state of the art. The goal of this text is to provide objective, comprehensive presentations of all aspects of robotic urologic surgery. There is a heavy emphasis on technical aspects of the procedure as well as patient-related outcomes and results. Establishment of an appropriate operative team is important to the success of any robotic surgery program and is presented in detail. Furthermore, in any situation, the economic consequences of expensive technology must be part of the equation and are specifically addressed in this text. The aim is not to promote robotic surgery but to help clinicians establish its appropriate role.

The editors are indebted to the many contributors who are responsible for the success of this endeavor. Many are true pioneers in the field, and all have done an outstanding job in preparing timely submissions. No attempt was made to develop a consensus of opinion, but all of the contributors provided both personal perspective and balance in their presentations.

Without doubt, robotic urologic surgery is here to stay. Equally certain is that the role of robotics in virtually all surgical disciplines, including urology, will expand. It is hoped that this text will help with the incorporation of robotics into urologic surgical practice to provide the best treatment outcomes for our patients.

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Ashutosh Tewari

CHAPTER 1

Prokar Dasgupta • Kirsten Rose • Ben Challacombe

Equipment and Technology in Robotics

INTRODUCTION

The word *robot* comes from the Czech *robota,*[1] meaning "forced work." It was first used by Karel Capek, a Czechoslovakian playwright and author in the 1920s. His work was often centered around his views on the potential danger of these machines, incorporating the idea of human makes robot, robot kills human. Machines performing tasks were looked at with fear at this time, with robots taking over the human race being a popular science fiction theme. Capek is now credited with the introduction of the term *robot.*

The definition of the term *robots* would state that they are "mechanical devices that sometimes resemble human beings and are capable of performing a variety of complex human tasks on command, or by being programmed in advance." Robots as we know them today were developed after World War II, resulting from the increased demand for automation in automobiles. However, the requirements of the surgical robots we use today, which are designed to be precise, accurate, and safe, have little in common with these industrial robots, which were characterized by their fast, strong, and repeatable actions.

Surgical robots were first used in the subspecialties of orthopedics and neurosurgery. In neurosurgery, stereotactic frames were developed using the fixed landmarks of the rigid cranium. These reference points were then used in conjunction with robots such as the Unimate Puma 560 (Programmable Universal Machine for Assembly, Danbury, CT) or the PUMA 200. This enabled the surgeon to maneuver the surgical arms to perform biopsies or the resection of mid-brain tumors in children using three-dimensional (3D) imaging. It was not until the 1990s that robots such as the ROBODOC (Integrated Surgical Systems, Sacramento, CA) were used in orthopedics. The combination of increased precision with the digitally stored osseous image enabled bones to be reamed with 10 times greater accuracy, allowing a reported 90% prosthesis contact.[2]

The National Aeronautics and Space Administration's (NASA's) Ames Research Center has also long been a pioneer in robotics and human/robot field testing. Starting in 1993 with the deployment of TROV, a teleoperated underwater vehicle, into the McMurdo Sound in Antarctica, through numerous remote science operations using the Russian-built Marsokhod Rover, to current tests using the Mars exploration rover prototype K9, Ames has tested human interface and autonomous technologies in many challenging environments. The Computational Sciences Division at NASA Ames Research Center has a long history and extensive experience in field robotics and human/robot field testing. Ames has been running robotic field experiments and has developed the staff and expertise to design and build robotic test platforms and embedded control systems. In 1999, in collaboration with Johnson Space Center, Ames ran ASRO, the first astronaut/rover field experiment, in which the Marsokhod rover acted as a scout, photographer, and field assistant to a suited astronaut. Field tests in 2003 and 2004 tested the Mobile Agents Architecture (MAA) for human-machine work systems.

In the early 1980s, surgical technique experienced a revolution with the introduction of minimally invasive surgery. The goal of minimally invasive surgery was to reduce patients' pain and recovery time from surgical procedures by minimizing the trauma of the larger incisions of traditional open surgery. The introduction of endoscopes and specialized tools to perform this type of surgery has also increased the technical complexity for the surgeon. The immediate difficulties facing an endoscopic surgeon were sixfold:

1. Lack of hand eye coordination
2. Lack of depth perception
3. Counterintuitive movements
4. Amplification of hand tremor
5. Limited degrees of freedom (DOF) as compared with open surgery
6. Surgical fatigue

The issues encountered by the surgeon include having to look at a screen that projects the image from the endoscope rather than looking at his or her own hands, thus interrupting hand-eye coordination. Conventional endoscopes also provide only a two-dimensional image, which means the surgeon loses depth perception. Some stereoscopic endoscopes do exist, but their performance has so far been limited by the resolution and contrast they are able to produce. Finally, the tools used are introduced into the body through ports placed in the abdominal wall. As the port acts as a fulcrum, the movement of the tip of the instrument occurs in the opposite direction to that of the surgeons' hand, making it counterintuitive and a difficult skill to master. The body wall also limits the movement of the instrument to only two directions, giving it just four DOF instead of six. All these issues make minimally invasive laparoscopic surgery a complex new skill mix for the surgeon to learn, with most procedures having longer learning curves than their open equivalents.

Although the previously mentioned difficulties can be compensated for by intensive practice, not every surgeon can become proficient in laparoscopic surgery. While pioneering laparoscopic surgeons were struggling to overcome these problems, the Defense Advanced Research Project Administration (DARPA) was funding telesurgical projects in the United States with the chief aim of enabling surgeons at remote hospitals to operate on soldiers injured in battle.[3]

EARLY ROBOTIC SYSTEMS: THE WICKHAM ERA

The limitations of laparoscopic surgery encouraged the introduction of robotic systems that can carry out precise tasks quickly and repeatedly without tiring. There is now mounting evidence for the use of these robotic systems within the field of urology. The first clinical use of a robot in urology was the PROBOT in 1989, which was used to assist in transurethral resection of the prostate (TURP).[4] The TURP robotic frame was developed in the late 1980s as a joint project between Guy's Hospital and the Mechanical Engineering Department at Imperial College, London, United Kingdom (Figure 1–1). The frame was constructed to support a six-axis Unimate Puma robot with a Wickham Endoscope Liquidiser and Aspirator.[5] Initially this device was tested on prostate-shaped potatoes, which confirmed that this robotic system was feasible and rapid. This was followed by a series of clinical trials, initially just on five patients, where it was shown to be safe and provided good hemostasis. Further studies also included the patients' postoperative flow rate, which was found to have significantly improved.[6]

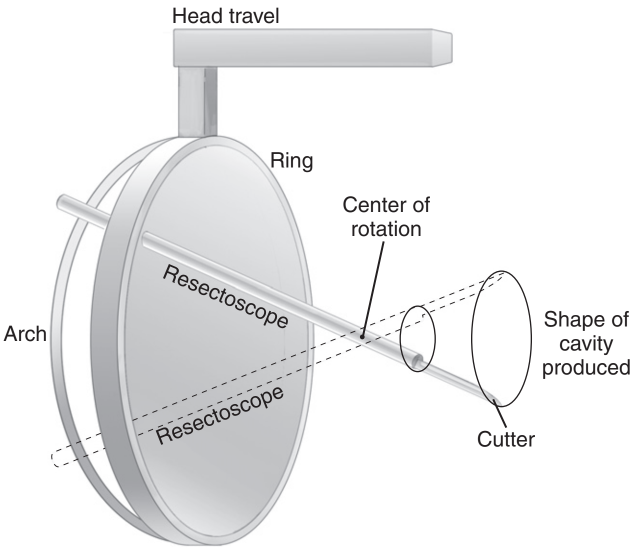

FIGURE 1–1 The Wickham TUR frame. *(Courtesy J. Wickham and S. Nathan.)*

SCARA

Because the prostate is a relatively fixed structure, it continued to be an ideal organ to further develop robotic-assisted procedures. The SR8438 Sankyo Scara robot was developed to perform transrectal ultrasound-guided prostate biopsies. The system allowed the surgeon to choose the biopsy site from the ultrasound images provided by the rectal probe before taking robotic-assisted biopsies of the prostate. Initial trials on animal models showed this method of obtaining prostate biopsies to be quicker and more accurate than the traditional method.[7] It also has good reliability because of the system's lack of drift. The robot can be remotely controlled and has been used with Integrated Services Digital Network (ISDN) lines as an early demonstration of telesurgery.

ENDOUROLOGIC SYSTEMS

As interest in robotics in urology grew, so did its clinical applications. Yet again, Wickham's group developed the first percutaneous nephrolithotomy (PCNL) robot in collaboration with Imperial College. The PCNL robot was a passive five DOF manipulator with an access needle that was mounted onto the operating table and guided by a C-arm. Positional sensors were used to record the position of the device, which was matched to the C-arm's coordinates. A personal computer displayed the access needle's trajectory on each fluoroscopic image, and the surgeon could manipulate its position. Initial experiments showed a targeting accuracy of less than 1.5 mm.[8]

The state-of-the-art robot for PCNL, the PAKY-RCM, has been developed to accurately position and insert a standard 18-gauge needle percutaneously into the kidney. This acronym stands for the **P**ercutaneous **A**ccess of the **K**idne**Y** robot-**R**emote **C**enter of **M**otion and was designed, engineered, and patented by the team at the Urobotics Laboratory, Johns Hopkins, Baltimore.[9] The PAKY-RCM robot consists of a seven DOF lockable manipulator, or passive arm,[10] connected to a three DOF active arm with a radiolucent needle driver (Figures 1–2 through 1–4). This is used to guide and actively drive a trocar needle in percutaneous access procedures. The RCM is a compact robot for surgical applications that can implement a fulcrum point located distal to the mechanism (usually the skin entry point). The robot can therefore

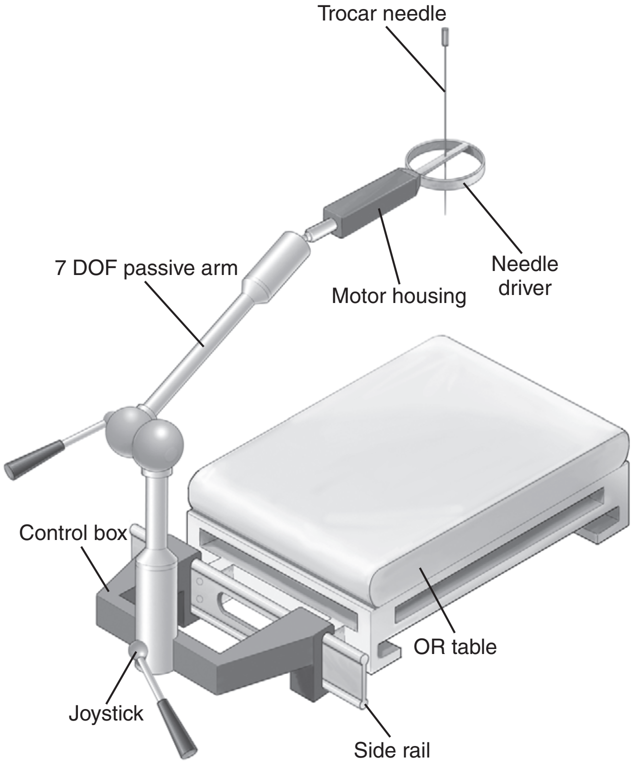

FIGURE 1–2 PAKY-RCM. *(Courtesy of the Urobotics Laboratory, Johns Hopkins, Baltimore, MD.)*

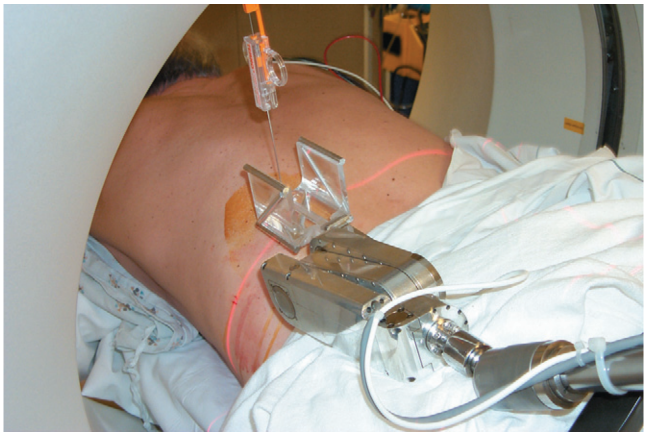

FIGURE 1–3 The z-PAKY being tested under computed tomography (CT) guidance. *(Courtesy of the Urobotics Laboratory, Johns Hopkins, Baltimore, MD.)*

precisely orientate a surgical instrument in space while maintaining the location of one of its points. The system was first evaluated using a porcine kidney model before initial clinical trials.[11] Comparison of robotic percutaneous access to the kidney to conventional methods on 23 patients proved robotic PCNL to be a feasible and safe method of obtaining renal access for nephrolithotomy. The number of attempts and time to access were comparable to those of standard manual techniques.[12] A Smart Needle has also been developed to be used in conjunction with the PAKY-RCM system. The needle detects the change in resistance upon successful entry to the renal collecting system and thus can confirm percutaneous access. The PAKY-RCM robot has been adapted for use in computed tomography (CT)-guided biopsies[13] and radiofrequency ablation procedures on the kidney.

HERMES AND AESOP

The Hermes Operating Room Control Center operates on voice and handheld touch-screen commands and lays the foundation for expanding the use of voice control technology in the operating room. It consists of a computer-control unit that is networked with multiple Hermes-ready devices and is controlled by a surgeon using simple verbal commands or an interactive handheld, touch-screen pendant. The system recognizes the surgeon's voice through a prerecorded voice card that the surgeon inserts into the system before the start of surgery. The surgeon controls devices such as an endoscopic camera, an endoscopic light source, a video cassette recorder, a video printer, and a laparoscopic insufflator. The system also provides visual and digitized voice feedback to the surgical team. Hermes can accommodate the integration of additional medical devices, including diathermy and various imaging systems.

AESOP, or Automated Endoscopic System for Optimal Positioning,[14] is one of the devices potentially under Hermes voice control, although it can operate independently. It positions an endoscope in response to the surgeon's commands, using either voice, foot, or hand control.[15] By imitating the form and function of a human arm, AESOP eliminates the need for a member of the surgical team to manually reposition the medical video camera (Figure 1–5). With precise and consistent movements, AESOP gives the surgeon direct control over a steadier operative field of view. AESOP responds to a vocabulary of 23 commands. Through simple commands such as "AESOP, move up," the surgeon can reposition the endoscope exactly where it is required. AESOP was the world's first U.S. Food and Drug Administration (FDA)-cleared surgical robot capable of assisting in minimally invasive procedures. Since its introduction, AESOP has assisted in more than 45,000 minimally invasive surgical procedures in more than 350 hospitals around the world. It is now regarded as a standard tool in performing laparoscopic radical prostatectomy and enables independent operating. Laparoscopic images with the AESOP are steadier with less camera changes and inadvertent instrument collisions compared with an inexperienced human assistant.[16]

MASTER-SLAVE SYSTEMS

The most advanced surgical robots currently are the "master-slave systems." The Zeus Robotic Surgical System and the da Vinci robotic surgical system (Intutitive Surgical, Sunnyvale, CA), which help surgeons eliminate hand tremor

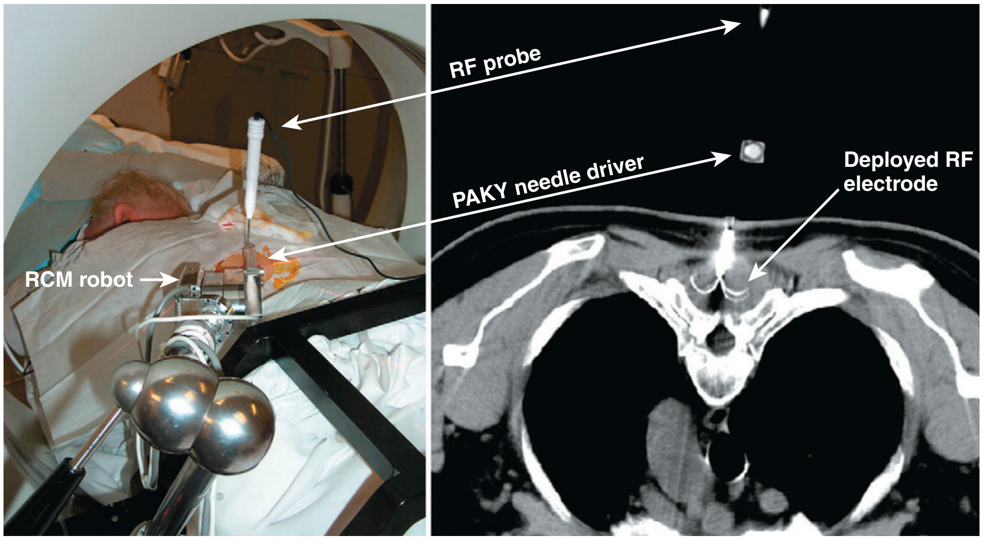

FIGURE 1–4 Computed tomography (CT)-guided remote center of motion (RCM) radiofrequency. *(Courtesy of the Urobotics Laboratory, Johns Hopkins, Baltimore, MD.)*

FIGURE 1–5 AESOP 3000. *(Courtesy of Intuitive Surgical.)*

and overcome dexterity and precision limitations, enable a new class of microsurgical procedures. Some who have argued that these are not true robots because they lack automation prefer the term *computer-assisted surgery* for operations performed with these machines.[17] This type of system was initially described by Bowersox in 1998, when the prototype Green Telepresence Surgical System (SRI, International, Menlo Park, CA) was used to perform nephrectomies, ureteral anastomosis, and cystotomy closure on anesthetized swine.[18]

Intuitive Surgical was founded in 1995 and licensed technology from Stanford Research Institute, Massachusetts Institute of Technology, and IBM's Watson Laboratory. The first prototype built in 1996 and tested in animals had two arms with wristed instruments and a third camera arm providing stereoscopic vision. The second version was tested on humans in Belgium in 1997. The alpha prototype of the da Vinci system was used for cardiac surgery in Paris and Leipzig. FDA trials followed in Mexico City in 1998, and the system was given approval for laparoscopic use in 2000 and thoracoscopic use in 2001.[19]

The master-slave systems comprise two major subsystems. One is the surgeon's console housing the CPU and display system, from which the surgeon handles the user interface and the electronic controller. The surgeon has a control panel, a clutch, and a camera control. The second subsystem is the patient side cart consisting of the robotic arms, of which there can be three or four including the camera arm. Both systems use 3D imaging to engulf the surgeon in a 3D video operating field. Zeus uses 3D glasses to achieve this, whereas the da Vinci uses binocular endoscopic vision. Until recently, da Vinci was in direct competition with the Zeus robot, but a corporate merger in 2003 resulted in Intuitive Surgical acquiring the rights to both machines. The Zeus has been phased out, making the da Vinci, with its superior performance, the unchallenged master-slave system. The da Vinci System (Figure 1–6) creates an immersive operating environment for the surgeon by providing both high-quality stereo visualization and restoring hand-eye coordination by projecting the image of the operative field on top of the surgeon's hand. The surgeon is made to feel like his or her hands are inside the patient's body and each of his or her movements is intuitive, unlike laparoscopic surgery. The da Vinci also restores the DOF lost in conventional