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Li-Ming Su *Editor*

Atlas of Robotic Urologic Surgery

Humana Press

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Edited by
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Humana Press

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*To my wife Maria and kids, Sean and Reilly, who are
my constant source of love, laughter and inspiration.
Special thanks to Linda H. Horne without whose dedication,
commitment and tireless efforts this book would not have
been possible.*

Preface

Few events have had as dramatic an impact on the field of urology as the introduction of robot surgery. The rapid adoption of robotics into the armamentarium of urologic surgery surpasses that of any other minimally invasive technology including shock wave lithotripsy, lasers, percutaneous surgery and laparoscopy. Most notably is the impact that robot-assisted laparoscopic radical prostatectomy has had on the practice pattern of clinically localized prostate cancer treatment in the USA as well as select centers worldwide. In only a few years, surgical practice in the USA has shifted from a predominance of open retropubic prostatectomy to robotic surgery. More recently, robotic surgery has expanded as an alternative treatment option for not only prostate cancer, but also a wide range of upper and lower urinary tract disorders.

This dramatic paradigm shift in urologic practice is a result of multiple factors, some of which relate to benefits to the operating surgeons and ultimately their patients. Robotic surgery has gained traction with urologists as it has offered the opportunity for many urologists, who have little to no experience with laparoscopy, to provide a minimally invasive surgical approach for their patients. The three-dimensional, high definition, and magnified view provided by the current robotic platform offers an unprecedented view of surgical anatomy, superior to that of open and conventional laparoscopic surgery. Along with other benefits such as motion scaling technology and articulating robotic instrumentation, surgeons are provided the opportunity of performing even more precise and meticulous surgery in a relatively bloodless operative field than ever before. Taken together, these benefits have translated in most cases into similar outcomes, but with reduced blood loss and transfusions, less pain, shorter hospital stays, and faster recovery times for patients undergoing robotic surgery as compared to traditional open surgery.

Despite the widespread adoption of robotics into urologic practice, robotic urologic procedures remain technically complex and the skill set required to perform robotic surgery differ significantly from that of traditional open surgery. Unlike open surgery where tactile feedback is often used as an intraoperative tool providing critical information, during robotic surgery, the surgeon is immersed in an environment absent of haptic feedback where operative decisions are made based instead on subtleties and nuances provided by visual cues. Visual cues such as vascularity, organ movement, distortion, and tissue adherence offer different and unique insights into the nature and behavior of organs and their interaction with surrounding structures such as blood vessels, fat, nerves and muscles. As a result, surgeons are required to think and interpret surgical dissection in a way that is unique and different from their training in open surgery.

The *Atlas of Robotic Urologic Surgery* was designed to provide a detailed, step-by-step guide to common robotic urologic procedures for the purpose of helping novice surgeons in their transition to robotic surgery and seasoned robotic surgeons to refine their surgical technique and expand their repertoire of robotic procedures. In addition, less commonly performed robotic procedures such as those for male infertility, pelvic organ prolapse, urinary tract reconstruction, and pediatrics are included. Each chapter is written by thought leaders in robotic urologic surgery with descriptive step-by-step text, complimented by figures and intraoperative photographs detailing the nuances of each procedure. Emphasis is placed on operative setup, instrument and equipment needs, and surgical techniques for both the primary surgeon as well as the operative assistant. The use of ancillary equipment and robotic instrument and endoscope exchanges are highlighted throughout the procedural text by tables designed to aid surgeons and their teams in improving efficiency. The hope is that this atlas will provide unique insights into robotic urologic surgery and reduce the learning curve of accomplishing these increasingly popular procedures.

FL, USA Li-Ming Su

Contents

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Part I
Background and Establishing a Robotics Team

Chapter 1
Robotics in Urology: Past, Present, and Future

Pierre Mozer, Jocelyne Troccaz, and Dan Stoianovici

Introduction

A robot is a mechanical device controlled by a computer. Medical robots have been classified in several ways. Three types were distinguished from an operational point of view [1]: remote controlled, synergistic, and automated or semi-automated robots. In the first two types, the physician has direct real-time control of the robotic instrument either from a console or by handling the instrument itself. The best known remote system is the da Vinci® Surgical System (Intuitive Surgical, Inc. Sunnyvale, CA), and examples of the synergetic class are the MAKO orthopedics robot (MAKO Surgical Corp., Ft. Lauderdale, FL) or Acrobot system (The Acrobot Company, Ltd. London, UK). For the later class, the physician does not have to continuously control the motion of the robot, but rather define its task and monitor the execution. Image-guided robots are commonly operated under this mode, for example, the Innomotion robot (Innomedic, GmbH, Herxheim, Germany. Acquired by Synthes West Chester, PA in March 2008) and our AcuBot robot for computed tomography (CT)-guided interventions [2].

Robots in different categories are significantly dissimilar from the technical point of view, having other design requirements. It is commonly the case that directly controlled robots have less precision requirements, because the motion is compensated by the physician, but have additional complexity for implementing the direct control of the physician. Image-guided robots do not normally need a surgeon console, but need to be more accurate and precise to operate without human compensation.

This chapter gives a short presentation of the achievements and developments in the field, a few key concepts of robotics and medical robotics, and several examples of these technologies commercial and under development.

Robots of the Past

The term *robota* was used for the first time in 1921, to indicate the idea of forced labor, in a Czech play written by Karel Capek (Rossoms's Universal Robot) and the term *robotic* was introduced by Isaac Asimov in 1950 in his novel *Runaround*. Several years later, Asimov defined three novelistic laws of robotics (a robot cannot hurt a human being, it must obey the orders given to it by a human being, and a robot must protect its own existence without infringing the first two laws) [3]. Although the term is relatively recent, the idea of an intelligent machine dates back to Antiquity, as, in Song XVIII of the Iliad, Hephaestus, the God of Fire, builds three-legged tables fitted with casters that are able to go back and forth on their own in the palaces of the Gods.

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The first master–slave robotic system was used to manipulate radioactive substances and was invented in 1954 by R. Goertz [4]. The first industrial robot, called Unimate, was invented by G. Deroe and J. Engelberger in 1961 and consisted of an articulated arm with hydraulic motorization used in the automobile industry [5].

Robots for medical applications have been initially derived from industrial robots. The first medical system, developed in the mid-1980s by Y. Kwoh and R. Young, was a neurosurgical stereotactic guidance system integrated with a CT scanner. The first patient was operated in 1985 [6] and despite its accuracy, the system did not appear adapted to surgery due to some drawbacks, such as safety, the time needed for the setup, and its limited workspace. Medical requirements for safety and specifications related to the fields of applications rapidly led to the development of dedicated robots in the field of urology.

From a historic point of view the first systems were robots with image-guided capabilities. Davies developed a robot for prostatectomies, called Probot [7], based on an industrial Unimate Puma robot constrained within a frame for safety consideration. The robot was guided by transrectal ultrasound (TRUS) images and it was the first robotic device used to remove tissue from a patient when it underwent its first clinical trial in March of 1991.

A few years later, the URobot system was developed in Singapore by Ng et al. The robot was designed to perform a transurethral and transperineal access to the prostate for laser resection in 2001 [8] or brachytherapy [9], respectively. At Johns Hopkins University, our team has developed several needle driving systems under various x-ray based guidance modalities, and performed numerous clinical tests for urology applications [2, 10–14]. Commercially, the German company Innomedic is pursuing the development of a system for guiding needles under direct magnetic resonance imaging (MRI) guidance.

Simultaneously, some others research teams worked on the concept of remote manipulation mostly for augmenting the performance of minimally invasive surgery [15]. The first system was named Artemis (Advanced Robotic Telemanipulator for Minimally Invasive Surgery) [16]. Computer Motion Inc. (Santa Barbara, CA) was able to develop the first robotic arm approved by the Food and Drug Administration (FDA) to hold an endoscope [17]. This system called AESOP (Automated Endoscopic System for Optimal Positioning) was a robotic arm with motorized joints controlled by the surgeon with hand and foot controls or through a speech recognition system. Early clinical use was reported [18] and the idea to use the same arm to drive surgical tools gave birth to the Zeus surgical system. This system consists of a surgeon's console and three separate robotic arms that are attached to the operating room table. The distance between the interface, by which the operator gives his instructions to the machine, and the patient can range from several meters to several thousand kilometers, opening the way to telesurgery [19]. Nevertheless, the Zeus was not FDA approved and another company, Intuitive Surgical, opened the field of robotic surgery with the da Vinci®. The da Vinci® robotic platform is a master–slave system with three or four arms allowing endowrist capabilities and a three-dimensional visualization of the surgical field. Even though several drawbacks have been echoed about its functionality and possible improvements, this system popularized the concept and instrumentation of robotic surgery in several medical fields. The first radical prostatectomy was reported in 2000 by Abbou et al. [20]. Some other applications in general surgery were explored [21], but even though the system was not purposely designed for urology, prostatectomy appears to be its best suited application.

Robots of the Present

Currently, the da Vinci® platform is the only robotic system used in common practice with more than 800 robots installed worldwide. In large majority the robots are used for robot-assisted laparoscopic radical prostatectomy

(RALP) [22]. Even if the review of published literature on RALP and open radical prostatectomy (ORP) is currently insufficient to favor one surgical technique, it seems that short-term outcomes of RALP achieve equivalence to open surgery with regard to complications and functional results [23]. Applications to bladder cancer, renal cancer, ureteropelvic junction obstruction, and pelvic prolapse have also been explored [24]. The main technical improvement since the first release of the system was the addition of a fourth robotic arm, yet other features especially with respect to improved sensory feedback could significantly improve its performance and surgeon acceptance.

A new class of robot, called synergistic [25], is under evaluation mainly for orthopedic surgery. This robot (MAKO Surgical Corp.) confines a bone cutting tool by hardware and software robotic means to a defined volume in space creating a "no-fly zone" defined by the surgeon based on preacquired images. Evaluation of the MAKO system for partial knee resurfacing is ongoing. Also for orthopedics, the Acrobot system can be used for unicompartmental knee replacement [26] or hip resurfacing surgery [27].

Robots of the Future

Current developments aim at creating robotic systems with decreased learning curves that would allow for safer and more homogeneous outcomes with less variability of surgeon performance, as well as new tools to perform more autonomous tasks in a less invasive way at lower costs. Conceptually, robotic developments are an integral part of the computer aided surgery (CAS) paradigm [28]. This integrates preoperative planning, intraoperative guidance, robotic assistance, and postoperative verification and follow-up. Augmented reality is a part of this concept including image fusion from various imaging modalities, such as preoperative CT with laparoscopic images [29]. Fusion of fluoroscopic and ultrasound images has been proposed to couple the intraoperative guidance of the real-time ultrasound with the higher imaging capabilities of the CT [30].

Based on the CAS concepts, future systems are expected to advance in the following two directions: improvements of remote manipulation robots for surgery, developments of image-guided robots for interventions, and possibly combining the two categories.

Remote Manipulation Robots

Current surgical robotic research shows a trend of size reduction compared to the da Vinci® system. For example, the NeuroArm (University of Calgary, Canada) proceeds with the development of a remotely controlled bilateral arm robot for neurosurgical operations. Part of the scope is to reduce its size to where the robot could be brought in the bore of an MRI scanner. Even though this is not yet possible, their current version is substantially smaller than the da Vinci®, and has additional features such as force feedback [31]. Another example is the VickY system [32], which is a very compact robot allowing to move a laparoscopic camera. Technical works to hold surgical tools on this platform are ongoing (Fig. 1.1).

Currently a major concern with the da Vinci® is the lack of haptic feedback. Several teams are pursuing additions to the existing system for augmenting sensory feedback [33] and with modified trocar instruments for allowing the measurement of manipulation forces [34].

A novel approach is pursuing the development of tools to be deployed in the peritoneal cavity and controlled externally with magnetic fields for reducing the number of transabdominal trocars and for increasing the range of motion and accessibility [35].

The development of natural orifice transluminal endoscopic surgery (NOTES) is potentially the next paradigm shift in minimally invasive surgery. The concept is to access to the peritoneal cavity without passing through the anterior abdominal wall. The first clinical case, performed in 2007, was a cholecystectomy in a

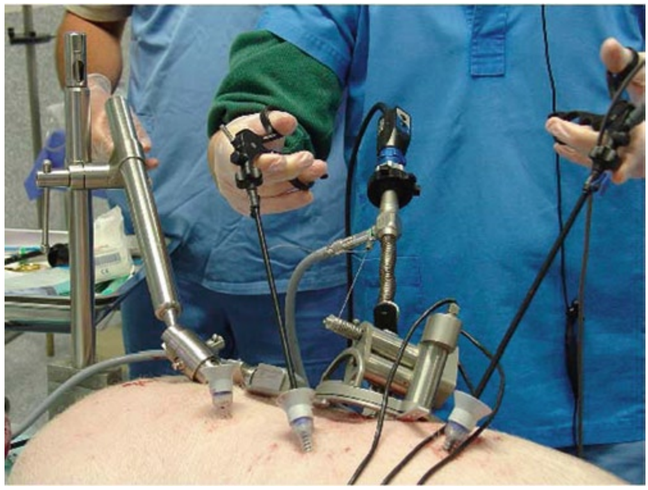

Fig. 1.1 VickY robot

woman via a transvaginal approach [36]. Nevertheless, NOTES procedures are performed using modified endoscopic tools with significant constraints, and new tools are necessary to allow the surgeon to better visualize and dexterously manipulate within the surgical environment. A two-armed dexterous miniature robot with stereoscopic vision capabilities is under development [37].

Direct Image-Guided Robots

Traditionally, image-guidance and navigation of instruments has been performed manually based on preacquired images with the use of spatial localizers such as optical [38] and magnetic trackers [39]. However, robots have the potential to improve the precision, accuracy, and reliability of performance in image-guidance interventions, because the tasks are done in a full digital way, from image to instrument manipulation.

Robots for interventions with needles or other slender probes or instruments can be connected to an imaging modality (CT, MRI, ultrasound, fluoroscopy, etc.). Targets and paths are defined in the image based on planning algorithms, and the robot aligns and may insert the needle accordingly. The true potential of needle delivery mechanisms relies on their ability to operate with, be guided by, and use feedback from medical imaging equipment.

Moreover, robots can do complex movements, impossible to perform by a human to limit tissue and needle deformations during the insertion. Indeed, mechanical laws dictate that the reduction of needle insertion force diminishes tissue deformations and target deflection. Mockup experiments with a prostate brachytherapy needle correlated deflections to the speed of needle insertion and correlated with the change in axial force [40].

Decreasing the force of needle insertion has been proposed with special movements for increasing the accuracy to reaching a target. Abolhassani [41] described an interesting approach during the puncture of a prostate phantom. The deflection of the needle is estimated using online force/moment measurements at the needle base and to compensate for the needle deflection, the needle is axially rotated through 180°. Results show on a prostate phantom with an 18-Gauge beveled-tip needle that the deflection at the target was reduced by as much as 90%. Nevertheless, applying just a rotation of the needle at the rate of 50 rpm is less complex and the results were similar. Results on needle rotation were confirmed by others teams, but concerns regarding tissue damage due to the "drilling" nature of the insertion were also raised, depending on the geometry of the needle point especially with the bevel. Meltsner et al. [42] showed that with a bevel point needle, the damage to the gelatin mockup used became greater when the rotation speed increases. To avoid this effect during the needle insertion, they suggested rotating only the barrel of the needle and not its stylet with the point. Podder et al. [43] proposed a system designed to insert multiple needles simultaneously for prostate therapies. Rotation was also used for reducing insertion forces.

Image Input

Image-guided robots have stringent requirements for imager compatibility, precision, sterility, safety, as well as size and ergonomics [28]. A robot's compatibility with a medical imager refers to the capability of the robot to safely operate within the confined space of the imager while performing its clinical function, without interfering with the functionality of the imager [44].

The current research trend is to embed the robot with the imager (CT, MRI, ultrasound, fluoroscopy, etc.) for reimaging during the intervention for relocalization, treatment planning updates, and quality control. We term these procedures direct image-guided interventions (DIGI). The performance of DIGI interventions is not new, in fact the routine TRUS biopsy is done under direct guidance; however, the new term is essential for distinguishing this important class of image-guided intervention (IGI) from navigation based on preacquired imaging data.

Among all types of imagers, the MRI is the most demanding, and the development of MRI-compatible robots is a very challenging engineering task [45]. But, this also makes MRI-compatible multi-imager compatible, if care is taken for the selection of radiolucent materials for the components in immediate proximity of the imaging site [44]. Due to the strong requirements needed to build a MRI-compatible robot, the following description of many robots under development is presented with respect to their capabilities of operation leading up to those used in conjunction with MRI.

Ultrasound and CT-Compatible Robots

Professor Brian Davies of the Imperial College in London, who pioneered the robotics filed in urology with the Probot [7], has also reported the development of a simple robot that performs similar to the brachytherapy template [46]. Rotation about the axis of the needle is added in order to reduce needle deflections. The system uses two-dimensional TRUS guidance and the report describes successful preclinical testing.

In the Robarts Research Institute (London, Canada) [47] and in the Nanyang Technological University (Singapore) [48], three dimensional reconstruction from a regular two dimensional TRUS probe has been investigated by sweeping the probe about its axis. This was integrated with a robot in a system for prostate brachytherapy or biopsy. Mockup tests demonstrated a precision on the order of 1 mm and a clinical study for biopsy is ongoing in Singapore.

Our URobotics laboratory at Johns Hopkins has also developed several versions of a CT-guided robot [2]. Recently, the AcuBot robot was instrumented with a new end-effecter, the revolving needle driver (RND). The RND is a fully actuated driver for needle insertion, spinning, release, and force measurement (Fig. 1.2). The driver supports the needle from its head, and provides an additional needle support guide in close proximity of the skin entry point. This is similar to holding the needle with two finger-like grippers, one from its head and one from its barrel next to the skin. The top one pushes the needle in and out, while the lower holds the guide to support the direction of the needle as close as possible to the skin. Both grippers can simultaneously release the needle automatically. Finally, the new driver is also equipped with a set of force sensors to measure the interaction of the nozzle with the patient and the force of needle insertion [49, 50].

MRI-Compatible Robots

The earliest work for MRI-guided prostate intervention robots was performed at the Brigham and

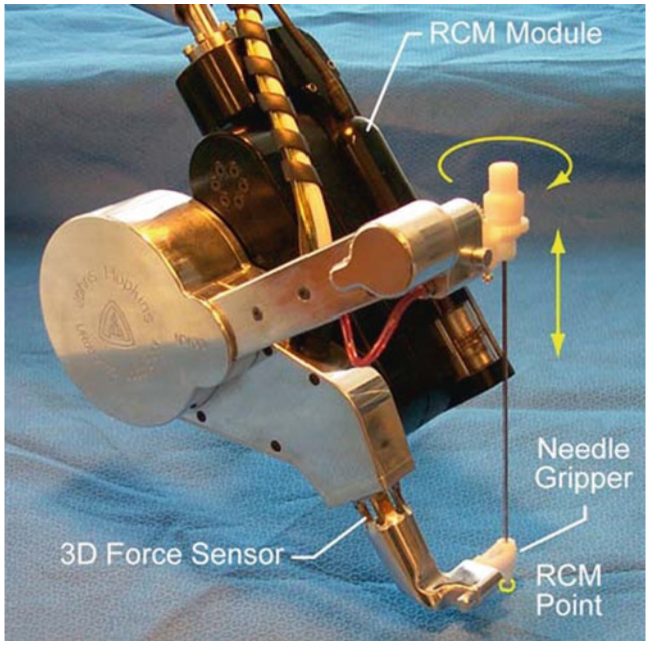

Fig. 1.2 Revolving needle driver on the AcuBot robot

Women's Hospital, Boston MA in collaboration with AIST-MITI, Japan [51]. A robotic intervention assistant was constructed for open MRI to provide a guide for needles and probes [52]. To minimize image interference from motors, the robot had to be located distally, at the top of the imager between the vertical coils of the MRI. To operate at the isocenter, long arms had to be extended, which made them flexible. The system assists the physician by positioning a needle guide for manual needle intervention. Applications included prostate biopsy and brachytherapy [53, 54].

The Institute for Medical Engineering and Biophysics (IMB), Karlsruhe, Germany reported several versions of a robotic system for breast lesion biopsy and therapy under MR guidance [55, 56]. Their last version used a cylinder for driving an end-effector axis [57], and their report gives a well-reasoned presentation of these advantages. This German institute is no longer active, but fortunately a spin-off company was created. The company (Innomedic, Germany) is developing a pneumatic robot for general CT- or MRI-guided needle procedures [58]. The robot orients the needle about the axial-sagittal planes for interventions targeting abdominal organs. However, a group from Frankfurt, Germany has recently used the Innomotion system for targeting the prostate [59, 60]. The limitations of the robot restricted the access to the transgluteal path (prone patient with needle pointing down) for which the needle path is much deeper than normal (~14 cm reported in the cadaver experiment) [60]. A 15 Ga needle was used to prevent deflections. Manual needle insertion was performed through the guide after retracting the table from the scanner. Even though the Innomedic system is not FDA approved and its designed application range does not include the prostate, it is approved for clinical use in Europe and is a commercial DIGI robot.

TIMC laboratory in France reported a light-weight MRI-compatible robot for abdominal and thoracic percutaneous procedures [61]. This robot, named LPR (acronym for Light Puncture Robot), has an original compact (15 × 23 cm) body supported architecture, which is naturally able to follow the patient body surface respiratory movements. It is entirely made of plastic, and uses MR-compatible pneumatic actuators powered by compressed air. The needle-holder puncture part includes clamps used to grasp the needle, and a translation unit (a fast linear pneumatic actuator), which is able to perform a fast puncture in a single motion (above 9 cm/s) to