Chapter 59

Robotic Systems: Past, Present, and Future

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59.1 Introduction

In the last decades we have witnessed the emergence of robotic surgery. The concept of "Medical Robotics" took time to become feasible and accepted by the medical community. A promoting factor for the development of these advanced medical instruments has also been the preceding development of minimally invasive surgery methods and laparoscopy in general surgery.

A robot, as defined by the American Society of Robotics, "is a reprogrammable, multifunctional device designed to manipulate and/or transport material through variable programmed motions for the performance of a variety of tasks." Thus a Robot must exhibit three key components:

1. Programmability; implies computerized or symbol-manipulating ability.
2. Mechanical capability; enabling it to act on its own environment.
3. Flexibility; can manipulate/transport in a variety of way.

Potential advantages of robotics in medical applications include remote, scaled, digital manipulation with precise and accurate positioning. Their ability to improve dexterity in minimally invasive approaches and perform operations remotely to reduce physician's radiation exposure has been an important factor in demonstrating the potential value of these technologies.

Robotic assistance in minimal invasive surgery is currently showing benefits to the patient with regard to length of hospital stay, return to full activity, and cosmetics. Despite the current cost of the robotic instruments several studies have shown that these may also become a cost-effective option. On the other hand there have been major concerns about their difficult compatibility with standard instrumentation, being technically demanding about safety, the loss of tactile feedback, and the lack of irrefutable clinical effectiveness.

Although, a robot has become a must have in every medical center involved in minimal invasive surgery, these technologies are still in their infancy and time only will show if these will become integral part of everyday practice as "the standard of care." In this chapter we will discuss the evolvement of medical robots, their current status, and give a perspective view of the ideas and projects currently under development.

59.2 History

The word "robot" was introduced by the Czech writer Karel Čapek in his satirical play "Rossum's Universal Robots" which premiered in 1921. The name was suggested by his brother Josef Čapek and was taken from the word "robota" meaning literally work or "slave labor." The term *robotic* was presented by Isaac Asimov in the year 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.[1]

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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.

The first programmable industrial manipulator was developed in the 1940s. George Devol, who is credited as the father of robotics, developed a magnetic process controller that could be used to manage these first robotic machines.

The beginning of the robotic age was marked by the development and integration of computers, when in 1954 the first robot used play back memory. The first master–slave robotic system was used to manipulate radioactive substances, invented in 1954 by R. Goertz.[2] 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.[3]

Since then, robots have been used in industry for nearly everything, from the processing and assembling of microprocessors to the manufacturing of large-scale industrial machinery.

In the late 1980s we witnessed the development of minimally invasive surgical techniques including laparoscopy. This brought the idea that surgeons may no longer need to directly handle tissue to perform an operation.

Minimally invasive surgery (MIS) revolutionized the concept of surgery. In MIS, special slender instruments are inserted through small skin incisions. Although MIS brought substantial advantages including the reduction of surgical trauma, patient recovery time, and improvement in cosmetics it also introduced new substantial difficulties. These include the loss of wrist articulation, touch feedback, 3-dimensional (3D) vision, eye–hand coordination, and typically poor ergonomics of the tools. These limitations made procedures requiring delicate dissections difficult and technically demanding if not impossible. As such, the range of minimal procedures that could be performed with MIS was limited. This has shown the potential advantages of using more advanced instrumentation for MIS, such as robots especially developed for surgery. Satava,[4] Ballantyne, and Moll[5] have suggested that laparoscopic surgery is a "transitional" technology leading to robotic surgery.

59.3 Classification of Medical Robots

A wide variety of surgical robots have been developed over the last decades. One classification method suggested by Taylor[6] would be based on *technology*, *application*, or *role*. A technology-based taxonomy might have categories such as autonomous and teleoperated robots, whereas an application-based taxonomy might have categories such as cardiology and urology. The problem with these two approaches is that, on either side, classifications may become quite esoteric and lose meaning for those outside the involved community. Furthermore, this is an artificial decoupling because the application that defines the problem is divorced from the technology that provides the solution.

Role-based classifications can be more useful because they are far-reaching and speak to technology developers as well as end-users. Such taxonomy can be a means of communication among all interested groups in describing needs, requirements, performance, and specifications.

A procedural role-based classification was suggested by Camarillo et al.[7] that can be divided into three discrete categories:

1. Passive role: The role of the robot is limited in scope or its involvement is largely low risk.
2. Restricted role: The robot is responsible for more invasive tasks with higher risk, but is still restricted from essential portions of the procedure.
3. Active role: The robot is intimately involved in the procedure and carries high responsibility and risk.

We suggest the use of a classification based on two criteria:

First, the operational point of view: (a) Remotely controlled, (b) Synergistic, and (c) 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 (Intuitive Surgical, Inc.), and examples of the synergetic class are the Mako orthopedics robot (Mako Surgical Corp.) or Acrobot system (Acrobot Company, Ltd). 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) and our AcuBot robot for CT-guided interventions.

Second, the localization method applied for the procedure: (a) visual (b) image guided; with the help of imaging equipment like magnetic resonance imaging (MRI), computed tomography (CT), ultrasound (US), or fluoroscopy.

59.4 Evolution of Medical Robots

Robots for medical applications have been initially derived from industrial robots. In 1985, the PUMA 560, the first medical robot was released by Kwoh et al. and was used to perform neurosurgical biopsies under Computed Topography guidance.[8] The robot was used to hold a fixture next to the patient's head to guide a biopsy instrument. Then it was locked in position, with power removed, while manually the surgeon used the fixture to orient drills and biopsy probes. Thus the robot was relegated to the role of a traditional stereotactic frame in neurosurgery. The procedure was performed with greater precision and took less time than the stereotactic brain surgery techniques used at the time. The Puma 560 was an improvement of the PUMA 200 produced by Unimation Limited and used for industrial purposes.

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.

Three years later, Davies and his team performed a transurethral resection of the prostate (TURP) using the Puma 560. For this, it was necessary to add two frameworks onto the puma robot, mainly for safety considerations.[9] This was the first urologic use of medical robot.

Shortly after, Unimation Limited Company was sold to Westinghouse Limited, who refused to allow the use of the robot for surgery purposes on the basis that it was unsafe, since the industrial robot was designed to be used inside a barrier away from all contact with people.

Thus, in spite of the encouraging preliminary results, the work on the PUMA robot was ceased.

The robotic system used for TURP eventually led to the development of ProBot, an automated robot system designed specifically for transurethral resection of the prostate. It was designed by the team at the Imperial College in London 1991.[10,11] The system had a 7 degrees of freedom (DOF) coupled to a motorized component to automate transurethral resection of the prostate for benign prostatic hypertrophy. The coordinates for resection were based on pre-operative prostate volume and shape determined by transrectal ultrasound (TRUS) scans. This was the first time that an active robot had been single used to remove tissue from a patient.

However, the dependence of ProBot on preoperative TRUS, the relative inaccuracies of the TRUS estimation, and the need for manual electrocautery for hemostasis hampered the widespread adoption of ProBot.

While ProBot was being developed, Integrated Surgical Systems (ISS), Inc. of Sacramento, CA, was clinically developing ROBODOC, a robotic system designed to machine the femur with greater precision in hip replacement surgeries. ROBODOC prototype was developed at IBM Research.[12]

The ROBODOC system allowed the surgeons to plan the procedure preoperatively by selecting and positioning an implant with respect to a preoperative computer tomography (CT) study and intraoperatively mill the corresponding canal in the femur with a high-speed tool controlled by a robotic arm. The ROBODOC system consists of an interactive preoperative planning system and a robotic system for intraoperative execution. ROBODOC has been tested internationally and has recently received Premarket Notification (510 k) from the Food and Drug Administration (FDA).

The introduction of these initial medical Robots, PUMA 560, ProBot, and ROBDOC, facilitated the acceptance of medical robots and gave a thrust for the development and adaption of a wider variety of robots.

The URobot system was developed in Singapore by Ng et al. The robot was designed to perform a transurethral and trans-perineal access to the prostate for laser resection in 2001[13] or brachytherapy,[14] respectively. At the 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.[15–20]

Simultaneously, other research teams worked on the concept of remote manipulation mostly for augmenting the performance of minimally invasive surgery.[21] The first system was named Artemis (Advanced Robotic Telemanipulator for Minimally Invasive Surgery).[22] Computer Motion Inc. (Santa Barbara, CA) was able to develop the first robotic arm approved by the FDA to hold an endoscope.[23] 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[24] 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 and made possible the first intercontinental surgery, operation Lindberg.[25] Nevertheless, the Zeus was not FDA approved and another company, Intuitive Surgical, (Sunnyvale, CA), opened the field of robotic surgery with the da Vinci® Surgical System. The da Vinci robotic platform is a master–slave system with three or four arms allowing endowrist capabilities and a 3D 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.[26] Some other applications in general surgery were explored,[27] but even though the system was not purposely designed for urology; prostatectomy appears to be its best-suited application.

59.5 Robots in Current Clinical Use

Currently, the da Vinci® platform is the main robotic system used in common practice with more than 1,200 robots installed worldwide. In large majority the robots are used for robotic-assisted laparoscopic radical prostatectomy (RALP).[28] 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.[29] It is worth indicating that nearly half of the Radical Prostatectomy Procedures done in the USA are RALP. Applications to bladder cancer, renal cancer, ureteropelvic junction obstruction, and pelvic prolapse have also been explored.[30] 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's acceptance.

The CyberKnife from Accuray (Sunnyvale, CA, USA) is a frameless robotic system for stereotactic radiosurgery. It uses image-guided radiotherapy (IGRT) and adaptive radiotherapy (ART) for stereotactic radiosurgery technique in the treatment of intra- and extracranial lesions and is being adapted for urologic prostate radiotherapy.[31]

In other fields of medicine, mainly orthopedic surgery, a number of operational systems have been developed and are being used but not as extensively as the da Vinci system. A new class of robots, synergistic,[32] is under evaluation mainly for orthopedic surgery. This Mako System 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 pre-acquired images. Another orthopedic system is the Acrobot system (Acrobot Company, Ltd) which can be used for unicompartmental knee replacement[33] or hip resurfacing surgery.[34]

59.6 Future Directions

Generally speaking; developments aim at improving existing robotic systems and introducing new systems with decreased learning curves that would allow safer and more homogeneous outcomes with less variability depending on surgeon performance, as well as new tools to perform more autonomous tasks in a less invasive way at lower costs.

Thus 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.

59.6.1 Remote Manipulation Robots

Although the da Vinci system proved to be a valuable tool in the surgery room, it still incorporates a number of drawbacks. The system is still bulky and hard to manipulate. Improvements in the system design making it smaller, lighter, and easier to move may prove helpful and new versions of the system are being developed.

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.[35] Another example is the VickY system,[36] which is a very compact robot allowing to move a laparoscopic camera. Technical works to hold surgical tools on this platform are ongoing and commercial developments have been recently started by EndoControl company (Grenoble, France).

The lack of haptic feedback of the da Vinci robot is considered by the surgeons to be a major limitation. It is often the case that the sense of touch is a determinant factor in the localization of nearby structures and controlling the margins of resection during RALP. In delicate balance with Neurovascular Bundle sparing, the part of the prostate to be resected is a crucial factor in the outcome of the operation. To overcome this, haptic feedback systems are being developed, several teams are pursuing additions to the existing system for augmenting sensory feedback[37] including modifying trocar instruments for allowing the measurement of manipulation forces.[38]

Another way to overcome the lack of feedback is by improving the localization of the robotic arms by better 3D visualization systems and the incorporation of intraoperative imaging systems. For example, the addition of Transrectal Ultrasound (TRUS) imaging during RALP may provide better comprehension of nearby organs including the neurovascular bundle (NVB).[39] A TRUS Robot was developed in our laboratory to provide a steady holding of the TRUS probe and allow remote manipulation (Fig. 59.1). Preliminary clinical study has shown the system as helpful in recognizing the NVB and nearby organs, and further research is being done in order to evaluate its assistance and navigational guidance to the surgeon during RALP.

Improved localization may be achieved also by the superimposition of 3D computerized reconstructed preacquired images over the real-time intraoperative laparoscopic view. This is referred to as Augmented Reality (AR).[40,41] It gives the surgeon a transparent visual anatomy of the internal structures or lesions through the overlying tissues. The source of the reconstructed images is based on pre-operative CT or MRI. These reconstructed images are then registered onto anatomic landmarks and tracked by the computer

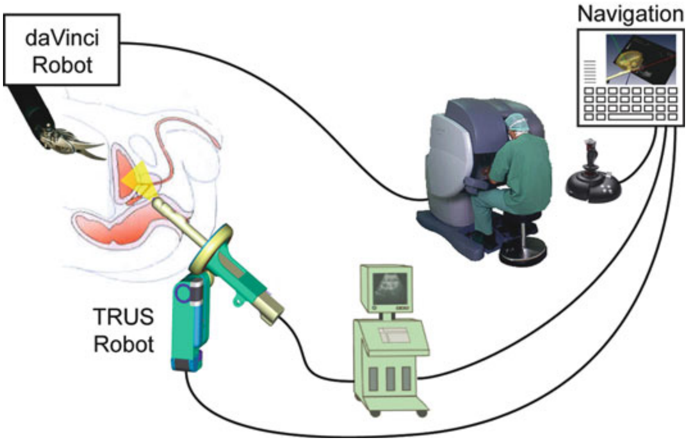

Fig. 59.1 Tandem robot-assisted laparoscopic radical prostatectomy system setup

according to the surgeon's dissection and camera movements.[40,41]

Better imaging can be achieved by image fusion from various imaging modalities, such as preoperative CT with laparoscopic images.[42] Fusion of fluoroscopic and ultrasound images has been proposed to couple the intraoperative guidance.[43] Real-time ultrasound can be fused with preoperative images with higher imaging capabilities like CT or MRI combining the advantages of different modalities.

Another 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.[44]

The development of natural orifice translumenal 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 woman via a transvaginal approach.[45] Nevertheless, NOTES procedures are performed using modified endoscopic tools with significant constraints. New tools are necessary to allow the surgeon to better visualize and dexterously manipulate within the surgical environment. This may be approached with help of newly designed robots specialized for NOTES. A two-armed dexterous miniature robot with stereoscopic vision capabilities is under development.[46] Snake like or serpentine robots are also being targeted toward this field, these robots will have multiple degrees of freedom, and will not fail if one joint locks/blocks and can be used trans-gastrically.[39] One such device is the CardioARM™ (Articulated Robotic MedProbe), a snake like surgical robot developed at Carnegie Mellon University, which hopes to allow cardiac surgeons to perform procedures through a single subxiphoid incision. The robot has a series of joints that automatically adjust to follow the course plotted by the robot's head, providing greater precision than the standard flexible endoscope can offer.[40] The same team is also developing a LaparoARM™, GastroARM™, and ArthroARM™ which will provide platforms for various endoscopic and laparoscopic procedures. These and other similar devices open the door for single incision or external scarless surgery.

59.6.2 Direct Image-Guided Robots

Image-guided robots have stringent requirements for imager compatibility, precision, sterility, safety, as well as size and ergonomics.[47] 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.[48]

The current research trend is to embed the robot with the imager (CT, MRI, ultrasound, fluoroscopy, etc.) for re-imaging 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 pre-acquired imaging data.

Traditionally, image guidance and navigation of instruments have been performed manually based on pre-acquired images with the use of spatial localizers such as optical[49] and magnetic trackers.[50] 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. This may compensate for organ reposition during the procedure caused by patient movement or by simple breathing.

Moreover, robots can do complex movements, impossible to perform by a human to limit tissue displacement and needle deformations during the insertion. Indeed, mechanical laws dictate that the reduction of needle insertion force diminishes tissue deformations and target deflection.

Decreasing the force of needle insertion has been proposed with special movements for increasing the accuracy to reach a target. Abolhassani[51] describes 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 were encouraging with reduction of nearly 90% of the deflection. Nevertheless, applying just a rotation of the needle at the rate of 50 rpm is less complex and the results were similar.[52] Podder et al.[53] proposed a system designed to insert multiple needles simultaneously for prostate therapies. Rotation was also used for reducing insertion forces.

Professor Brian Davies of the Imperial College in London, who pioneered the robotics filed in urology with the Probot,[54] has also reported the development of a simple robot that performs similar to the brachytherapy template.[55] Rotation about the axis of the needle is added in order to reduce needle deflections. The system uses 2D TRUS guidance and the report describes successful preclinical testing.

In the Robarts Research Institute (London, Canada)[56] and in the Nanyang Technological University (Singapore),[57] 3D reconstruction from a regular 2D 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 robots.[15] 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. 59.2). 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.[58,59]

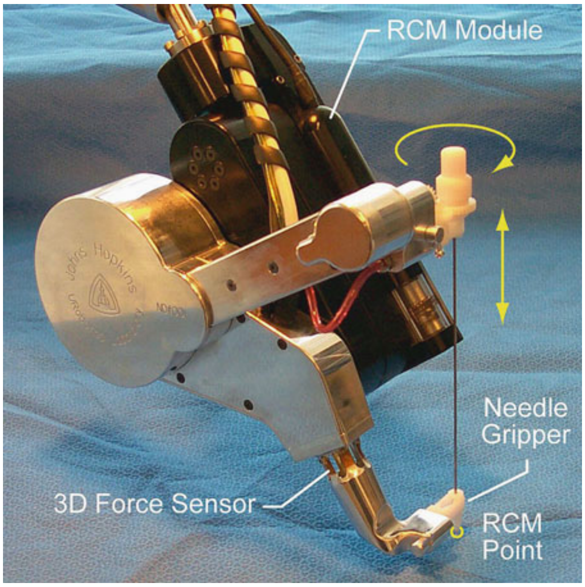

Fig. 59.2 Revolving needle driver on the AcuBot robot

59.6.3 MRI-Compatible Robots

Among all types of imagers, the MRI is the most demanding and the development of MRI-compatible robots is a very challenging engineering task.[60] But, this also makes MRI compatible robots to be multi-imager compatible, if care is taken for the selection of radiolucent materials for the components in immediate proximity of the imaging site.[48] 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.

The earliest work for MRI-guided prostate intervention robots was performed at the Brigham and Women's Hospital (BWH), Boston, MA, in collaboration with AIST-MITI, Japan.[61] A robotic intervention assistant was constructed for open MRI to provide a guide for needles and probes.[62] 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.[63,64]

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.[65,66] Their last version used a cylinder for driving an end-effector axis,[67] 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.[68] 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 Innomedic system for targeting the prostate.[69,70] 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). 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 lightweight MRI-compatible robot for abdominal and thoracic percutaneous procedures.[71] 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 are able to perform a fast puncture in a single motion (above 9 cm/s) to perforate the skin or organs walls. Mockup experiments are on going to measure system accuracy in the MRI.

Our group at Johns Hopkins has also developed an MRI-compatible robot for prostate access.[72] MrBot, was constructed to be multi-imager compatible, which includes compatibility with all classes of medical imaging equipment (ultrasound, X-Ray, and MR based imagers).[48] All robotic components are constructed of nonmagnetic and dielectric materials. To overcome MRI incompatibilities a new type of motor was purposely designed for the robot. This, PneuStep,[73] is a pneumatic motor using optical feedback with fail safe operation and it is the only fully MRI compatible motor.

The robot presents 6 DOF, 5 for positioning and orienting the injector, and 1 for setting the depth of needle insertion. Various needle drivers can be mounted in the robot for performing various needle interventions. The first driver was developed for fully automated low dose (seed) brachytherapy[74–77] (Fig. 59.3).

Compared with the classic template of needle guide holes, commonly used in TRUS interventions, the robot gives additional freedom of motion for better targeting. For example, the skin entry point may be chosen ahead of time and targeting can be performed with angulations, which is impossible with the template. As such, multiple needle insertions can be performed through the same skin entry point. Moreover, angulations also allow for reducing pubic arch interference, thus allowing for targeting otherwise inaccessible regions of the prostate.

The robot is controlled from a unit remotely located outside the imager's room, either in the control room of the imager or in other proximal space. The robot is connected to the control cabinet by a bundle of hoses. This allows for all MRI-incompatible components of the system to be located outside the MRI room.

Precision tests in tissue mock-ups yielded a mean seed placement error of 0.72 ± 0.36 mm.[76] With different needle drivers, the MrBot applies to various automated DIGI, such as biopsy, therapy injections,

Fig. 59.3 MrBot robot for MRI-guided prostate interventions

and thermal or radiofrequency ablations. The system is presently in preclinical testing with cadaver and animal experiments, but tests show very promising results and clinical trials are expected soon.

59.6.4 Image-Augmented Remote Manipulation Robots

The combination of the two classes presented above, remote manipulation and image-guided robots, is a very likely, highly promising direction of future developments. Augmenting guidance from medical imagers to surgical procedures could substantially improve the way that operations are being performed and would give a clear undisputable advantage for using robotic technologies in surgery.

The NeuroArm robot under development in Canada is a good example of these technologies.[35] Even though it may not yet operate inside the MRI scanner as planned, this may operate next to the MRI scanner and take advantage of recently acquired images to guide the surgery. This does not qualify as MRI safe and compatible, but is a "mini da Vinci" with force feedback. Image processing algorithms used in robotic surgery could also improve the localization of the surgical tools[78] and intraoperative analyses.[79]

59.7 Conclusion

As described above, substantial advances have been made in urology robotics since the first adoption in surgery. This field has become one of the most active areas of applied research. Medical robotic developments span across several scientific fields and disciplines: mechanical and electrical engineering, computer science, and medicine. The delicate process of robot advance has to take into consideration and satisfy all contributing developers that, in addition to the particularities of the field such as sterilization, medical safety, and imager compatibility, make it a very challenging and highly demanding research activity. On the other hand, there is enormous demand from patients and surgeons for less invasive surgical techniques that include medical robots.

We expect that the demand for medical robots will continue to expand, leading to the development and adoption of a wider variety of systems with better performance and cost-effectiveness that can apply to a larger population base. Hopefully, robot advances that we now experience will soon reflect in substantially better clinical outcomes and improved quality of life for the patients.

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