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EQUIPMENT AND TECHNOLOGY IN ROBOTICS.

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Summary.- We review the evolution and current status of robotic equipment and technology in urology. We also describe future developments in the key areas of virtual reality simulation, mechatronics and nanorobotics. The history of robotic technology is reviewed and put into the context of current systems. Experts in the associated fields of nanorobotics, mechatronics and virtual reality simulation simulation review the important future developments in these areas.

Keywords: Robotic. da Vinci™. Technology. Nanorobotics.

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INTRODUCTION

We have reached an interesting time in the field of surgical robotics. Over the past 5 years the imagination of patients and surgeons alike has been captured by the arrival of robotic-assisted surgery, telesurgical manipulators, and telepresence surgery. Robotic-assisted laparoscopic surgery in particular, has dominated headlines and symposium proceedings throughout the world in recent years, and lead to increasing patient demand for "robotic surgery". The bulk of this demand is due to the proliferation of da Vinci™ surgical systems (Intuitive Surgical, CA), especially in the USA where over 400 systems have been installed.

Urologists have been quick to embrace this technology and robotic-assisted laparoscopic radical prostatectomy (RALRP) is the most commonly performed robotic procedure performed worldwide. From 766 cases performed in 2002, over 48,000 are projected for 2007 (1). This accounts for 39.5% of the radical prostatectomy market in the USA.

But the monopoly which the da Vinci™ system holds has led to stagnation in the development of the field of robotic-assisted surgery. This technology has its roots in the Stanford Research Institue (SRI) Green Telepresence System which was developed in the early 1990's by Philip Green and other researchers at Stanford. The commercial licence for this technology was subsequently acquired by Fredrick Moll, MD, to found Intuitive Surgical in 1995. The prototype da Vinci™ system was launched in 1997 and little has been done to update the system since its Food & Drugs Administration (FDA) approval in 2000. Therefore the technology remains very expensive, very bulky, and somewhat outdated.

This paper outlines the interesting developments which have led to the current status of robotic technology and equipment today. However, as much of this has been described before (2,3), we will concentrate on the very exciting future technologies in development, especially the areas of virtual reality simulation, mechatronics and nanorobotics.

Definitions and history:

A surgical robot has been defined as "a computer-controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks" (4). Strictly speaking, the current popular surgical "robots" do not satisfy this definition, and some authors have suggested the term "computer-assisted surgery" more accurately describes the current generation of robotic devices (5). A description of "off-line" and "on-line" robots has been used to discriminate between machines carrying out pre-programmed tasks and those carrying out actions in response to ongoing commands ("master-slave" type devices) (6). Whatever the conclusion of that pedantic debate, the term "robotic" is in popular use to describe the range of technology under discussion here.

The early pioneers in this field included Wickham et al from Guy's Hospital and Imperial College, London, who developed the PROBOT in the late 1980's. The PROBOT used a robotic frame, which guided a rotating blade to complete transurethral resection of the prostate (TURP). Initial studies on prostate-shaped potatoes were followed up by clinical trials in patients to demonstrate safety and feasibility of the technology (7). This was a truly autonomous device ("off-line robot"), satisfying the definitions outlined above. However convincing differences over conventional TURP were not demonstrated.

Other urological robots have included the percutaneous renal access robot, PAKY-RCM which demonstrated superior accuracy but longer operating (access) times when compared to humans in a randomised control trial of transatlantic tele-robotics (8,9).

Robotic laparoscope manipulators:

The development of laparoscope manipulators such as the Automated Endoscopic System for Optimum Positioning (AESOP™, Intuitive Surgical, CA) and EndoAssist™ (Armstrong Healthcare, UK) has certainly found a niche in laparoscopic urological procedures. These devices hold the laparoscope under voice, pedal or infra-red motion control and provide steadier images with less instrument collisions than a human assistant (10). These are particularly useful in procedures such as laparoscopic radical prostatectomy, freeing the assistant to use 2 ports,

while ensuring very steady images. They also enable the concept of solo-surgery, dispensing with the need for surgical assistants (11).

Master-Slave Systems:

It is the daVinci™ surgical system (Intuitive Surgical, CA) which has generated the most headlines with regard to robotic-assisted surgery. It developed in the mid-1990's from the SRI Green Telepresence System, while a competitor, the ZEUS™ system (Compuer Motion initially; now owned by Intuitive Surgical), was also undergoing clinical evaluation. This is a master-slave system ("on-line" robot) rather than a true autonomous robot. The surgeon sits at a console remote from the patient, controlling 3 or 4 robotic arms, which are docked through the laparoscopic ports. Three dimensional (3D) vision, 7 degrees of freedom (DoF) of movement, and intuitive movements of the robotic instruments are among its proposed benefits over conventional laparoscopic surgery. The da Vinci™ technology, its advantages and disadvantages are described in detail elsewhere (3).

Force Sensing and Tissue Identification - Current and Future Developments

With the advent of specialised surgical robots such as the da Vinci™ surgical system, surgeons are given advanced tools that assist during complex operations and help to improve the outcome of surgical procedures. These highly sophisticated robotic devices incorporate advanced technologies such as precision mechanics, enhanced stereo vision and advanced motion control algorithms enabling tremor-free and intuitive handling of the operating tools. However, there are limitations. Most notably, the surgeon loses all tactile sensation when operating with the aid of a
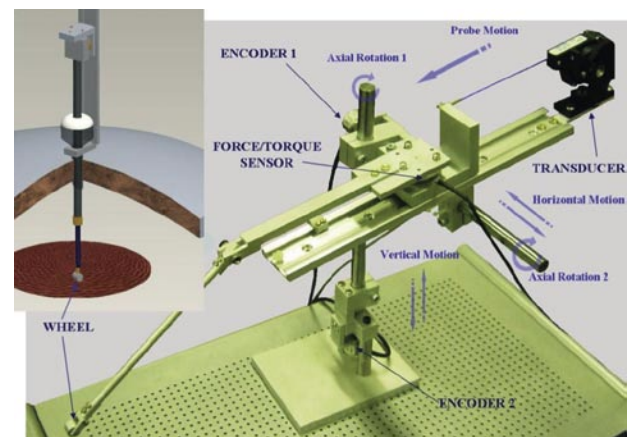

FIGURE 1. Indentation device employing wheeled probe for rapid soft tissue characterisation.

robot. The sense of touch which is readily available during open surgery provides the surgeon with valuable information about the operating site. The inability to palpate organs during an operation can lead to a misjudgement of interaction dynamics between tool and soft tissue. Recent studies have revealed that the lack of tactile sensation during robot-aided surgery can lead to an increase in tissue trauma and accidental tissue damage, and surgeons provided with force feedback significantly improve their performance (12,13).

Current research at a number of research institutes aims at equipping surgical robots with sensors and feedback mechanisms to re-establish the surgeon with tactile perception.

Owing to advances in micro-technologies, there is now a clear trend towards developing miniaturised sensors that can measure the manipulation forces at the point where the tool comes into contact with soft tissue. Recently, a surgical gripper at the end of a laparoscopic tool has been integrated with a strain gauge sensor (14). The sensor's hexapod structure made from an aluminium alloy provides a light weight and rigid solution to acquire force and torque signals along all six axes with a high resolution of 0.05 N and 0.25 N in radial and axial direction, respectively with a range of up to 20 N. A MEMS micro gripper driven by a piezoelectric actuator integrated with semiconductor strain gauges mounted on a microfabricated elastic surface (flexure) has been developed allowing soft tissue property characterisation and realistic palpation using a haptic interface (15).

Advances have also been made in employing piezoelectric materials to measure the contact forces at the tip of surgical tools. Micro-machined force array sensors have been developed that can be mounted on surgical tools (16,17). The developed sensors claim to have a high sensitivity and linear behaviour over a wide range of up to 15 N, allowing realistic palpation feedback.

Very promising results have also been achieved based on fibre optic measuring principles. Miniature force sensors can be created using fibre optic cables that carry light signals -which are modulated in response to the applied forces- from a sensing region to an opto-electronic converter. Recently, a 5-mm diameter force sensor integrating three fibre-optic sensor elements into the tip of a surgical tool was developed. This sensor can measure forces along three axes with a sensitivity of 0.04 N and a range of up to 2.5 N (18). The main advantages of these sensors are that they are not affected by electromagnetic interference and compatible with magnetic resonant imaging systems. Exploiting this, a three degree-of-freedom optical fibre force sensor was used in an MR-compatible neurosurgery robot to measure tool-tissue interaction forces (19).

Accurate sensors and appropriate actuators that reconstruct the measured forces in the user's hand are both necessary components of haptic interfaces that realise truthful remote touch sensing. An alternative feedback mechanism is the use of force sensors for the identification of soft tissue (i.e. areas of increased stiffness or softness) providing the surgeon with visual cues on the location and severity of any organ abnormalities. Attempts to identify tissue have let to the development of a number of devices. A uni-axial stretching device is used by Brouwer et al. to measure porcine tissue response both in-vivo and ex-vivo (20). Another device was developed to investigate the in-vivo viscoelastic properties of tissue under uni-axial small deformations (21). A motorized endoscopic grasper which was used to test abdominal porcine tissues in-vivo and in-situ with cyclic and static compressive loadings is also described (22). A mechanical probe developed by the Harvard Biorobotics Laboratory, attempts to identify the location and properties of tumours based on static indentation tests (23). Recently conducted research at King's College London aims at the development of devices that consider a series of distributions measured as a wheeled probe (see figure 1) slides across the tissue surface. This approach departs from the previous one of static indentations, allowing the identification of whole regions of organ tissue in short time (24).

Nanotechnology:

In the same way as the development of micro-technology in the 1980s has led to new tools for surgery, emerging nanotechnologies will similarly permit further advances providing better diagnosis and new devices for medicine. Nanorobots are expected to enable significant new capabilities for diagnosis and treatment of disease for patient monitoring and minimally invasive surgery (25,26).

The ability to manufacture nanorobots may result from current trends and new methodologies in fabrication, computation, transducers and manipulation. The hardware architecture for a medical nanorobot must include the necessary devices for monitoring the most important aspects of its operational workspace: the human body.

Teams of nanorobots may cooperate to perform predefined complex tasks in medical procedures (27). To reach this aim, data processing, energy supply, and data transmission capabilities can be addressed through embedded integrated circuits,

using advances in technologies derived from nano-technology and Very Large System Integration (VLSI design) (28). Complementary Metal Semi-Conductor (CMOS) VLSI design using deep ultraviolet lithography provides high precision and a commercial way for manufacturing early nanodevices and nanoelectronics systems. The CMOS industry may successfully drive the pathway for the assembly processes needed to manufacture nanorobots, where the joint use of nanophotonic, carbon nanotubes and nanocrystals, may even accelerate further the actual levels of resolution ranging from 248nm to 157nm devices (29). The appropriate interdisciplinary effort will impact on assembly nanodevices and nanoeletronics to build nanorobots (30). To validate designs to achieve a successful implementation, the use of Verification Hardware Description Language (VHDL) is the most common methodology utilized in the integrated circuit manufacturing industry. Nanorobots can be useful in a large range of biomedical applications for future drug delivery applications, such as dosage regimens based on predicted pharmacokinetic parameters for chemotherapy in anti-cancer treatments (31,32). A range of different signals are directly correlated to specific medical problems. Chemical signals can serve for medical target identification and actuation. A single tumor cell can be characterized as a typical endothelial cell mutation with profound consequences for patients suffering from cancer. Endothelial cells have a large number of functions and may play an important role in human health. They also serve as part of the structure forming the inside blood vessels,

which are spread throughout every single organ or system comprising our body.

Factors like low energy consumption and high-sensitivity are among some of the advantages of nanosensors. Nanobioelectronics using nanowires as material for circuit assembly can achieve maximal efficiency for applications regarding chemical changes, enabling new medical applications (30). Using chemical sensors nanorobots can be programmed to detect different levels of E-cadherin and beta-catenin as medical targets in primary and metastatic phases. Integrated nanosensors can be utilized for such a task in order to find different concentrations of E-cadherin signals (33-35). Beyond sensors, nanorobots may be designed with appropriated space to carry chemotherapy for future cancer drug delivery. Such approach allows maintaining the drug carrier for a time longer as necessary into the bloodstream circulation, avoiding the current resulting extravasation towards non reticuloendothelial-located cancers and the high degenerative side-effects (36).

Figure 2 demonstrates a nanorobot developed by Adriano Cavalcanti at the CAN Center for Automation in Nanobiotech, Sao Paulo, Brazil.

The role of virtual reality simulation and robotics
Minimally invasive surgery has long been associated with training issues. At their inception novel surgical techniques must be learned by all grades of surgeon and once in wide use trainees must be able
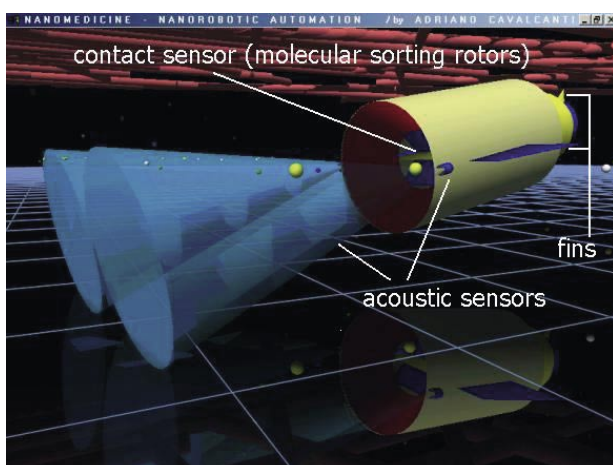

FIGURE 2. A nanorobot employing nanosensors and advanced nanorobot control design features. Courtesy of Adriano Cavalcanti, www.nanorobotdesign.com
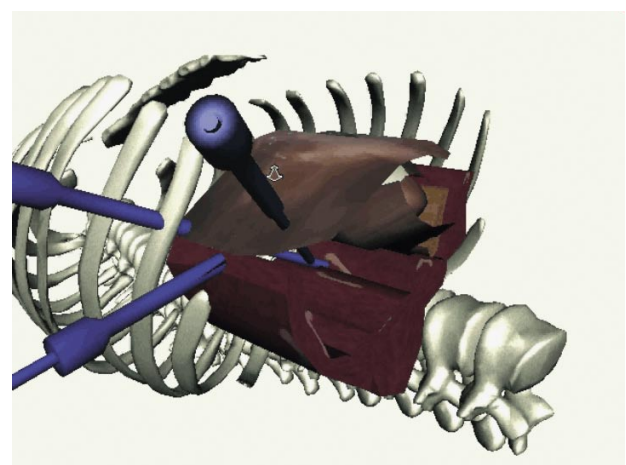

FIGURE 3. Virtual reality simulator for laparoscopic renal surgery. Courtesy of Mentice, Goteborg, Sweden.

to learn techniques safely. From this point of view the evolution of laparascopic surgery training provides a good template for robotic techniques.

Robot assisted procedures are complex operations in which precision is vital, a far from ideal learning environment; hence the need for other training environments. Also with robot assisted surgery there is a huge infrastructure cost associated with both the docking robot and the operating console. It is not within the budget of many institutions to provide a fully serviced training robot.

Virtual reality has been shown to be effective for surgical training and has the benefits of providing a reproducible operating environment in which metric parameters can be used to monitor operator performance (37,38). The ability to regularly incorporate individual patient anatomy into a surgical simulator and practice prior to surgery is only a few years away.

Virtual reality has shown itself as the premier training option in laparascopic surgery due to the evolution of haptic feedback instruments, these instruments provide the operator with tactile sensations akin to real surgery.

The prospect of using virtual reality to simulate robot assisted procedures is incredibly exciting. From the development point of view haptic feedback is not required thereby removing a great deal of programming time and research from any project which is necessary in order to incorporate the increased number of degrees of freedom. For a VR robotic simulator only the operating console is required saving the expense of the robotic device.

Current developments in VR software are progressing towards the fully interactive abdomen and pelvis; the ability to alter the software to include robotic instruments is not far off. Figure 3 demonstrates a VR simulator for laparoscopic renal surgery currently under development by Mentice, Goteborg, Sweden, and Guy's Hospital, London.

The future of robotic surgery in conjunction with VR may include a surgeon "pre-operating" on the same patient where the VR anatomy has been produced directly from the patients imaging.

CONCLUSIONS

The introduction of robotic technology into urology in the late 20th and early 21st century has heralded an exciting time for surgeons. However, it is clear that such technology is in its infancy, at least in clinical surgery. The exciting potential developments in mechatronics, nanotechnology and virtual reality simulation outlined in this paper will lead to a huge leap to the next generation of robotic technology and equipment.

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