

# Robot-Assisted Surgery



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## 1 Introduction: Robotic Surgery

The introduction of novel technologies substantially changed our approach to patients with surgical indications over the last decade. The number of robotic procedures performed per year is rapidly increasing all over the world and more and more centers are equipping with this technology [1]. Data suggest an overall trend for conversion from open surgery to robotic-assisted surgery in many surgical specialties [2]. The da Vinci Surgical System has dramatically changed the landscape of minimally invasive surgery providing the surgeon with substantial advantages in dexterity of the instruments, tremor filtration and a better visualization of the surgical field with primary surgeon camera control compared to laparoscopy [3]. The

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main advantages are observed when operating in a deep and narrow field and when intracorporeal suturing and fine tissue dissection are required [4].

The increasing implementation of robotic systems determined profound changes in the surgical practice in particular in Urology, Gynecology, Cardiac, General and Thoracic surgery. There was a profound change in the management of patients with prostate, bladder and kidney disease. For example, when considering the case of prostate cancer, robot-assisted radical prostatectomy (RARP) has now become the gold standard surgical treatment modality in many centers [5]. A robot-assisted approach for partial nephrectomy (RAPN) has shown benefits over the open approach including a reduced blood loss, postoperative pain and length of stay [6]. Finally, a recent systematic review comparing robot-assisted radical cystectomy (RARC) with open cystectomy showed that RARC benefited from fewer perioperative complications, greater lymph node yield, lower blood loss and a shorter length of stay [7].

The aim of this chapter is to review the evolution of robotic surgery and focus on the technical innovations that has been developed since the first robotic system obtained the approval from the FDA for laparoscopic surgery in 2000. A special emphasis was placed on the development of novel devices and their potential future clinical applicability.

## 2 Evolution: History of Robotic Surgery

The term “robot” derives from “*robota*” which is a Check term to describes a forced labour or *activity* [8]. The use of robots is commonplace in industry, where the machines can undertake ultra-precise and pre-programmed tasks many times, while in medicine they have only been recently adopted to enhance the delivery of care.

The definition of robot suggests a machine capable of performing repetitive tasks autonomously with, if any, different amount of artificial intelligence. There are many types of robotic systems currently available in the healthcare sector. *Active* systems essentially work autonomously and undertake pre-programmed tasks. *Semi-active* systems allow for a surgeon-driven element to complement the pre-programmed element of these robot systems. Lastly the *master–slave* systems lack any of the pre-programmed or autonomous elements of the previous systems. They are entirely dependent on the activity of the surgeon, in fact they just replicate the hand movements of the surgeon and transmit them to laparoscopic surgical instruments. Most of the robots adopted in the healthcare are not true robots because they lack independent motions or pre-programmed actions. They are rather master-slave machines that assist the surgeon in various procedures, rather than independently perform tasks [9].

The first robotic system adopted in medicine was the PUMA 560. Kwoh et al. used this robotic system to undertake neurosurgical biopsies with greater accuracy

[10]. The same system was later used by Davies et al. to undertake a transurethral resection of the prostate (TURP) [11]. Later the Integrated Surgical Supplies Ltd developed the PROBOT which was specifically designed to undertake a TURP. In essence, it was a robot with a rotating blade able to complete the process of prostatic resection [12]. In the non-urological field, the ROBODOC system was developed to improve the precision of hip replacement surgery and was the first to achieve a formal Food and Drug Administration (FDA) approval [13].

The United States (US) military were first to recognise the potential significance of linking doctors (distant from the battlefield) to soldiers, in order to reduce the mortality and morbidity during the fields of conflict. A similar concept was used to develop innovation in medical field in particular in minimally invasive surgery. The idea was to connect surgeons to the surgical field with technology [14].

The ZEUS platform developed by Computer Motion and the DaVinci platform by Intuitive Surgical were the pioneers that have dominated the field of robotic surgery for a decade pushing back the frontiers of minimally invasive surgery. After that the Intuitive Surgical acquired Computer Motion in 2004 [15] and after a successful US FDA regulatory approvals, for almost 2 decades [1].

The Computer Motion was founded by Dr. Yulun Wand in 1990 and the goal was initially to build an endoscopic holder. Computer Motion developed the first automated endoscopic system for optimal positioning (AESOP). It essentially enabled surgeons to voice control the positioning of a laparoscopic camera system. It was the first surgical robot to receive FDA clearance [16].

The ZEUS system was a three arms system where one arm held the camera and a further two arms were used to hold surgical instruments. When launched, the ZEUS system was using the AESOP camera system [17]. The surgical console included a high-backed chair with armrests, controlling the instruments with dedicated chopstick like handles. The surgical field was visualized on a two (2D) or three-dimensional (3D) video system and the instruments provided only 4 degrees of freedom. The Conformite Europeenne (CE) and the FDA approvals were obtained in 1999 for cardiovascular surgery. The most impressive demonstration of this system was performed by Marescaux et al. Surgeons in New York City successfully removed a gallbladder from a 68-year-old woman in Strasbourg, France [18]. In the Urological field there were only few human urological applications of the ZEUS system, such as pelvic lymph node dissection and pyeloplasty [19].

### 3 Current Robots Available

Four generations of the da Vinci system have been introduced over the last 20 years. Technological refinements has been continuously implemented and at currently, the American company Intuitive Surgical owns >1500 patents.

### 3.1 *DaVinci Family*

Intuitive Surgical was founded by Dr. Fred Moll, his assistant Dr. John Freund and the Engineer Robert Younge [16]. The system takes its name from the artist Leonardo da Vinci and it is inspired by his study of human anatomy and his development of automatons and robots. The da Vinci platform developed by Intuitive Surgical is a three-to-four-armed system with the central arm holding a binocular lens. Besides the superior 3D vision a unique selling point were advanced instruments with articulated wrist to seven degrees of freedom (Endowrist technology). The da Vinci system had the CE mark in 1999 and full FDA approval since 2001.

The da Vinci platform was designed for robot-assisted coronary artery surgery, and the first cases were performed at the Heart Centre of Leipzig [20]. The first Robot-assisted laparoscopic radical prostatectomy was pioneered in 2001 in the Henry Ford Hospital [21].

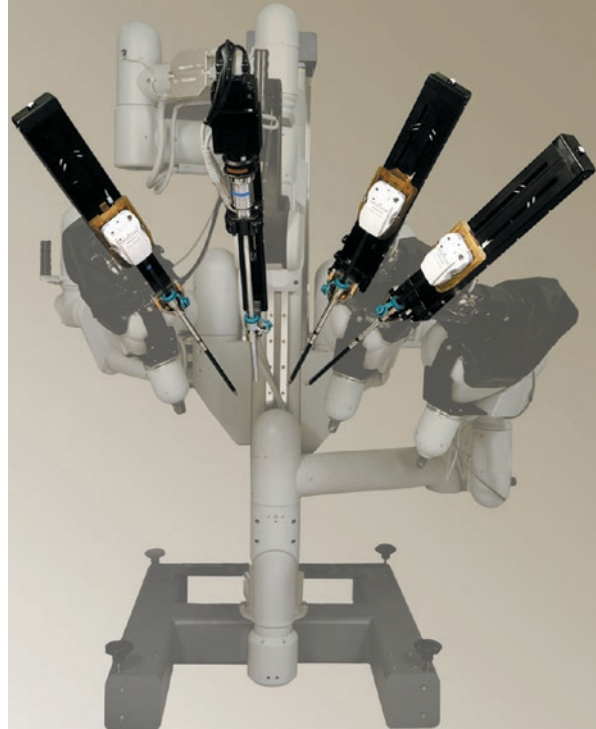
#### 3.1.1 **Da Vinci Standard and S-HD**

Intuitive Surgical, Inc. was founded in 1995 and the first (standard) da Vinci robotic surgical system was introduced to the market in 1999. The da Vinci robot technology including three-dimensional vision, EndoWrist instrumentation, Intuitive motion, ergonomic superiority and surgical precision, and has surmounted the difficulties preventing the widespread adoption of laparoscopic RP (LRP). The first upgrade occurred in 2003, with the addition of a fourth robotic arm, allowing the console surgeon greater control of retraction. In 2006, the da VinciS system was released, offering high definition vision and TilePro, a multi-image display feature. The latest model, da Vinci® Si (2009), has dual console capability, allowing for collaborative surgical opportunities.

The first da Vinci surgical system (Standard) was launched to the market in 1999. It was a closed console robot with three robotic arms mounted on a cart offering a 3D vision, EndoWrist instrumentation, superior ergonomic and surgical precision (Fig. 1). The first upgrade occurs in 2003 with the addition of a fourth robotic arm, allowing the surgeon a better control during retraction. In 2006 the da Vinci S system was released, offering a better range of motion, longer instruments, implementation of bipolar energy, and an optional high definition video system and the possibility to install the fourth arm (Fig. 2).

The unique features of the da Vinci systems were its Endowrist technology with 7 degrees of freedom and loop-like handles enabling ergonomic working, including a clutch mechanism. The operative surgeon sits at the surgeon console, views the surgical site in a three-dimensional binocular viewer, and controls movements of the surgical instruments using two master controllers and dedicated foot switches. The technical support of the da Vinci Standard and S ended in 2015 and 2018 respectively.

**Fig. 1** da Vinci Standard robotic system



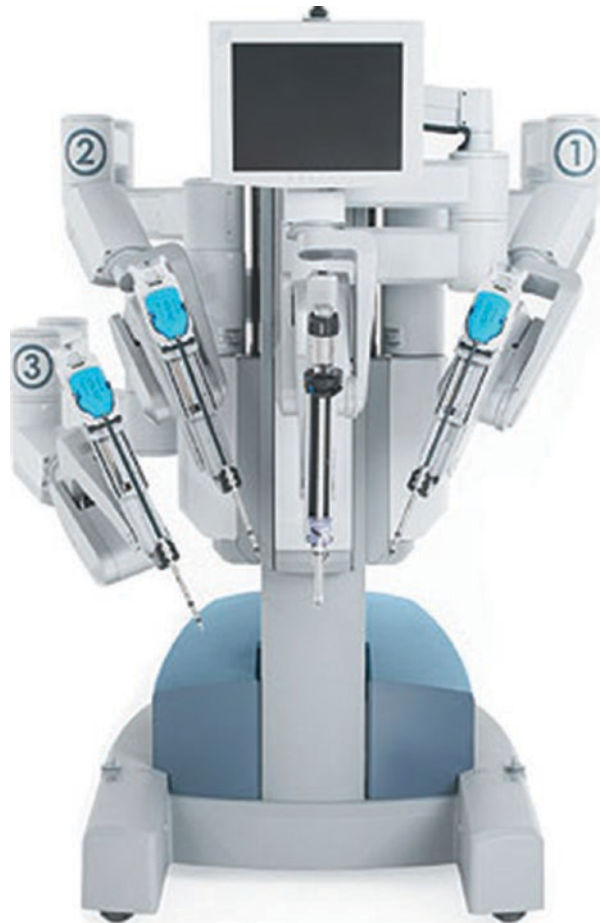
### 3.1.2 Da Vinci Si

The da Vinci Si system was launched in 2009 with full CE mark and FDA approval. Its unique features were high definition (HD) video technology, finger-based clutch mechanism and the possibility to use the intraoperative fluorescence (Fire-Fly technology) with an optional camera (Fig. 3). The surgeon console has been equipped with a touch screen display for setting up preferences and operating parameters, and a newly designed foot switch that allows the surgeon to toggle between operating modes and activation of electro-surgical energy to instruments. The da Vinci Si dual console allows two surgeons to collaborate during surgery, representing an ideal training platform (Fig. 4). The da Vinci Si system also allows use of the Intuitive Surgical single-site platform, providing flexible instruments with only 4 degrees of freedom (VesPa system) [22, 23].

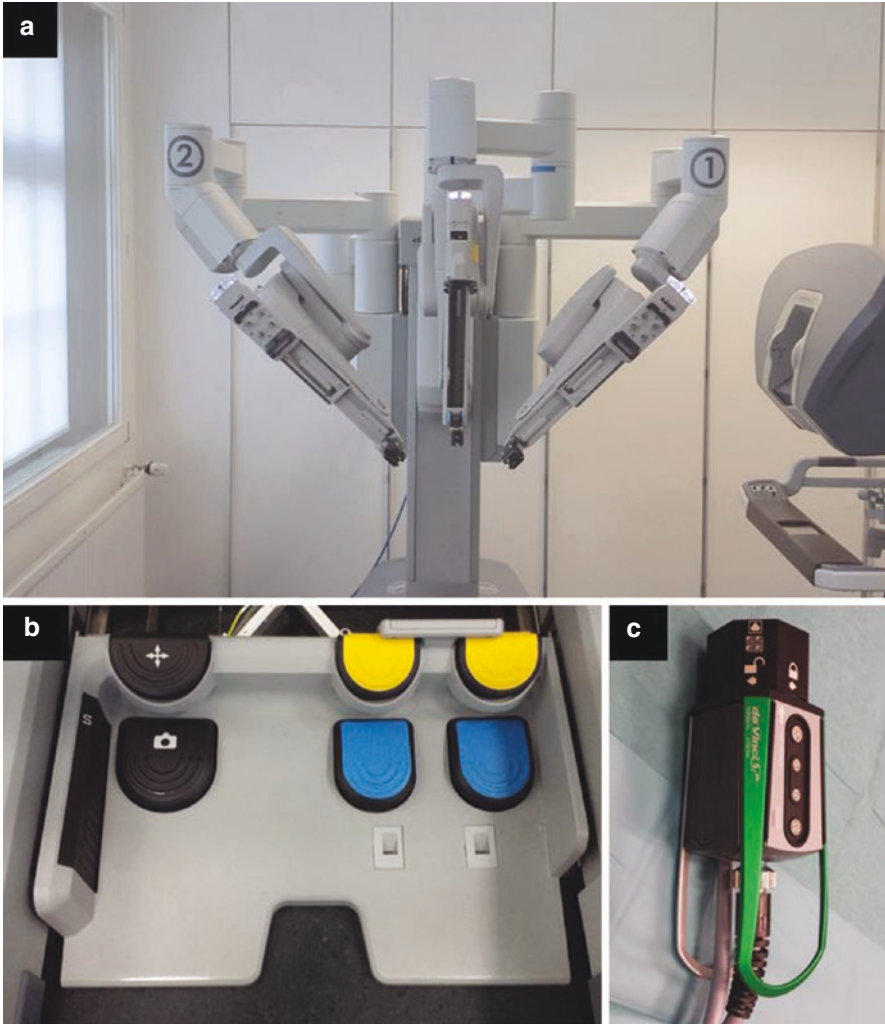
### 3.1.3 Da Vinci Fourth Generation (Xi, X)

The da Vinci Xi robot has been completely redesigned compared to the previous generations (Fig. 5). Has been launched in 2014 with CE mark and FDA approval. It consists of four arms mounted on a rotating boom that allows the docking of the

**Fig. 2** da Vinci S-HD robotic system



robot from any side (Fig. 6a). A new laser guided system for docking has been implemented. A green target is projected from the cart's overhead boom, which is aligned to camera port. When the camera is inserted and the "targeting button" pressed, the remaining robotic arms automatically optimise their positions in order to minimize clacking (Fig. 6b). The arms architecture has been completely redesigned in order to minimize the instrument clashing and to allow the positioning of trocar ports closer than the previous version and in in line fashion (Fig. 6c). A unique feature is the new 8-mm 3D high definition (HD) camera that can be liberally placed in any of the four ports ('camera hopping') (Fig. 6d). This feature can be important for specific multi-quadrant procedures, such as colorectal surgery. Moreover the 30° up and down function allows to change the vision directly from the console. The Fire fly technology is incorporated in the camera and it should not be acquired as an optional. An advanced and specifically designed operating table is available as optional. It can be connected to the system and moved while the robotic



**Fig. 3** (a) da Vinci Si robotic system, (b) da Vinci Si pedals, (c) da Vinci Si camera

arms are connected ('table motion' technology) (Fig. 7). Many technological advancements are available for the new Xi robotic platform, including new stapling devices and 7 degrees of freedom flexible instruments for single-site surgery. Finally this system is compatible with the new robotic SP platform designed for robotic single-port surgery (SP999).

In 2018, Intuitive Surgical introduced the da Vinci X system with the intent to offer a more affordable version of the Xi platform (Fig. 8). The X system is equipped with all the most advanced technologies present of the Xi model mounted on a Si system-like chart. It uses the same instruments and the same camera as the Xi



**Fig. 4** da Vinci dual console

model, however it doesn't offer the docking flexibility and the compatibility for SP platform as the big brother.

### 3.1.4 DaVinci SP

To date, the experience of robotic laparo-endoscopic single site (R-LESS) surgery has involved modification of existing robotic systems using single-access ports, specialised semi-rigid curved instruments, and software modifications (VesPa system) [22, 23]. The disadvantages were principally related to the availability of only 4 degrees of freedom instruments and the extremely difficult bed-side assistance due to limited range of motion and impossible simultaneous use of multiple instruments [24].

The da Vinci SP (single port) robotic platform has been specifically created for single site surgery in order to overcome many limitations of up to date R-LESS surgery (Fig. 9). Moreover it has been designed to offer advantages over the standard multi-arm systems, when operating in spaces with difficult access. Indeed all the instruments are included in a single port, which is introduced through a single abdominal wall incision. Once introduced, the flexible instruments, including the optic, can separate and achieve triangulation thanks to a snake-style wrist [25].

The da Vinci SP platform has several unique and novel features compared to the multiport systems [25]. This platform is equipped with a single robotic arm docked

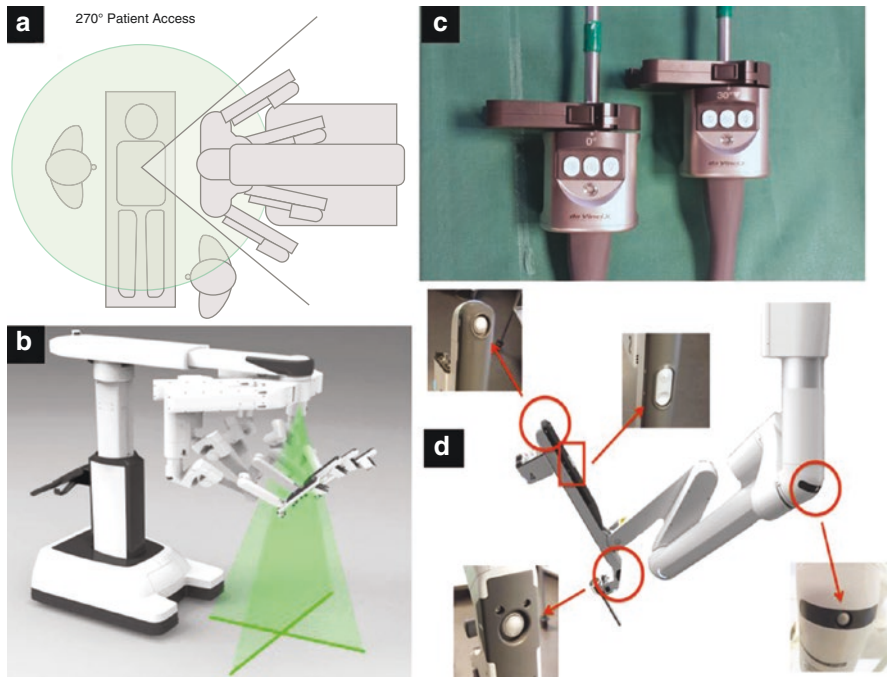


**Fig. 5** da Vinci Xi robotic system

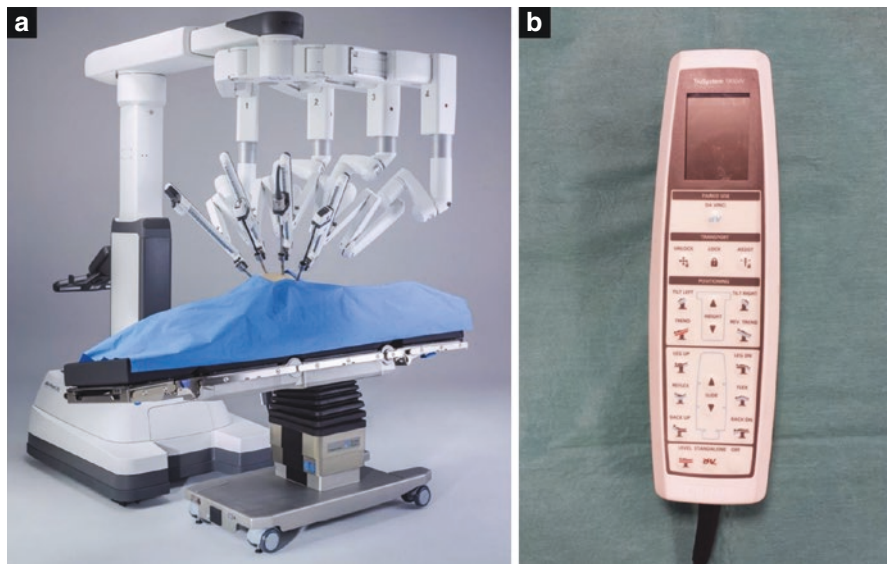


to a 25 mm multichannel port (Fig. 10a). It has a fully articulating  $12 \times 10$ -mm oval camera and three 6 mm instruments able of 7 degrees of freedom (Fig. 10b). All instruments and the camera have a double articulating design (i.e., wrist and elbow) (Fig. 10c). A virtual guidance system allows the surgeon to visualize the spatial relations of each arm and the camera during surgery. An extra-clutch has been designed, by which the surgeon can move the camera and working arms independently or as a single unit during surgery. The surgeon console design on the da Vinci SP Surgical System is identical to the standard da Vinci system except for an the already mentioned extra foot switch [26] (Fig. 10d).

The first generation SP platform (SP999) was designed to use the same base and column of the da Vinci XI patient side cart, but with a different configuration of the surgical arms and manipulators in order to drive the unique SP instruments and camera through a single port. The Intuitive Surgical da Vinci SP999 platform gained FDA approval for single-port surgery in urology in 2014 [27]. However Intuitive decided not to market and instead focus on developing the purpose-built platform,



**Fig. 6** (a) da Vinci Xi docking flexibility, (b) da Vinci Xi docking laser, (c) da Vinci Xi 0 and 30° digital camera, (d) da Vinci Xi arm architecture



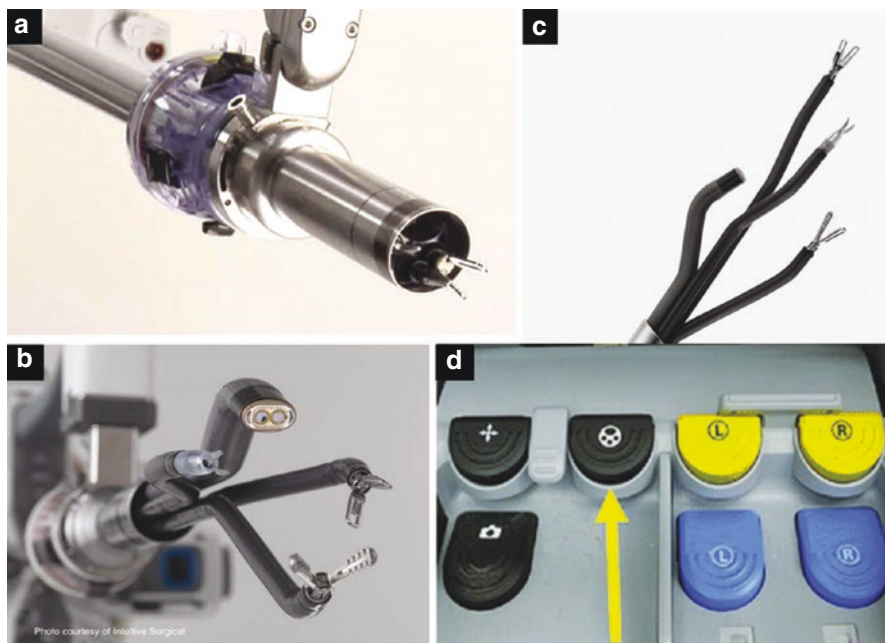
**Fig. 7** (a) da Vinci table with table motion technology, (b) da Vinci table remote controller

**Fig. 8** da Vinci X robotic system



**Fig. 9** da Vinci SP robotic system





**Fig. 10** (a) da Vinci SP port, (b) da Vinci SP camera, (c) da Vinci SP instruments, (d) da Vinci SP extra clutch pedal

the SP1098. This system is yet to receive the CE and FDA approval and remains in the development stage.

The second generation SP surgical system (SP1089) is equivalent to the predicate device SP999 in terms of technological characteristics, and has identical indications for use. It basically an updated version of the first generation SP999. The surgeon console, vision and patient cart were modified to incorporate the latest mechanical, electrical, and user interface technology of the cleared multi-port da Vinci Xi Surgical System (IS4000). An integrated monopolar energy monitor was also added to the Vision Cart. Modifications were also made to the EndoWrist SP instruments and accessories to improve manufacturability, robustness, reliability, cleaning ability, and ease of use while enhancing safety and maintaining the same ability to perform surgical tasks. In order to accommodate the modified instruments and to improve ease of use, the instrument arm and instrument drives were updated as well.

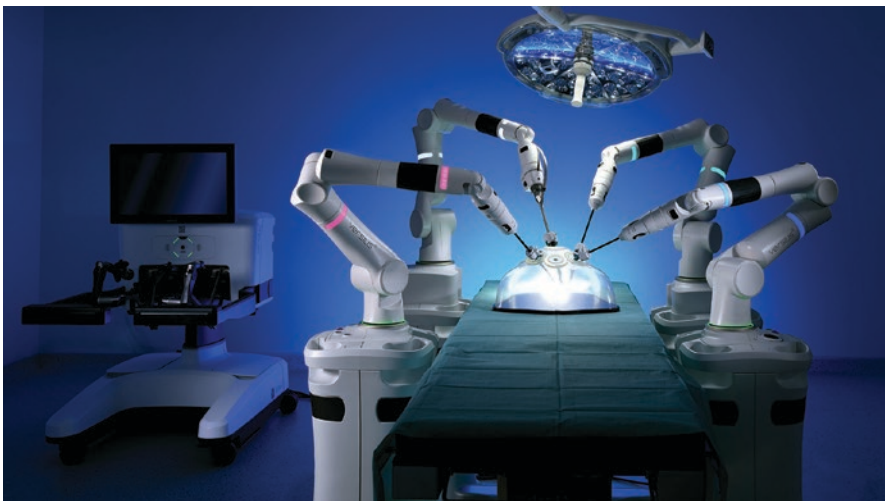
It has been investigated in pre-clinical trials involving a small number of patients and showed that R-LESS with the second generation SP1098 platform is feasible, however it will require further investigation to compare with conventional multi-port robotic surgery [28–30].

### 3.2 *CMR Versius*

The Versius Surgical System is the new tele-operated robotic surgical system designed to assist surgeons in performing minimally-invasive surgery designed by CMR Surgical (Cambridge, UK).

The design of the Versius differs significantly from that of the Da Vinci Surgical System. The robotic arms are modular providing an increased arm positioning and flexibility. Each instrument and visualisation arm is attached to its own wheeled cart to form a compact and mobile bedside unit (Fig. 11). Each bedside unit is connected with cables to the console representing the world's smallest clinical robot on the market. It is a reconfigurable system, the number of bed side units that can be used per surgery varies between 3 and 5. The bed side units or robotic arms are mobile and can be interchanged. The robotic instruments mimics the articulation of the human arm and the wristed instrument tip provides seven degrees of freedom allowing greater surgical access than standard laparoscopic surgery (Fig. 12). The Versius surgeon console is open, and can be operated at either a standing or a seated position, and all the robotic device control has been placed on-board handheld control units, removing the need for foot pedal controls (Fig. 13). The console has a 2D/3D screen and the surgeon sits straight with 3D glasses, while others can sit and watch the surgery behind the surgeon [31].

In 2019 the safety and effectiveness of the system has been demonstrated for urological [32] and general surgery [33] procedures in the preclinical setting. The assessment was performed on cadaveric and porcine models. Several types of



**Fig. 11** Versius robotic system



**Fig. 12** Versius robotic arms during pelvic box training

**Fig. 13** Versius handheld control units



abdominal surgeries were tested in cadavers, with the lead surgeons evaluating a range of port and bedside units positions. All surgeries were completed successfully. A radical nephrectomy, a cholecystectomy and a small bowel enterotomy were also performed safely and effectively in a live animal model.

Finally, Puntambekar et al. has recently demonstrated the feasibility, safety and efficacy of radical hysterectomy performed with the Versius robotic systems in clinical setting on 30 patients [34].

### **3.3 *Telelap ALF-X***

Telelap ALF-X is a robotic platform designed by the Italian healthcare company Sofar Surgical Robotics (Milan, Italy). An initial patent was registered in 2007. In 2015 Sofar Surgical Robotics has been acquired by TransEnterix (Morrisville, NC, USA). Telelap ALF-X obtained the CE clearance for indications in general surgery, gynaecology, urology and thoracic surgery in 2016. The first devices has been sold in Italy and early clinical reports of robot-assisted hysterectomies were published by an Italian group in Rome (Italy) [35].

It uses an open console, laparoscopy-like handles and arms mounted on separate carts. The TELELAP Alf-X system offers a novel approach to remotely operated 3-dimension endoscopy by adding haptic sensation, an eye-tracking system, and a high degree of configuration versatility. The ALF-X system instruments are reusable with lower disposable costs compared to the present robots [36].

### **3.4 *Senhance Robot***

TransEnterix, a US medical device company is focused on the commercialization of a the Senhance robotic system. The platform received the FDA approval for laparoscopic surgical procedures in general, cardiac, colorectal, gynaecologic, head and neck, thoracic and urologic surgical procedures.

The robot system comprises three arms, each individually mounted on its own cart. Recently a fourth robotic arm has been approved by the company. Senhance instruments are similar to traditional laparoscopic instrumentation, however they provide haptic feedback from the cable-actuated arms, and 7 degrees of freedom. Additionally, the Senhance incorporates a novel eye-tracking technology, which centers the camera image at the point the surgeon is looking at. Finally the Senhance system is compatible with many of the currently available visualizations systems including fluorescence technology [2].

From November 2018 to March 2019 a total of 100 procedures using the Senhance robotic platform were performed in general and colorectal surgery, gynaecology, and urology at the in Klaipeda University Hospital (Klaipeda, Lithuania) with excellent outcomes [37].

## **4 Upcoming Robots**

Nowadays the Da Vinci intuitive system is the only leader on the marked. New companies are engaged in designing new robotic systems in order to propose an alternative to the well-established DaVinci platform [35–40]. However, mainly

because of issues related to patenting, their clinical applications remain limited. Nevertheless, the landscape of robotic surgery is expected to witness significant changes as new technologies might soon become available.

#### 4.1 Avatera (*The German Robot*)

Since 2012, Avateramedical (Jena, Germany) have been developing the Avatera surgical platform in cooperation with Force Dimension (Nyon, Switzerland) and with Tübingen Scientific (Tübingen, Germany) (Fig. 14). The Avatera robot features a closed console with an integrated seat using a microscope-like technology for in-line 3D image with full HD resolution. Four robotic arms are mounted on a single cart and 5 mm instruments with 6 degrees of freedom are applied. Patents were registered in 2012 and 2013. The system has only been used in experimental animal trials. The validation process for CE certification was initiated in 2017 [38].

**Fig. 14** Avatera robotic system (“the German robot”)





## 4.2 *MicroSurge (Medtronic)*

Medtronic is developing a new robotic platform together with German Aerospace Center (DRL). In 2010 the first experimental results of MiroSurge were published. The main strength of the system is its versatility, indeed the system has been designed to be expandable and useful in multiple surgical applications [41]. In 2015 Medtronic completed the acquisition of Covidien and the company became able to develop all necessary instruments and it is currently working on the tenth prototype of this system. MiroSurge consisted of three lightweight arms mounted on the operating table, and an open console with the surgeon sitting in front of an autofocusing monitor. The robotic arms are designed to have seven joints with serial kinematics, comparable to human arms. Instruments are driven by micro-motors providing tactile feedback via potentiometers. Patents were registered in 2012 and 2013. Medtronic plan has been to launch the device in the USA in 2018, however this is still not happening [42].

## 4.3 *REVO-I (The Korean Robot)*

In Korea, a new robotic platform has been developed, called REVO-I by the Yonsei University and other Korean academic and industry groups, Meerecompany (Hwasong, Korea). It consists of an open console and a four-arm system mounted on a single cart. The system uses 8 mm instruments with 6 degrees of freedom that are reusable for 20 surgical procedures. A tactile feedback system is an important feature in robotic surgery as it has been shown to decreased grasping forces and it may improve surgical outcomes [43]. The patent was registered in 2014 and the first experiments with this system were published in 2016. A RPN was successfully performed using the REVO-I robot platform on a porcine model. The only limitation was a lack of range of motion in the needle driver if compared to the Da Vinci surgical platform [39, 40]. The approval for human trials was received in South Korea.

# 5 Technology in Robotic Surgery

Technology is constantly affecting the field of minimally invasive surgery. Many innovations have been integrated within recent robotic surgical systems leading to numerous benefit for the surgeon and patients. New generation robotic systems are equipped with the newest technological refinements in order to improve vision, dexterity and assist the surgeon during the operation (image-guided surgery). Fluorescence imaging, Tactile feedback, Single site surgery, Virtual reality and Image-guided surgery and are all hot topics for the next generation robotic surgeons.

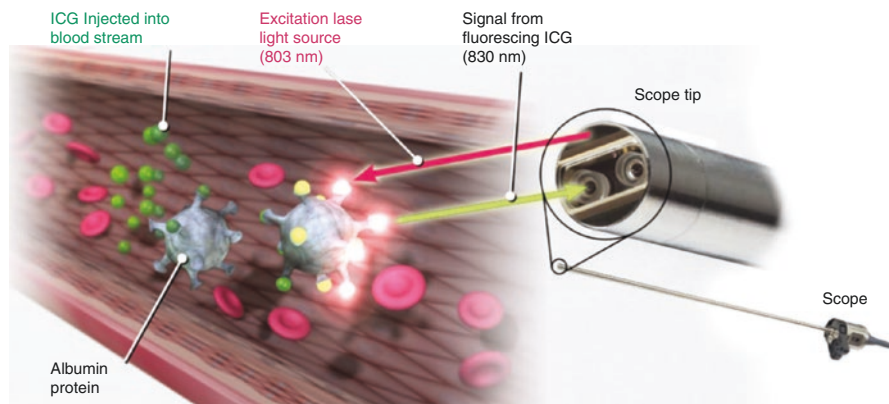
## 5.1 Fluorescence Imaging

Since 2011 the potential uses of near-infrared fluorescence imaging (NIRF) in surgery has been investigated. The technology of fluorescence imaging can be applied in several fields of minimally invasive surgery. It is able to provide an enhanced anatomical view of the surgical field with visual assessment of vessels, blood flow and tissue perfusion. It is capable to improve the identification of key anatomical landmarks and pathological structures for oncological and non-oncological procedures [39].

The indocyanine green (ICG) is a water-soluble molecule which binds albumin and immediately allows visualization of both the vasculature and contours of anatomic structures (Fig. 15). It has been approved for intravenous administration by FDA since 1959 [44]. It has been also proven to potentially improve the perioperative surgical outcomes during some procedures without compromising the oncological adequacy [45].

The last (fourth) generation of DaVinci platforms has been equipped with this technology by default, while on the previous (third) generation models it was available as an optional. Indeed a specific camera equipped with a near-infrared laser, easily recognizable by the green graphics is needed to use this technology. The system is called “Firefly System” and is capable to provide real-time endoscopic visible near-infrared fluorescence directly on the console and it is activable by the surgeon in any moment [46].

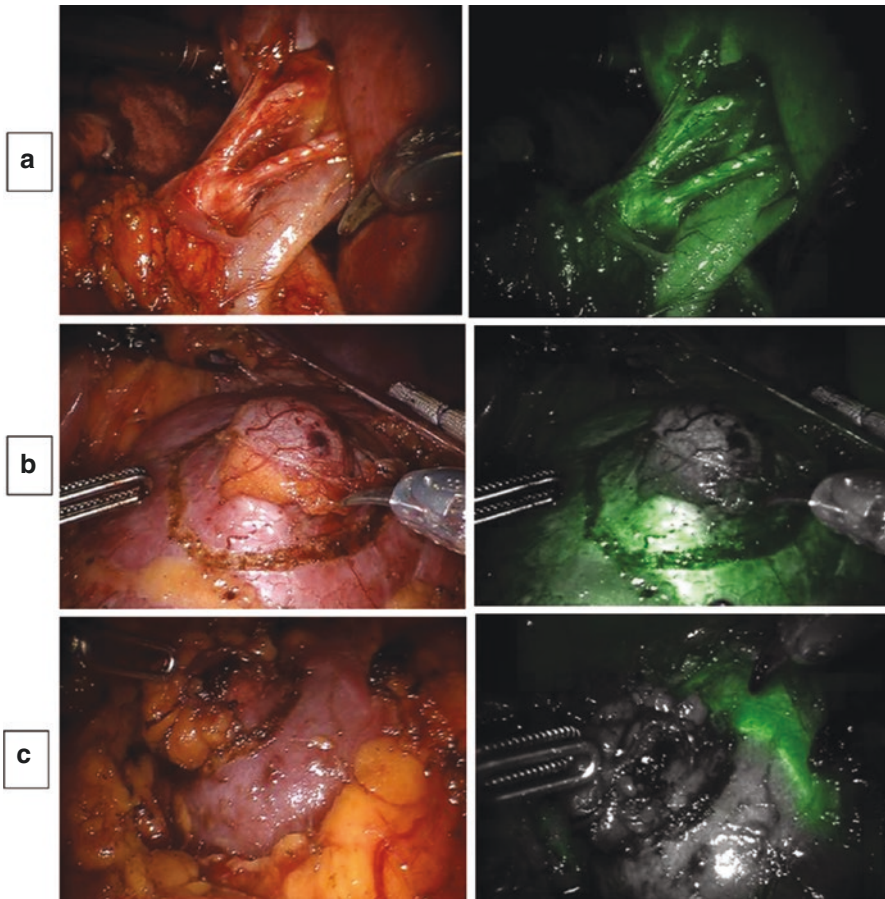
The applications of NIRF/ICG are multiple, as for example it permits to identify diseased parenchyma or assess the lymphatic pathways. This has made a significant impact on facilitating challenging reconstructive and oncologic robotic procedures. It has been proven to be effective for selective/super-selective clamping of arteries during robot-assisted partial nephrectomy and in differential perfusion assessment during renal mass resection [47, 48]. It allows to differentiate various types of adrenal pathologies (pheochromocytoma, metastatic RCC, lymphangioma,



**Fig. 15** Intuitive Firefly technology

adrenocortical adenoma, adrenal haemorrhagic cyst, adrenal simple cyst, cystic lymphangioma) and to perform a safe adrenal-sparing surgery [49, 50]. It has been found to achieve a more scrupulous diagnostic approach during extended pelvic lymph node dissection (ePLND) and sentinel node biopsy in patient with prostatic cancer [51, 52]. Recent studies have shown to reduce morbidity during superficial and deep inguinal nodes in patient with penile cancer [53]. Despite many applications the level of evidence is low, indeed further investigation is needed to improve the understanding of this technology (Fig. 16).

Moreover the near-infrared fluorescence imaging could be used also without ICG dye. In fact the white light of the endoscope illuminates green during Firefly mode allowing simultaneous vision of the surrounding tissues. In literature there is only a publication report three different procedures performed using Firefly mode without ICG [54].



**Fig. 16** Fluorescence applications: (a) renal pedicle dissection, (b) renal tumor excision, (c) renal hilum selective clamping

## 5.2 Tactile Feedback

A widely criticized disadvantage associated with robotic systems is the absence of tactile feedback. The physical connection between the surgeon's hands and the robotic instruments is removed when operating with robotic assistance and the haptic sensation such as the tension of a suture, texture of tissue, and even collisions between robotic arms is physically imperceptible. In addition, the robot system is capable of creating varying forces that far exceed tissue tolerances resulting in tissue tearing and the risk of suture ruptures [55] (Fig. 17).

The current most widely used robotic surgical system Da Vinci is limited by the lack of tactile or haptic feedback that may be useful when performing complex and delicate surgical tasks. At the same its clinical relevance in the performance of robot-assisted surgery is still controversial. Many expert robotic surgeons suggest that the lack of a tactile feedback can be adequately compensated using visual cues such as tissue deformation and retraction during tension. Moreover there are several technical and practical challenges that need to be overcome to implement direct haptic capabilities top the hands of the surgeon in complex surgical systems.

Reiley et al investigated the use of a visual force feedback during surgical knot tying with the da Vinci robotic system equipped with force-sensing instruments tips and real-time graphic overlays. The study showed a lower suture breakage rate and

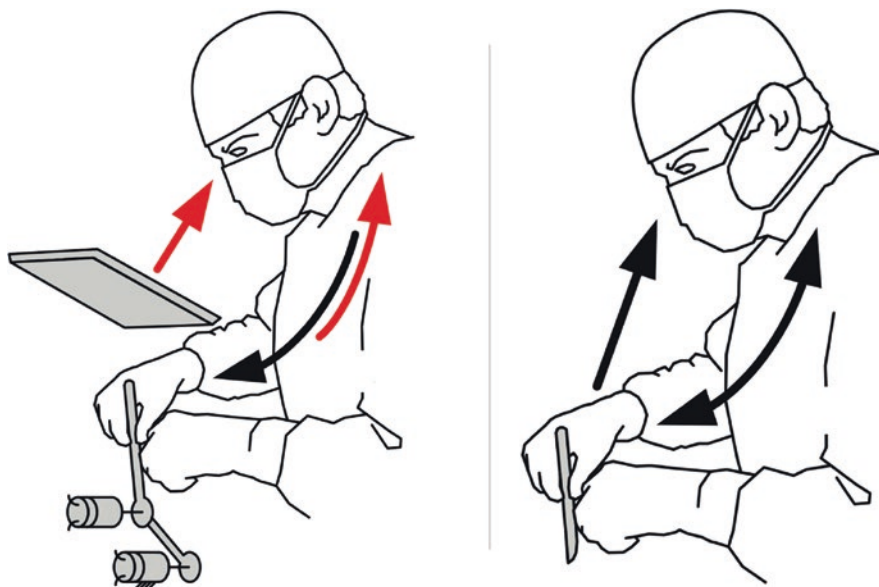


Fig. 17 Tactile and Visual feedback

peak applied forces when using the visual force feedback. Measurable benefits, however, were lacking among experienced users [56].

Another preliminary study investigated the feasibility and potential benefits of sensory substitution in providing haptic feedback in the context of robotic-assisted knot tying [57]. In conjunction with the Johns Hopkins University Department of Mechanical Engineering, a tension measuring device (TMD) was constructed, allowing the measurements of the tension (in newtons) on both the left and right hand during robotic assisted knot tying. A visual colour bar scale was developed to render applied suture tensions to the operating surgeon. The results demonstrated a significantly greater and more consistent tensions applied to suture materials, without breakage, during robotic knot tying with haptic feedback compared to knots tied without feedback.

An interesting research investigate the grasping forces with the application of a tactile feedback system in vivo and the incidence of tissue damage incurred during robotic tissue manipulation [43]. A waterproof sensor was mounted on da Vinci robotic instrument and was capable to evaluate the force output and data acquisition. A control system was designed to convert forces detected at the grasper tips to pressures at the surgeon's fingertips. Pneumatic actuators provided pressure stimuli to fingertips using hemispherical silicone balloons, targeting the slow-adapting mechanoreceptors through constant deformation of the finger pad. The in vivo application of integrated tactile feedback in the robotic system demonstrates significantly reduced grasping forces, resulting in significantly less tissue damage. This tactile feedback system may improve surgical outcomes and broaden the use of robotic-assisted minimally invasive surgery in a wider spectrum of clinical care [58].

Finally another study investigated the capability of the surgeon's experience to compensate for the lack of haptic feedback of the robotic system da Vinci Si HD [59]. 25 surgeons divided in two groups (experts vs non-experts) underwent a specific test to assess their ability to recognize the thickness of custom made membranes, without the availability of haptic feedback. The expert surgeons scored significantly better than the non-expert showing that the personal expertise seems to overcome the lack of a feedback haptic sensor. Moreover the high-definition images combined with 3D binocular vision cues of the da Vinci robotic surgical system compensates for the lack of tactile information.

### ***5.3 Single Site Surgery***

The concept of laparo-endoscopic single site (LESS) surgery has been proposed to minimise the surgical morbidity during minimally invasive procedures. The aim was further improve the benefits of conventional multiport surgery by decreasing the number of surgical incisions leading to improved cosmesis, postoperative pain, recovery time as well as postoperative incisional hernias [60]. At the same time a number of obstacles such as poor ergonomics, loss of triangulation, instrument

clashing, limited tissue retraction and lack of space for surgical assistant ergonomic challenges and other technical difficulties precluded its widespread application [61].

Before the presentation of the new da Vinci SP platform, the Intuitive Surgical single-site platform was available for robotic laparo-endoscopic single site (R-LESS) surgery [62]. It represented a definitive step forward compared to standard LESS surgery. The main features were the 5 mm semi-rigid instruments allowing only 4 degrees of freedom, which were inserted through a couple of curved cannulas. The cannulas were placed in a crossing over fashion through a multi-trocar port which allowed the triangulation of the instruments. When the single-site instruments were docked into the da Vinci Si System, they were automatically reassigned so the right hand of the Surgeon's Control will control the left instrument and vice versa.

However the technical approach of R-LESS using the Intuitive Surgical single-site platform was limited by many drawbacks. The main were the non-availability of 7 degrees of freedom Endowrist technology for the instruments and the extremely difficult bed-side assistance due to limited range of motion and impossible simultaneous use of multiple instruments [28].

## 5.4 *Virtual Reality*

Originally developed for gaming, virtual reality is now spreading in many fields. The healthcare sector is one of the biggest adopters of virtual reality, in particular as a means of training the next generation of medical professionals. Virtual reality (VR) has played an important role in training robotic surgeons to gain valuable experience but in a safe environment. VR is a useful tool to improve familiarity with the robotic console, three-dimensional vision and wristed instruments [63, 64].

There are many VR simulator on the market. Thanks to the huge technological improvements of the last years, a wide array of VR simulator are available on the market. Many of them are designed for basic skill acquisition, while others are designed for the acquisition of entire procedures. The newest simulators are able to recreate an entire surgical procedure as for example a RARP. VR simulation has been demonstrated to improve surgical performances in a risk-free environment [65, 66].

## 5.5 *Image-Guided Surgery*

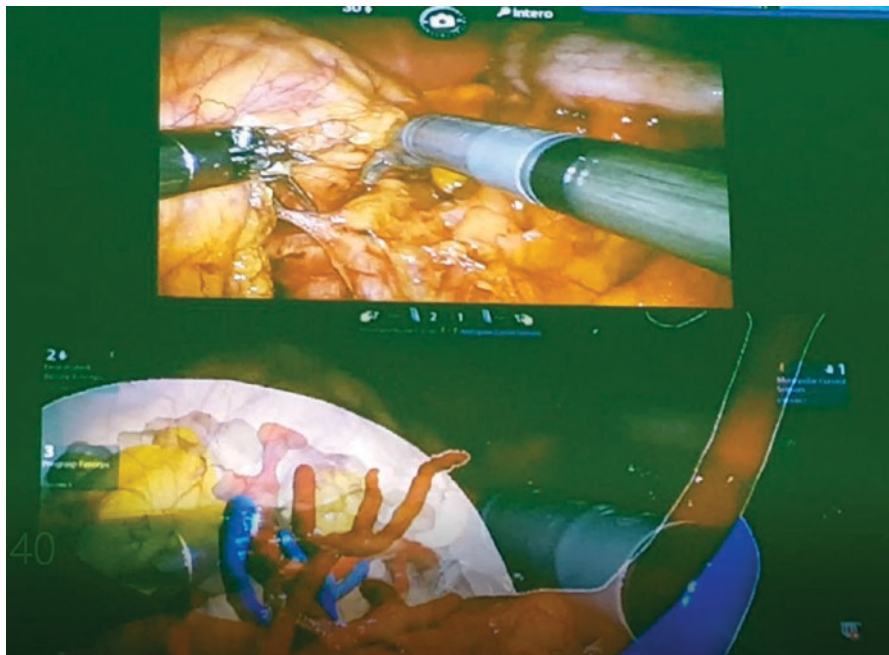
Image-guided surgery (IGS) is the use of a real-time correlation of the operative field to a preoperative imaging data set that reflects the precise location of a selected surgical instrument to the surrounding anatomic structures [67]. In many procedures, the surgeon has a limited view of the operating field and cannot visualize structures beyond the exposed surfaces. In minimally invasive surgeries, particularly during endoscopic procedures, the surgeon is also confronted with difficult

hand-eye coordination problems. Better use of the three-dimensional imaging can improve surgical visualization and help the surgeons overcome these limitations. In particular, enhanced reality visualization, in which the surgeon’s field of view is augmented with additional structural information, can provide useful guidance in planning and executing the surgery. Robotic surgery offers the unique opportunity to integrate 3D virtual renderings and real-time images from the endoscopic camera in the robotic console (Fig. 18).

Porpiglia et al. described the first clinical experience with a novel software for augmented-reality robot-assisted radical prostatectomy. Preoperatively, the MRI images were segmented in order to obtain a 3D reconstruction of the prostate and the surrounding structures. In order to allow a better visualization of the images during the operation an elastic 3D model was. Using the TilePro facility of the da Vinci surgical system the virtual image of the prostate was superimposed onto the endoscopic view of the surgical field. The surgeon was able to perform less invasive procedures when using IGS with potential better functional outcomes for the patient [68].

ICG can be used also during robot-assisted partial nephrectomy in order to better visualize renal masses and perform a more effective selective clamping during the enucleation of the tumor [69].

There is an increasing interest in this technology among the new-generation robotic surgeons. It is gaining interest because of its potential to improve patient



**Fig. 18** Image guided surgery

outcome following oncologic surgery. At the same time, IGS is still in an embryonal phase of its development. Further investigation is needed to improve and make this technology usable and profitable [70].

## 6 The Future of Robotic Surgery

In the operating room of the future, robots will be an integral part of the surgical team, working alongside human surgeons to make surgeries safer, faster, more precise and more automated. In the meantime Telementoring and Telesurgery are progressing quickly as a subset of Telemedicine. With the amalgamation of technological communication and surgery, Telesurgery and Telementoring are having a tremendous impact on next generation surgeons.

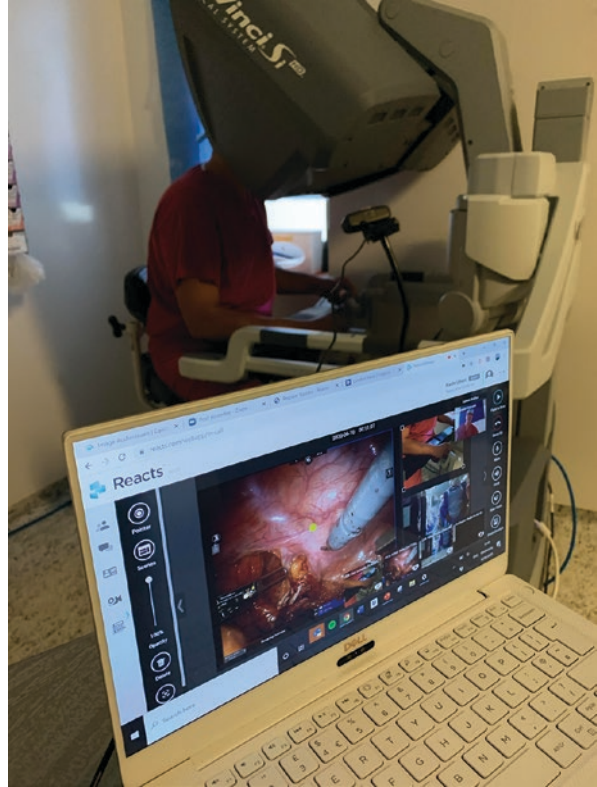
### 6.1 *Telementoring and Telesurgery*

Telemedicine is an expanding field that can help clinicians connect with patients when in-person medical visits are not possible. During COVID pandemic for example it has been used as rescue management for chronic pain patients [71].

Telesurgery uses wireless networking and robotic technology to allow surgeons to operate on patients who are distantly located, while telementoring can be used as a guidance to by another expert surgeon who is in a different geographic location (Fig. 19). With the advancement of technology, both telementoring and telesurgery are becoming more practical and cost-effective also for minimally invasive urological surgery [72]. Indeed minimally invasive surgery lends itself well to telesurgery and telementoring techniques mainly because the images of the surgical field are projected via cable to the surgical console and to additional screens. As such, the exact same images as the primary surgeons can be seen on another screen. An impressive demonstration of Telesurgery was performed by Marescaux et al. when they performed a successful transatlantic gallbladder removal from a 68-year woman in Strasbourg [18].

Telementoring and Telesurgery can take various forms, based on the increasing level of interaction between proctor and trainee. Instruction from the mentor could be as simple as verbal guidance while the mentor is watching a real-time video of the operation. In its more advanced iterations, telementoring can progressively involve indicating target areas on the local monitor screen (telestration), taking over as the assistant by controlling the operative camera or an instrument via robotic arms (tele-assisted surgery), or actually performing the surgery remotely (telesurgery) [72].



**Fig. 19** Telementoring

Telesurgery and Telementoring can provide high-quality surgery where limited human and economic resources exist, as for example in underserved locations, such as rural areas, battlefields, and spacecraft. They virtually eliminate the need for long-distance travels, allowing surgical collaboration amongst surgeons at different medical centers in real-time [73].

5th-Generation Mobile Communication (5G) offers a high potential for the further development of telemedicine. The high data transmission volume, low latency and a high quality of service are important requirements for real-time Telesurgery and Telementoring applications [74].

Advanced technology has opened new avenues for long-distance observation and interaction through telesurgery and telementoring. Although the medicolegal implications of an active surgical intervention by a proctor are not clearly defined, the role as an observer should grant immunity from malpractice liability. Legal and ethical implications linked to the use of telemedicine, telesurgery should be clarified [75].

## 6.2 *Engineering of Robotics (Aerospace and Automation)*

A robotics engineer is a designer, who is responsible for creating robots and robotic systems that are able to perform duties in Industries like manufacturing, aerospace and medicine. Through their creations, a robotics engineer helps to make jobs safer, easier, and more efficient, with many benefits even in healthcare.

Robot engineering is a wide field where professionals are working on and developing different type of projects. They are building, configuring, and testing, as well as designing software systems to control their robots. At the same time they are analysing and evaluating the prototypes they have created. Monitoring is generally a never-ending task, since technology is constantly changing and advancing. The cost calculation and technical support including the maintenance are essential to make the project beneficial, both for the producer and the costumer. Finally teaching plans and structured training curricula allow to make the best use of the robotic systems.

The goal of robotic technology in medicine is not to replace human surgeons, but to augment their capabilities and better assist during difficult operations. Indeed, human surgeons are essential during decision making process that can't be left to a robot (ex.to indicate a specific treatment or to develop a new surgical technique). On the other hand, a robot with high-power computing and sub-millimeter precision will be able to control complex instruments and navigate through spaces in the body that a human surgeon can't access. For this reason a close cooperation between engineers and surgeons is the best recipe to obtain the success.

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