Chapter

Intelligent Information-Guided Robotic Surgery

Ryu Nakadate and Makoto Hashizume

Abstract

Laparoscopic surgery is minimally invasive, providing various benefits for patients. On the other hand, it is technically demanding for physicians due to limited dexterity of tools, limited vision. In order to cope with those limitations, recent various engineering technologies are trying to help surgeon. Robotics is one of the major technologies in this field. Until today, da Vinci has been only one such robot. But recently, many other robotic systems are under development. Those new robots are introduced in this chapter first. Other than robotics, or in conjunction with robotics, navigation technologies are getting popularity in clinical use. Navigation is a technology that provides useful information such as preoperative images or distance between tool and lesion, etc. to surgeon. Our experience in clinical use of navigation system in robotic surgery is introduced. Finally, technologies applied for the training of surgeon are introduced and described.

Keywords: robotic surgery, navigation surgery, computer-aided surgery, surgical training, endoscope

1. Introduction

In order to access the lesion, large incision on the healthy part of the patient, such as body surface is inevitable in the conventional (so-called open surgery) surgery. One of the modalities of the surgery which tries to minimize the incision on the healthy organ is laparoscopic surgery. The access to the lesion in the abdominal cavity is through several small incisions which sizes are about 5–10 mm. A long, slim camera and surgical devices are inserted from those incisions to the abdominal cavity. The surgeons perform surgical procedures such as incision, dissection, and suturing by manipulating those surgical devices watching a display of camera image. Compared with the conventional open surgery in which the large incision on the patient skin is made, the laparoscopic surgery provides the patients less postoperative pain and shorter hospital stay, which are the major benefits to the patients. On the other hand, the laparoscopic surgery demands high level technical skills of the surgeons because of several reasons. The surgeons lose direct vision, and only two-dimensional indirect vision through the display is available [1]. The indirect vision sometimes takes the sense of orientation and ability of the depth perception away from surgeons. All surgical devices are slim and long. The precise manipulation of the tip of those devices is very difficult. Also the mirror effect, the phenomenon in which the device in the patient body goes opposite direction to the handle outside the body, makes those manipulations more difficult [2]. The surgeons cannot directly touch the organs in the body. Palpation or feeling the applied force is not possible. Most of the surgical devices are straight, do not have bending wrist. Those devices provide surgeon much less dexterity than the fingers and hands. In order to cope with those restrictions, long training time, experience, and practices are required for the laparoscopic surgeons. However, as those limitations are mainly technical issue, we believe the technologies can contribute to overcome those limitations. In this chapter, we introduce recent various technologies for laparoscopic surgery. First, we will overview the current worldwide surgical robotics. There is a dominant player in this field, da Vinci surgical system. However, several new robots by start-ups are in the pipeline. Then, we will introduce the robotics with the flexible endoscope as a new trend in the robotic surgery. They are also in the pipeline of the many companies, about to launch to the market. We think this field is promising as future minimally invasive surgery. After that, the technologies in the navigation and training are described.

2. Robotics for the laparoscopic surgery

In this field, the da Vinci surgical system (**Figure 1**) [3] of Intuitive Surgical, Inc. (US) has been a dominant robot since its FDA approval in 2000. As of August 1, 2018, 4666 units are installed in the world. Nearly 1 million procedures in the world are performed annually by using da Vinci [4]. Majority of da Vinci applications are urology and gynecology which are about one-third of the total procedures each [4]. Including the colorectal application in the other one-third, you can find that the da Vinci surgery is mostly used in the pelvic cavity. This is probably because pelvic cavity is narrow and deep, thus laparoscopic approach is challenging for those organs such as prostate, uterus, colon, and rectum.

Generally speaking, the robot for laparoscopic surgery provides three-dimensional vision, dexterity, and intuitiveness. In fact, three-dimensional vision is not a robot specific feature. However, it is inevitable in order to exert the robotic dexterity. To understand the dexterity, let us explain the degrees of freedom. For example, in order to perform full dexterity by a grasping device, it requires seven degrees of freedom. First, the tip of the grasper has to be reached at desired position in three-dimensional space (X-Y-Z axis). Therefore, at least three degrees of freedom are required. Then, the tip of the grasper also has to change orientation at the desired position. The orientation is defined by rotations around X, Y, Z axis. Thus, it requires another three (rotational) degrees of freedom. Last, one degree of freedom is open/close motion of the grasper. Conventional laparoscopic forceps have only five degrees of freedom (three positional, one rotational around the shaft,

Figure 1.
da Vinci surgical system ©2018 Intuitive Surgical, Inc.

and one grasping), resulting limited dexterity. da Vinci has wrist at the tip of the forceps, providing seven degrees of freedom. This is one of the key technologies of the laparoscopic surgical robot. Intuitiveness means that the operator's hand and device tip are synchronized in the three-dimensional vision. The computer of the robot calculates the device position, so that the direction of the device movement in the display is the same as surgeon's hand. Furthermore, the computer calculation is considering the line of sight in order to secure the hand-eye coordination. Those features are basically the same in the other emerging new robots.

There exist a lot of researches on surgical robots in academic institutes. However, sometimes they are very early stage, and it is unknown how long they take time until they reach at clinically usable phase. Here, we will introduce surgical robots which have already been in the market or are in the pipeline of the industrial companies.

2.1 Senhance surgical platform

Senhance surgical robotic system (**Figure 2**) [5–7] was originally developed in Europe under the name of "ALF-X", and then sold to US company TransEnterix, Inc. It received CE mark and cleared FDA for major laparoscopic surgery. The Senhance system has three independent robotic arms for instruments and camera. Each arm stands on the floor, has long beam as seen in **Figure 2**. Various types of the forceps are available and can be attached to the robotic arms. Unique features which are different from da Vinci are gaze control system of camera and force feedback. At the control cockpit, the eye motion of the operator is monitored and is used for the camera motion. If the operator moves head forward, the camera moves closer to the object. The company claims cost effectiveness as other emerging robot company than intuitive surgical do so [7].

2.2 Versius surgical robotic system

Versius surgical robotics system (CMR Surgical Ltd., UK) also contains independent robotic arms for each instruments, but the size of the robotic arms are designed smaller (**Figure 3**). As the foot print of each robotic arm is 38 × 38 cm, it is portable, does not require large space, and setting up is easy. Comparing with 8 mm da Vinci instrument, CMR provides thinner, 5.8 mm instrument with wrist. It is under development, and not yet CE Marked nor 510(k) cleared.

2.3 Verb surgical

Johnson & Johnson (Ethicon) and Google (Verily Life Sciences) have jointly established Verb Surgical Inc. (US). Their goal is not only robotics but also

Figure 2.
Senhance surgical robotic system (©2018 TransEnterix, Inc.).

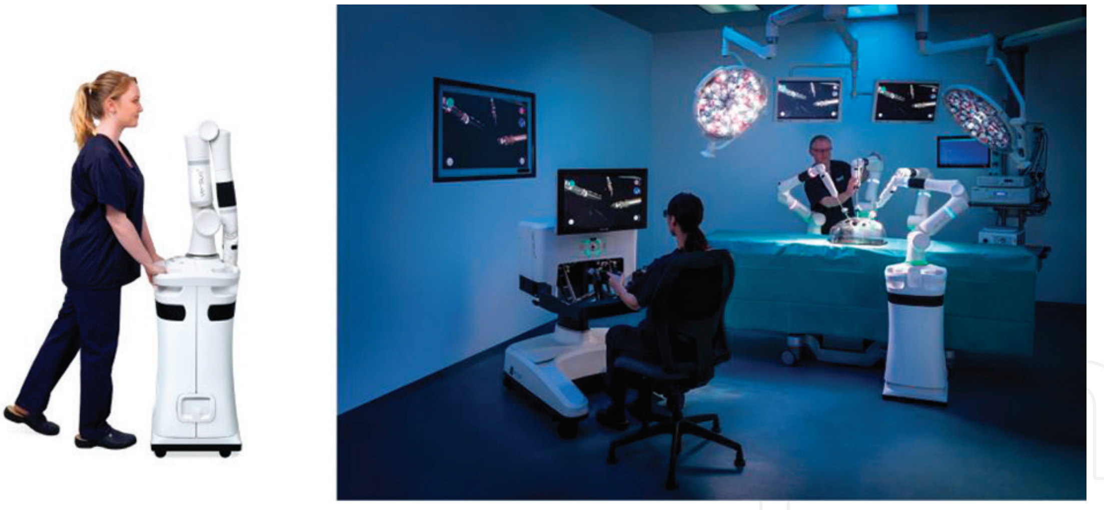

Figure 3.
Versius surgical robotic system (©2018 CMR Surgical Ltd., UK).

visualization, advanced instrumentation, data analytics, and connectivity. The details of the appearance of the robot, function, cost, etc. have not been published.

2.4 MiroSurge system

German aerospace center (DLR) developed MiroSurge system (**Figure 4**) [8, 9]. It also has independent, light weight, and compact robotic arms for each instrument, which could be fixed directly on the operating bed. Force feedback feature is implemented to the instruments. Unique feature is that the operator can move the robotic arm directly by hand touching the arm. By using this function, for example, an assistant operator can easily make a room at bed side. Medtronic is licensed this robot.

2.5 da Vinci SP

da Vinci SP (Intuitive Surgical) is a single port surgical system [10–13]. A camera and three 6-mm instruments are bundled inside a 25-mm cannula. Thus, they can be inserted into the patient body from single incision. Each instrument has seven degrees of freedom, including "elbow" and "shoulder". The camera also has multi-bending neck, so that the camera head movement is independent of instruments, and operator can look down the devices. Although initial position of

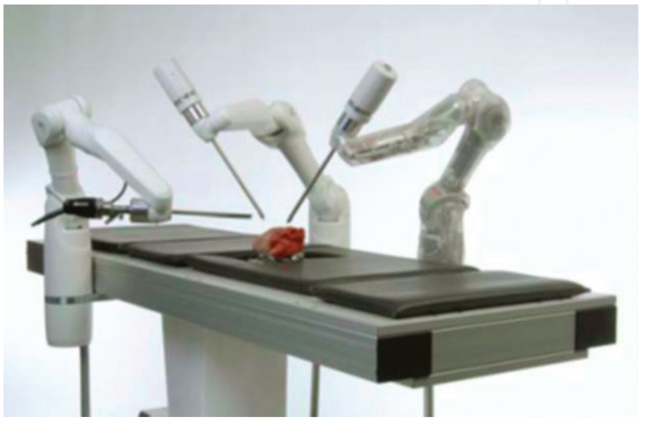

Figure 4.
MiroSurge system. Reprinted by permission from Springer Nature: Springer Nature [8].

the instruments inside the cannula is straight, the "elbow" and "shoulder" make triangulation possible inside the body. It has cleared FDA for urologic procedures. The other applications which the company is aiming at are rectum [11], laryngeal [12, 13] (through natural orifice), and other abdominal procedures.

2.6 SPORT surgical system

SPORT surgical system (TITAN Medical, Canada) is also a single port surgical system. It has two articulating instruments and a camera, in a cannula (**Figure 5**). It is under development, and the company expects its FDA clearance in 2019.

2.7 Endoscope holding robot

In the history of the surgical robot, AESOP (Computer Motion, Inc., US) [15], an endoscope holding robot, was one of the pioneers, which was launched in 1994. Although AESOP discontinued, there are some new camera holding robots. Their purpose is mainly to solve the issue of human resources in hospital. Viky (EndoControl, France) [16] is a compact camera holder which can be mounted on the operation bed (**Figure 6**). Freehand (Freehand 2010 Ltd., UK) [17] is also mounted on bed. SoloAssist (AKTORmed, Germany) [18], MTG-H100 (Hiwin Technologies Corp, Taiwan), and EMARO (Riverfield Inc., Japan) stands on the floor. Various control methods are employed, such as voice, head movement, and joystick.

Figure 5.
SPORT surgical system. Reprinted by permission from Springer Nature: Springer Nature [14].

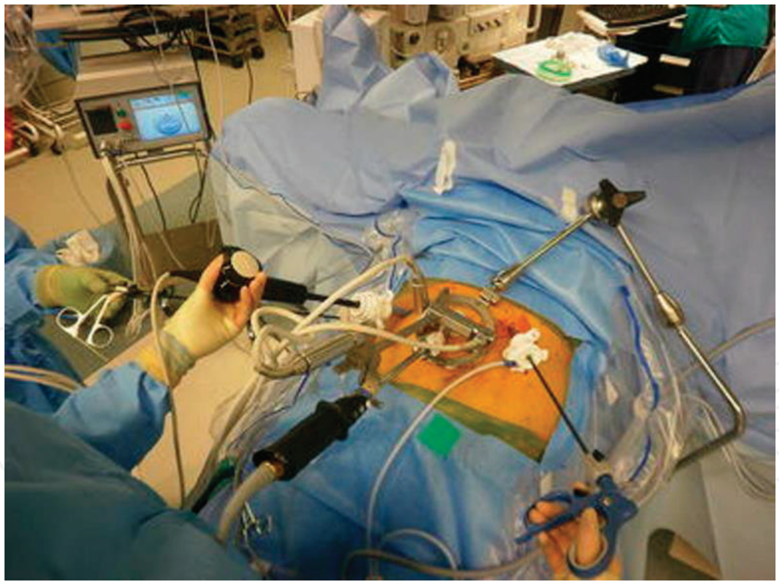

Figure 6.
Viky, reprinted by permission from Springer Nature: Springer Nature [16].

3. Robotics for the flexible endoscopic surgery

Natural orifice transluminal endoscopic surgery (NOTES) was introduced in 2004 [19]. It is the surgery using flexible endoscope instead of rigid laparoscope. As access to the lesion is through the natural orifice (mouth and anus), no incision on the patient skin, but on the organ inside body such as gastrointestinal wall instead is required. Conventional flexible endoscopes and instruments were not enough effective to perform this surgical procedure. So, several companies developed multi-tasking platform [20–25] (**Figure 7**). They basically contain flexible endoscope, articulating instruments, and grasping and cutting devices. They were not motorized, but manually actuated using wire transmission. However, NOTES is still in the experimental phase because this procedure was still technically difficult even using those platforms. Most of those platforms are discontinued. However, if new, effective device were introduced in the future, NOTES could be clinically accepted.

Endoscopic submucosal dissection (ESD) is another surgical procedure using flexible endoscope [28, 29]. ESD is applied only for gastrointestinal mucosal cancer. Therefore, it has limited coverage of organ compared with NOTES. ESD has been clinically accepted and prevailing especially in Asian countries. Although ESD

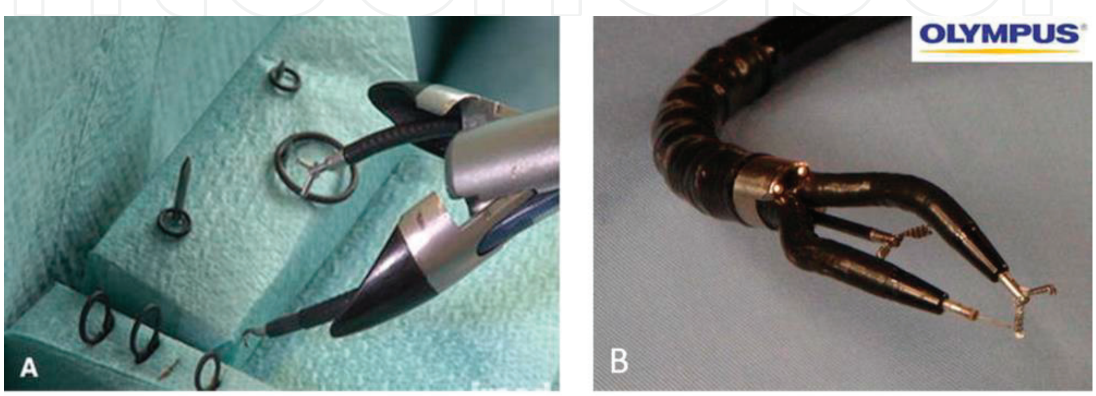

Figure 7.
Examples of manually driven multi-tasking platform. (A) ANUBISCOPE (IRCAD & Karl Storz Endoskope), reprinted by permission from Springer Nature: Springer Nature [26]. (B) EndoSAMURAI (Olympus, Japan), reprinted by permission from Springer Nature: Springer Nature [27].

procedure is easier than NOTES, it still requires high skill of flexible endoscope and long training time like laparoscopy [30, 31]. Some of the recent robotic surgical systems for flexible endoscope are aiming at ESD procedure.

In this section, recent surgical robots for flexible endoscope are introduced. At present, there is no major robot in this field. But many are under development or just have been launched. We believe flexible endoscope surgery will be next major target of surgical robot industry.

3.1 STRAS

ANUBISCOPE (IRCAD & Karl Storz Endoskope) [20, 21] was developed for NOTES and ESD procedure. The system composed of a custom made flexible endoscope with two articulating instruments. It was not motor driven but manually driven system. Strasburg University jointly developed motorized version, STRAS with Karl Storz and IRCAD [32–35]. By using vision computation technology, they applied automated target tracking [32] and position detection of the instruments [33]. This project is still in the phase of academic research. Some animal trials have been carried out [34, 35].

3.2 Endomaster

Endomaster (Endomaster Pte Ltd., Singapore) has also two articulating robotic instruments. It has "shoulder" and "elbow" joints in its instruments instead that all other platforms have consecutive bending section. The prototype (**Figure 8**) uses a conventional two channel endoscope but latest version uses custom made

Figure 8.
EndoMaster prototype, reprinted by permission from Springer Nature: Springer Nature [36].

endoscope. This company is a spin-off of Nanyang Technological University, Singapore. HOYA Corporation, Japan, one of the endoscope manufacturers joined the project. It is still under development. ESD, endoscopic full thickness dissection, NOTES trials in animal model, and a human trial have been carried out [36–40].

3.3 Medrobotics

Flex robotic system (Medrobotics Corporation, US) has also two 4-mm articulating arm and endoscope (**Figure 9**). Unique feature is the snake-like endoscope [41–44]. By using two sets of shape-locking sheath, the endoscope can move follow-the-leader manner like snake. As the length of the endoscope is short, it can be applied for larynx, rectum from natural orifice, and percutaneously abdominal cavity. Flex robotic system has already cleared FDA for colorectal surgery.

3.4 K-Flex

Korea Advanced Institute of Science and Technology (KAIST), South Korea has been developing K-Flex [45]. Two 3.7-mm articulating instruments and an endoscope are in a flexible sheath. The sheath has wire driven bending section at the end. This bending section has two independently controllable bending parts, so that view angle can be changed. They established a spin-off company, EasyEndo Surgical Inc., to commercialize this system.

3.5 Monarch platform

Auris Health, Inc. (US) is a potential company which can develop flexible endoscopic robot [46]. They have already cleared FDA and launched the Monarch platform in 2018, which is a bronchoscopy treatment robot. They previously acquired Hansen Medical, which had technology for bending catheter for cardiovascular use. At the moment, they focus on lung treatment.

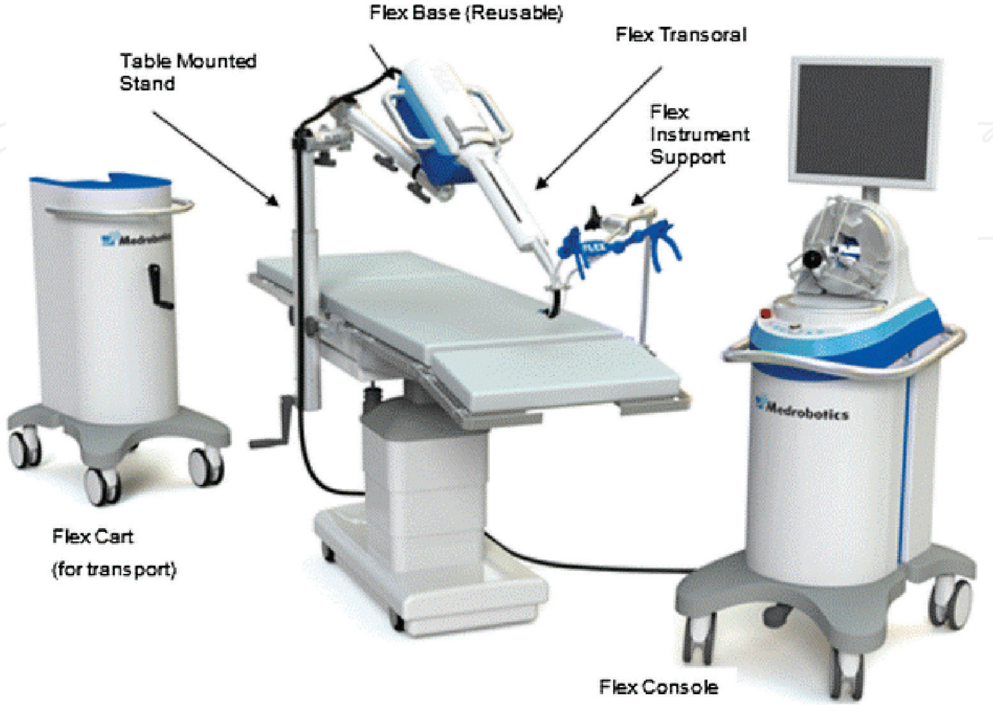

Figure 9.
Flex robotic system, reprinted by permission from Springer Nature: Springer Nature [41].

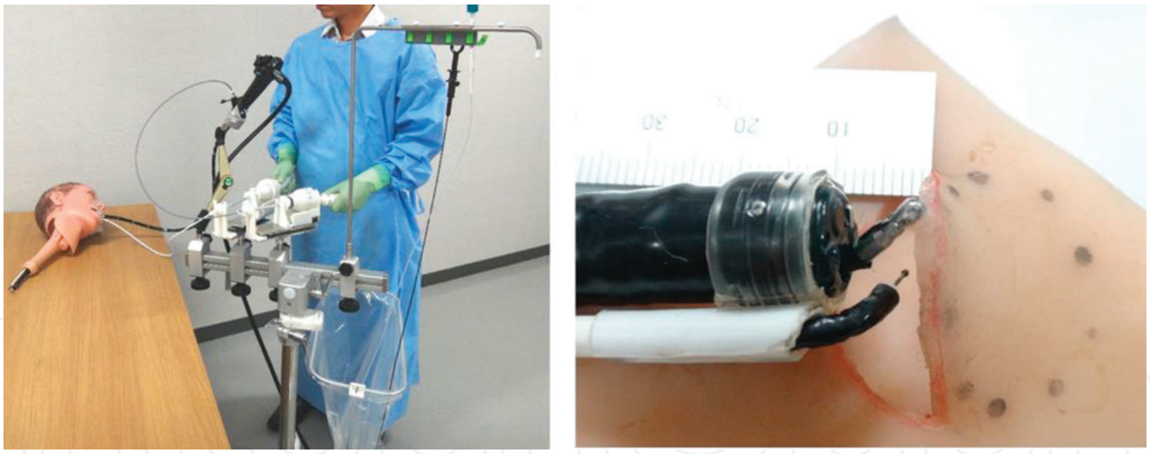

Figure 10.
ESD platform (manually driven) of Kyushu University, Japan.

Figure 11.
ESD platform (motorized) of Kyushu University, Japan.

3.6 Kyushu University ESD robot

We have also been developing flexible endoscopic platforms for ESD in manually driven version [47, 48] (**Figure 10**) and motorized version [49] (**Figure 11**). They composed of conventional flexible endoscope, two 2.6-mm articulating instruments, and an additional channel. By using standard endoscope for ESD, total system cost is minimized. The diameter of instruments is very thin because the standard endoscope has 2.8 mm channel. Control part on a stand is designed, so that both handles of the instruments and endoscope are close to the operator. Animal experiments have been carried out [47, 48].

4. Other robotic application

4.1 Teleoperation

Telesurgery is one of the possible applications of surgical robot for the purpose of medicine in rural area, space, and battle field. In principle of surgical robot, master controller (operator site) and surgical robot (patient site) are connected only by signal. So even if the whole system is in a room like da Vinci, they are teleoperation robot in nature. In the case of long distance between operator site and patient site, delay in the signal transmission is not negligible. Therefore, fast transmission lines are chosen and employed. Marescaux et al. demonstrated telesurgery experiment on human patient between US and France [50]. We also have also successfully carried out animal telesurgery experiments several times between Japan and Korea, Japan and Thailand by using our own robot system (**Figure 12**) [51, 52]. In this study, we have employed relatively low cost ISDN line and low latency CODEC technology.

4.2 MRI compatible robot

Anatomy identification is sometimes difficult during laparoscopic surgery. If surgeon can see vessel, nerve, and lesion under the organ surface, it will be strong merit for safety and quality of the operation. For this purpose, we used intraoperative open bore type MRI for real-time image acquisition and developed a laparoscopic surgical robot which can be placed inside the MRI gantry (**Figure 13**) [53]. As MRI has strong magnetic field, no magnetic metal such as stainless steel cannot be used. Our robot was made of mainly engineering plastic and titanium alloy. Also, we chose ultrasonic motors instead of magnetic motors. The system consists of two forceps and a camera. Additionally, needle insertion device can be attached. The surgeon console display shows the camera view, pre-operative MR image, and intraoperative real-time MR image. We have successfully demonstrated animal experiment by live porcine model.

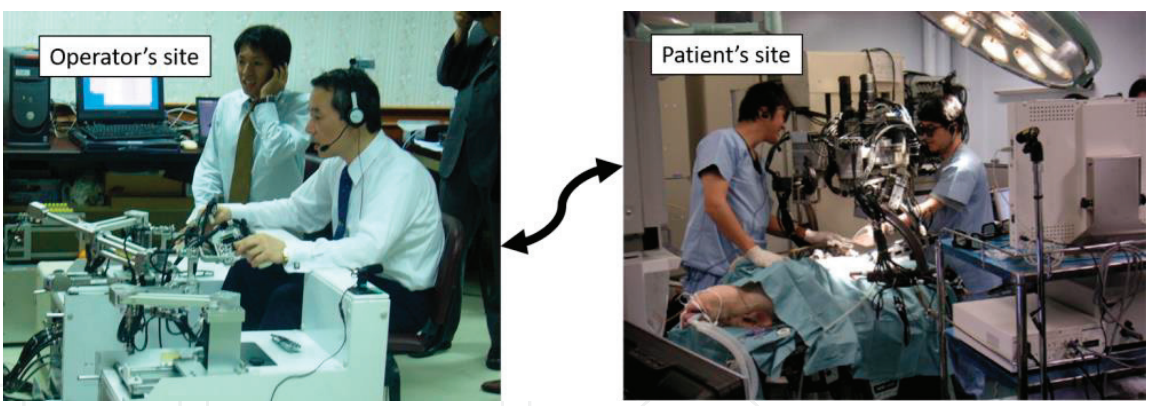

Figure 12.
(Left) Master console (right) patient site of the teleoperation robot.

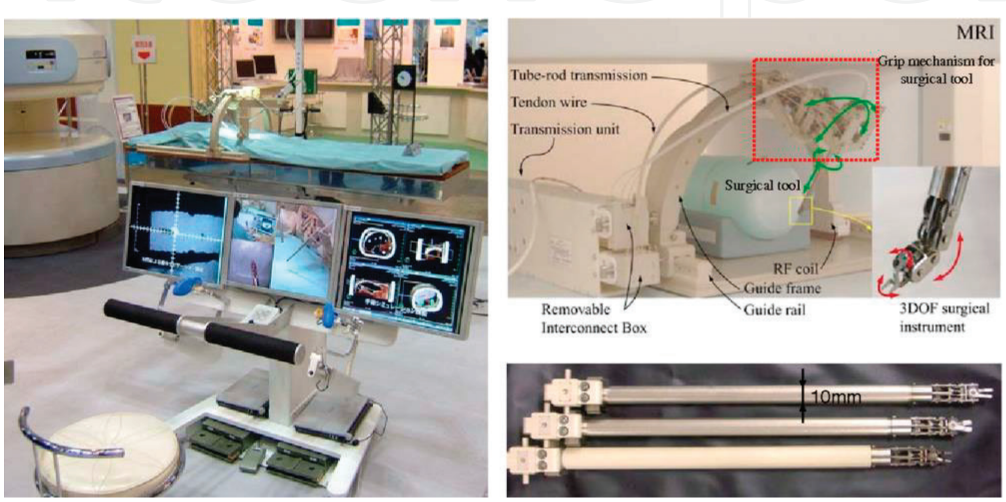

Figure 13.
MRI image-guided surgical system, reprinted by permission from Springer Nature: Springer Nature [53].

5. Navigation

Navigation in surgery includes various techniques. In brain and ENT surgery where the organ deformation are relatively small, the navigation system which detects the real-time position of the instrument in the preoperative three-dimensional image by using optical position sensors is often used. In laparoscopic surgery, as the organ movement is large, such precise position detection is not required. But sometimes surgeon requires to refer to the segmented preoperative image during the procedure in order to confirm anatomical structure. The problem was that it is very difficult to compare current two-dimensional camera image and preoperative three-dimensional image. In order to solve this problem, we have developed real-time viewer software and sensor system especially for da Vinci partial nephrectomy (**Figure 14**) [54, 55]. This system detects the robot camera angle by position sensor mounted to the da Vinci arm by our own attachment (because da Vinci does not allow to output such data). According to the camera angle, the system computes corresponding view in the three-dimensional preoperative image and displays at the small sub-display under the main display. By this navigation system, the surgeon can see the preoperative image in the same angle of current camera image. We found it very useful, and it is clinically used every time in our hospital.

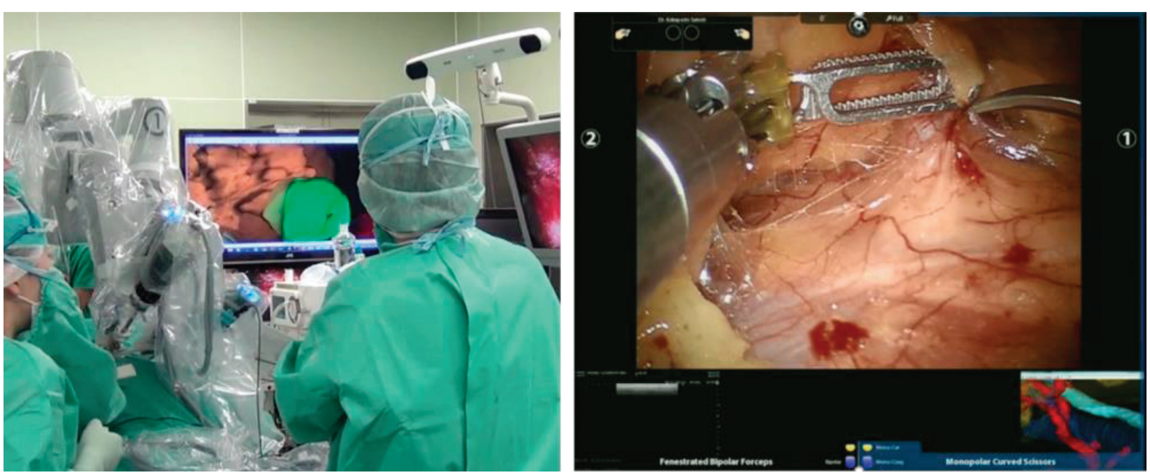

Figure 14.
Navigation system for da Vinci surgery.

6. Training

Training in laparoscopic surgery is important for surgeons. Also, studies about effective training method are important for better learning curve. There are many surgical simulators using computer graphics, rubber phantom, and harvested animal organ. However, measuring surgical skill quantitatively was very difficult. Quantification of skill is important not only for qualifying each surgeon but also for evaluating the effectiveness of training method. We have developed a suture simulator and evaluation software (**Figure 15**) [56, 57]. The phantom mimicking small intestine, made of four layers and string braided rubber, is used for the task. The task is anastomosis of the defect on the intestine by three interrupted sutures. The result is evaluated by five category including completion time, air leakage test, etc. The trainees can be fed back each time by score. Scoring system was developed using data previously obtained from skilled surgeons performing suture on this phantom. By using this simulator, significant difference between the trainees' scores before and after training was observed [57].

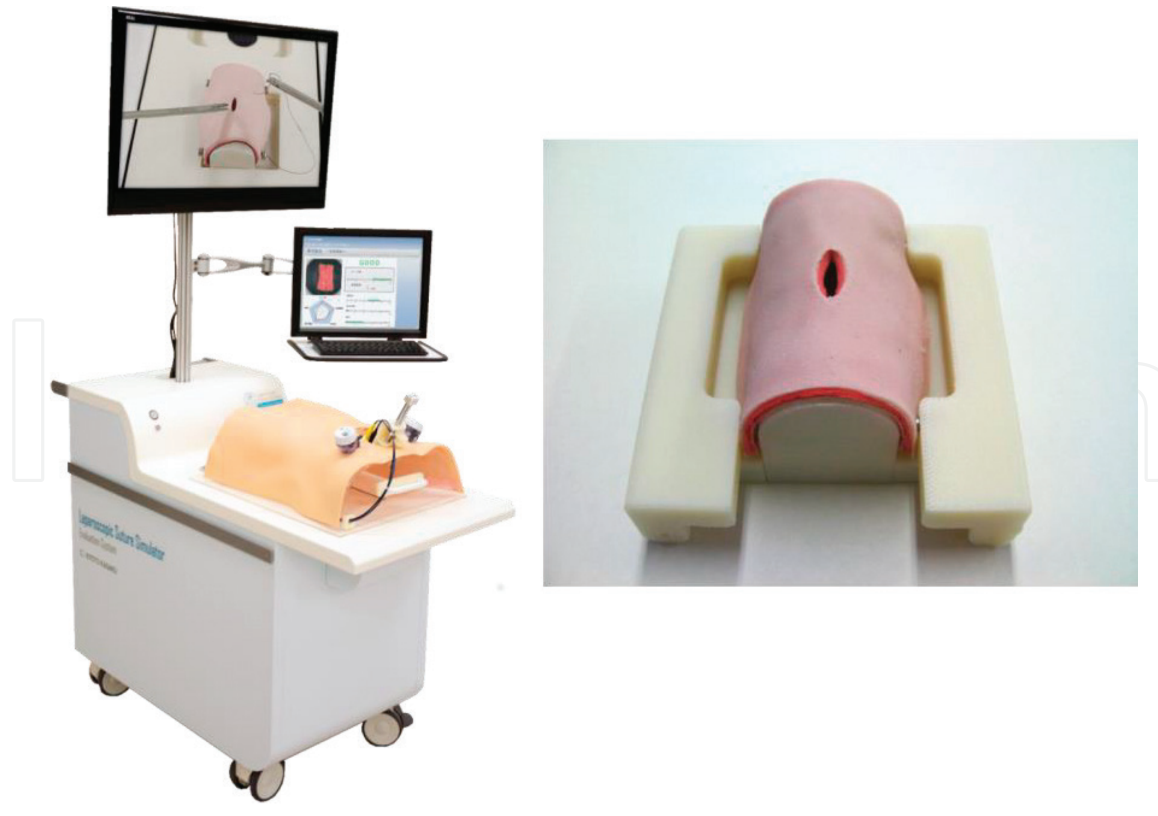

Figure 15.
Training simulator.

7. Conclusion

In this chapter, we introduced current and near future available laparoscopic/flexible endoscopic surgical robots, examples of other advanced robotic applications, and technology of navigation and training.

Conflict of interest

Ryu Nakadate and Makoto Hashizume received researching fund from Hogy Medical Co Ltd., Japan. This work was partially supported by JSPS KAKENHI Grant Number 16H03195.

Author details

Ryu Nakadate[1] and Makoto Hashizume[2]*

1 Center for Advanced Medical Innovation, Kyushu University, Fukuoka, Japan

2 Kitakyushu Chuo Hospital, Fukuoka, Japan

*Address all correspondence to: mhashi@dem.med.kyushu-u.ac.jp

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