The Role of Technology in the Implementation and Learning of Minimally-Invasive Surgery

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Abstract. The assimilation of the surgical techniques by the resident doctors should not affect patients' safety. Practicing certain surgical gestures in a repetitive manner allows a better understanding of the technique and the correct acquisition of the manual skills. The use of simulators as a part of the training programs has considerably reduced the number of surgical errors and has improved the operative time and the quality of robotic and laparoscopic surgical procedures. The latest technologies, like 3D vision, next generation instruments, the use of intraoperative imaging have enabled the development of minimally-invasive surgery, so that a number of laparoscopic and robotic procedures have become the standard of care. Our objective was to evaluate the manner in which the latest technologies influence the development of minimally invasive surgery (laparoscopic and robotic). Also, we assessed the main parameters that influence the learning curve of these two types of minimally invasive approach. We observed that the use of the robotic platform during the learning curve allows the performance of laparoscopic procedures with the same accuracy, but with much lower costs.

Key words: robotic surgery, laparoscopic surgery, surgical simulators, learning curve

1 Introduction

The assimilation of the surgical techniques by the resident doctors should not affect patients' safety. In fact, the learning of a surgical technique is the capacity of one doctor to reproduce in a correct and timely manner a surgical intervention. The possibility of practicing certain surgical gestures in a repetitive manner will only allow a better understanding of the technique and the correct acquisition of the manual skills.

In this aspect several concepts have been developed that will allow the repetition of certain surgical gestures and acquisition of the needed surgical skills. This way, the training programs, modern technology (medical robots, flexible instruments, 3D imaging, intraoperative imaging) and the simulators' use have the purpose to reduce the learning curve by practicing, repeating and acquiring the surgical techniques. There are two different situations in the learning process:

- The resident doctors have a double learning curve, one of the surgical technique and one of the surgical approach (robotic and laparoscopic)
- The doctors with open surgery experience, who are already aware of the surgical technique and will only have to acquire knowledge regarding the surgical approach (laparoscopic or robotic)

After the introduction of the robotic surgery in the clinical practice, the majority of the surgeons have crossed directly from the open surgery to the robotic one. [1] In these robotic centers some interventions (radical prostatectomy, partial nephrectomy, hysterectomy) have been subsequently performed exclusively using the robotic approach. This way young doctors have had the opportunity to learn a number of surgical procedures directly by robotic approach. An identical situation was seen in laparoscopy, this approach being exclusively used for certain surgical interventions as cholecystectomy or radical nephrectomy. [22]

Our objective was to evaluate the manner in which the latest technologies influence the development of minimally invasive surgery (laparoscopic and robotic). Also, we assessed the main parameters that influence the learning curve of these two types of minimally invasive approach.

2 Impact of advances in technology on surgical procedures

Minimally invasive approach (laparoscopic, robotic, single site or by natural orifices) has completely changed the surgical armamentarium in recent years. Patients have smaller or no skin incisions, a faster recovery, lower post-operative pain, lower blood loss, a shorter hospital length of stay, a more rapid social reintegration and an improved quality of life. For the surgeons, the technical advances in minimally invasive surgery have led to an enhanced visualization of the anatomical structures, improved dexterity, tremor filtering and the possibility of performing very precise procedures. But all these come with important costs for the healthcare system, thus limiting their availability. As a result, the most widespread minimally invasive surgical technique is laparoscopy.

Laparoscopy implies the insertion of surgical instruments into the abdominal cavity through small incisions (up to 12 mm). Despite all the advantages of a minimally invasive approach, laparoscopy poses some challenges with regard to the lack of depth perception and tactile feedback, a steep learning curve and physical burdens to the surgeon, like inadequate ergonomy, muscular fatigue and exhaustion. A number of techniques have been developed in order to overcome these challenges: the 3D endoscope, next generation instruments and the intra-operative fluorescence and imaging.

2.1 The 3D visualization

Classic laparoscopy was initiated at the end of 1980s and is based on a 2 dimensional (2D) image displayed on a monitor, which gives a lack of depth perception, so the surgeon performs the tasks using visual indicators to judge instrument position and depth. This fact can be a considerable challenge, especially when performing very complex surgical steps that require precision and dexterity, like lymphadenectomy, urethro-vesical anastomosis after radical prostatectomy or anastomosis between urethra and neobladder after radical cystectomy. New systems that try to overcome these limitations have upgraded to the 3 dimensional (3D) stereoscopic vision. The first 3D systems were still rudimentary, using the technique of active optic shuttering of alternating high-frequency signals emanating from a 3D screen and causing eye strain, headache, dizziness, disorientation, physical discomfort and poor visualization. Newer 3D systems use passive micropolarization technology and are believed to limit surgeon fatigue, by providing superior depth perception and resolution. [37]

The 3D visualization offers three types of advantages: for challenging procedures, for the learning curve and for the ergonomy of the surgeon.

2.1.1 Advantages for challenging procedures

Several studies have confirmed the superiority of 3D over the 2D laparoscopy, concluding that the 3D vision simplifies complicated procedures [8], improves orientation in the abdominal cavity and reduces the operative time [40]. Also, the 3D imaging improves the measures of performance, regardless the surgeon’s previous laparoscopic experience [31], enabling the surgeon to approach difficult procedures earlier during the learning curve.

One of the most demanding and complex procedures in urology is radical cystectomy with pelvic lymphadenectomy with/without neobladder construction (the complete removal of the urinary bladder, the prostate and the pelvic lymph nodes in patients with muscle-invasive, non-metastatic bladder cancer). This surgery poses some challenges because it requires a precise dissection of major blood vessels and inside the deep pelvis, which restricts the movements of the instruments. The surgeon must dissect the virtual space between the bladder, prostate and the rectum and around the major blood vessels, maintaining the balance between the oncological results (the complete removal of the tumor) and the possibility of digestive tract or vascular complications. The use of 3D imaging for performing radical cystectomy has been shown to reduce the total operative time and the duration of pelvic lymph node dissection in comparison with 2D, without altering the results in terms of blood loss, postoperative complications, hospital length of stay or total costs of the procedure. [38]

Another urologic procedure that has an important impact on the patient's quality of life is radical prostatectomy and urinary incontinence is one of the functional complications that are associated with this surgery. Laparoscopic 3D approach has shown shorter operative time, reduced blood loss and higher early continence rates in comparison with 2D vision. [6]

2.1.2 Advantages for the learning curve

The 2D video systems and the instruments with fewer degrees of freedom slow down the learning curve of the surgeons. In order to facilitate the training, robotization of laparoscopic instruments and interface and 3D vision become crucial. [20]

When comparing subjects with various experience in laparoscopy, 3D visualization was associated with a shorter time to completion of the tasks and improved task precision for peg transfer, pattern cutting and suturing/knot tying in comparison with a 2D system. [37] Also, when comparing subjects with standard laparoscopic experience in performing tasks using daVinci robot, the 3D vision shows a significant improvement in performance times and error rates in comparison with 2D vision, independent of the ergonomic advantages of the robotic system. [10]

2.1.3 Advantages for the ergonomy of the surgeon

Although it has shown an improvement in patient outcomes and quality of life, laparoscopic surgery associates a greater amount of stress, muscular fatigue, discomfort and exhaustion for the surgeon [36], due to the need of performing repetitive and precise movements in a restricted space with ergonomically inadequate instruments. The 3D technology enables the surgeon to have depth awareness and a better visualization of the operative field, thus being able to perform complex surgeries with a more accurate technique. Subjects with no experience in laparoscopy showed an improvement in the operative time and the number of mistakes made when using 3D visualization. Also, this system seems to increase the accuracy and execution speed for the most complex surgical steps. As a result, the 3D vision is considered to ensure a lower mental workload, with a considerable difference in frustration, when compared with 2D in subjects with no experience in laparoscopy. [15]

2.2 Next generation instruments

Minimally invasive surgery ensures smaller skin incisions, improved cosmetics, reduced post-operative pain and shorter recovery time. Single-site surgery aims to enhance these advantages by positioning all the instruments through a solitary port. But a number of challenges arise from this approach, due to the coaxial access of the instruments through the incision, reduced triangulation, reduced range of motion and instrument collision. [16]

Several technical advances have been made in order to overcome these challenges, leading to the development of articulated or magnetic instruments and endoscopes.

2.2.1 Articulated instruments

Articulated instruments seek to restore triangulation by rotating through 360° and articulating by up to 80° at their effector end. Using this type of instruments in conventional laparoscopy has been shown to improve performance in novices and to allow experts to maintain their performance. [25] On the other hand, the use of articulated instruments in single-site surgery has not demonstrated so far the superiority over straight instruments. The only significant improvement in surgeon performance was shown in the peg-transfer task when using a combination of one straight and one articulated instrument. [12]

2.2.2 Magnetic instruments

Irrespective of the type of minimally invasive approach, single-site or natural orifices surgery, the movement of the instruments is restrained by the access port. Investigation of possibilities of removing these constraints, led to the development of magnetically driven instruments. These instruments are formed of an external (outside the abdominal wall) and an internal unit (inside the abdominal wall), which interact by transferring the mechanical power from the driving magnet to the driven one, thus performing the surgery. The surgical devices have the advantage to be fully inserted into the abdominal cavity, achieve access to all abdominal quadrants, without the conventional rigid link connection with the external unit. The power and torque is transmitted from the external unit across the abdominal wall through magnetic linkage. This concept of magnetic instruments is still under investigation, but shows great potential so far to replace conventional abdominal surgery, taking the surgical robotics to the next level. [21]

2.3 Intraoperative imaging

Nowadays, patient safety and accuracy of the procedure have become the two main targets of surgical approach. Every technique has several limitations, whether it is laparoscopic or robotic-assisted. New imaging techniques have been implemented in order to enhance the surgeons' understanding of anatomical structures, like intraoperative ultrasound or near-infrared fluorescence.

Partial nephrectomy is a surgical technique that represents the removal of a kidney tumor with a minimal amount of healthy surrounding tissue, with the intent of preservation of the renal function. This technique is recommended for kidney tumors smaller than 4 cm and can be performed by minimally invasive approaches – laparoscopic or robotic. Robotic partial nephrectomy has shown important advantages in terms of learning curve and warm ischemia time (renal ischemia during tumor excision caused by the clamping of renal blood vessels). [7, 28] Usually during the tumor excision, the ischemia time is necessary in order to ensure a lower blood loss and increased visualization of the surgical field. Studies have shown that prolonged ischemia time can impair the renal function, so zero-ischemia or selective ischemia partial nephrectomy (clamping only the arteries that supply blood to the part of the kidney where the tumor is located) have been recently developed. Moreover, the increasing experience in partial nephrectomy enables the use of this technique for more complex, endophytic tumors.

At the present time, partial nephrectomy poses two main challenges: to minimize the warm ischemia time by selective clamping and to ensure complete removal of endophytic tumors. Various imaging techniques can be used to assist these two surgical steps, and one of the most widely spread is intra-operative ultrasound. The use of a specific microbubble contrast substance with intra-operative ultrasound can enable the identification of renal microvasculature in real time, thus facilitating the identification of the tumor and selective arterial clamping, with a decreased risk of positive surgical margins and permanent loss of nephrons. [3]

2.4 Fluorescence

Near-infrared fluorescence seems to have the greatest potential for entering the clinical practice in the near future, by offering an increased tissue visualization using widely available dyes like indocyanine green or methylene blue. [33] The near-infrared system is available for minimally invasive surgery techniques, both laparoscopic and robotic (since 2010), which can switch from white-light mode to near-infrared mode. The ability to merge these two modes into a single real-time image is still under development for the robotic system.

The physical and chemical characteristics of indocyanine green enables the possibility of better visualization of blood vessels, bile ducts, sentinel lymph nodes or lymphatic vessels. [34] As a result, the clinical applications of fluorescence in robotic surgery are [13]:

- ***recognition of vascular anatomy*** - reduces the risk of iatrogenic damage, especially at the beginning of the learning curve; it ensures the identification of mesenteric arcades during intracorporeal ileal neobladder construction in order to preserve the blood supply [23]; also, it can be used to assist superselective clamping during partial nephrectomy, thus facilitating zero-ischemia technique and shortening the learning curve [9]

- ***evaluation of organ and tissue perfusion*** – mostly used in general surgery in order to evaluate the microcirculation and viability of tissues, in an effort to early recognize ischemia of the stumps and to reduce the anastomotic leak and stricture rates [17]; to assess blood perfusion of the transplanted kidney [5]

- ***visualization of biliary anatomy*** during cholecystectomy, in order to prevent bile duct injuries [14]

- ***identification of lymph nodes* –** with the purpose of excising only metastatic lymph nodes, providing an accurate staging and better oncologic outcomes, with decreasing complications [32]

- ***identification of specialized tissue*** – for example, the nerves or nerve-bundles, in order to avoid iatrogenic damage and preserve their functionality [13]

- ***identification of lesions-based on vascular and metabolic pattern*** – in order to preserve the organ and excise only the tumor: identification of renal tumors during partial nephrectomy (malignant lesions are hypofluorescent in comparison with normal tissue) [39]; identification of adrenal tumors (hypofluorescent) and performing partial adrenalectomy [24]

3 Learning minimally-invasive surgery

3.1 Laparoscopy learning curve

Traditional laparoscopy learning curve is generally longer due to the 2D imaging, rigid instruments, a low degree of instruments movement, diminished tactile feedback, physiological tremor and reduced ergometry. Due to these limitations an increased number of complications have been encountered during the learning curve of a certain technique (urinary fistula in urology or the common biliary duct injury in general surgery). As well, the use of traditional laparoscopy is limited in complex cases that will require reconstructions or intracorporeal sutures (digestive surgery or intracorporeal urinary diversions). From the ergonomical point of view, traditional laparoscopy is more demanding using mainly the upper arms muscles (biceps and flexor carpi ulnaris). In the robotic surgery the trapezius muscle is mainly involved, but this phenomenon is mostly encountered in inexperienced doctors. These ergonomy differences lead to superior performance for the robotic surgeons. [19]

3.2 Robotic surgery learning curve

The robotic approach corrected the main disadvantages of the traditional laparoscopy. This way the 3D imaging is offering depth, the flexible instruments are offering a wide range of movements, there is no physiological tremor and the ergonomy is excellent. The patient is the main beneficiary of all the advantages offered by the robotic surgery: the blood loss, postoperative pain and the hospitalization period are considerably reduced compared to the traditional laparoscopy. [30]

The robotic surgery advantages allow a shorter learning curve for the surgeons especially in the case of complex interventions (reconstructions and intracorporeal sutures) or stressful interventions (cardiovascular surgery).

The advantages offered by the robotic surgery in case of complex interventions have been evaluated in a study that included medical students with no previous laparoscopic, robotic or simulator experience. The subjects have done intracorporeal digestive sutures by traditional laparoscopic or robotic approach using three attempts. In the robotic group, the sutures have been done more rapidly compared to the laparoscopy group (460 seconds vs 600 seconds, $p<0.0001$) and with a better quality, less errors and less vital organs injuries. The performances improved during the three robotic attempts but did not modify during the laparoscopy attempts. This fact suggests a more difficult learning curve for the traditional laparoscopy. The subjects practicing intracorporeal sutures complained of work overload and important psychological pressure. [35]

On the other hand, the stress level during procedures is different for a beginner compared to an experienced surgeon. For a beginner, the stress level is lower in robotic compared to laparoscopic procedures. [18] For an experienced surgeon, the level of intraoperative stress is similar for both laparoscopic and robotic surgery. However cardiovascular adaptation (blood flow and vascular resistance) is better for the robotic surgeons compared to the ones in the traditional laparoscopy group. In highly stressful environment the robotic approach allows a more accurate performance with less errors. The performance of robotic interventions which associate a high level of stress offers better long term health results for the surgeons. [27]

3.3 The role of laparoscopy in the robotic surgery learning curve

The implementation of robotic surgery can be achieved without previous laparoscopy experience, the leap from open surgery to robotics being possible. However the surgeons with previous laparoscopy experience acquire more rapidly the skills for the robotic surgery especially in the case of complex interventions (intracorporeal sutures). These observations are valid for all surgical specialties (urology, gynecology, general surgery or thoracic surgery). [26]

This way the previous experience in laparoscopy allows the surgeons to perform more rapidly. This phenomenon is valid as well for the surgeons crossing from robotic surgery to laparoscopy. The explanation for this phenomenon is that both approaches are based on the physical and cognitive elements. The physical elements are represented by the characteristics of these two surgical approaches (imaging, instruments, etc). The cognitive elements once acquired in laparoscopy could be afterwards transferred to robotics and backwards. This cognitive aspect explains the more rapid learning curve in robotics for the surgeons with previous experience in laparoscopy and in laparoscopy for the robotic surgeons. [4]

3.4 The role of robotic surgery in the laparoscopy learning curve

Using the robotic surgery platform during the laparoscopy learning curve could be very important for the surgical techniques acquisition.

A study which evaluated the laparoscopy learning process included gynecology resident doctors with and without previous surgical experience. Some of the doctors had been included in the laparoscopy training, which did not include the robotic platform, while another group used the robotic platform in the training. The learning curve included the following parameters: hands synchronization, cutting and sutures. The use of the robotic platform lead to > 50% better performance for the junior doctors with no surgical experience as well as for the doctors with previous surgical experience. [22]

3.5 Simulators

The robotic systems are composed of two parts:

- the console – used by the surgeon to generate tasks
- the robot – to deliver tasks

The console and robot activity could be reproduced with the help of simulators. There are two types of simulators:

- physics (mechanics) – the box type which can deliver tasks under video control (laparoscopy simulators)

- virtual – based on a computer which can generate a virtual reality (robotic simulators).

At the present, there are five different systems of robotic simulators (RoSS simulator, Simsurgery educational platform, ProMIS simulator, Mimic dV-Trainer system and daVinci Skill Simulator). These simulators are based on developing the eye-hand coordination capacity and the objective is tissue manipulation, dissection, sutures and performing knots. [1] The main role of these simulators is the acquisition of surgical skills during the training programs. The simulators offer as well the opportunity to evaluate and monitor the level of surgical skills acquisition. [11]

Residents who have completed a training in laparoscopy performed more correctly the intracorporeal knots and sutures, have a reduced operating time and commit fewer errors. [2] Also, trainings conducted on virtual simulators lead to a reduced operative time and improved surgical performance compared to mechanical ones. Mechanical simulators require two people for performing the training compared to virtual simulators. The additional person is needed to control video quality and for evaluating training quality by offering feedback. For the virtual simulation, the evaluation is performed by the computer. However, mechanical simulators are much cheaper and offer the advantage of increased realism (eg tactile sensation present). Currently there is a concern for the construction of simulators that combine virtual reality and mechanical simulators. [29]

4 Personal experience

The experience of the Urology Department of the Cluj-Napoca Municipal Hospital includes open surgery, laparoscopy (since 1996) and robotics (since 2009). Implementing robotic surgery took place after a prior experience in laparoscopy for a senior surgeon and one inexperienced in laparoscopy junior surgeon. Previous training in laparoscopy allowed senior surgeon to perform urological robotic interventions of great difficulty: radical prostatectomy, partial nephrectomy, radical cystectomy with ileal intracorporeal neobladder. Since 2015 we started a program of three-dimensional laparoscopy and the main advantage is lower costs for laparoscopy (3D laparoscopy implementation costs represented ~5% of the costs of implementing robotics). For this purpose we evaluated how prior experience in robotic radical prostatectomy (250 cases) has influenced the adoption of 3D laparoscopic radical prostatectomy. Between March 2015 and January 2016 we performed 76 3D laparoscopic radical prostatectomies. The evaluated parameters were operative time, conversion rate, blood loss, transfusion rate and the duration of maintaining the catheter. Operative time was shorter for 3D laparoscopic surgery compared with the robotic one (132 minutes vs 210 minutes). Blood losses were comparable (mean blood loss 300 ml for both types of approach), but transfusion rate was higher for robotic radical prostatectomy (6 cases vs 1 case). No cases of conversion were recorded in either group. The duration of preservation of the bladder catheter was 7 days for robotic radical prostatectomy and 14 days for 3D laparoscopy. The advantages for 3D laparoscopic approach are lower costs and reduced operative time. For the robotic approach the advantages are shorter need of drainage and bladder catheter and shorter hospital stay. Although the learning curve in laparoscopic radical prostatectomy is higher, prior experience in robotics and 3D image allowed a quick and safe implementation of this procedure.

5 Conclusion

The latest technologies, like 3D vision, next generation instruments, the use of intraoperative imaging have enabled the development of minimally-invasive surgery, so that a number of laparoscopic and robotic procedures have become the standard of care. The use of simulators as a part of the training programs have considerably reduced the number of surgical errors and have improved the operative time and the quality of robotic and laparoscopic surgical procedures. The use of the robotic platform during the learning curve allows the performance of laparoscopic procedures with the same accuracy, but with much lower costs.

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