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The learning curve of robot-assisted laparoscopic surgery

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1. Introduction

Endoscopic surgery has proven to be beneficial to the patient with regard to reduction of hospital stay, postoperative pain and earlier return to daily activities. After its introduction, development of new instrumentation improved and facilitated endoscopic performance (Yohannes et al, 2002). Despite this development, laparoscopic procedures have been limited by fixed distances, restricted freedom of motion of the surgical instruments, impaired visualization and small working space (Sarle et al, 2004). With the introduction of surgical robotic systems an attempt was made to overcome these technical difficulties. Many conventional laparoscopic procedures have been duplicated with assistance of a surgical robotic system. Endoscopic cardiac procedures, that were not feasible before applying conventional laparoscopic techniques, are currently performed robotically-assisted. Several advantages of robotic surgery compared to conventional laparoscopy have been identified: additional degrees of freedom of motion, downscaling of movements, enhanced stability (both of visualization and surgical instrumentation), restoration of the eye-hand target axis, elimination of the fulcrum effect and improved ergonomics for the surgeon. These features are supposed to enhance surgical performance by improved accuracy, dexterity and visualization. Consequently, it can be expected that endoscopic surgical skills are more easily mastered and the learning curve is shortened. The learning curve can be defined as the amount of practice (in time or number of repetitions) necessary to achieve a consistency of a specified parameter. A time-action analysis, the time to complete a task, the number of actions required and the number of errors made, are parameters used to evaluate the learning curve for a specific task. In daily practice, other parameters viz. conversion rate, operating time, blood loss, morbidity and hospital stay are used to assess the learning curve for a specific procedure. Most advanced endoscopic procedures are characterized by a long learning curve. Learning curves are associated with prolonged operative times, increased patient morbidity and higher costs. These difficulties might delay further implementation of advanced endoscopic techniques. Although a surgical robotic system might impose as the ideal endoscopic instrument, most clinical studies have not shown benefit with regard to operative time compared to conventional endoscopy. The objective of this study is to systematically review the available literature to evaluate the impact of a surgical robotic system on the learning curve of endoscopic procedures compared to conventional endoscopy.

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2. Methods

A computer-assisted search was performed in the medical databases Medline (from January 1966 to June 2007), Embase (from January 1988 to June 2007) and the Cochrane Database of Systematic Reviews, using a combination of the keywords "Learning curve, robot, telemanipulation and computer-assisted surgery". After identifying relevant titles, the abstracts of these studies were read to decide if the study was suitable. Two authors (EO and DN) independently read the abstracts. A manual search of reference lists of studies thus obtained was conducted for any relevant articles not found in the computerized search.

2.1 Criteria for inclusion

Clinical and experimental studies eligible for inclusion had to describe a learning curve for robot-assisted procedures. Articles in languages other than English, German or French were excluded. Articles, in which a summary of different procedures executed with the aid of a robotic surgical system was described, were excluded.

3. Results

In total 21 studies were identified. Most excluded studies were case reports, small series or reports of the author's experience with a variety of surgical procedures using a robotic system without evaluation of a learning curve. The search resulted in 10 experimental studies on laparoscopic skills. In general surgery, articles reporting a learning curve were mostly those describing robot-assisted cholecystectomy and robot-assisted antireflux surgery (fundoplication), respectively 7 and 4 studies. There were some incidental reports of other surgical procedures viz. gastric bypass (3) and aortoiliac surgery (1). Reports on other fields than general surgery as urology and cardiac surgery were not included for evaluation. As a result this review concentrates on the learning curve of robot–assisted standard experimental exercises, laparoscopic cholecystectomy and laparoscopic fundoplication.

4. Robot-assisted laparoscopic skills

Ten experimental studies described standardized exercises with either Zeus (4/10) or Da Vinci (6/10) robotic system. In all studies basic endoscopic tasks such as transferring beads/ rings, rope passing, knot tying and suturing were reported. The drills were predominantly performed by laparoscopic novice participants sometimes compared with laparoscopic experienced surgeons. In 6 studies (Prasad et al, 2001; Yohannes et al, 2002; Maniar et al, 2004; Nio et al, 2005 ; Blavier et al, 2006; Heemskerk et al, 2007) the robotic learning curve (RLC) was compared to the manual learning curve (MLC). In most studies the learning curve was defined on the basis of 2 parameters; completion time and amount of errors, often given as a combined score. Results are shown in table 1. In most studies the initial performance using the robotic system was inferior to the conventional laparoscopy. Although a rapid improvement of robotic performance was observed, conventional laparoscopic performance was rarely equalled. In all but one study a significant improvement of outcome parameter after time was shown, which suggested a significant learning curve. Only one study (Heemskerk et al, 2007) showed a flat RLC from the beginning. Most novice participants showed an initial inferior performance in comparison to laparoscopic experienced participants. This resulted in a steeper early phase of their RLC.

When RLC and MLC were compared results were not conclusive. When steeper learning curves were described in either the robotic of conventional laparoscopic group, they were attributed to an initially worse performance.

	Robotic system	Skill	No. of repetitions	Participants LN/LE	Parameter	Learning curve
Yohannes	Da Vinci	Dexterity task Suturing/Knot-tying	5	4LN/4LE	Time	Yes
Prasad	Zeus	Bead transfer Rope pass	5	17LN/11LE	Calculated score (time + error) Precision score	Yes
Maniar	Zeus	Bead transfer Rope pass	15	20LN	Calculated score % improvement	Yes
Heemskerk	Da Vinci	Bead drop/transfer Needle cap Suturing	3	8LN	Time Accuracy	No
Blavier	Da Vinci	Passing needle through rings	6	10LN	Performance score Error score Ambidexterity score	Yes
Nio	Zeus	Suturing Knot-tying	20	1LN/1LE	Number of actions / stitch or knot	Yes
Chang	Zeus	Knot-tying	> 5 -14 h training	8?	Time Composite score	Yes
Hernandez	Da Vinci	Suturing	5	7N/6E	OSATS Time	Yes
Narazaki	Da Vinci	Pick and place Needle passing Suturing	4 weeks training*	7LN	Time (Travelling distance)	Yes
Ro	Da Vinci	5 drills	5-6	17 LN/2LE	Performance score (time+error)	LN :Yes LE : No

LN: laparoscopic naive, LE: laparoscopic experienced, OSATS: objective structured assessment of surgical skills
* 6 sessions of training

Table 1. Learning curve. Results of robotic skill studies

5. Robot-assisted laparoscopic cholecystectomy

Seven robot-assisted cholecystectomy studies describing the learning curve were identified. Four series were comparative studies (Perez et al, 2003; Guilianotti et al, 2003; Caratozollo et al, 2005; Heemskerk et al, 2005) and 3 series consisted of consecutive patient series

(Chitwood et al, 2001; Ruurda et al, 2002; Vidovszky et al, 2006). In 6 studies the Da Vinci was used, in only one the Zeus-AESOP robotic system. Laparoscopic experienced surgeons performed the laparoscopic cholecystectomy. The set-up time and operative time were used as the parameters for the learning curve. Four studies (Caratozollo et al, 2005, Vidovszky et al, 2006, Ruurda et al, 2002, Chitwood et al, 2001) showed a decrease of the robotic set-up time, but in only 2 studies this decrease was significant (Chitwood et al, 2001;Vidovszky et al, 2006). In one study robotic set-up time did not change in time (Heemskerk et al, 2005) and 2 studies did not report on the robotic set-up time (Perez et al, 2003, Giulianotti et al, 2003).
The operating time decreased in 3/7 studies (Perez et al, 2003, Giulianotti et al, 2003; Caratozzolo et al, 2005), of which 2 studies showed a significant decrease. All 3 studies reported that the mean robotic operative time at the end of the series was equal compared to manual laparoscopic cholecystectomy. One study mentioned that 20 operations were needed to complete the learning phase. (Guilianotti et al, 2003). No major intra-operative complications occurred. Conversion was necessary 7/219 times as a result of severe cholecystitis, poor visualization or obscure anatomy. The conversion rate was not higher in the robotic laparoscopic cholecystectomy. No study mentioned at which moment of the learning curve conversion was necessary. Three studies mentioned mechanical problems such as a malfunctioning/interfering of the robotic arms, which necessitated repositioning of the robotic arms and exchange of instruments (Caratozzolo et al, 2005; Vidovszky et al, 2006) and in one case detachment of the robotic instrument resulted in a minilaparotomy (Ruurda et al, 2002).

	Robotic system	No. of patients	Surgeon (LN/LE)	Parameter	Learning curve	Conversion
Caratozzolo	Zeus	29	2LE	Set-up time Operative time	Yes Yes	2/29
Heemskerk	Da Vinci	N=12*	1LE	Set-up time Operative time	No No	0/12
Vidovsky	Da Vinci	N=51	NR	Set-up time Operative time	Yes, significant No	3/51
Ruurda	Da Vinci	N=35	3LE	Set-up time Operative time	Yes No	1/35
Chitwood	Da Vinci	N=20	LE	Set-up time Operative time Combined time	Yes, significant No Yes, significant	0/20
Perez	Da Vinci	N=20	3 LE	Operative time	Yes, significant	0/20
Giulianotti	Da Vinci	N=52**	NR	Operative time	Yes, significant	1/52

LN: laparoscopic naive, LE: laparoscopic experienced, NR not reported
* Vs. historical robotic series;** 14 procedures were combined procedures (with fundoplication, hepatic and gastric resection)

Table 2. Learning curve of robot-assisted laparoscopic cholecystectomy

6. Robot-assisted anti-reflux surgery

Four fundoplication studies showed the learning curve of experienced surgeons all performed with Da Vinci. Only one study compared the RLC with the MLC (Morino et al, 2006). The decrease in set-up time and operative time was used to compare the mean results of the first and second part of the series to assess the learning curve. The set-up time, reported in 2 studies (Chitwood et al, 2001; Wykypiel et al 2003), decreased but not significantly. The operative time decreased in 3 studies. One study reported equivalence in operating time when compared with conventional laparoscopic fundoplication already after 2 procedures (Wykypiel et al 2003). Another study reported that 20 robotic procedures were necessary to complete the learning phase (Guilianotti et al, 2003). Two conversions due to operative complications, not related to the robotic system were reported. No mechanical problems were described. Results are shown in table 3.

	Robotic system	No. of patients	Surgeon LE/LN	Parameter	Learning curve	Conversion
Giulianotti	Da Vinci	N=49	NR	Operative time	Yes, significant	2/49
Chitwood	Da Vinci	N=14	LE	Set-up time Operative time	Yes, NS Yes, significant	NR
Wykypiel	Da Vinci	N=10	LE	Set-up time Operative time	Yes, significance nr Yes, significance nr	0/10
Morino	Da Vinci	N=25	LE	Operative time	No, significance nr	0/10*

LN: laparoscopic naive, LE: laparoscopic experienced, NR not reported, NS not significant
*1 conversion to manual laparoscopy

Table 3. Learning curve robot-assisted laparoscopic fundoplication

7. Discussion

Few reports on the learning curve of robotic surgery are available. Studies to compare robotic with conventional laparoscopic learning curves were even scarcer. To measure the learning curve of robotic surgical performance a diversity of parameters was used throughout most studies. These parameters were not always well defined. Furthermore, a great variety of practice/time was used to define an early or late experience phase of the learning curve. An experience bias was expected in most clinical series, because of prior laparoscopic experience of the participating surgeons. All these issues limit an objective evaluation of the learning curve of robotic surgery. However, although robotic systems are supposed to be “intuitive” in use, this technique showed to have a learning curve. This was most clearly demonstrated for laparoscopically inexperienced persons.

A long learning curve might prevent implementation of a new technology, but the most important feature of a new technology, despite its learning curve, should be its advantage for the patient or the surgeon. Does it result in a reduction of morbidity or mortality? Does it facilitate and enhance laparoscopic surgical performance? These important questions remain unanswered with the current data. Furthermore, the financial cost-benefit should also be considered (Heemskerk et al, 2005).

A learning curve consists of an initial steep phase in which performance increases rapidly. When the change in improvement slows down, the learning curve reaches a plateau phase, in which variability in performance is small. The number of repetitions in most reported experimental series are to low to reach the consistency which characterizes the end of the learning curve. Only the first and steepest part is evaluated, in which the most improvement is expected. However, in 9/10 studies a learning curve was described, with the majority of participants being laparoscopically naïve. When compared to laparoscopic experienced participants the RLC of the laparoscopic naïve persons was steeper, due to inferior performance at the beginning. This suggests more impact of a robot on laparoscopic naïve persons, whereas a laparoscopic experienced person quickly adapts to the advantages of operating robotically (fulcrum effect) and benefits of his prior laparoscopic experience.

In the clinical series more “repetitions” are performed. As for the robot-assisted laparoscopic cholecystectomy, in 3/7 studies no learning curve was described for the robotic operative time, although a learning curve for the robotic set-up time was seen in all reported studies. All 4 comparative studies described equal operative times for robotic assisted cholecystectomy with conventional laparoscopic cholecystectomy after 20-50 procedures. All procedures were done by experienced laparoscopic surgeons. Proficiency for a conventional laparoscopic cholecystectomy is reached after 30 procedures (Dagash et al, 2002).

Only in one out of the four studies no learning curve was observed for robot-assisted fundoplication operative time. Set-up time showed a learning curve in all studies. One study, which compared RLC and MLC of fundoplication reported equal operative times after only two robotic procedures. Proficiency of a conventional laparoscopic fundoplication is said to be reached after 28 procedures. The variability in operating time remains high for this procedure even in the late phase of surgical experience (Dagash et al. 2003).

Most advantage of a robotic system is expected in advanced or complicated operative procedures. A laparoscopic cholecystectomy might be too simple, since it does not necessitate fine and complex movements. It might not be the appropriate procedure to evaluate the robotic learning curve. Although a laparoscopic fundoplication asks for more skill, most advantage of a robotic system is expected only during suturing of the wrap, which is a small part of the total procedure. Total operative time is not an accurate parameter to evaluate performance and learning curve.

An expected learning curve for the robotic set-up time was found, but not quantified in most studies. However, the clinical importance of a small increment in total operative time due to robotic set-up time is low, especially when operative times are long.

The use of robotic systems in laparoscopic surgery does not obviate the learning curve. Application of this technology has its own learning curve with respect to set-up of the system and getting accustomed to the specific features of the robotic systems. The limited data suggest that this learning curve is comparable with conventional laparoscopic surgery. Laparoscopically naive surgeons might benefit more from the advantages of a robotic system such as 3-D visualization and the absence of the fulcrum effect. This results in a steeper first phase of the robotic learning curve. However, experienced laparoscopic surgeons benefit from their prior laparoscopic experience shortening the robotic learning curve when compared to novice surgeons.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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