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Rapid adaptation of robotic gastrectomy for gastric cancer by experienced laparoscopic surgeons

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Abstract

Background Robotic surgery for gastric cancer patients has been increasing because of its many advantages over conventional laparoscopic surgery. Despite the suggestion that robotic surgery may lessen the learning curve for complex laparoscopic procedures, little is known about the learning curve for robotic gastrectomy. This study aimed to assess the learning curve of robotic gastrectomy for patients with cancer by analyzing the operation time.

Methods The first 20 consecutive cases of robot-assisted distal gastrectomy with lymphadenectomy for gastric cancer performed by three experienced laparoscopic surgeons' using the da Vinci system were collected and reviewed. A nonlinear least-squares method was developed and used to analyze the learning curves.

Results Overall, the mean operation time was 247.3 ± 45.7 min, depending on each surgeon's laparoscopic experience and the patient's characteristics. After control was used for confounding factors, the stabilized operation time decreased to 211.8 min. The operation time stabilized at 8.2 cases and was reduced 111.4 min from the first case. A stable operation time was reached in 9.6 cases by surgeon A, in 18.1 cases by surgeon B, and in 6 cases by surgeon C. The stable operation time was 149.2 min for surgeon A, 127.1 min for surgeon B, and 236.8 min for surgeon C, and the reduction in operation time from the first case to stabilization was 233 min for surgeon A, 76.7 min for surgeon B, and 154.6 min for surgeon C.

Conclusions Surgeons with sufficient experience in laparoscopic gastrectomy can rapidly overcome the learning curve for robotic gastrectomy. In addition, the surgeon's experience with laparoscopic gastrectomy affects the operation time after stabilization and the reduction in operation time.

Keywords Gastrectomy · Learning curve · Robotic surgery

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The application of cutting-edge robotic technology in minimally invasive surgery has proved to be one of the most successful solutions to the many drawbacks of laparoscopy. The surgical robot was introduced to alleviate the difficulty of laparoscopic surgery and to facilitate the expansion of minimally invasive surgery for more complicated procedures. Various fields of surgery such as digestive surgery, pediatric surgery, gynecology, urology, cardiothoracic surgery, and otorhinolaryngology have already used robot assistance for many of their advanced procedures [1–6].

Because of its numerous advantages over conventional laparoscopic surgery, robotic surgery for gastric cancer has rapidly gained a heightened level of interest. The safety and effectiveness of robotic gastrectomies for systemic lymph node dissection have already been reported [7–10]. The next area of investigation involves defining the operative outcomes and identifying the potential benefits for the patients or surgeons to ensure the appropriate application of robotic gastrectomy.

Laparoscopic gastrectomy for early cancer has been an important treatment method since its introduction in 1991 [11]. The benefits of laparoscopic gastrectomy, particularly laparoscopically assisted distal gastrectomy (LADG), over open gastrectomy have been reported in terms of better early postoperative and comparable long-term oncologic outcomes [12, 13].

Together with these results, several studies have investigated the learning curve for laparoscopically assisted gastrectomy [14–16]. Although some reports have already addressed the technical feasibility of robotic surgery in the field of gastric cancer [7–10], the learning curve for robotically assisted distal gastrectomy with lymph node dissection for gastric cancer has never been reported. This study therefore aimed to assess the learning curve for robot-assisted distal gastrectomy with lymph node dissection for gastric cancer by analyzing the initial experience of three different surgeons with robot-assisted distal gastrectomy.

Methods

Patients and data collection

For this study, three individual surgeons (S.-S. Park, M.-C. Kim, and W. J. Hyung) provided their experience of their first 20 consecutive cases performed at different institutions. The study enrolled 60 patients with gastric cancer who underwent robot-assisted distal subtotal gastrectomy using the da Vinci surgical system (Intuitive Surgical Inc., Sunnyvale, CA, USA).

All the data from the three surgeons were collected through a retrospective review of prospectively collected data. Since the introduction of the da Vinci system to the three institutions, the same prospectively designed database has tracked all da Vinci robot-assisted gastrectomy with lymphadenectomy for gastric cancer despite minor variations at each institution. Patient demographics, underlying diseases, data on the surgical procedure (including operative time), and data on perioperative monitoring including complications and length of hospital stay were recorded in the database.

Surgeon characteristics

Before starting robotic surgery, all three surgeons had overcome the learning curve by performing more than 50 laparoscopic gastrectomies [14–16]. Surgeon A had performed the most laparoscopic gastrectomies (400 cases). Surgeon B had managed 177 cases of laparoscopic gastrectomies and also had devised the procedure for the robotic gastrectomy used as the basic technique by the other two surgeons. Surgeon C's laparoscopic gastrectomy caseload was 68 at the time of his first robot-assisted distal gastrectomy.

Operative factors

The detailed robot-assisted distal gastrectomy procedures did not differ from LADG except in the use of articulating robotic instruments, which allowed greater dexterity and a wider range of motion for a precise operation in a three-dimensional view at the console [7]. The operative procedures have been described in detail previously [7, 9].

The anastomosis types (gastroduodenostomy or gastrojejunostomy) and approaches (intracorporeal or extracorporeal anastomosis) were selected according to tumor location and individual surgeon preference. The extent of lymph node dissection, the pathologic classification, and the tumor staging were rated according to the International Union Against Cancer [17] and the Guidelines of the Japanese Gastric Cancer Association [18, 19].

Statistical analysis

Data were derived retrospectively from the database and elaborated by SAS version 9.1 statistical analysis software (SAS Institute, Cary, NC, USA). Statistical differences between the continuous variables among the three surgeons were evaluated by a nonparametric analysis of variance called the Kruskal–Wallis H test. Fisher's exact test or Pearson's χ^2 test were used for categorical variables.

This study focused primarily on statistical modeling of the learning curves for robotic surgery by the three surgeons. To find the stable operation time (a), the reduced time amount by experience (c_1), and the number of cases (c_2) beyond which the operation time becomes stable, we considered the following parametric nonlinear regression model:

$$y_t = a + \varepsilon_t + \begin{cases} c_1 \times \left(1 - \frac{3t}{2c_2} + \frac{1}{2}\left(\frac{t}{c_2}\right)^3\right), & t < c_2, \\ 0, & t \geq c_2, \end{cases} \quad (1)$$

where for $t = 1,\ldots, T$, y_t is the measured operation time for case t. We estimated the three parameters (a, c_1, c_2) using the nonlinear least squares method, which assumes $\varepsilon_t \sim N(0,\sigma^2)$ for simplicity of the model.

Figure 1 illustrates the sequential operation time generated by the model shown in Eq. 1, which originates from the "spherical covariance function" used in the field of spatial data analysis (see Cressie [20] for more detail). As shown in Fig. 1, it was assumed that the operation time for any surgeon would gradually decrease over time and in some cases would become stabilized or converged to some constant time.

Here, we restricted the range of c_2 ($1 \le c_2 < T$). We also used the regression model with some covariates (x_{1t}, …, x_{pt}) to adjust for the confounding factors (age, gender, body mass index [BMI], reconstruction type, and extent of lymph node dissection. The modeling equation shown earlier then could be extended as follows:

$$y_t = a + \beta_1 x_{1t} + \cdots + \beta_p x_{pt} + \varepsilon_t + \begin{cases} c_1 \times \left(1 - \frac{3t}{2c_2} + \frac{1}{2}\left(\frac{t}{c_2}\right)^3\right), & t < c_2, \\ 0, & t \ge c_2. \end{cases} \quad (2)$$

All the statistical results based on a two-sided test were obtained by the SAS software (version 9.1.3; SAS Institute). We considered the level of significance to be an α of 0.05 and regarded a P value less than 0.05 as statistically significant.

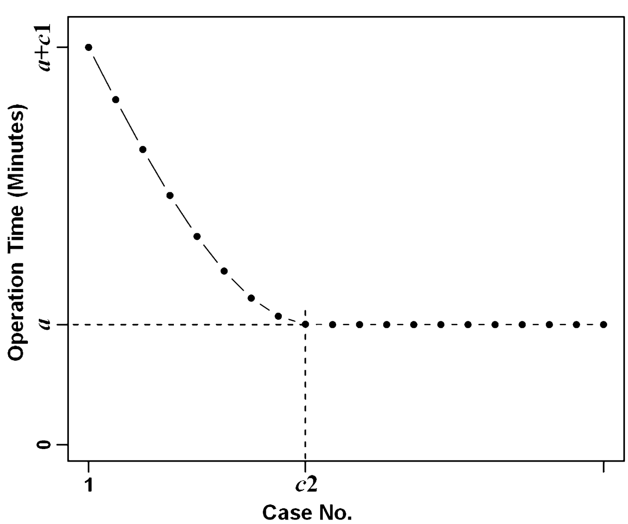


Fig. 1 Sequential operation times generated by the nonlinear regression model, with a indicating stabilized operation time, $c1$ indicating reduced operation time from the first case to stabilization, and $c2$ indicating the number of cases performed before the operation time becomes stable

Results

Patient demographics and tumor characteristics according to the surgeons (Table 1)

The 33 men and 27 women in the study were in three groups, and their mean age was 52.6 ± 13.1 years. The patients in surgeon C's group were younger than the patients in the other two groups. The mean BMI of the patients was 23.4 ± 3.3 kg/m^2, and surgeon A's group had the lowest BMI ($P = 0.009$).

Some of the patients (31.7%, 19/60) had medical comorbidities including cardiac problems (angina, atrial fibrillation, and hypertension), pulmonary diseases (chronic obstructive lung disease and a history of pulmonary tuberculosis), and others (e.g., diabetes, gallstone, gout, and hepatitis C virus infection). Of the 60 patients, 11 (18.3%) had a history of minor operations such as appendectomy, cesarean section, and resection for uterine myoma through a low midline incision.

The mean tumor size in surgeon B's group (2.3 ± 1.3 cm) was smaller than in surgeon C's group ($P = 0.022$). The T and N classifications of most patients were T1 (46/60, 76.7%) and N0 (51/60, 85%). However, surgeon A's group had two T3-stage patients, one N3-stage patient, and one N2-stage patient (of the two T3-stage patients, the one was N3 and the other was N2). None of the tumors had margin involvement.

Operation-related factors (Table 2)

The overall mean operation time was 247.3 ± 45.7 min. Regarding the extent of lymph node dissection, surgeons A and C performed mainly D2 dissection (17/20, 85% and 14/20, 70%), whereas surgeon B performed D2 dissection in only 3 (15%) of 20 cases. For anastomosis, Billroth-I gastroduodenostomy ($n = 36$, 60%) or Billroth-II gastrojejunostomy ($n = 24$, 40%) reconstructions through extracorporeal ($n = 51$, 85%) or intracorporeal ($n = 9$, 15%) approaches were dependent on the surgeon's preference. Surgeon C performed all reconstructions in an extracorporeal manner.

Sequential operation time fitted by the nonlinear regression analysis without correction of confounding factors (Fig. 2)

The raw data from the actual operation times for the first 60 cases of robotic gastrectomies performed by the three surgeons are plotted on the graph in Fig. 2A. The fitted operation time in Fig. 2B was computed by the nonlinear regression analysis shown in Eq. 1, as previously described in the "Statistical analysis" section. As shown in Fig. 2B,

Table 1 Patients' demographic and tumor characteristics

	Overall	Surgeon A	Surgeon B	Surgeon C
Gender (male:female)	33:27	12:8	11:9	10:10
Age (years)	52.6 ± 13.1	55.6 ± 15.0	54.1 ± 13.3	47.8 ± 9.7[a]
BMI (kg/m^2)	23.4 ± 3.3	21.6 ± 3.3	24.2 ± 2.4	24.4 ± 3.4
ASA class (1:2:3)	36:21:3	6:11:3	17:3:0	13:7:0
Medical co-morbidity (yes:no)	19:41	10:10	3:17	6:14
Previous abdominal surgery (yes:no)	11:49	4:16	0:20	7:13
Tumor size (cm)	3.2 ± 1.9	3.2 ± 1.9	2.3 ± 1.3	3.9 ± 2.2
T stage (T1:T2:T3)	46:12:2	11:7:2	19:1:0	16:4:0
N stage (N0:N1:N2:N3)	51:6:2:1	17:1:1:1	18:2:0:0	16:3:1:0
Proximal resection margin (cm)	4.4 ± 2.6	4.7 ± 2.2	3.5 ± 2.3	4.1 ± 3.7
Distal resection margin (cm)	5.1 ± 2.6	5.0 ± 2.6	4.8 ± 2.5	5.6 ± 2.9

Data are expressed as the number or mean ± standard deviation as appropriate

BMI body mass index, *ASA* American Society of Anesthesiologists

[a] Statistically significant difference from the other two groups

Table 2 Operation-related factors

	Overall	Surgeon A	Surgeon B	Surgeon C
Operation time (min)	247.3 ± 45.7	261.7 ± 43.1	241.9 ± 36.0	238.3 ± 54.7
Extent of LN dissection				
D1 + β:D2	26:34	3:17	17:3	6:14
Reconstruction method				
B-I:B-II	36:24	12:8	16:4	8:12
Intracorporeal:extracorporeal	9:51	7:13	2:18	0:20
Conversion	0	0	0	0

Data are expressed as the number or mean ± standard deviation as appropriate

B-I Billroth I gastroduodenostomy, *B-II* Billroth II gastrojejunostomy, *LN* lymph node

the overall operation time stabilized at 231.5 min after 9.1 cases, a reduction of 108.5 min from the first surgery.

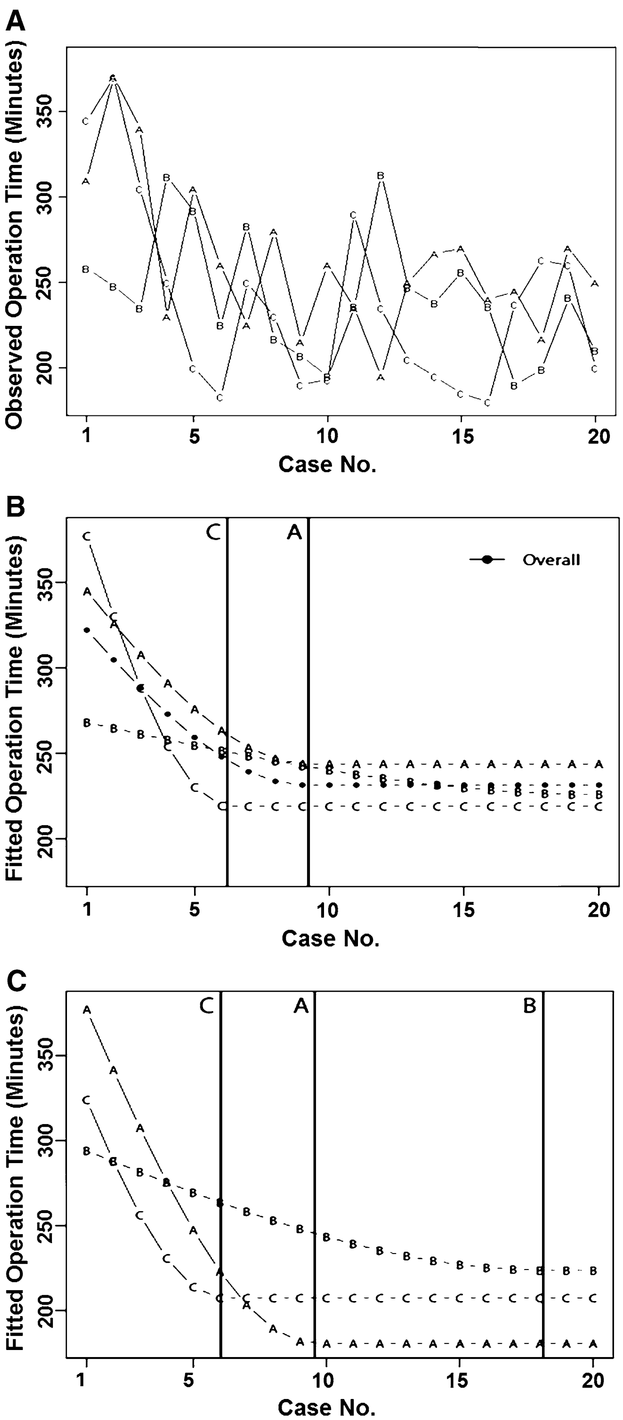
The operation behaviors differed greatly between the three surgeons. For Surgeon A, the stable operation time of 243.8 min was reached in 9.2 cases. Similarly, surgeon C had a stable operation time of 219 min after 6.2 cases, whereas the initial operation time for surgeon C was much longer than for surgeon A. In contrast to surgeons A and C, the operation times for surgeon B did not stabilize and continued to decrease beyond the 20th case. His initial time was much shorter than those of the others.

Factors affecting operation time analyzed by the nonlinear regression model with linear combinations of the confounding factors (Fig. 2C; Table 3)

Some basic characteristics of each patient were quite heterogeneous. We used the nonlinear regression model with linear combinations of the confounding factors (Eq. 2) to adjust for these factors. The parameter estimation results were obtained based on factors such as age, gender, BMI, reconstruction type, and extent of lymph node dissection. Table 3 shows that for overall performance, the operation time decreased to 211.8 min, the number of cases managed before the operation time became stable was 8.2, and the reduced operation time was 111.4 min. Among the confounding factors listed earlier, only gender (female vs. male) was statistically significant. The operation time for the women was shorter than for the men by 23 min ($P = 0.032$).

For surgeon A, the stable operation time was 149.2 min, and the reduced operation time was 233 min. The number of cases managed before the operation time stabilized was 9.6. The extent of lymph node dissection had a positive influence on surgeon A's operation time in that it was 78.5 min longer for D2 patients than for D1 patients. However, for surgeon B, the stable operation time turned out to be 127.1 min after the 19th case, although neither of the two estimates was statistically significant. None of the variables considered as confounding factors had any influence on surgeon B's operation behavior.

Finally, the statistical results from surgeon C's group show that the stable operation time of 236.8 min occurred after the sixth case and is shorter than case numbers of the other two surgeons. In addition, we can see that the



◀ **Fig. 2** **A** Scattered plot showing actual operation times for the robotic gastrectomies of three surgeons. **B** Patterns of sequential operation times fitted by the model of overall cases shown in Eq. 1 (*filled circles*) for surgeon A (A), surgeon B(B), and surgeon C(C). The *solid line* denoted as A and C shows the number of cases needed for stabilization of the operation time for surgeon A (6.2 cases) and surgeon C (9.2 cases). **C** Patterns of sequential operation times fitted by the model shown in Eq. 2 for surgeon A (A), surgeon B(B), and surgeon C(C). The *solid line* denoted as A, B, and C shows the number of cases needed for stabilization of the operation time for surgeon A (9.6 cases), surgeon B (9.6 cases), and surgeon C (6 cases). Surgeon A had managed the most cases of laparoscopic gastrectomy (400 cases) when he performed his first robotic distal gastrectomy. Surgeon B, a deviser of robotic gastrectomy, had performed 177 cases of laparoscopic gastrectomy before his first robotic gastrectomy. Surgeon C had the smallest experience performing laparoscopic gastrectomies (68 cases) before has first robotic gastrectomy

operation time increased as age decreased and that BMI increased for the patients in surgeon C's group.

Postoperative course (Table 4)

The mean hospital stay was 5.3 days in surgeon A's group, 5.7 days in surgeon B's group, and 9.7 days in surgeon C's group. Six postoperative complications occurred (3 wound complications, 1 intraabdominal abscess, 1 duodenal stump leakage, and 1 common bile duct injury). For the common bile duct injury, the patient underwent a choledochojejunostomy on postoperative day 2. Other complications were treated by conservative nonsurgical management. No cases of mortality were reported.

Discussion

The analyses of initial robotic gastrectomies performed by experienced laparoscopic surgeons showed that stabilization of the operation time for robotic distal gastrectomy was achieved within 10 cases. Furthermore, among the surgeons who had overcome the learning curve for laparoscopic gastrectomy, the stabilized operation time was shorter and the reduction in operation time was greater for the surgeon with more laparoscopic gastrectomy experience than for the surgeon with less laparoscopic experience.

Robotic surgery has been shown to reduce the learning curve for complex minimally invasive procedures such as cardiac surgery and urology due to its many advantages over laparoscopic and open surgeries [21–24]. Robust analyses of the learning curve for laparoscopically assisted gastrectomy showed that experience managing more than 50 cases of LADG with systemic lymphadenectomy for early gastric cancer was required to achieve proficiency and to reach a plateau of the learning curve [14–16]. As expected in this study, stabilization of the operation time for robot-assisted distal gastrectomy was much faster (less than 10 cases) than for LADG.

Because the operative procedure of robotic gastrectomy is largely similar to that of laparoscopy, based on the same surgical principle [8], we may expect that experience performing laparoscopic gastrectomy ensured early adaption of robotic gastrectomy due to its similar operative characteristics. Interestingly, the time required to adapt robotic surgery and the factors affecting the operation time were

Table 3 Stabilization of operation time and its confounding factors calculated by Eq. 2

	Overall performance		Surgeon A		Surgeon B		Surgeon C	
	Estimate	*P*	Estimate	*P*	Estimate	*P*	Estimate	*P*
Stable operation time	211.8	<0.001	149.2	0.034	127.1	0.146	236.8	0.004
Reduced operation time	111.4	<0.001	233.0	<0.001	76.7	0.017	154.6	0.029
Case no. converged	8.2	<0.001	9.6	<0.001	18.1	0.061	6.0	0.032
Age	−0.2	0.615	0.6	0.350	−0.7	0.253	−2.5	0.018
Gender[a]	−23.0	0.032	−9.9	0.644	−22.7	0.117	−32.9	0.219
BMI	1.7	0.296	−1.6	0.513	5.5	0.114	5.2	0.030
Reconstruction type[b]	17.6	0.067	29.7	0.097	33.4	0.113	5.6	0.795
Extent of LN dissection[c]	−7.0	0.491	78.5	0.032	−16.3	0.518	−9.9	0.623

P values were obtained by the non-linear regression analysis from Eq. 2

SD standard deviation, *BMI* body mass index, *LN* lymph node

[a] Female versus male

[b] Billroth II gastrojejunostomy versus Billroth I gastroduodenostomy

[c] D2 lymph node dissection versus D1 lymph node dissection

Table 4 Postoperative outcomes

	Surgeon A	Surgeon B	Surgeon C
Hospital stay (postoperative days)	5.3 ± 0.6 (5–7)	5.7 ± 1.0 (5–8)	9.7 ± 4.4 (6–26)
Postoperative complications			
Wound seroma	2	1	0
Intra-abdominal abscess	0	0	1
Duodenal stump leakage	0	0	1
Common bile duct injury	0	0	1
Time to passage of flatus (days)	3.1 ± 1.0 (2–5)	2.9 ± 0.2 (2–3)	2.7 ± 0.9 (2–5)
Mortality	0	0	0

Data are expressed as the number or mean ± standard deviation (range) as appropriate

different for each surgeon's laparoscopic experience. For surgeon A, who had the largest experience with laparoscopic gastrectomy, the initial operation time for the first case was similar to those of the other surgeons. However, when the stable operation time was reached, his reduced operation time was the longest after adjustment for the potential factors affecting the operation time. The adjusted stable operation time was 149.2 min. This adjusted time was estimated with all the confounding factors that affect operation time counted as reference values. However, the situation for this stabilization cannot be met in clinical practice.

On the other hand, surgeon C, whose experience was the smallest, had the longest stabilized operation time when the factors affecting operation time were considered despite his most rapid stabilization of the operation time. We may explain the difference in the number of cases needed by surgeon C for operation stabilization as rapid adaptation of the robotic surgical system. Another possible explanation is that surgeon A's difficulty adjusting his surgical procedure to the robotic surgical system compared with surgeon C was due to his rather fixed standard of laparoscopic procedure based on his huge experience of laparoscopic gastrectomy. When a surgeon with abundant experience in the field of minimally invasive surgery tries to adapt to robotic procedures, his or her expertise may hamper the adaptation of new technical challenges.

For surgeon B, no factor significantly affected operation times, and his learning curve did not reach a plateau within his initial 20 cases. We suppose the reason for this finding is that surgeon B, as the innovator of the robotic gastric cancer procedure, already had adapted his minimally invasive surgical techniques to standardize the robot-assisted distal gastrectomy procedure. Therefore, surgeon B had an immediately stabilized operation time but showed the least reduction in operation time among the three surgeons. However, after adjustment of the factors affecting operation time, the operation time of surgeon B was stabilized after 18 cases. Therefore, the learning curve effect of robotic distal gastrectomy was overcome within 20 cases regardless of the experience or background of the surgeons included in this study.

Surgeon C had the least laparoscopic gastrectomy experience despite management of more than 50 learning cases for laparoscopic gastrectomy. As shown in Fig. 2B, his adaptation of minimally invasive skills to the robotic surgical system gastrectomy was excellent in terms of operation time reduction and rapid stabilization of his learning-curve. On the other hand, he spent the longest time in surgery after correcting the factors affecting his operation time, as shown in Table 3. He also had more complications than the other surgeons. Furthermore, his operation time was affected by patient factors such as age and BMI. In light of these findings, it seems that his ability to adapt and accept new technology readily could be attributed to his relatively smaller experience performing laparoscopic gastrectomy. However, his relative lack of experience also contributed to his inability to reach the level of operative competency achieved by the other two surgeons. The stable operation time of surgeon C in this study may not be the final value of his learning curve for minimally invasive surgery and could be an extension of the laparoscopic learning curve.

Regarding the factors related to operation times, a high BMI was closely related to increased operation time [25–28]. Several reports describe the association between patient gender and BMI as increased operation time [25, 28]. Lee et al. [25] reported that BMI was high for male patients and that operation times for males were significantly longer than for groups with low BMI and females. However, we found that these factors could be overcome by the surgeon's expertise based on sufficient experience.

In the current study, only surgeon C was affected by BMI ($P = 0.030$). This factor did not affect the operative time of the more experienced surgeons (surgeons A and B). One important factor related to operation time for robotic gastrectomy shown in our results was gender ($P = 0.032$), possibly because females have less visceral fat than males with the same BMI [29]. In males, fat tissues are predominantly distributed in the upper body, whereas in females, fat tissues are predominant in the hip and thigh areas [30, 31]. Considering these phenomena, the effect of a male patient's visceral fat distribution can be attributed to the effect of gender for overall surgical performance.

Another possible explanation is the relatively narrow BMI range of the patients in this study compared with studies performed in western countries. The effect of BMI on operation time in this study was limited.

This is the first study to investigate the learning curve for robotic distal gastrectomy by analyzing the operation time of three surgeons with different backgrounds and laparoscopic gastrectomy experiences. To assess the learning curves, we used a new parametric nonlinear regression model. Our novel statistical model assessed the surgeons' sequential operative times using three parameters: stable operative time, reduced operative time, and number of cases beyond which the operative time became stable. This statistical analysis is similar to the "spherical covariance function" used in the spatial statistics research field. The model shown in Eq. 1 can simply be extended to the model shown in Eq. 2 with some potential confounding factors. Using this new statistical method, we could identify the learning curve period for robotic gastrectomy.

The limitations of this study include the fact that only results from surgeons with large experience performing laparoscopic gastrectomy were analyzed. Furthermore, we could not validate the new statistical method (i.e., the parametric nonlinear regression model) for analyzing the learning curve using results from surgeons with different experiences or backgrounds of gastric cancer surgery. It is possible that stabilization of operation time can be achieved within different numbers of cases according to analysis of data from surgeons with different backgrounds and data including more than 20 cases. Our results based on a small initial experience made it impossible to evaluate the changes before and after the learning curve period.

Because operation time was considered as the only parameter of the learning curve effect, lack of learning curve evaluation based on the quality of surgery (e.g., cumulative sum, CUSUM analysis) is another limitation of this study. Further study on the robotic gastrectomy learning curve for surgeons without previous experience performing laparoscopic gastrectomy and evaluation of the learning curve for robotic gastrectomy using a different statistical method such as CUSUM analysis is warranted. Moreover, study of the learning curve for a procedure other than robotic gastrectomy is necessary to validate the methodologic reliability of our new statistical method of learning curve evaluation (i.e., the parametric nonlinear regression model of sequential operative times).

In conclusion, the learning curve for robotic gastrectomy can be overcome rapidly when the robotic procedure is performed by surgeons with sufficient experience in laparoscopic gastrectomy. In addition, it is thought that this study can provide valuable insights into training and educational issues regarding robotic gastrectomy.

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