Retrospective Cohort Study

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Enlightenment of robotic gastrectomy from 527 patients with gastric cancer in the minimally invasive era: 5 years of optimizing surgical performance in a high-volume center – a retrospective cohort study

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Background: Learning curves have been used in the field of robotic gastrectomy (RG). However, it should be noted that the previous study did not comprehensively investigate all changes related to the learning curve. This study aims to establish a learning curve for radical RG and evaluate its effect on the short-term outcomes of patients with gastric cancer.

Methods: The clinicopathological data of 527 patients who underwent RG between August 2016 and June 2021 were retrospectively analyzed. Learning curves related to the operation time and postoperative hospital stay were determined separately using cumulative sum (CUSUM) analysis. Then, the impact of the learning curve on surgical efficacy was analyzed.

Results: Combining the CUSUM curve break points and technical optimization time points, the entire cohort was divided into three phases (patients 1–100, 101–250, and 251–527). The postoperative complication rate and postoperative recovery time tended to decrease significantly with phase advancement ($P<0.05$). More extraperigastric examined lymph nodes (LN) were retrieved in phase III than in phase I (I vs. III, 15.12 ± 6.90 vs. 17.40 ± 7.05, $P=0.005$). The rate of LN noncompliance decreased with phase advancement. Textbook outcome (TO) analysis showed that the learning phase was an independent factor in TO attainment ($P<0.05$).

Conclusion: With learning phase advancement, the short-term outcomes were significantly improved. It is possible that our optimization of surgical procedures could have contributed to this improvement. The findings of this study facilitate the safe dissemination of RG in the minimally invasive era.

Keywords: gastric cancer, learning curve, robotic surgery

Introduction

Gastric cancer (GC) rank fifth for incidence and fourth for mortality globally[1]. Despite recent advances in the comprehensive treatment of GC, radical gastrectomy is still the only curative method[2].

In the last 20 years, surgery for GC has become minimally invasive, and the benefits of minimally invasive laparoscopic surgery are widely accepted by surgeons. In several multicenter studies in Asia (KLASS-01[3,4], KLASS-02[5], JCOG0912[6], JLSSG0901[7] and CLASS-01[2]), researchers have demonstrated

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that laparoscopic gastrectomy in patients with GC has better short-term outcomes than open surgery and does not affect the long-term oncological outcomes of patients. However, laparoscopic surgery still has inherent drawbacks[8]. To overcome the limitations of laparoscopic surgery and achieve better surgical outcomes, the da Vinci robotic surgical system was developed[9]. Compared with conventional laparoscopic surgical tools, the da Vinci robotic system offers operator-controlled high-definition 3D vision, greater instrument freedom, tremor filtration, and better ergonomic advantages that may lead to better perioperative outcomes[10,11]. Our team has reported the results of several prospective studies on the safety and efficacy of robotic gastrectomy (RG) compared with laparoscopic surgery in GC patients[8,10]. For example, in complex radical total gastrectomy, robotic systems may provide a more precise operating environment and reduce the surgical burden[8]. The results of our prospective randomized controlled study show that robotic surgery is associated with lower complication rates, faster postoperative recovery, and better short-term outcomes[10]. A umbrella review encompassed 14 meta-analyses comparing outcomes between laparoscopic gastrectomy and RG with curative intent in patients with diagnosis of resectable GC[12]. The authors also observed that RG resulted in lower surgical blood loss, reduced length of hospital stay, and faster recovery of bowel function. Thus, in RG, robotic surgical systems may be beneficial for both patients and experienced surgeons.

Learning curves have been widely used in the field of robotic surgery, such as for prostate cancer, lung cancer, and rectal cancer[13–16]. Learning curves have been used to evaluate surgical procedures in terms of understanding changes in trends in surgical outcomes, assist senior surgeons in developing training programs, and help build confidence in beginners. Currently, learning curves for radical RG have been examined in several studies[17–25]. However, most of these studies involved a small number of cases, and the study outcomes were limited to the operation time and complication rate. Researchers have not further or comprehensively explored other learning curve-related changes in short-term outcomes.

In addition, with the development of minimally invasive procedures, future robotic system operators usually have extensive experience in laparoscopic surgery. In this study, we were the first to explore the learning curve of radical RG among operators who performed more than 300 laparoscopic GC surgeries and the first to construct a referenceable learning phase for performing RG in the minimally invasive era.

HIGHLIGHTS

- In this study, we were the first to explore the learning curve of robotic gastric cancer (GC) surgery on surgical outcomes among operators who performed more than 300 laparoscopic GC surgeries and the first to construct a referenceable learning phase for performing robotic GC surgery in the minimally invasive era.
- Our study showed that with phase advancement, patients had decreased complication rates, shorter recovery times, and reduced medical-related costs.
- Our optimized 10-step robotic lymphadenectomy procedure may be beneficial to new surgeons in the robotic gastrectomy field, especially for surgeons in China, Japan, and Korea, where GC is highly prevalent, to provide a good reference.

Materials and methods

Study design and patients

This retrospective analysis was conducted on the clinicopathological data of patients undergoing radical RG at our center between August 2016 and June 2021. The inclusion criteria were as follows: (1) pathologically confirmed gastric adenocarcinoma; (2) no distant metastases; and (3) treatment with R0 resection. The exclusion criteria were as follows: (1) distant metastases found intraoperatively; (2) preoperative treatment with neoadjuvant chemotherapy or radiotherapy; and (3) incomplete general clinical information. A total of 527 patients were eventually included. All procedures in this study were performed by the two corresponding authors, and the operators performed more than 300 laparoscopic radical GC surgeries. Patients treated after 2017 were staged using the 8th edition of the American Joint Committee on Cancer (AJCC) tumor staging system, while those treated before 2017 were staged using the 7th edition. We retrospectively collected and rechecked the pathological data of the latter group according to the 8th edition of AJCC staging[26]. This study was approved by the institutional review board (IRB number: 2023KY020) and, where applicable, followed the Strengthening The Reporting Of Cohort Studies in Surgery (STROCSS) criteria and guidelines[27] (Supplemental Digital Content 1, http://links.lww.com/JS9/C635). Due to the retrospective and observational design, the IRB waived the need for informed consent for this study (Supplementary Fig. 1, 2, Supplemental Digital Content 2, http://links.lww.com/JS9/C636).

Surgical techniques

All RG procedures were performed using the da Vinci Surgical System (Da Vinci Si and, since 2021, Da Vinci Xi; Intuitive Surgical, Inc.). The decision to perform a total or distal gastrectomy was based on the location and size of the tumor. All patients underwent multiport RG and gastrectomy with a D2 lymphadenectomy in accordance with the Japanese guidelines for GC[28], and the decision to dissect No. 10 lymph nodes (LN) was based on the intraoperative exploration of the tumor site and the experience of the primary surgeon. Prophylactic splenectomy was not recommended. The type and mode of reconstruction (in vivo or ex vivo) were selected according to the preference of the primary surgeon. Intraoperative frozen section analysis was routinely performed to determine that the margins were negative. Details of the procedure have been disclosed in a previous article[8,10]. An optimized 10-step robotic lymphadenectomy was established and stabilized after 100 cases. The tips and tricks of the optimized procedure are summarized in the Supplementary Material (Supplemental Digital Content 3, http://links.lww.com/JS9/C637).

Outcome measures

Overall complications were defined as grade 2 or higher using the Clavien–Dindo grading system[29,30]. Morbidity and mortality were assessed within 30 days after surgery. Each complication was previously defined[31,32].

Laboratory tests, including white blood cell (WBC) count, hemoglobin (Hb), and albumin (Alb) tests, were conducted within 7 days before surgery and on the first, third and fifth postoperative days.

The LN dissection rate was defined as the number of patients in whom the LN station was examined divided by the total number of patients who required retrieval in the corresponding LN station[33]. LN noncompliance was defined as the absence of LNs from more than 1 LN station that should have been excised[33–35]. In addition, we divided the LNs into two regions: perigastric regions (stations 1–6) and extraperigastric regions (stations 7–10, 11p, and 12a)[33].

The total cost during hospitalization was calculated as the sum of the direct and indirect costs[36–38]. Indirect costs were defined as the sum of the administrative and facility costs, as previously described[36–38].

A 'textbook outcome' (TO) was defined as negative resection margins, examination of ≥ 15 LNs, no severe complications, no reinterventions, no unplanned ICU admissions, hospital stay ≤ 21 days, no hospital readmission ≤ 30 days after discharge, and no mortality within 30 days after surgery[39]. When all eight desired health outcomes were realized, a TO was achieved.

The overall survival (OS) time represents the time from surgery to the time of the last follow-up, the time of death, or the time up to the end of the follow-up database (such as loss to follow-up or death from other diseases). Recurrence-free survival (RFS) represents the time from the first diagnosis to the first recurrence after surgery or tumor-related death.

Statistical analysis

All data were processed using STATA (version 16.0) and R software (version 3.5.0). Continuous data are summarized as the mean and SD. Nonparametric tests (Kruskal—Wallis *H* test and Jonckheere–Terpstra test) were used to compare characteristic variables between groups. Chi-square or Fisher exact tests were used to compare categorical variables between groups.

Learning curves related to operation time[40,41] and postoperative hospital stay[42] were established using cumulative sum (CUSUM) analysis. CUSUM analysis detects deviations between the raw data of each individual case and the mean value of the cohort, each of which accumulates in a sequential manner[19]. Thus, the CUSUM was defined as $\sum_{i=1}^{n}(xi - \mu)$, where x is the operation time or postoperative hospital stay in each case and μ is the mean operation time or postoperative hospital stay of the cohort. Using this method, the CUSUM curve portrays trends in data that are not discernable with other approaches.

A logistic hazards regression model was used to analyze the independent prognostic factors of a TO. The RFS and OS rates were calculated by the Kaplan—Meier method, and the differences were assessed with log-rank tests. A *P*-value <0.05 was considered statistically significant.

Table 1

Clinicopathological characteristics.

Variable	Total	Phase I (1–100)	Phase II (101–250)	Phase III (251–527)	*P*
Age, years	59.6 (10.8)	57.1 (10.4)	60.4 (11.3)	60.2 (10.5)	0.023
Male	382 (72.4)	72 (72.0)	112 (74.6)	198 (71.4)	0.775
BMI, kg/m^2	23.2 (3.1)	22.9 (2.8)	22.9 (3.2)	23.3 (3.2)	0.503
ASA score					0.263
1	47 (8.9)	7 (7.0)	13 (8.7)	27 (9.7)	
2	449 (85.2)	91 (91.0)	129 (86.0)	229 (82.7)	
≥ 3	31 (5.9)	2 (2.0)	8 (5.3)	21 (7.6)	
RATG	279 (53.0)	46 (46.0)	64 (42.6)	169 (61.0)	0.001
Reconstruction					0.001
Billroth I	16 (3.0)	10 (10.0)	2 (1.3)	4 (1.4)	
Billroth II	232 (44.0)	44 (44.0)	84 (56.1)	104 (37.6)	
Roux-en Y	279 (53.0)	46 (46.0)	64 (42.6)	169 (61.0)	
Tumor size, cm	38.4 (21.6)	35.6 (23.2)	41.3 (19.4)	37.9 (22.1)	0.009
pT					0.004
1	177 (33.6)	38 (38.0)	36 (24.0)	103 (37.2)	
2	58 (11.0)	9 (9.0)	24 (16.0)	25 (9.0)	
3	209 (39.7)	30 (30.0)	64 (42.7)	115 (41.5)	
4	83 (15.7)	23 (23.0)	26 (17.3)	34 (12.2)	
pN					0.083
0	225 (42.7)	50 (50.0)	52 (34.7)	123 (44.4)	
1	97 (18.4)	15 (15.0)	25 (16.7)	57 (20.6)	
2	87 (16.5)	13 (13.0)	30 (20.0)	44 (15.9)	
3	118 (22.4)	22 (22.0)	43 (28.7)	53 (19.1)	

ASA, American Society of Anesthesiologists; RATG, Robot-assisted total gastrectomy.

Results

Patient characteristics

Table 1 shows the general clinicopathological data of the 527 patients who underwent radical RG for GC. The mean age at diagnosis was 60 ± 11 years, and the male-to-female ratio was 2.63:1. The mean BMI of the whole group was 23.2 ± 3.1 kg/m^2, and the percentage of American Society of Anesthesiologists (ASA) class I and II patients was 94.1% (496/527 cases). The mean tumor size was 38.4 ± 21.6 mm.

Intraoperative results, postoperative recovery, and postoperative complications

The percentage of patients who underwent radical total gastrectomy was 52.9% (279/527 cases). The mean operation time was 197 ± 40 min, and the mean intraoperative bleeding was 39.6 ± 36.3 ml. The mean number of examined LNs for the whole group was 41.8 ± 14.1. The pT stage was pT4a in 15.7% (83/527 cases), and the pN stage was N3 in 22.4% (118/527 cases). The mean postoperative time to ambulation was 2.2 ± 0.6 days, and the mean postoperative hospital stay was 9.2 ± 4.7 days. A total of 14.4% (76/527 cases) of patients had grade 2 or higher postoperative complications (Table 2).

Analysis of learning curve break points

Learning curves related to operation time and postoperative hospital stay were examined by CUSUM analysis. The learning curve could be divided into three phases according to the operation time, with the first break point being 100 cases and the second break point being 247 cases; the first and second break points of the learning curve for postoperative hospital stay were 101 and 248 cases, respectively (Fig. 1). The learning curves for different surgeons are presented in Supplementary Fig. 3 (Supplemental Digital Content 2, http://links.lww.com/JS9/C636). Referring to the break points of the learning curve and considering the time point of surgical technique optimization, the whole cohort was divided into three phases, namely, phase I (cases 1–100), phase II (cases 101–250), and phase III (cases 251–527). Table 1 demonstrates a comparison of the general

Table 2

Comparison of intraoperative results and postoperative recovery among the three phases.

Variable	Total	Phase I (1–100)	Phase II (101–250)	Phase III (251–527)	P
Operative time, min	197.3 (40.3)	188.2 (38.6)	193.3 (36.3)	202.7 (42.2)	0.010
Estimated blood loss, mL	39.6 (36.3)	30.6 (15.3)	54.6 (57.0)	34.8 (22.4)	0.001
Lymph node harvest, N	41.8 (14.1)	40.4 (13.5)	41.6 (13.1)	42.1 (14.9)	0.502
Clavien–Dindo Classification					0.046
< 2	451 (85.6)	79 (79.0)	126 (84.0)	246 (88.8)	
≥ 2	76 (14.4)	21 (21.0)	24 (16.0)	31 (11.2)	
Time to ambulation, days	2.2 (0.6)	2.2 (0.4)	2.1 (0.5)	2.3 (0.6)	0.001
Time to first flatus, days	3.4 (0.8)	3.4 (0.8)	3.3 (0.6)	3.5 (0.9)	0.446
Time to first liquid intake, days	4.1 (1.1)	4.9 (0.9)	4.1 (0.9)	3.8 (1.1)	0.001
Time to first semifluid intake, days	5.7 (1.3)	6.7 (1.5)	5.8 (1.2)	5.3 (1.2)	0.001
Postoperative hospital stay, days	9.2 (4.7)	10.2 (3.5)	9.6 (5.6)	8.6 (4.5)	0.001

clinical information of the patients in the three phases, with differences in surgical approach, tumor size, and pT stage (all $P < 0.05$).

Supplementary Figure 4 (Supplemental Digital Content 2, http://links.lww.com/JS9/C636) shows the trend of clinical staging in the three phases. The proportion of cT4 patients was significantly higher in both phases II and III than in phase I (cT4: II vs. I: 48.6 vs. 25.0%, $P = 0.001$; III vs. I: 40.7 vs. 25.0%, $P = 0.026$), whereas there was no significant difference in the proportion of cT4 patients between phases II and III.

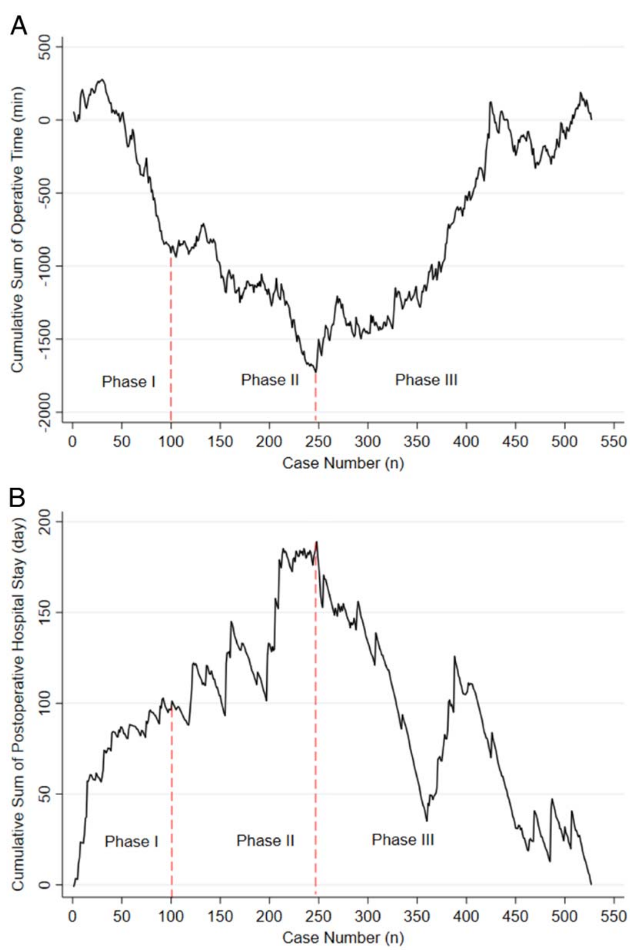

Figure 1. Cumulative sum (CUSUM) curve of operation time (A) and postoperative hospital stay (B).

Comparison of intraoperative results, postoperative recovery, and postoperative complications in the three phases

The operation time tended to increase with increasing phase ($P = 0.010$), whereas there was no stage-related trend in the change in intraoperative blood loss. There was a significant decreasing trend in the time to the first liquid and semiliquid diet after surgery, as well as the duration of postoperative hospital stay (all $P < 0.05$) (Table 2).

The incidence of postoperative complications tended to decrease significantly with increasing phase ($P = 0.046$) (Table 2), and further stratified analysis of different types of complications showed that there were no significant differences in the incidence of anastomotic leakage, wound-related problems, ileus, abdominal infection, or lymphatic leakage among the different phases (all $P > 0.05$). However, the incidence of abdominal bleeding, postoperative pneumonia, and postoperative hepatic insufficiency decreased significantly with increasing phase (all $P < 0.05$) (Table 3).

Analysis of preoperative and postoperative laboratory indicators showed that the WBC count on postoperative day 5 was significantly lower in phase III than in the first two phases (all $P < 0.05$), with no significant difference between phases I and II ($P > 0.05$). There were no significant differences in the Hb values at various time points among the different phases (all $P > 0.05$). The ALB value on postoperative day 3 was significantly better in phases II and III than in phase I (all $P < 0.05$), with no significant difference between phases II and III ($P > 0.05$) (Supplementary Table 1, Supplemental Digital Content 4, http://links.lww.com/JS9/C638, Supplementary Fig. 5, Supplemental Digital Content 2, http://links.lww.com/JS9/C636).

Comparison of the LN dissection status among the three phases

Overall, the total number of examined LNs was similar in the three phases of patients (40.39 ± 13.47 vs. 41.62 ± 13.05 vs. 42.06 ± 14.87, respectively, $P = 0.502$). Further stratified analysis of the extent of LN dissection into perigastric regions (stations 1–6) and extraperigastric regions (stations 7–10, 11p, and 12a) revealed that the number of examined LNs in the extraperigastric

Table 3

Comparison of postoperative complications among the three phases.

	Phase I (1–100)	Phase II (101–250)	Phase III (251–527)	*P*
Anastomotic leakage	3 (3.0%)	6 (4.0%)	3 (1.3%)	0.135
Wound problem	0 (0.0%)	2 (1.3%)	0 (0.0%)	0.080
Abdominal bleeding	6 (6.0%)	2 (1.3%)	1 (0.4%)	0.001
Ileus	0 (0.0%)	0 (0.0%)	2 (0.8%)	0.404
Abdominal infection	6 (6.0%)	10 (6.7%)	6 (2.6%)	0.051
Lymphatic leakage	0 (0.0%)	0 (0.0%)	1 (0.4%)	0.636
Pneumonia	14 (14.0%)	16 (10.6%)	12 (5.3%)	0.003
Hepatic	6 (6.0%)	1 (0.7%)	1 (0.4%)	0.001

regions gradually increased with increasing phase and that the number of examined LNs in the extraperigastric regions was significantly higher in phase III than in phase I (17.40 ± 7.05 vs. 15.12 ± 6.90, respectively, $P = 0.005$), with no other statistically significant differences among the phases (all $P > 0.05$) (Fig. 2A).

Stratified analysis of patients according to preoperative cT stage revealed that the number of examined LNs in extraperigastric regions was significantly higher in the subgroup of patients with cT3-4 disease ($P = 0.002$), with no difference compared with the subgroup of patients with cT1-2 disease ($P > 0.05$) (Fig. 2A).

Figure 2B shows the mean number of examined LNs at each station in the three phases. The number of examined LNs at stations No. 2, No. 8a, and No. 12a all increased significantly with increasing phase (all $P < 0.05$).

A comparison of LN noncompliance in patients among the three phases is shown in Figure 2C. There were no significant differences among the three phases in the analysis of all patients or in the analysis stratified according to cT stage (all $P > 0.05$). However, in the analysis of the whole population, there was a decreasing trend in the LN noncompliance rate as the phase increased.

Table 4 shows the cN stage versus the pN stage the three phases. There was a significant increase in the proportion of escalated LN stages after phase I (29.0% vs. 47.3% vs. 41.1%, $P = 0.015$), with no significant difference between phases II and III ($P > 0.05$).

Comparison of TO rate among the three phases

Comparison of the TO rate in the overall population among the three phases showed a TO rate of 71% in phase I, 72% in phase II, and 81.6% in phase III. A two-by-two comparison showed a significantly lower TO rate in both phases I and II than in phase III ($P < 0.05$), whereas there was no significant difference in the TO rate between phases I and II ($P > 0.05$). Stratified analysis of patients according to cT stage showed similar outcomes in the subgroup of patients with cT3-4 disease as in the overall population (all $P < 0.05$) (Fig. 3).

Multivariable analysis confirmed that patient age and phase of surgical learning curve were independent factors of a TO (all $P < 0.05$) (Table 5).

Cost analysis among the three phases

Analysis of the costs incurred during the hospitalization of patients in the three phases revealed that the overall costs were significantly lower in the third phase than in the first two phases ($P = 0.001$). Further stratified analysis revealed no significant differences in indirect costs among the three phases ($P > 0.05$). Although direct costs were significantly lower in phase III than in the first two phases ($P = 0.001$), there was no statistically significant difference between phases I and II ($P > 0.05$) (Supplementary Table 2, Supplemental Digital Content 5, http://links.lww.com/JS9/C639).

Survival outcomes

In the whole group, 144 patients (27.3%) were classified as having stage IA disease; 47 (8.9%), stage IB; 65 (12.3%), stage IIA; 74 (14.1%), stage IIB; 74 (14.1%), stage IIIA; 73 (13.8%), stage IIIB; and 50 (9.4%), stage IIIC (Fig. 4A). In all, 96 patients were excluded from the survival analysis (less than 24 months after surgery). Postoperative follow-up confirmed acceptable 2-year survival. The median OS time was 36 ± 4.1 months, and the 2-year OS rate was 83.1% (Fig. 4B). The median RFS time was 35 ± 2.6 months, and the 2-year RFS rate was 82.8% (Fig. 4C).

Discussion

In this study, we used clinicopathological data from 527 patients who underwent radical RG at our institution between August 2016 and June 2021 to establish important points for optimizing the surgical outcomes of radical RG. Our study showed decreased complication rates, shorter recovery times, and reduced medical-related costs with increasing phase.

In several studies, researchers have explored the learning curve of radical RG[17–25]. In a small-sample study, researchers set the break points for radical RG at 12 and 17 cases[18]. The results of an earlier small-sample study at our center showed a learning curve break point of 21 cases for RG[36]. However, both studies included only a small number of cases, and further validation with larger-center data is still needed. Two other large-sample multicenter studies set the learning curve break point for radical RG between 18 and 25 cases[17,19]. Although both studies included a large number of cases, the study outcomes were mainly centered on postoperative complications, and the researchers did not analyze changes in other outcomes carefully or comprehensively. In this study, we are the first to report the surgical experience of surgeons who performed more than 500 radical RG procedures at our center. We used the operation time and postoperative hospital stay as study variables for the learning curve, and established two important points for radical RG (100 and 250 procedures), which are similar to those of robotic pancreatic surgery[43]. There are several possible reasons for the break points corresponding to larger numbers of cases in this study than in previous studies of RG. First, this difference may be related to the larger total number of cases. This study is the largest empirical report of cases at a single center to date, and the break points are inherently different from those in small-sample studies. Second, the previous large-sample study by Zheng-Yan *et al.*[19] did not show a complete learning curve, and the researchers may not have explored potential changes in surgical outcomes that could result from higher break points. In addition, we optimized surgical

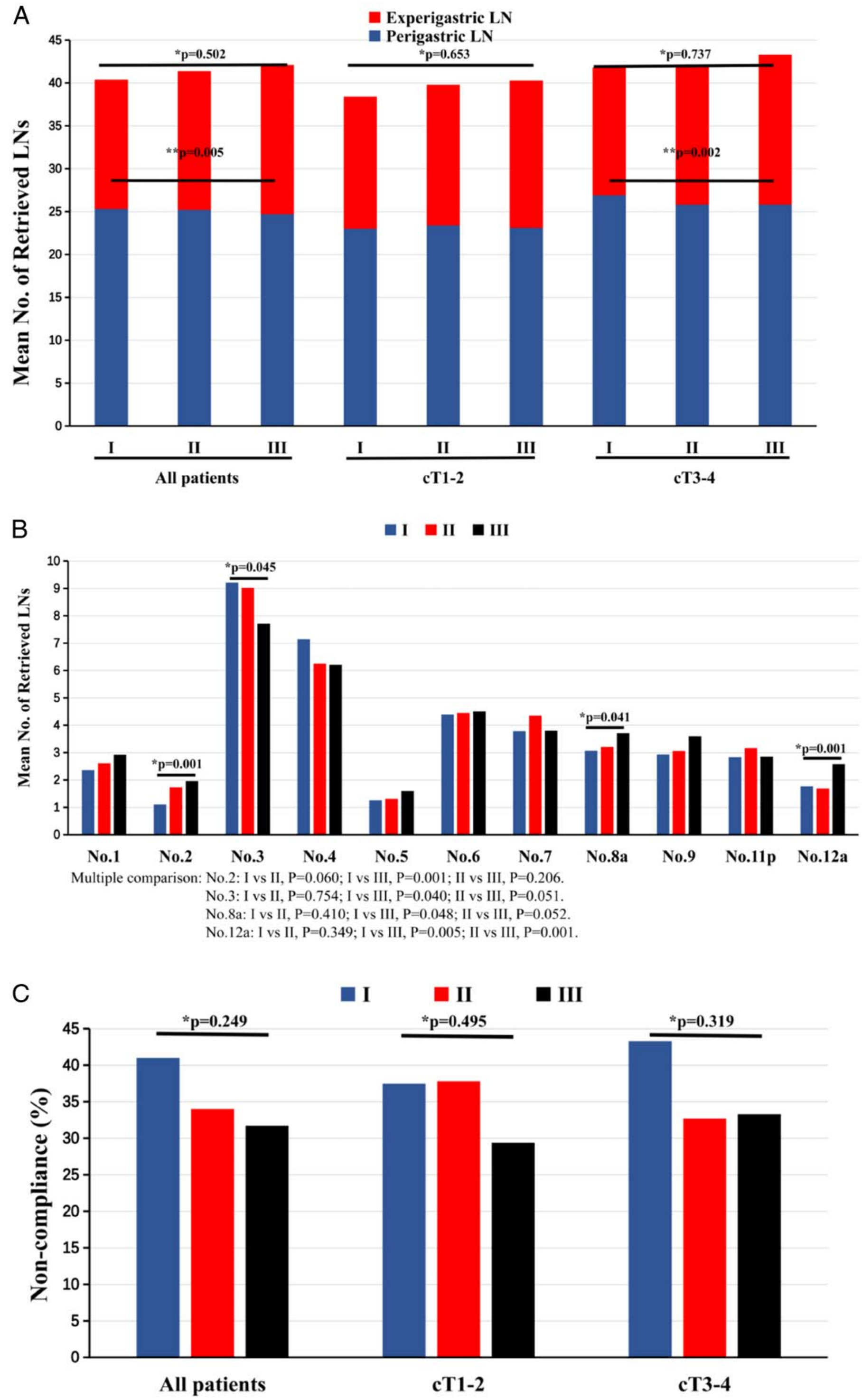

Figure 2. Comparison of the lymph nodes (LN) dissection status among the three phases. A, Comparison of the total number of examined LNs among the three phases. Overall, the total number of examined LNs was similar in the three phases of patients (*$P = 0.502$). The results were also similar in the subgroup of patients with cT3-4 (*$P = 0.653$) or cT1-2 (*$P = 0.737$) disease. Further stratified analysis revealed that the number of examined LNs in extraperigastric stations was significantly higher in phase III than in phase I (**$P = 0.005$), with similar results in the subgroup of patients with cT3-4 disease (**$P = 0.002$). B, Comparison of the number of examined LNs at each station in the three phases. C, Comparison of the LN noncompliance rate among the three phases.

Table 4

Comparison of nodal upstaging among the three phases.

	Phase I (1–100)	Phase II (101–250)	Phase III (251–527)	*P*
Nodal upstaging, No. (%)	29 (29.0)	71 (47.3)	114 (41.1)	0.015
Upstage, No. (%)				
cN0 to pN1	7 (7.0)	6 (4.0)	17 (6.1)	0.543
cN0 to pN2	3 (3.0)	10 (6.6)	10 (3.6)	0.256
cN0 to pN3	2 (2.0)	10 (6.6)	6 (2.1)	0.035
cN1 to pN2	3 (3.0)	15 (10.0)	34 (12.2)	0.029
cN1 to pN3	13 (13.0)	22 (14.6)	30 (10.8)	0.503
cN2 to pN3	1 (1.0)	8 (5.3)	17 (6.1)	0.122

techniques and improved the process (see Supplementary Material, Supplemental Digital Content 3, http://links.lww.com/JS9/C637) when we had 100 robotic gastrectomies experience. Based on our optimized 10-step procedure, the surgical process has become more stable and efficient, which may be beneficial for surgeons to further improve their proficiency in surgery. Lastly, our study aims to document the learning experiences of a high-volume Eastern center regarding RG. Our findings may suggest that even experienced laparoscopic surgeons need to be mindful of the initial learning curve when performing this specialized surgical technique. For instance, surgeons must adjust to the shifting roles between the primary operator and assistants, where the latter provide reduced support to the former, and the primary surgeon concurrently assumes the responsibility of managing the camera during the procedure. Moreover, our results still necessitate further validation through multicenter studies encompassing data from both low-volume and high-volume centers. Overall, this large-sample study illustrates the complete learning curve of RG for GC at our center. The findings contribute to the existing evidence and offer new insights into the learning curve of RG. The impact of experience from high-volume surgical centers on surgical outcomes deserves clinical attention.

Improvements in intraoperative outcomes and short-term postoperative outcomes have been the focus of studies related to surgical learning curves[44–46]. In a single-center, large-sample study that included clinical data from 450 patients undergoing robot-assisted pancreaticoduodenectomy, the authors concluded that after the learning curve crossed the break point (250 cases), patients had a significantly lower incidence of postoperative pancreatic fistula and a shorter postoperative hospital stay[43]. In this study, the complication rate significantly decreased with increasing phase, including the overall complication rate and the rates of abdominal bleeding and pneumonia in the stratified analysis. This finding is consistent with existing research results[17,19,22]. A study conducted at a single center in the Western world reveals that the incidence of postoperative complications following RG for GC is safely manageable[47]. The authors suggest that the controllable occurrence of complications may be attributed to the minimal surgical tissue damage caused by the robotic surgical system. As surgeons gain more experience, they may reduce the surgical trauma to patients, leading to less overall functional impairment and facilitating postoperative recovery. Furthermore, with an increase in the number of patients

Table 5

Uni-variate and multivariate logistic regression analyses of TO in all patients.

	Univariable		Multivariable	
Variable	HR (95% CI)	*P*	HR (95% CI)	*P*
Sex				
Female	1			
Male	1.216 (0.764–1.937)	0.410		
Age (years)				
< 60	1		1	
≥ 60	0.652 (0.427–0.996)	0.048	0.635 (0.413–0.975)	0.038
ASA				
1	1			
2	1.481 (0.763–2.875)	0.139		
3	1.220 (0.440–3.378)	0.702		
BMI (kg/m^2)				
< 25	1			
≥ 25	0.774 (0.499–1.201)	0.253		
Surgical approach				
RATG	1			
RADG	0.758 (0.504–1.142)	0.185		
Reconstruction				
Billroth I	1			
Billroth II	0.885 (0.242–3.230)	0.853		
Roux-en Y	0.676 (0.187–2.441)	0.550		
Tumor location				
Non-lower	1			
Lower	1.394 (0.926–2.096)	0.111		
Tumor diameter (mm)				
< 50	1			
≥ 50	0.764 (0.494–1.183)	0.228		
Pathological T Stage				
T1	1			
T2	1.077 (0.531–2.185)	0.837		
T3	1.072 (0.667–1.724)	0.773		
T4	0.980 (0.532–1.805)	0.948		
Pathological N Stage				
N0	1			
N1	1.157 (0.659–2.029)	0.612		
N2	1.301 (0.714–2.369)	0.390		
N3	1.262 (0.740–2.153)	0.393		
Phase				
I	1		1	
II	1.050 (0.600–1.839)	0.864	1.121 (0.636–1.975)	0.693
III	1.810 (1.067–3.069)	0.028	1.908 (1.119–3.253)	0.018

ASA, American Society of Anesthesiologists; RADG, Robot-assisted distal gastrectomy; RATG, Robot-assisted total gastrectomy; TO, textbook outcome.

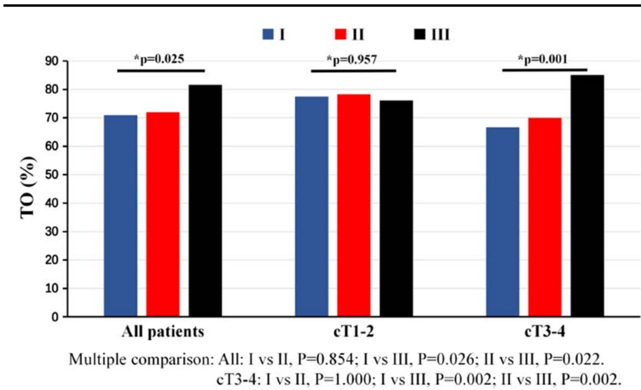

Figure 3. Comparison of the textbook outcome rate among the three phases.

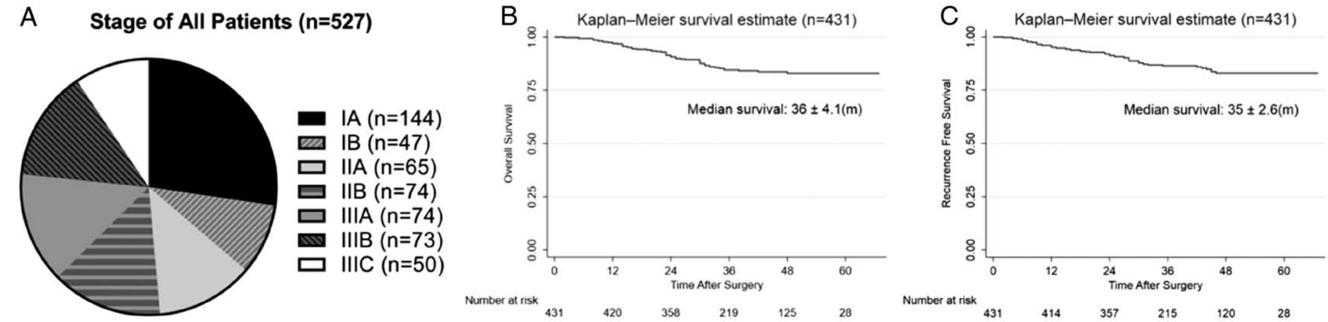

Figure 4. Cases of different stages in our study and long-term survival (96 cases were excluded from the survival analysis). A, Cases of different stages in our study ($n = 527$). B, Kaplan—Meier analysis of overall survival. C, Kaplan—Meier analysis of recurrence-free survival.

undergoing radical RG, the level of perioperative management may also improve, potentially leading to a decrease in the incidence of postoperative complications.

However, in this study, the decreases in the operation time and intraoperative bleeding were not significant, which may be related to the relaxation of surgical indications; for example, when radical RG was first performed, operators tended to choose patients with early-stage disease and perform simple procedures[17]. In contrast, with increasing surgical experience and improved surgical skills, the proportion of total gastrectomies increased significantly, and patients with more advanced cT stages were included. In addition, neoadjuvant chemotherapy for GC is now becoming a standard option in the perioperative period[48], and in the future, RG will probably be routinely performed in patients after neoadjuvant chemotherapy. However, most patients treated with neoadjuvant chemotherapy are in an advanced clinical stage and have tissue edema and fibrosis, all of which make surgery more difficult[49,50]. Our study also provides useful evidence for the rational application of robotic surgery in patients with GC after neoadjuvant chemotherapy in the future.

Performing thorough LN dissection and increasing the number of examined LNs during radical RG are important for accurately staging and improving the prognosis of GC patients[51–54]. However, there is controversy as to whether enhancing the learning curve of RG can increase the number of examined LNs. No learning curve-related trend in the number of examined LNs was found in the studies by Zhou and Kim *et al.*[17,18] Li was the first to propose that passing the break point of the learning curve can lead to a significant increase in the number of examined LNs[19]. In the present study, we found that although the total number of examined LNs in the three phases showed only a mild increasing trend, a two-by-two comparison showed that the number of examined LNs in extraperigastric regions was significantly higher in phase III than in phase I. In addition, we found for the first time a change in the learning curve-related LN noncompliance rate, and although the differences among the phases were not statistically significant, the decreasing trend observed is still of concern to surgeons. Interestingly, we also found a significant improvement in the escalation of the postoperative LN stage in phases II and III, suggesting that more thorough LN dissection by robotic surgery resulted in more accurate postoperative staging and reduced staging bias.

The use of a single factor to evaluate health services may not scientifically reflect the true level of health services[55]. Thus, it is more reasonable to use a combined definition of a TO to assess the outcomes of surgical treatment[56]. The original concept was introduced by the Dutch Upper Gastrointestinal Cancer Audit group[57]. Subsequent definitions of TO in clinical research have been largely adapted based on the unique characteristics of individual databases. Levy *et al.*[58] analyzed clinical data from patients registered in the Population Registry of Esophageal and Stomach Tumors in Ontario (PRESTO) between 2004 and 2015, establishing TO criteria specific to GC patients in PRESTO. In comparison to the initial TO definition, PRESTO TO omitted 'radical resection according to the surgeon at the end of surgery' and merged intraoperative and postoperative complications while retaining all other TO variables. Upon evaluating the PRESTO TO definition, we recognized its incorporation of crucial indicators for surgical quality control[39,58]. Given that our study's population consists of patients undergoing radical surgery, we adopted the PRESTO TO definition to assess patients' TO achievement rates in our research. We are the first to report an increase in the TO rate associated with learning curve phases in radical RG, with similar results in a population with cT stage 3–4 disease. Multivariable regression analysis confirmed stage elevation as an independent factor in achieving a TO.

There are still some limitations to this study. First, this was a single-center retrospective study, and some potential bias is still unavoidable. We would be grateful if another center could provide external validation data. Second, both operators involved in this study performed more than 300 laparoscopic radical GC surgeries, and beginners need to cautiously interpret the results. However, laparoscopic radical GC surgery is now widely accepted internationally[2], and most operators will usually already have extensive experience in laparoscopic surgery when they begin performing RG. Importantly, we suggest that even experienced laparoscopic surgeons focus on the learning curve and technical optimization when performing radical RG and select appropriate patients at the beginning of the learning curve. After gaining a certain level of experience, the transition to more difficult procedures can be made gradually. Third, the mean BMI of the patients in this study was 23.2; thus, the results may not be directly applicable to Western populations with higher BMIs. However, our optimized 10-step robotic lymphadenectomy procedure may be beneficial as a reference for new surgeons in the RG field, especially for surgeons in China, Japan, and Korea, where GC is highly prevalent. Fourthly, due to the limitation of follow-up time, this study did not further investigate the impact of the learning curve for RG on long-term outcomes such as quality of life, dysphagia, dumping, and survival. However, we hope that future studies will address this issue to further elucidate the benefits of radical RG for GC patients.

Conclusion

In this study, we established two important points in clinical practice (100 and 250 cases) by analyzing clinical data from 527 patients undergoing radical RG over 5 years. We found lower complication rates, faster postoperative recovery times, lower surgical costs, and higher TO rates as the surgical learning phase increased. In addition, our findings still require prospective validation with external data, especially in Western populations.

Ethical approval

This study passed the Institutional Review Board (IRB) of the FJMUUH (IRB number: 2023KY020).

Consent

The need for informed consent was waived due to the retro spective nature of the study.

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Author contribution

Z.X., J.L., C.-M.H., C.-H.Z.: conception/design; Z.X., J.L., J.L., K.-X.X., B.-b.X., D.W., H.-L.Z., J.-W.X., J.-B.W., J.-X.L., Q.-Y. C., P.L., C.-M.H., C.-H.Z.: collection and/or assembly of data; Z.X., J.L., J.L., K.-X.X., B.X., H.-L.Z., C.-M.H., C.-H.Z.; data analysis and interpretation; Z.X., J.L., B.-b.X., H.-L.Z., C.-M.H., C.-H.Z.: manuscript writing.

Conflicts of interest disclosure

All the authors declare that they have no potential commercial conflicts of interest relevant to this article.

Research registration unique identifying number (UIN)

1. Name of the registry: Clinical Trials.gov.
2. Unique identifying number or registration ID: NCT057 15775.
3. Hyperlink to your specific registration (must be publicly accessible and will be checked): https://www.clinicaltrials.gov/ct2/show/NCT05715775?cond=Learning+Curve+and+Optimization+of+Robotic+Gastrectomy&draw=2&rank=1.

Guarantor

Zheng CH had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. Zheng CH had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. De-identified data about the individual participants will be shared with researchers of further studies on reasonable request. Request for data sharing will be handled in line with the data access and sharing policy of Fujian Medical University Union Hospital.

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