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Identification and Categorization of Technical Errors and Hazard Zones of Robotic Versus Laparoscopic Total Gastrectomy for Gastric Cancer

A Single-center Prospective Randomized Controlled Study

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Objective: The current research aimed to conduct a detailed analysis of intraoperative surgical performance, short-term outcomes, identify and categorize technical errors, and hazard zones enacted during total gastrectomy performed robotically and laparoscopically by surgeons. Prospective research is needed to determine whether the technical advantages of robotic surgery translate to patient outcomes.

Background: At present, a growing number of clinical studies have demonstrated that the quality of intraoperative surgical performance has a direct impact on the clinical outcomes of the patient. The current research aimed to conduct a detailed analysis of intraoperative surgical performance and short-term outcomes, and identify and categorize technical errors, and hazard zones enacted during total gastrectomy performed robotically and laparoscopically by surgeons.

Methods: Eighty-two patients were recruited and participated in this study, with 40 cases undergoing RTG and 42 cases for LTG. Patients undergoing RTG and LTG were recruited and randomized into the study. Six consultant/attending surgeons participated in this study and all surgical procedures were recorded. The unedited surgical video recordings were handed over to third-party experts for granular analysis of the procedures using objective clinical human reliability analysis for the quality of intraoperative performance, technical errors, and intraoperative complications.

Results: The technical errors enacted and identified in the RTG and the LTG were 46.11 ± 5.63 versus 58.79 ± 8.45 ($P < 0.001$), respectively. The highest number of technical errors was identified during the dissection of the supra-pancreatic lymph nodes (task zone 3), including No. 5, 7, 8a, 9, 11p, and 12a to complete the nodal clearance around the celiac artery and its trifurcation (7.29 ± 1.88 vs 9.43 ± 2.24, $P < 0.001$) in both RTG and LTG. The number of lymph nodes harvested with RTG was higher than LTG (35.36 ± 7.51 vs 30.54 ± 6.95, $P = 0.016$), especially in the upper margin of the pancreas (13.32 ± 4.17 vs 9.36 ± 3.81, $P < 0.001$). The total cost of hospitalization in the RTG group is 3% more than the LTG group ($15953.41 ± 3533.91 vs $12198.26 ± 2761.27, $P < 0.001$).

Conclusions: This study offers compelling objective clinical human reliability analysis evidence demonstrating that RTG facilitates significantly superior technical performance compared with LTG. Whether examining short-term clinical outcomes or intraoperative operations, the robotic surgery system consistently outperforms laparoscopic surgery. Lymph node dissection in the supra-pancreatic region emerged as a major hazard zone in both procedures.

Key Words: gastric cancer, intraoperative errors, OC-HRA, robotic surgical procedure, surgical outcomes

(*Ann Surg* 2025;282:37–45)

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Y.Z. and Z.J.: conceived and designed the study. Z.J., S.C., and B.T.: drafted the manuscript. D.W., C.T., X.T., and S.L.: completed data acquisition, data management, and statistical analysis. C.T., X.L., Z.L., Y.T., and Z.N.: revised manuscript critically for important intellectual content.
Trial registration: chictr.org.cn: ChiCTR2000039193.
This study was funded by Shandong Provincial Natural Science Foundation, China (No. ZR202103040182); Natural Science Foundation of Shandong (ZR2023QH103). The National Natural Science Youth Foundation of China (No. 82103577).
The authors report no conflicts of interest.
Supplemental Digital Content is available for this article. Direct URL citations are provided in the HTML and PDF versions of this article on the journal's website, www.annalsofsurgery.com.

DOI: 10.1097/SLA.0000000000006585

Gastric cancer is the fifth most common malignant tumor and ranks third in tumor-related mortality.[1] In the past 20 years, operations of gastric cancer have gradually evolved from traditional open surgery to minimally invasive surgery.[2–4] Since Kitano et al[5] first reported the application of laparoscopic gastrectomy in patients with gastric cancer in 1994, laparoscopic surgery has been widely accepted by surgeons due to its minimally invasive advantages.

Although laparoscopy has many advantages, there are still some shortcomings including the visual constraints and mechanical difficulties. It also requires a different set of techniques, skills, and practice to master. Therefore, it is associated with a long learning curve and operation time.[6] The Da Vinci robotic surgery system as the first FDA (Food and Drug Administration) approved robotic surgical platform was introduced in 2000 and has promoted minimally invasive surgery to a new level. In 2002, Hashizume et al[7,8] performed the first gastrectomy for gastric cancer using the Da Vinci robotic surgical platform. The system has a real three-dimensional surgical field of vision, a 10-fold magnified visual lens, a stable instrument arm (with 7 degrees of freedom), and uses good ergonomic design principles. This reduces the discomfort, fatigue, and job burnout of surgeons.[9,10] The Da Vinci system is especially suitable for long-time surgery, breaks through the technical barriers of laparoscopic surgery, and has made great progress in clinical application.[9–14]

Numerous retrospective studies have demonstrated that robotic radical gastrectomy reduces blood loss, increases lymph node harvest, and decreases postoperative morbidity.[15–19] However, these benefits remained unconfirmed by randomized controlled trials (RCTs).[20,21] It could be argued that better technical execution is likely to be associated with improved patient outcomes in terms of long-term survival as reported studies have indicated that good technical execution of cancer operations accounts for 26% of the variation in patient outcomes.[22,23] It has also been shown that the objective and reliable measurement of intraoperative surgical skill in complex cancer interventions played a crucial role in the improvement of the quality of cancer surgery and was significantly associated with clinical and pathologic outcomes.[23,24] In view of the ongoing uncertainty on the benefits and technological performance of robot-assisted gastric cancer surgery for patients, the primary aims of this study were to: (1) determine whether robot-assisted total gastrectomy (RTG) or laparoscopic total gastrectomy (LTG) can provide the better intraoperative technical performance and (2) identify the most hazardous zone (area) during total gastrectomy (TG).

METHODS

Design and Patients

A single-center, prospective, randomized controlled study was conducted at the affiliated Hospital of Qingdao University from October 2020 to April 2023. The study was designed in accordance with the requirements of the Ministry of Health of China released Measures for the Ethical Review of Biomedical Research Involving Humans (For Trial Implementation) in 2007 and the applicable Chinese laws and regulations. The study was registered with ChineseClinicalTrialRegistry (registration number: ChiCTR2000039193). Ethical approval to conduct the study was obtained from the Ethics Committee of the affiliated Hospital of Qingdao University (ethics batch number: QYFYKYLL957311920). The study adhered to the ethical guidelines set forth by the advisory organization of the provincial health administrative department overseeing the research centre's province.

Patients who underwent radical resection of RTG and LTG were included in the study. Information on the nature of the study and recruitment process including randomization was provided and explained to the potential subjects of this study and written information was provided to the patients. Consent forms were signed off their own will based on their full understanding of this study. The signed informed consent forms were kept at the research centre where the forms were properly and safely kept for review at any time during audit and inspection.

These 2 types of surgery were performed as a consecutive series by the same group of experienced gastric cancer surgeons. The admission criteria for the study were as follows: (1) age of the patient was 18 to 80 years old, regardless of gender, (2) patients who underwent TG according to the fifth edition of Japanese guidelines for the treatment of gastric cancer, (3) patients with gastric adenocarcinoma diagnosed by endoscopic biopsy, (4) patients whose preoperative clinical stage was that cancer with ulcerative lesions surrounded by a tumorous bank and has grown through the stomach wall and into nearby organs or tissues (cT2-4a), cancer has not spread to nearby lymph nodes or has but no distant metastasis (N0/+), cancer no distant metastasis present [less than M0; adjusted according to the eighth edition of American Joint Council on Cancer staging system[25]], (5) patients with Karnofsky Performance Status score ≥ 60 or Eastern Cooperative Oncology Group score ≤ 2, (6) patients with the American Society of Anesthesiologists grade ≤ 3, and (7) the patients and their families signed informed consent. Exclusion criteria were as listed: (1) patients who had previously received gastrectomy, endoscopic mucosal resection, or endoscopic submucosal dissection of the digestive tract, (2) patients who developed other malignant diseases in the past 5 years, (3) patients with heart, lung, liver and kidney insufficiency or a history of cerebral infarction, (4) patients who required emergency operation because of complications of gastric cancer (bleeding, obstruction or perforation), (5) patients who planned to undergo minimally invasive surgery and eventually change from minimally invasive surgery to open surgery due to various factors, and (6) patients who had previous upper abdominal surgery (except for the history of laparoscopic cholecystectomy). Withdrawal criteria: (1) no evidence of distant metastasis was found before the operation, but patients with distant metastasis were confirmed by intraoperative exploration/postoperative pathologic examination, (2) patients who proved to be unable to complete D2 lymph node dissection/R0 resection due to tumor, (3) patients with other diseases who needed surgical treatment at the same time, and (4) patients who voluntarily requested to withdraw from this study or discontinue treatment due to personal reasons rather than clinical reasons.

The patients in both groups were managed according to the perioperative management of enhanced recovery after surgery[26] programs and all treatment measures were the same in both groups except for the surgical operative platforms of which either robot-assisted surgery or laparoscopic surgery was used.[20,21,26–28] The "random number table method" approach was used to randomly allocate patients into undergoing RTG and LTG. Initially, a total of 86 patients with gastric cancer were randomly assigned to the robot group and laparoscopy group (random number table method) in which 42 patients were included in the robot group and 44 patients were assigned in the laparoscopy group. The flowchart of this study is shown in Figure 1.

Surgical Procedure

All patients underwent contrast-enhanced computed tomography (CT) imaging before surgery, with surgical planning guided by a multidisciplinary treatment team consultation. During this meeting, imaging radiologists were consulted to assess and define the oncology staging based on the CT results. Surgical decisions were made by analyzing

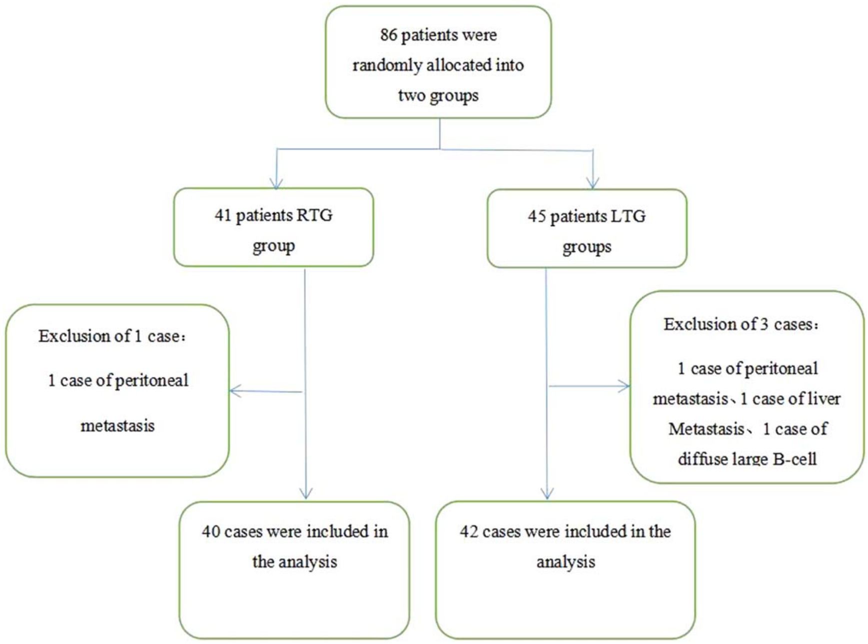

FIGURE 1. Flowchart of patient allocation.

the shape and variations of the perigastric artery using preoperative CT angiography.[28] To ensure accurate tumor staging, laparoscopic exploration of the entire abdomen was performed; if distant metastases were found, the patient was excluded from the study to ensure good quality control. Radical TG with D2 lymph node (LN) dissection was performed according to the fifth edition of Japanese guidelines for gastric cancer treatment.[29]

All surgeons involved in this study were highly experienced specialists, each having performed over 300 minimally invasive surgeries. To ensure consistent surgical quality, all robotic surgeries were conducted by the same expert surgeon, who has performed more than 300 RTGs. To define the definition and identification of various technical errors that could be enacted during the execution of both operations,[30,31] a Delphi consensus conference (DCC)[28] was carried out among 6 expert surgeons. The DCC achieved an inter-rater agreement for error description and task zones (TZs) of 85%. Both operations were divided into 8 TZs to identify the task with the highest errors committed by the surgeon. The TZs defined by the DCC experts were:

- Zone 1: Complete the separation of CO_2 pneumoperitoneum to greater omentum.
- Zone 2: No.4d/d and No.6 (i/a/v) LNs were harvested, and omentum and duodenal transection were separated.
- Zone 3: Clean No.7, No.8a, No.9, No.11p LNs.
- Zone 4: Clean No.5 and No.12a LNs.
- Zone 5: No.1, No.3 LNs and adipose tissue of the lesser curved side were removed.
- Zone 6: Clean No.19 and No.20 LNs.
- Zone 7: Clean No.2, No.4 (sa/b) LNs.
- Zone 8: Digestive tract reconstruction.

Definition and Data Collection

According to the standards of Japanese guidelines for the treatment of gastric cancer,[29] all patients were treated with radical gastrectomy for the purpose of cure, and thorough D2 lymph node dissection was performed and Roux-en-Y (functional end-to-end esophagojejunostomy or overlap) digestive reconstruction using a linear stapler under complete robotics or laparoscopy.[32]

The baseline case data are shown in Supplemental eTable 1 (Supplemental Digital Content eTable 1, http://links.lww.com/SLA/F346). Pathologic tumor staging was defined in accordance with the eighth American Joint Council on Cancer staging system.[25] The clinical data of the patients was prospectively collected in the database of our center, and the disease course records of the patients were strictly kept.

Objective clinical human reliability analysis (OC-HRA) data: OC-HRA has been a well-validated and established method to assess the quality of surgical technical performance as it has the ability to analyze the surgical procedures from the granular level of technical errors enacted during surgery.[30,31,33–38]

We adopted the validated and established method for error identification as described by Tang and colleagues (2004) in the OC-HRA framework. According to this method, any action or omission that resulted in a negative consequence or extended the duration of the surgical procedure by necessitating corrective measures and fell outside the "acceptable limits" was classified as a consequential error. In contrast, an action or omission that increased the likelihood of a negative consequence but did not directly lead to one—though it could have under slightly different circumstances—was categorized as an inconsequential error.

For the purposes of this study, the TG procedure was divided into 8 distinct TZs. A hazard zone was defined as a phase or TZ within the surgical procedure where technical errors are most likely to occur, characterized by a high frequency and severity, with potential adverse effects on patient outcomes. OC-HRA categorizes technical errors into 2 types: consequential errors requiring immediate corrective action (such as hemostasis for bleeding or repair

TABLE 1. Surgical Outcomes Postoperative Recovery in the RTG and LTG Groups

Variables	RTG (n = 40) Mean ± SD/N (%)	LTG (n = 42) Mean ± SD/N (%)	*P*
Surgical outcomes			
Total operative time (min)	235.93 ± 49.90	261.79 ± 65.28	0.102
The robot/laparoscope time (min)	199.75 ± 44.27	205.25 ± 66.01	0.716
The assisted time (min)	70.32 ± 7.85	59.93 ± 4.82	< 0.001
Estimated blood loss (mL)	47.50 ± 21.71	79.68 ± 19.66	< 0.001
Total examined LNs	35.36 ± 7.51	30.54 ± 6.95	0.016
Examined supra-pancreatic LN	13.32 ± 4.17	9.36 ± 3.81	< 0.001
Total metastatic LNs	3.57 ± 5.88	2.86 ± 3.65	0.587
Intraoperative transfusion	0	0	—
Positive resection margin	0	0	—
Open conversion	0	1 (3.6)	1.000
Postoperative recovery			
Amylase in drainage fluid (U/L)	312.84 ± 531.49	494.58 ± 441.79	0.042
Drainage on the first day after operation (mL)	117.50 ± 50.73	131.32 ± 91.29	0.487
Bowel function recovery (h)	73.93 ± 5.00	78.64 ± 9.16	0.020
First liquid diet after surgery (h)	77.93 ± 4.99	83.64 ± 9.16	0.005
Postoperative hospital stays (d)	8.63 ± 6.49	9.93 ± 3.55	0.357
Postoperative chemotherapy interval (d)	31.14 ± 5.79	38.55 ± 7.63	0.001
Unplanned reoperation	0	0	—
Unplanned readmission	0	0	—
Medical cost ($)	15953.41 ± 3533.91	12198.26 ± 2761.27	< 0.001

LTG indicates laparoscopic total gastrectomy; RTG, robot-assisted total gastrectomy.

of bowel injury), and near misses or inconsequential errors that do not immediately impact the operation's course or lead to evident complications. The errors were all recorded through unedited surgical videos. These data were statistically analyzed.

Intraoperative bleeding, especially minimal oozing occurred frequently in the present series of cases due to the impaired visualization of the operative field. A grading system for the bleeding episodes was developed and met the consensus of the expert surgeons as shown in Supplemental eTable 2 (Supplemental Digital Content eTable 2, http://links.lww.com/SLA/F346).

All video recordings were reviewed by a senior expert in gastrointestinal surgery and a member (D.W.) of the Hospital Quality Control Committee. Before the study, he completed 8 months of training in human factors engineering, an essential prerequisite for proficient OC-HRA use, under the guidance of an expert clinical scientist in OC-HRA (B.T.) from the University of Dundee. Thereafter, 10 videos of LTG and RTG were independently analyzed by him and the expert OC-HRA scientist. Interrater reliability between the two reviewers reached 87%. To ensure the accuracy of OC-HRA, assessments of video recordings, constant checks, and supervision were conducted by a Research Committee that consisted of an expert clinical scientist in OC-HRA and 6 expert surgeons.

Sample Size and Statistical Analysis

The calculation of sample size in this study is based on historical data and hypotheses, and 2 groups of independent sample rates are selected as noninferior tests. Referring to the results of previous studies, the incidence of postoperative complications in robotic and laparoscopic patients with gastric cancer was 12.75% and 13.62% respectively. According to the random proportion at 1:1, assuming that the significance level was $\alpha = 0.025$ and the test efficiency was $1\text{-}\beta = 80\%$, it was calculated that the total sample of this study needed 82 patients (RG group 41 cases, LG group 41 cases). The quantitative data of normal distribution was compared by *t* test, the quantitative data of non-normal distribution was compared by Mann-Whitney *U* test, the classified data were expressed by frequency and percentage, the disordered data were compared by χ^2 test or Fisher exact probability method, and the ordered data were compared by Mann-Whitney *U* test. All analyses were conducted using IBM SPSS Statistics26, and the statistical difference was set to $P < 0.05$.

RESULTS

Basic Characteristics

The basic characteristics of the patients in the 2 groups were included in Supplemental eTable 1 (Supplemental Digital Content 1, http://links.lww.com/SLA/F346). From October 2020 to April 2023, 82 patients were recruited and participated in this study. Forty cases underwent RTG, whereas 42 cases for LTG, which had matched baseline data. Following the strict admission criteria, a total of 86 patients were initially included in the study. One patient in the RTG group dropped out of the study due to peritoneal metastasis, thus, 40 patients were recruited in the RTG group. In the LTG group, 3 patients withdrew from the study: one due to peritoneal metastasis, another due to liver metastasis, and one due to diffuse large B-cell lymphoma, leaving a total of 42 patients in the LTG group.

Surgical Outcomes

The results of the operation are shown in Table 1. The difference in operation time between RTG and LTG was mainly reflected in the auxiliary operation time (70.32 ± 7.85 vs 59.93 ± 4.82 minutes, $P < 0.001$; establishment of Trocar, docking, and withdrawal of instrument arm, removal of specimens through an auxiliary small incision, examination of operation area, placement of drainage tube and other nonendoscopic operation steps). The estimated intraoperative blood loss in the RTG group was lower than that in the LTG group (47.50 ± 21.71 vs 79.68 ± 19.66 mL, $P < 0.001$), with a higher number of lymph nodes dissected (35.36 ± 7.51 vs

TABLE 2. Comparison of Errors Between RTG and LTG

Variable	RTG Mean ± SD	LTG Mean ± SD	P
Errors during operation			
Total no. of errors	46.11 ± 5.63	58.79 ± 8.45	< 0.001
Total no. of bleeding	12.61 ± 4.10	15.54 ± 4.32	0.019
Bleeding grade 1	5.50 ± 2.50	6.14 ± 2.40	0.237
Bleeding grade 2	6.21 ± 2.47	8.32 ± 2.74	0.008
Bleeding grade 3	0.89 ± 0.79	1.07 ± 0.90	0.470
Bleeding grade 4	—	—	—
Bleeding grade 5	—	—	—
Insufficient visualization (not fully exposed)	4.07 ± 2.00	6.14 ± 1.76	< 0.001
Lack of visualization of instrument tip	3.68 ± 1.47	4.25 ± 1.86	0.288
Instruments interfere with each other	1.71 ± 1.05	1.75 ± 1.01	0.913
Improper tumor handling (improper gripping of the tumor)	0.11 ± 0.32	0.07 ± 0.26	0.642
Cuts are made when not sufficiently exposed	0.46 ± 0.74	0.43 ± 0.79	0.687
Dissection on the wrong plane	1.57 ± 0.88	1.71 ± 0.98	0.383
Adverse events			
Lens cleaning	8.71 ± 3.00	11.71 ± 1.98	< 0.001
Tissue avulsion	1.14 ± 1.43	1.57 ± 1.79	0.499
Tissue slippage	2.71 ± 1.51	5.04 ± 1.04	< 0.001
Little traction	3.46 ± 1.88	5.39 ± 0.88	< 0.001
Excessive traction	3.68 ± 1.93	2.50 ± 1.93	0.028
Heat burns other tissues or organs	1.86 ± 1.15	2.11 ± 1.03	0.406
Blunt intestinal injury	0.07 ± 0.26	0.07 ± 0.26	1.000
Acute intestinal injury	0.25 ± 0.52	0.29 ± 0.66	0.991

LTG indicates laparoscopic total gastrectomy; RTG, robot-assisted total gastrectomy.

30.54 ± 6.95, $P = 0.016$), especially in the upper margin of the pancreas (13.32 ± 4.17 vs 9.36 ± 3.81, $P < 0.001$) within RTG. There was no significant difference in intraoperative blood transfusion, positive rate of incisal margin, and conversion to laparotomy between the two groups ($P > 0.05$).

Error Analysis and Distribution in the Various Task Zones

The total number of errors was lower in the RTG group compared with the LTG group (46.11 ± 5.63 vs 58.79 ± 8.45, $P < 0.001$), as was the total bleeding times (12.61 ± 4.10 vs 15.54 ± 4.32, $P = 0.019$), bleeding grade 2 (6.21 ± 2.47 vs 8.32 ± 2.74, $P = 0.008$), and insufficient visualization of the surgical field (4.07 ± 2.00 vs 6.14 ± 1.76, $P < 0.001$; Table 2). There were also significant differences in lens cleaning between the RTG group compared with LTG group (8.71 ± 3.00 vs 11.71 ± 1.98, $P < 0.001$), tissue slippage (2.71 ± 1.51 vs 5.04 ± 1.04, $P < 0.001$), too small traction (3.46 ± 1.88 vs 5.39 ± 0.88, $P < 0.001$) and excessive traction (3.68 ± 1.93 vs 2.50 ± 1.93, $P < 0.028$; Table 2).

TABLE 3. Number of Missteps in Each Step During RTG and LTG

Step	RTG Mean ± SD	LTG Mean ± SD	P
1	3.64 ± 1.13	4.93 ± 2.43	0.065
2	7.29 ± 1.88	9.43 ± 2.24	< 0.001
3	10.04 ± 1.64	13.46 ± 3.23	< 0.001
4	4.21 ± 1.66	4.75 ± 2.10	0.347
5	5.43 ± 1.40	6.18 ± 1.96	0.159
6	8.54 ± 2.50	12.36 ± 2.92	0.001
7	4.25 ± 1.76	5.21 ± 2.06	0.081
8	2.43 ± 1.14	2.54 ± 1.20	0.807
All	46.11 ± 5.63	58.79 ± 8.45	< 0.001

LTG indicates laparoscopic total gastrectomy; RTG, robot-assisted total gastrectomy.

Identification of Hazard Zone of Dissection During Robot-assisted Total Gastrectomy and Laparoscopic Total Gastrectomy

The comparison of the number of errors in each operation step between the two groups is shown in Table 3. There are significant differences between the two groups in steps 2, 3, 6, and 7. The highest number of technical errors was identified during TZ3, during the dissection of the supra-pancreatic lymph nodes (No. 5, 7, 8a, 9, 11p, and 12a) to achieve nodal clearance around the celiac artery and its trifurcation (7.29 ± 1.88 vs 9.43 ± 2.24, $P < 0.001$ in both RTG and LTG). Furthermore, this study meticulously documented specific operational errors in each step of both robotic and laparoscopic surgeries, presenting the frequency of different error types as a percentage in Table 4 and Supplemental eTable 3 (Supplemental Digital Content eTable 3, http://links.lww.com/SLA/F346). Notably, a higher incidence of consequential errors, particularly bleeding from small vessels, was observed during the dissection of subpyloric lymph nodes (TZ2; RTG:- 20.40% vs LTG: 20.23%), which was higher than other TZs, however, the errors rate in TZ2 was lower than in TZ3 (RTG: 21.25% vs LTG: 22.67%). Comparing errors occurring during TZ3 in LTG, surgeons made significantly fewer errors during RTG (10.04 ± 1.64 vs 13.46 ± 3.23, $P < 0.001$).

Intraoperative bleeding accounted for 50% of technical errors identified (Table 2), predominantly stemming from small blood vessels. Major venous injuries included the right gastric omentum vein, short gastric vein, and coronary vein. The primary cause of bleeding was due to insufficient visualization of the energy instrument tip during surgery, resulting in dissection in the wrong tissue plane. Arterial injuries during surgery were relatively low and caused by anatomic errors in the wrong tissue plane or insufficient field of view exposure. These errors were more common during LTG compared with RTG (6.14 ± 1.76 vs 4.07 ± 2.00, $P < 0.001$). In addition, one patient suffered liver damage due to spatial positioning errors when using double straight needles to suspend the liver during laparoscopic surgery for field-of-view exposure, a complication not encountered during RTG.

Short-term Surgical Outcomes

The postoperative recovery is shown in Table 1. The amylase in the abdominal drainage fluid of the RTG group was lower than that of the LTG group (312.84 ± 531.49 vs 494.58 ± 441.79 U/L, $P = 0.042$). The recovery time of postoperative intestinal function in the RTG group was lower compared with the LTG group (73.93 ± 5.00 vs 78.64 ± 9.16 h, $P = 0.02$), as well as the first fluid diet time (77.93 ± 4.99 vs 83.64 ± 9.16 h, $P = 0.005$), and a shorter interval time of adjuvant chemotherapy after the operation (31.14 ± 5.79 vs 38.55 ± 7.63 days, $P = 0.001$). There was no postoperative death in both the RTG group and the LTG

TABLE 4. Percentage of Intraoperative Errors in Each Step During RTG

	Intraoperative error(%)							
Variable	**TZ1**	**TZ2**	**TZ3**	**TZ4**	**TZ5**	**TZ6**	**TZ7**	**TZ8**
Errors during operation								
Total no. of errors	7.9	15.8	21.77	9.14	11.77	18.51	9.99	5.71
Total no. of bleeding	12.18	20.40	21.25	13.03	11.61	10.76	5.38	4.53
Bleeding grade 1	18.83	20.78	24.68	11.69	14.94	3.89	2.59	1.29
Bleeding grade 2	8.05	19.54	17.24	14.94	10.34	13.22	8.62	8.05
Bleeding grade 3	0	24.00	32.00	8.00	0	36.00	0	0
Bleeding grade 4	0	0	0	0	0	0	0	0
Bleeding grade 5	0	0	0	0	0	0	0	0
Insufficient visualization (not fully exposed)	7.02	24.56	16.67	7.02	10.53	20.18	9.65	4.39
Lack of visualization of instrument tip	1.94	1.94	14.56	0	28.16	37.86	14.56	0.97
Instruments interfere with each other	0	8.33	8.33	4.17	39.58	33.33	4.17	2.08
Improper tumor handling (improper gripping of the tumor)	0	66.67	0	0	0	33.33	0	0
Cutting was made with an electrical energy apparatus without lifting the surrounding tissue for a clear view	0	15.38	38.46	0	0	38.46	7.69	0
Dissection on the wrong plane	0	4.55	56.82	31.82	0	0	6.82	0
Adverse events								
Lens cleaning	8.61	12.30	20.90	7.79	9.02	14.75	15.98	10.66
Tissue avulsion	12.50	21.88	25.00	0	21.88	18.75	0	0
Tissue slippage	3.95	14.47	32.89	7.89	1.32	21.05	5.26	13.16
Little traction	4.12	15.46	28.87	8.25	6.19	23.71	5.15	8.25
Excessive traction	7.77	25.24	23.30	0	12.62	28.16	1.94	0.97
Heat burns other tissues or organs	9.62	3.85	11.54	30.77	3.85	13.46	26.92	0
Blunt intestinal injury	100	0	0	0	0	0	0	0
Acute intestinal injury	14.29	14.29	14.29	0	0	0	57.14	0

RTG indicates robot-assisted total gastrectomy; TZ, task zones.

group. In terms of medical expenses, the total cost of hospitalization in the RTG group was 3% more than the LTG group (15953.41 ± 3533.91 vs 12198.26 ± 2761.27 \$, $P < 0.001$).

Postoperative Complication

Supplemental eTable 4 (Supplemental Digital Content eTable 4, http://links.lww.com/SLA/F346) presents the details of postoperative complications, categorized according to the Clavien-Dindo grade system. The overall incidence of complications in the 2 groups was similar (17.5% vs 23.8%, $P = 0.477$). This study further compared the specific incidence of complications including anastomotic leakage, pneumonia, abdominal infection, intra-abdominal bleeding, gastrointestinal bleeding, pleural effusion, lymphatic fistula, pancreatic fistula, incision dehiscence and infection, and intestinal obstruction. There was no significant difference between RTG and LTG in the occurrence of the previous complications ($P > 0.05$).

DISCUSSION

This study represents the first prospective randomized controlled examination to meticulously analyze the quality of surgical performance in RTG compared with LTG. By focusing on the granular level of assessment, it addresses the ongoing debate regarding the advantages of robot-assisted versus laparoscopic surgeries. The primary objective was to objectively evaluate the resection quality of RTG and LTG procedures for gastric cancer. The study's findings confirmed the superior quality of surgical technical performance in RTG compared with LTG. Moreover, it has also provided detailed information about the technical errors enacted within a series of subtasks during the procedures. More importantly, the task of lymph node dissection of the supra-pancreatic region where the highest technical errors were enacted, has been identified as the major hazard zone in both RTG and LTG.

Our results also demonstrated a slight increase in cost associated with RTGs compared with LTGs although this was based on a single-center experience. However, with a well-established and efficiently managed robotic surgery service system, these costs can be minimized. Moreover, the benefit of better surgical technical performance and short-term surgical outcomes would justify the minimal increment of cost associated with RTGs. These findings hold significant implications for understanding the technical challenges encountered during complex TG. Notably, this is even more challenging with laparoscopic surgery, where a higher number of technical errors were identified and categorized compared with robot-assisted surgery. The robotic surgery platform offers distinct advantages in optimizing minimally invasive techniques, bridging the gaps in exposure limitations commonly encountered in laparoscopic procedures. This study provides a comprehensive analysis of technical errors in both laparoscopic and robotic surgeries, offering surgeons valuable insights into specific areas for skill enhancement and improvement from an alternative perspective.

The study has demonstrated that RTG provides a superior operating platform compared with laparoscopic surgery, aligning with existing clinical outcomes.[39–41] However, it is important to acknowledge that the long-term benefits of RTG, including survival rates, have not yet been fully understood or established.[20,21] To determine whether the superior technical execution observed with the robotic approach translates into improved 5-year cure rates and reduced locoregional recurrences, an RCT comparing the long-term survival outcomes between RTG and LTG for

TG is necessary. Such a study would provide definitive evidence regarding the potential advantages of RTG.

We are currently following up with both patient groups, acknowledging that it takes time to generate, collect, and analyze long-term outcome data, making this the focus of our future research. Meanwhile, our current study highlights the importance of objective and reliable assessments of intraoperative surgical skills in complex cancer procedures. Importantly, substantial variation in technical performance among credentialed surgeons has been reported, with this variability significantly associated with clinical and pathologic outcomes.[23] Better technical execution is likely to be associated with improved patient outcomes in terms of long-term survival. The high quality of intraoperative surgical performance also suggests the potential for significantly better long-term clinical outcomes. Therefore, the findings from this study hold substantial promise for the development of advanced feedback systems. Such systems could benefit both established surgeons and surgical trainees, offering valuable insights into the complexities of both LTG and RTG.

Surgery inherently carries risks, making it imperative to continuously seek ways to enhance safety. The concept of a "hazard zone" has been extensively studied and applied in high-risk industries like aviation and nuclear power plants. In these fields, extra care and essential measures are implemented to manage critical aspects of operations, as failure to do so could lead to catastrophic disasters. Only recently the concept of a surgical "hazard zone" has been developed and utilized to strive for optimal performance and improve quality and safety in surgical procedures,[34–37] it is an emerging area that has garnered the attention of the surgical community. The hazard zone of a surgical procedure was defined as the phase of the procedure where surgical technical errors are most likely to occur with high frequency and severe consequences with potential adverse effects on patients. To address these challenges, additional training or modified techniques should be considered to mitigate or ideally avoid technical errors within the hazard zone of a surgical procedure.[35–38]

In this study, we analyzed the quality of lymph node dissection in the RTG and LTG groups by assessing the number of retrieved lymph nodes and operational errors during the procedures, with a focus on superior pancreatic lymph node dissection along the abdominal aorta blood vessels. Our investigation revealed that intraoperative errors and adverse events were more likely to occur during lymph node dissection in the superior pancreatic area (TZ3) in the LTG group. This was largely attributed to challenges such as a limited visual field, challenging exposure to the operative area, complex vascular anatomy, and difficult lymph node dissection in the LTG group. Consequently, adverse events and intraoperative areas often occur here. In contrast, the number and severity of technical errors observed in all subtasks with RTG were significantly lower than those with LTG. However, the subtask of TZ3 of lymph node dissection in the supra-pancreatic region had the highest occurrence rate among the subtasks of RTG. As such, the superior pancreatic area (TZ3) emerged as a major hazard zone common to both RTG and LTG procedures. TG necessitates continuous lymph node dissection in various regions, a critical objective in radical resections for gastric cancer closely linked to long-term survival outcomes.[42] The data of our study offer surgeons a roadmap for taking additional precautions, seeking further training, or adopting improved techniques specifically when conducting lymph node dissection in this hazardous area during either RTG or LTG procedures. Therefore, identifying hazard zones and challenging phases not only enhances surgical performance but also holds value for surgical training and education, especially for surgeons who are new to or gaining experience in performing these procedures.

By achieving a better execution, robotic-assisted surgery enabled cancer surgeons to increase the probability of an R0 resection. Identification of TZs is important for the safe and optimal execution of major resections for cancer. In these potentially curative resections, the surgeon is the final link in the multidisciplinary treatment timeline that determines the patient outcome.[21–24] In essence, the surgeon's quality of the resection will determine the patient's long-term disease-free survival or the development of locoregional recurrence and, ultimately, cancer-related mortality within a few years.[21–24]

The successful collection and analysis of data from this prospective randomized clinical trial hold significant promise for advancing surgical education. We anticipate these data will provide valuable insights into the technical errors associated with TG, particularly in laparoscopic (LTG) and robotic (RTG) procedures. These insights are crucial for developing error-reduction systems based on objective information about the nature and mechanisms of these intraoperative errors. By identifying the types of errors and the specific phases or TZs where they are most likely to occur, this study aims to enhance the training of surgeons, especially those early in their experience, helping them avoid critical mistakes and thereby shortening the learning curve.

Incorporating advanced learning systems with proactive feedback mechanisms, focused on preventing rather than merely reacting to intraoperative complications, will be vital for improving surgical performance. Identifying hazard zones, such as those in the supra-pancreatic region, where anatomic challenges and limited accessibility increase the risk of errors, can serve as critical warnings for surgeons during both LTG and RTG procedures.

Furthermore, the data generated from this study could lay the groundwork for developing artificial intelligence (AI) and machine learning systems designed to master surgical operations, objectively assess performance, and improve outcomes in TG. Similar AI-based systems have already been successfully applied to other procedures, such as laparoscopic cholecystectomy,[43] and could represent the next significant step in surgical education and performance enhancement.

By integrating detailed subtasks, technical errors, and hazard zones into an algorithm, there is potential to create a sophisticated warning system tailored specifically for LTG and RTG. This system could automatically identify intraoperative errors and prompt timely, appropriate decisions. The adoption of an AI-based learning system would not only enhance surgeons' cognitive understanding and technical proficiency but also contribute to ensuring high-quality outcomes for patients undergoing these procedures.

This study has the following limitations: (1) This RCT trial was conducted from one center and the cases were performed by 6 well-established cancer surgeons. Therefore, these data may not fully represent the diverse spectrum of surgical practices, thus, there is still a need to design and conduct multicentre RCT studies. (2) Although this study suggested that RTG had better intraoperative performance, fewer surgical errors, and better short-term clinical outcomes compared with LTG, longer follow-up is needed to determine whether these results can translate into improvements in tumor prognosis to which the data is currently lacking. (3) Further validation is also needed to determine whether the relationship between intraoperative technical errors and complications presented in the hazard zones can serve as the foundation for robotic and laparoscopic surgery training to shorten the learning curve and achieve optimal surgical outcomes. (4) The OC-HRA used in this study belongs to the postsurgical evaluation system and cannot identify and correct any operative errors during surgery.

CONCLUSIONS

This study offers compelling OC-HRA evidence demonstrating that RTG facilitates significantly superior technical performance compared with LTG. Whether examining short-term clinical outcomes or intraoperative operations, the robotic surgery system consistently outperforms laparoscopic surgery. Lymph node dissection in the supra-pancreatic region emerged as a major hazard zone in both procedures, with surgeons exhibiting the highest technical error rate in this area. These findings underscore the advantages of RTG over LTG and highlight the importance of recognizing and addressing hazard zones in surgical procedures for optimal patient outcomes.

ACKNOWLEDGMENTS

The authors thank all the patients and their families as well as the research staff who assisted.

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